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Developing a generic System Dynamics model for building stock transformation towards energy efficiency and low-carbon development

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According to the International Energy Agency (IEA), globally the annual rate of building energy intensity reduction needs to increase to at least 2.5% to keep buildings on track with the IEA's Sustainable Development Scenario. Achieving this ambition would require the expansion, strengthening and enforcement of mandatory building energy codes and standards, accelerated and scaled-up adoption of advanced technologies and best practices in new construction and retrofits, and enhanced access to finance to leverage the much-needed investments in sustainable buildings in the market. All these actions would require strong and specific policy measures that are well designed and implemented effectively.

Ex-ante evaluation is an integral part of designing policies. Modelling plays a key role in the evaluation process by allowing for the investigation of the trajectories of energy and emissions and enabling experimentation with potential policy interventions, therefore exploring possible pathways towards transformation to a highly energy efficient and low-carbon building sector. There are a range of modelling paradigms applicable to model building stock energy use, either from a top-down perspective or a bottom-up perspective. We focuse specifically on System Dynamics, a powerful modelling approach used in policy design and analysis, featuring a capacity to model and investigate dynamic complexities arising from the model structures, causal relationships, feedback loops, non-linearities and time lags of the system in question. Its emphasis on stock-and-flow dynamic relationships makes System Dynamics well placed to model building stock. The energy use of a building stock is determined by stock turnover dynamics, increased energy demand due to incoming new buildings that are more energy efficient, decreased energy demand due to removal of inefficient old buildings, and gains in energy savings through energy retrofits involving building envelopes and systems.

Previous System Dynamics models for stock-level building energy use share some common structural and behavioural characteristics with respect to building aging dynamics and energy-related retrofits. From a methodological perspective, these are, either explicitly or implicitly, based on assumptions that appear to be questionable or implausible in the real world. The common three-vintage structure pre-defines a fixed profile of building lifetime distribution that may be significantly different from reality. A related concern is that buildings within a vintage (a stock) are implicitly assumed to be subject to the same risk of being demolished regardless of their actual age and physical conditions. Although retrofits are a key measure to improve building energy efficiency, it is unrealistic to have a building undergo multiple rounds of retrofits within a short timeframe. Similarly, retrofitting a building soon after it is built, or demolishing a building soon after it is retrofitted, makes little economic or technological sense in the real world. Although these studies have begun to address some of the stock-flow dynamics in the building sector, the identified shortcomings call into question the robustness of the models, the resultant emergent behaviours of stock dynamics and energy performance, and the subsequent analysis of policies based on these models.

This paper presents an improved model to address these fundamental structural and behavioural limitations. The proposed model is generic and flexible, enabling adjustments to meet various requirements and settings. It can be extended to accommodate increased granularity and enhanced level of sophistication, or expanded boundary of modelling. Structurally, with available empirical data, the sub-stocks of retrofitted buildings can be further divided to model various lengths of the period between retrofits. Functionally, additional structures and variables can be added to the model to enhance its utility, such as feedback loops linking demolition and new construction to model future stock growth, embodied energy and carbon due to production of building materials, building construction, retrofit and demolition activities, stock of existing heating technologies and possible future trends of technology mix to model carbon emissions of heating. When building demolition is of less concern, e.g. buildings are generally long-lived and/or the period of modelling is short relative to building lifetime, the model can be straightforwardly reduced to a three-vintage or single stock structure as found in existing models. Similarly, the multiple retrofit option can be easily reduced to a single retrofit or no retrofit structure, but at the same time retains the ability of avoiding unrealistic modelling results of previous models. The reduced form version of the model will be useful when the interest of modelling is in general behavioural dynamic patterns of building stock and energy, rather than in detailed representation of model structures and variables for accurate numerical values of stock or sub-stock level performance indicators.

In summary, this generic model is well placed to be used as a stand-alone model or as part of a larger model for building stock energy use in various national or sectoral contexts. Its transparency and flexibility will enable further extensions and improvements in evaluating policy interventions targeting transforming buildings towards greater energy efficiency and low carbon development.

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