Exploring the application of qualitative and quantitative generic model structures in investigating dynamic complex phenomena: the case of rebound effects

Daniel Guzzo[1], Igor Czermainski de Oliveira[1], Daniela Pigosso[1]

[1] Technical University of Denmark

1 Abstract

The issues of repeatability, agility and reliability are critical predicates in model-based investigations through System Dynamics (SD). Generic model structures such as archetypes, canonical situational models, and molecules have been extensively used as a means to reach domain-specific insight (Eberlein and Hines 1996; Hines 1996; Kim and Anderson 2011; Lane and Smart 1996; Paich 1985; Senge et al. 1994; Wolstenholme 2004). Although the concept and application of generic model structures is fundamental to SD research and practice, there are still important gaps that prevents the community moving forward. First, it is unclear how the different types of generic structures complement each other in model building. Second, the potential uses of those structures into supporting more or less participatory modelling approaches have been insufficiently investigated and the potential synergies in using qualitative and quantitative generic model structures have been little investigated. Finally, apart from the molecules, the collections of generic model structures are still ad-hoc and unsystematic, with mostly personal libraries that hinder model reuse at large. In this study, three model-based investigation exercises are presented to explore different applications of qualitative and quantitative generic model structures in investigating a specific type of dynamic complex phenomenon – rebound effects (RE) in sustainability-oriented innovation. RE are systemic responses that offset the initial intentions of sustainability-oriented actions, hindering the achievement of the full potential of sustainable solutions (Guzzo et al. 2024; Hertwich 2005). RE are a fertile ground for examination through the SD lenses.

1) Archetype-based investigation of a problem domain

The purpose of this modelling exercise was to make use of a comprehensive set of archetypical structures of rebound mechanisms (Guzzo et al. 2024) to help in the conceptual modelling of rebound effects investigations in Circular Economy (CE) innovation patterns (Pieroni, McAloone, and Pigosso 2019). We specifically investigated the use of collaborative services through sharing platforms, leading to the identification of causal chains explaining: (1) the direct effects in resource consumption, (2) the network mechanisms that improve the utility of the service as more people join; and (3) rebound mechanisms that ultimately offset the potential sustainability gains of sharing platforms. This approach followed in this exercise can contribute to repeatability (as the archetypical structures of rebound mechanisms provide consistency to investigations); agility (as conceptual models can be reached more rapidly by building upon the set of structures); and reliability (as the archetypical structures for rebound mechanisms and CE innovation patterns are based on extensive literature review).

2) Using molecules to validate domain-specific archetypes

The purpose of this modelling exercise was to make use of the well-known set of molecules of structure (Eberlein and Hines 1996; Hines 1996; Hines et al. 2011) to test the validity of the archetypical structures representing rebound mechanisms (Guzzo et al. 2024). The exercise involved using the molecules of structure facilitated by the Assemblies feature available on Stella Architect™ to disaggregate one well-known rebound mechanism (i.e., income mechanism) into stock-flow structures that could help further explain it. We make explicit the process of identifying critical dynamics from the rebound mechanism and associating them to existing molecules until reaching an operational model capable of explaining the dynamics of the income rebound mechanism through quantitative analysis and automated structural analysis (i.e., Loops that Matter). The quantitative examination enabled to explain the dynamics of the income rebound mechanism and identify its magnitude in a stylised case. The structural analysis made explicit a hidden balancing feedback loop relevant to the mechanism under examination, and a similar approach could be used to investigate the rebound mechanisms as well as to investigate inter-mechanisms dynamics. This approach followed in this exercise can contributes to repeatability

and agility (due to the process developed to reaching operational models), and to reliability (due to building upon archetypical structures and molecules).

3) Developing case-specific investigations within a problem domain

The purpose of this modelling exercise was to pave the way for case-specific models for the investigation of the occurrence of rebound effects through the systematic use of generic structures. First, setting the scope of the investigation requires a critical analysis of the known causal mechanisms leading to rebound effects, which determine: (i.) the key sub-models for investigation, (ii.) critical dynamics for investigation, (iii.) existing models or literature that can explain those dynamics, and (iv.) the set of eligible molecules for model building. Following, the strategy to operationalise case-specific investigations requires dealing with the trade-offs between disaggregation and scalability, while making use of known but fundamentally different strategies of development of building block libraries to facilitate model building (Karl 2016) and the possibility of creating meta-models for more automated operational models (ElSawah, McLucas, and Ryan 2015). The possibility of a meta-model connecting the building blocks is included.

Finally, a comparative analysis show to which extent the three modelling exercises diverge into the breadth of investigation, case-specific insight potential, and theory building potential. Finally, four research avenues are presented to advance discussions about using generic model structures for enhanced repeatability, agility and reliability in model-based investigations through SD: (1.) open the still "silent and siloed use" of generic model structures, (2.) organise the uses and distil procedures to apply generic model structures, (3.) further develop paradigms for scalability and modelling automation based on generic model structures, and (4.) help dealing with the process of aggregation to reach explanatory insight from large models. Advancing the systematic use of qualitative and quantitative generic model structures to enhance the field's ability to provide domain-specific insight in an era with pressing needs for science-based decision-making.

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