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Towards a multi-scale framework for modelling and improving the life cycle environmental performance of built stocks

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Abstract

Cities are complex sociotechnical systems, of which buildings and infrastructure assets (built stocks) constitute a critical part. As the main global users of primary energy and emitters of associated greenhouse gases, there is a need for the introduction of measures capable of enhancing the environmental performance of built stocks in cities and mitigating negative externalities such as pollution and greenhouse gas emissions. To date, most environmental modelling and assessment approaches are often fragmented across disciplines and limited in scope, failing to provide a comprehensive evaluation. These approaches tend to focus either on one scale relevant to a discipline (e.g. buildings, roads, parks) or particular environmental flows (e.g. energy, greenhouse emissions). Here we present a framework aimed at overcoming many of these limitations. By combining life cycle assessment and dynamic modelling using a nested systems theory, this framework provides a more holistic and integrated approach for modelling and improving the environmental performance of built stocks and their occupants, including embodied, operational, and mobility-related environmental flows, as well as cost, and carbon sequestration in materials and green infrastructure. This comprehensive approach enables a very detailed parametrisation that supports testing different policy scenarios at a material, element, building and neighbourhood level, and across different environmental flows. We test parts of our modelling framework on a proof-of-concept case study neighbourhood in Melbourne, Australia, demonstrating its breadth. The proposed modelling framework can enable an advanced assessment of built stocks, that enhances our capacity to improve the life cycle environmental performance of cities.

Keywords

Life cycle assessment; Urban metabolism; Material flow analysis; Buildings; Bottom-up; Industrial Ecology

1. Introduction

Cities are responsible for 56-78% of all anthropogenic energy use (Grubler et al., 2012) and associated greenhouse gas emissions (IPCC, 2014). In parallel, construction materials within cities represent more than 50% of all accumulated material stocks (Krausmann et al., 2017) and require significant amounts of embodied resources, such as water (Miller, Horvath, & Monteiro, 2018) . It is therefore critical to understand the resource flows and environmental effects resulting from constructing, maintaining and operating buildings and infrastructure assets (built stock) to address the challenges of climate change and finite resources (IPCC, 2018) (Wiedmann et al., 2015).

Current approaches for quantifying environmental effects associated with cities are typically fragmented, discipline-based (e.g. engineering) and focus on one particular life cycle stage (e.g. the 'use' phase for operational energy efficiency) or scale of the built environment (e.g. building scale) (Ramaswami et al., 2018) (details of this fragmentation are provided in Section 2). Models and studies that try to address these shortcomings typically fail to resolve all of them. Life cycle assessment studies which have quantified the environmental flows across the different life cycle stages of a city tend not to adopt a multi-scalar approach, often focusing on the building scale alone and ignoring environmental effects occurring across scales (e.g. for mobility or infrastructure) (Chastas, Theodosiou, & Bikas, 2016; Chau, Leung, & Ng, 2015; Cole, 2020; Dixit, 2017). They also tend to underestimate embodied environmental flows due to methodological limitations, i.e. flows associated with the production of construction materials (see Crawford *et al.,* 2018). In their review of life cycle assessment studies applied at a city scale, Lotteau, Loubet, Pousse, Dufrasnes, and Sonnemann (2015) identified only 18 studies, of which very few rely on a bottom-up approach that enables results to be disaggregated. Simultaneously, studies focusing on material flows and built stock modelling (*inter alia* Muller, Hilty, Widmer, Schluep, and Faulstich (2014), Kleemann, Lederer, Rechberger, and Fellner (2016) and Wiedenhofer, Steinberger, Eisenmenger, and Haas (2015)) often leave associated embodied flows (i.e. environmental flows associated with the production, installation, and maintenance and replacement of construction materials) out of scope. In a review of studies on the life cycle assessment of built stocks, Mastrucci, Marvuglia, Leopold, and Benetto (2017), identify that there is a need for more detailed bottom-up studies that rely on dynamic stock models and integration with geographical information systems. As cities are dynamic systems, capturing their constantly evolving nature is paramount to evaluating and improving their environmental performance. However, very few studies rely on dynamic models to simulate a range of future scenarios for cities (Ramaswami et al., 2018).

A number of prominent researchers in the field have called for more holistic frameworks that better capture the complexity of urban systems (Acuto, Parnell, & Seto, 2018; Ramaswami et al., 2018), and transformational climate actions across all systems, sectors, levels and scales (Hurlimann, Moosavi, & Browne, 2021). Currently, there is a notable gap when it comes to models that can quantify environmental flows across spatial, temporal and procedural boundaries.

We propose a framework that enables a comprehensive modelling and assessment of the environmental performance of the built environment within cities that seeks to capture the environmental flows across the various boundaries aforementioned. This paper presents the theoretical basis of the modelling framework and its required scope and functionalities. We demonstrate the broad scope of the modelling framework and its relevance to multiple stakeholders and sectors of the built environment, including architects, engineers, urban designers, landscape architects, planners, building owners, managers and occupants, and city councils.

2. Limitations of current approaches

Existing studies and approaches for quantifying the environmental performance of the built environment are usually compartmentalised and tend to focus on one scale of the built environment (e.g. buildings) or one life cycle stage (e.g. occupancy).

At the building scale, environmental performance has typically been associated with operational energy efficiency, driven by building regulations such as the Energy Performance of Buildings Directive (European Parliament and the Council of the European Union, 2002). The need to incorporate additional environmental flows (e.g. greenhouse gas emissions and water) as well as different life cycle stages has been demonstrated by studies adopting a more holistic life cycle approach (see Blengini and Di Carlo (2010), Stephan, Crawford, and de Myttenaere (2013)). The number of studies on the life cycle environmental performance of buildings has been increasing rapidly over the last decade as evidenced by recent review papers (Cabeza, Rincón, Vilariño, Pérez, & Castell, 2014; Chastas et al., 2016; Chau et al., 2015; Dixit, 2017)). However, existing studies on the life cycle environmental performance of buildings typically suffer from two main shortcomings. Firstly, most of the studies rely on the so-called 'process analysis' technique to compile the life cycle inventory, significantly underestimating embodied environmental flows (Crawford et al., 2018; Islam, Ponnambalam, & Lam, 2016; Majeau-Bettez, Strømman, & Hertwich, 2011; Suh et al., 2004; Treloar, 1997)). Secondly, existing studies tend to focus solely on the building scale, failing to incorporate environmental effects occurring at larger scales of the built environment, such as the embodied environmental flows of infrastructure or those associated with the mobility of occupants. Seminal work by Stephan and colleagues across geographic regions has demonstrated the significance of including these aspects (Stephan & Crawford, 2014a; Stephan, Crawford, & de Myttenaere, 2012; Stephan et al., 2013; Stephan & Stephan, 2014, 2016).

At the neighbourhood and city level, environmental performance is usually assessed using either material flow analysis and building stock modelling (see Hu et al. (2010), Marcellus-Zamora, Gallagher, Spatari, and Tanikawa (2016), Tanikawa, Fishman, Okuoka, and Sugimoto (2015) and Tanikawa and Hashimoto (2009)), urban metabolism (see *inter alia* Kennedy, Pincetl, and Bunje (2011) and Zhang (2013)), or more recently urban energy analysis (Keirstead, Jennings, & Sivakumar, 2012), urban building energy analysis (Reinhart & Cerezo Davila, 2016) and life cycle assessment (Lotteau et al., 2015). A critical limitation of these approaches, with the exception of urban building energy analysis and some life cycle assessment studies (Mastrucci et al., 2017), is the very limited use of a bottom-up approach which typically uses detailed information about small scale systems (e.g. materials and construction assemblies) and builds the model from this level up. That means that average top-down values are typically used to model entire building stocks within a neighbourhood (e.g. an average amount of steel per square metre of office building). This approach is often beneficial for rapid and large-scale assessments and requires less data and information about individual buildings. It can provide estimations of city-wide, nation-wide, or even continent-wide (see Peled and Fishman (2021), who use night time satellite imagery to estimate the material stock of Europe) material intensities and flows over space (and potentially time), which can be enough to inform policy making. Similarly, Sartori, Sandberg, and Brattebø (2016) and Sandberg, Sartori, Vestrum, and Brattebø (2016) develop dynamic building stock models using average floor areas and construction and demolition activities to study the evolution of energy use in the Norwegian built stock. However, top-down approaches do not enable a more refined characterisation of environmental flows at smaller scales. This is particularly true for stock models which do not integrate enough information on the quality of materials, their location, quantities and their evolution through time (Lanau et al., 2019). Another limitation is the lack of integration across models. In their review of urban energy systems, Keirstead et al. (2012) identify that almost no model quantifies embodied energy, demonstrating the lack of integration of life cycle assessment into these models. Similarly, the review by Lotteau et al. (2015) reveals the lack of integration of material stock modelling into life cycle assessment studies of neighbourhoods. While Resch and Andresen (2018) propose a consistent database model to account for embodied greenhouse gas emissions of buildings and neighbourhoods, they do not take into account different built assets, nor operational and transport flows. Resch, Andresen, Cherubini, and Brattebø (2021) improve that model to account for emissions reduction over time, adding a dynamic modelling approach to recurrent embodied greenhouse gas emissions and end-of-life greenhouse gas emissions, which is laudable, but also does not consider operational nor mobility-related flow. To this date, only a few studies have attempted to combine top-down and bottom-up approaches, for example urban metabolism and life cycle assessment (Goldstein, Birkved, Quitzau, & Hauschild, 2013), or material stock and flow modelling and life cycle assessment (Lausselet, Urrego, Resch, & Brattebø, 2021; Stephan & Athanassiadis, 2017, 2018).

In light of the above, there is a need for a more comprehensive life cycle environmental assessment modelling framework that is applicable across, and capable of assessing, different scales of the built environment, at a high data resolution. Without such a framework, decisions based on partial information can simply shift environmental effects to a different life cycle stage or scale of the built environment (Stephan et al., 2013). This contributes to addressing the challenge of combining a detailed and comprehensive assessment, as clearly flagged by leading academics in socio-metabolic research:

> *"A high level of detail in evaluating technologies and production processes or identifying potentially critical materials, though, is often at odds with capturing system-wide effects such as resource availability, rebound effects or problem shifting related to substitution, lock-in (legacies), leakage or rebound effects" (Haberl et al., 2019).*

At a higher level of abstraction, existing approaches to environmental assessment often cater for single disciplines and there is currently no modelling framework that enables a joint-approach that can be used across multiple disciplinary groups. This is needed to blur disciplinary boundaries and address the interdisciplinary challenges inherent in improving the environmental performance of the built environment.

3. A comprehensive framework for modelling and assessing the environmental performance of the built environment

Designing an approach to capture and quantify environmental flows across multiple scales of the built environment through time requires the combination of different theoretical frameworks. The framework we propose combines nested systems theory, life cycle assessment and dynamic modelling (shown in Figure 1).

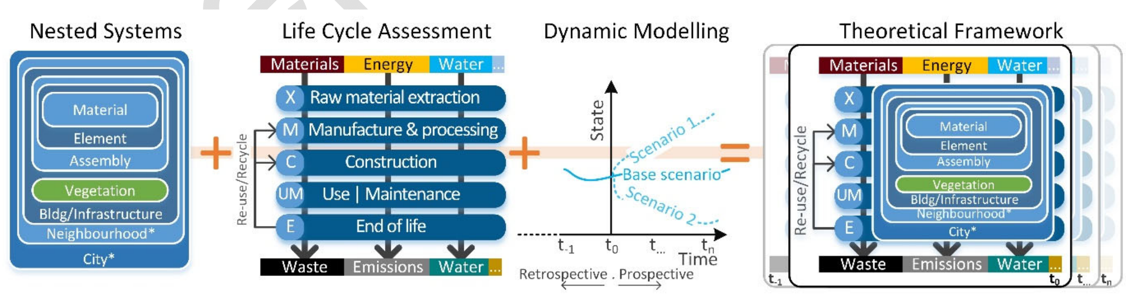

Figure 1: Theoretical basis of the proposed environmental assessment framework, combing nested systems theory, life cycle assessment and dynamic modelling frameworks to enable a comprehensive coverage of environmental flows.

Nested Systems Theory: The nested systems theory (Walloth, 2016) studies interactions between systems (a complex entity that processes inputs, outputs and internal flows) contained within each other, such as buildings within neighbourhoods within a city, or systems containing sub-systems, as an example, a wall containing different construction materials. This theory has been proposed for urban systems which are nested by nature and is therefore ideal to model built stocks and vegetation in the built environment. By providing the theoretical framing to replicate the nested organisation of urban systems, the nested systems theory enables us to capture their interactions with greater accuracy. This nested approach is used to devise the architecture of the modelling framework (see Section 3.1).

Life Cycle Assessment Framework: The life cycle assessment framework for buildings is used in conjunction with the nested systems theory to quantify the environmental flows of a building or infrastructure asset at different stages of its life cycle, in line with the European Standard 15978 (2011). Life cycle assessment is an internationally established and standardised tool for quantifying the environmental flows associated with any good or service, in this case the built stocks in cities. It involves the compilation of an inventory that covers all the resource inputs, and outputs of waste and pollutants for a product, across the different stages of its life cycle. The life cycle assessment framework can also be used to quantify life cycle financial flows for buildings, as documented in the International Standard 15686-5 (2017). By covering the multiple life cycle stages of each nested system, the life cycle assessment framework adds the temporal dimension and provides an established and rigorous approach for quantifying environmental and financial flows across the built environment.

Dynamic Assessment Framework: The dynamic assessment framework is superimposed with the nested systems theory and the life cycle assessment framework to enable more robust prospective assessments by considering the potential and likely changes to parameters over time. Since built stocks are the most durable goods that humanity produces, with some buildings still in use millennia after construction, trying to capture the dynamic (and uncertain) evolution of their environmental performance over time is important. Dynamic assessment uses scenarios to model potential evolutions of parameters over time, based on realistic assumptions and past observations. This enables the exploration of varied futures and can support decision-making under uncertainty. This retrospective and prospective modelling capacity is explained in more detail in Section 4.10.

The combination of nested systems theory, the life cycle assessment framework and the dynamic assessment framework, provides a theoretical basis that supports the goal and scope of the proposed assessment framework. The resulting theoretical framework is used as a basis for the development of a bottom-up decision-making modelling framework to inform the design of new and retrofitting of existing built stocks, for an improved environmental performance of the built environment.

3.1. Developing a decision-making framework for the built environment

The theoretical framework described above can be used as the basis of a functional modelling framework for stakeholders of the built environment to inform their decision-making processes in order to improve the overall life cycle environmental performance of built assets. The aim of this modelling framework would be to provide a single, consistent, holistic, transparent and transposable calculation engine for assessing and improving the life cycle environmental performance of the built environment, across multiple scales, through time and for multiple stakeholders. The modelling framework can be implemented into a 'software' or web-based interactive platform allowing usability for different stakeholders. Further, through this web-based platform, the software would provide discipline-specific interfaces, which form part of a common calculation engine. This will help reduce the compartmentalisation of environmental assessment and provide a more rigorous approach across disciplines and stakeholders, facilitating more rapid and effective exchange of information. An inter-disciplinary approach is critical considering the complex interactions between all elements of the built and natural environments. This would assist each discipline to ensure their decisions and designs result in net improvements to life cycle environmental performance. Further discussion of the target audience of the modelling framework and its potential uses is provided in Section 6.

This modelling framework will enable architects, engineers, landscape architects, urban designers, planners and city councils to work together to design better buildings, infrastructure and cities, optimising and balancing environmental performance across the many lifecycle stages, scales of the built environment, and over time (Hürlimann et al., 2021). Figure 2 provides an overview of potential uses of the modelling framework by different disciplines and demonstrates their interconnectedness across the different scales of the built environment.

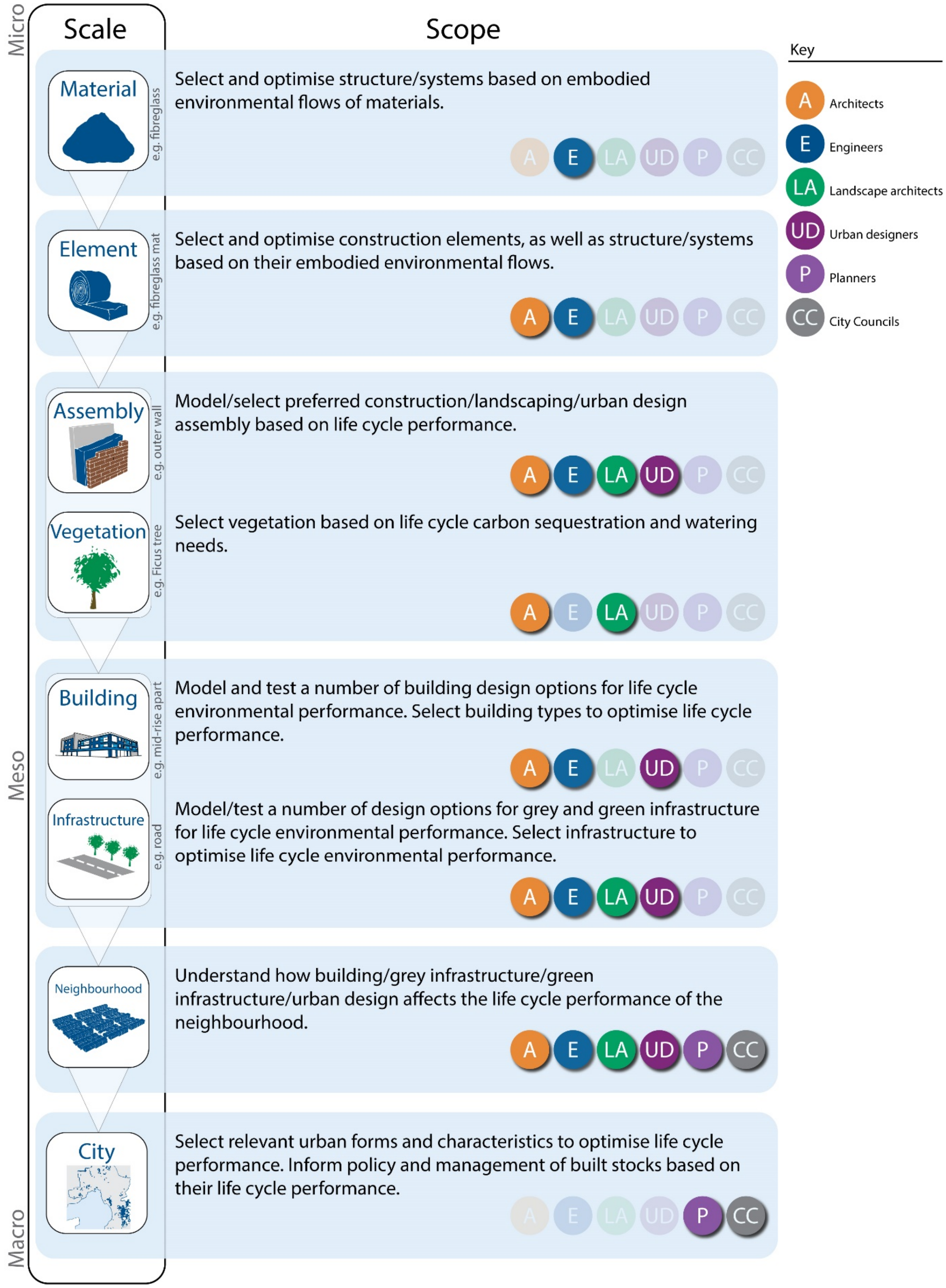

Figure 2: List of uses for the decision-making modelling framework, by scale and disciplinary stakeholders of the built environment

As depicted in Figure 2, a spectrum of scales is considered: from materials and elements (defined as finished products, e.g. an aluminium window frame is an element, while powder-coated aluminium is a material), assemblies which are groups of materials or elements (including vegetation as natural assemblies) at the micro scale, to buildings and infrastructures at the meso scale, and finally the combination of these units in the neighbourhood or city at the macro scale.

The scope of the proposed modelling framework is depicted in Figure 3 and includes modelling environmental flows associated with raw material extraction, material manufacture and processing, construction, operation and maintenance and the end-of-life of built stocks. Carbon sequestration in timber-based building materials is also taken into account as it can significantly affect the greenhouse gas emissions balance of a building (Churkina et al., 2020; Head, Levasseur, Beauregard, & Margni, 2020). Material flows required for building and infrastructure construction and demolition, as well as for maintenance and replacement are included, along with material stocks as these represent the bulk of the material footprint of a city (Athanassiadis, 2016; Stephan & Athanassiadis, 2017). Environmental flows associated with the mobility of dwellers are also included at the larger scales (neighbourhood and cities) to account for the context, as advocated by Steemers (2003) Stephan et al. (2012), Stephan and Crawford (2014a, 2014b), Bastos, Batterman, and Freire (2015) and Lausselet, Ellingsen, Strømman, and Brattebø (2019). Financial flows associated with the purchase of construction materials, construction, and ongoing operation and maintenance are also taken into account to facilitate decision making, following International Standard 15686-5 (2017). The change in land value due to development is also considered to enable more realistic decisions, as the residual land value is highly dependent upon the highest and best utilisation of the land. We deem it critical to include a financial evaluation to take into account the real-world feasibility of potential solutions.

In terms of life cycle stages, this modelling framework also includes re-use and recycling following European Standard 15978 (2011) and further development of these attributes. The proposed modelling framework takes into account the important role of green infrastructure and nature-based solutions in regulating environmental flows in cities (Baró & Gómez-Baggethun, 2017; Moosavi, Browne, & Bush, 2021) by capturing the flows linked to growing and maintaining urban trees, notably the sequestration of greenhouse gas emissions as carbon, and water requirements. Assessments relying on life cycle thinking in the area of urban green infrastructure have been deemed scarce by Petit-Boix et al. (2017). The authors find that parks, street trees, lawns and urban forests have received less attention than other green infrastructure types (e.g. nature-based water infrastructure) in terms of carbon sequestration. In a study by Strohbach, Arnold, and Haase (2012) the authors show that approximately 10 trees per ha in urban parks would potentially offset the emissions from construction and maintenance of the park after 50 years. Similarly, Birge and Berger (2019) show that 3-10 trees, and up to 6,116 trees are required to offset the remaining greenhouse gas emissions of a net zero operational energy villa (including user mobility) and a standard villa in Abu Dhabi, respectively. The comprehensiveness of this modelling framework helps ensure that decisions made to improve environmental performance at one life cycle stage or scale of the built environment result in net overall benefits, rather than inadvertently reducing performance in other areas.

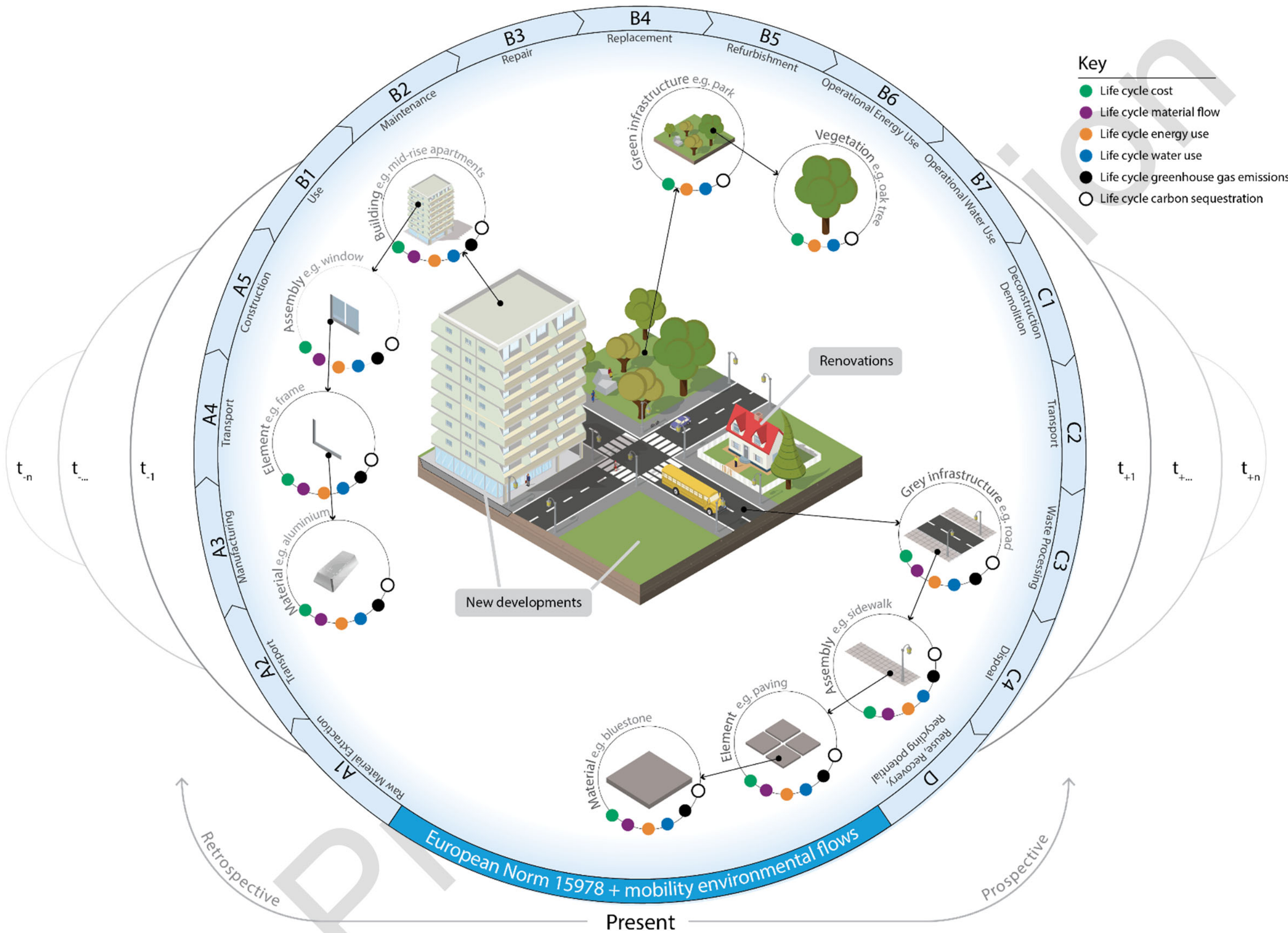

Figure 3: Scope of the decision-making modelling framework for multi-scale environmental assessment of the built environment

The modelling framework relies on two core approaches to support the features and scope outlined in Figure 3, namely object-oriented programming and comprehensive algorithms for quantifying environmental and financial flows.

Object-oriented programming (Lutz, 2013) defines objects, i.e. a data structure comprising variables or *attributes* and dedicated functions or *methods*, which can be used to perform specific actions (Alic, Omanovic, & Giedrimas, 2016; Lutz, 2013). For instance, an *Assembly* object would include attributes such as:

- assembly type, for example 'outer wall';
- functional unit, for example 'm^2'; and
- list of nested components with their quantities, for example 'Concrete panel – 1m^2', 'Fibreglass insulation – 0.1 m^3', 'Waterproof barrier – 1 m^2', 'Bricks 100mm thick – 0.9m^2', 'Mortar – 0.01m^3'.

This *Assembly* object would also include dedicated methods such as *get_embodied_flows* or *get_weight*. This type of architecture provides the required flexibility and modularity to develop the functionalities required. It enables nesting objects within each other, where a nested object or a list of nested objects simply become attributes of the parent object, and allows relevant methods to be added to each object. A *building* object can have a method named *get_architects_attributes,* which retrieves a list of building attributes specified by architects and links them to associated environmental and financial performance outcomes. Another benefit of object-oriented programming is the modularity that the code offers. Additional objects (e.g. *tunnel*), attributes (e.g. *periodic table of elements* for a *material)* and methods (e.g. *get_rare_metals*) can be added over time with minimal change to the code. This provides ample opportunities for extending the modelling framework in the future. The modelling framework could be implemented in the open-source language Python (Python Software Foundation, 2019), a general purpose language that enables a wide range of tasks through its use of libraries, such as *pandas* (Augspurger et al., 2017) for data analysis.

Comprehensive methods and algorithms for quantifying environmental and financial flows are the other core characteristic of this modelling framework. This is critical to ensure a broad coverage of the studied nested systems across space, time and environmental flows. These algorithms are described in detail in the Modelling Methods section below. Essentially, the algorithms cover the entire supply chains that support the production of construction materials, the construction and maintenance of a building or infrastructure asset, its operation, and urban mobility. Carbon sequestration in green infrastructure is also taken into account, which helps with decisions on creating appropriate spaces for trees in the public realm and plant type selections with regards to their CO_2 sequestration capability and potential other attributes. In parallel, financial costs are quantified comprehensively using the Net Present Value technique, capturing capital, maintenance and recurring costs over time and discounting them to their current value. The Methods section details the parametrisation of the modelling framework.

It is important to highlight the significant uncertainty present in the proposed modelling framework. The modelling framework relies on data that varies in reliability and availability. In addition, the temporal evolution of parameters represents an increased uncertainty in the modelling framework as predicting the future is speculative at best (Brown, 2004). The modelling framework incorporates interval analysis and what-if scenarios to explore the temporal evolutions, which are detailed in Sections 4.9 and 4.10, respectively. These were chosen based on the uncertainty matrix of Brown (2004) and its interpretation by Refsgaard, van der Sluijs, Højberg, and Vanrolleghem (2007).

4. Modelling methods

This section provides the main equations and methods used to quantify material stocks and flows, as well as embodied, operational and transport flows, carbon sequestration, life cycle cost and valuation, and uncertainty estimates. All equations are provided in Appendix A: Mathematical Formulations.

4.1. Material stocks and flows

Material stocks and flows are calculated based on the geometry of a building or infrastructure as well as the assemblies used (an assembly is an assemblage of different materials that serves a particular function in a building, such as an 'outer wall'). Each assembly comprises elements and/or materials as well as specific quantities of each, e.g., one square metre of outer wall can contain 0.3 m^3 of cellulose fibre insulation. The quantity of each assembly in a building/infrastructure is generated using a simplified geometrical model, in this instance the amount of outer walls in m^2 is obtained by multiplying the perimeter by the floor-to-ceiling height. The quantities of elements and materials in a building/infrastructure (their inventory or stock) are derived from the quantities of assemblies. Throughout a specified period of analysis, elements and assemblies are replaced based on average useful lives or element/assembly survival curves. This replacement results in additional material flows, which are quantified using the same approach. This quantification approach has been tested successfully in Stephan and Athanassiadis (2017, 2018). At a neighbourhood and city scale, the rate and quantity of construction and demolition is set using previous trends as a baseline. Other scenarios can be modelled to reflect the multiple potential futures of a built stock and inform decision-making. The re-use and recycling of materials and elements can be modelled in new buildings and infrastructure. This is based on the type of material and its remaining service life (based on years in service and anticipated condition at the time of re-use/recycling). The dynamic nature of material flows, through replacement, re-use or recycling is therefore captured in the modelling framework.

4.2. Embodied environmental flows

Embodied environmental flows are quantified using a hybrid life cycle assessment approach that combines bottom-up process data on material production, collected from industries, with top-down macroeconomic input-output data that provides average environmental effects for a sector of the economy (Crawford et al., 2018). The hybridisation of process and input-output data is performed using the Path Exchange hybrid analysis (PXC) technique developed by Treloar (1997) and validated by Crawford (2008). Using hybrid data ensures that the entire supply chain of a product, in this case built environment objects, is taken into account. Using the PXC hybrid approach ensures that embodied environmental flows are not underestimated, as is usually the case in existing models that rely solely on process data, which has been shown to lead to system boundary truncation (Manfred Lenzen, 2000; Majeau-Bettez et al., 2011; Suh et al., 2004).

The modelling framework uses so-called hybrid coefficients for construction materials that represent the amount of energy, water, and greenhouse gas emissions embodied in their production from cradle-to-gate (stages A1-A3 in the European Standard 15978 (2011)). These are compiled using a semi-automated modelling framework for hybridisation, described in Stephan, Crawford, and Bontinck (2018). The first database of hybrid coefficients, produced using this semi-automated approach, is the recent EPiC database of embodied environmental flows (Crawford, Stephan, & Prideaux, 2019). Both the initial embodied flows of a building and infrastructure, as built, and the recurrent embodied flows (associated with material replacement over time (stage B4 in the European Standard 15978 (2011))) are quantified. In addition, carbon sequestration in timber-based materials is also taken into account using models developed by Head et al. (2020). It is important to mention that the value of these coefficients can be modified through time based on technological changes. This is captured in the mathematical formulation below and described in Section 4.10.

Embodied flows associated with a building are calculated as per Equation 1 by iterating over assemblies, over their nested elements and their nested materials, and in turn, multiplying the material quantities by the relevant hybrid coefficient. This equation is valid for any embodied flow, by consistently using relevant indicators throughout, e.g. for embodied energy, using energy-related indicators in GJ. The embodied flows associated with the transport of materials to site (A4), the construction activity (A5) and all other non-material related expenditures are added using pure input-output data. This approach is also used to quantify life cycle environmental flows for infrastructure. It is important to note the dynamic nature of this assessment that is a function of the year during which a building is constructed, and a material replaced. Practically, data of hybrid coefficients and input-output environmental satellite will almost never be available for each year of a period of analysis. For retrospective analyses, the closest datasets matching quality requirements might be used. For prospective analyses, the hybrid coefficients and the input-output data will be corrected based on dynamic modelling through scenarios, as described in Section 4.10.

4.3. Operational environmental flows

Operational energy and GHG emissions associated with heating, cooling, ventilation, hot water, lighting, appliances and cooking are also included. Energy use and emissions for heating and cooling are computed using existing and verified models, such as Energy Plus, by connecting the modelling framework directly to these simulation engines. This avoids duplication and relies on trusted software in the field. Heating and cooling flows are quantified for each building and summed for built stocks in neighbourhoods and cities. These energy balance model will be streamlined and simplified, using standardised schedules based on the building archetype when assessing an entire built stock. This will improve runtime. If electricity bills or energy usage data are available, these could be used to validate the chosen archetypal definition, or be used to override simulation results, although the parametrisation will be lost.

Non-thermal operational energy and GHG emissions are based on the type of building, its occupancy pattern, number of appliances and systems as well as power ratings. Similarly, Operational water is modelled based on the built asset type, occupancy pattern, number of water fixtures and systems, and water requirements for green infrastructure. Equation 2 describes how non-thermal operational energy and operational water are calculated.

Parametrising operational energy and GHG emissions allows the user to control individual parameters and evaluate their effects. All operational energy use is expressed in final, delivered and primary energy terms. The latter encompasses all losses in the energy supply chain and is therefore critical in determining GHG emissions. These Scope 2 emissions are quantified by multiplying primary energy use by relevant emissions factors based on the energy sources used. Considering the greenhouse gas emissions associated with the electricity grid is critical to evaluate the net zero life cycle greenhouse gas emissions potential of a building, as demonstrated by Martinopoulos (2020) and Stephan and Stephan (2020) A long-term climatic modelling framework evaluates the global warming potential of these GHG emissions into the future based on the date of their emission, as illustrated by Kendall (2009).

Modelling operational flows differs according to the scale of assessment. When evaluating a building, a more detailed modelling framework is appropriate to make decisions. However, at the neighbourhood and city scales, the thermal energy use of built stocks can be modelled using static thermodynamic equations to significantly reduce the runtime of the modelling framework. This approach works well in heating-dominated climates (Reinhart & Cerezo Davila, 2016). These static equations are applied on a building and infrastructure level and take into account their specific geometry and embedded systems.

The life cycle operational energy or water flows of a built asset are obtained as per Equation 3 by iterating over the end-uses within the building and multiplying their power/water ratings by their operating time, taking into account upstream losses. This quantity is multiplied by the period of analysis when a constant demand is assumed. Different scenarios can be modelled due to the dynamic nature of the modelling framework, as described below. The same approach is used to model green infrastructure assets.

Note that operational greenhouse gas emissions are calculated based on energy use, by multiplying primary energy use by relevant greenhouse gas emissions factors in $kgCO_2e/GJ^{Primary}$. (e.g. from Therefore, non-energy-related operational greenhouse gas emissions are not taken into account in the framework, as these are assumed to be insignificant. Importantly, non-energy-related embodied greenhouse gas emissions, which are associated with specific chemical processes and can be significant for particular materials, are taken into account. End-of-life emissions associated with bio-based materials, life cycle stage C in European Standard 15978 (2011), are also taken into account.

4.4. User-transport flows associated with the mobility of residents

The user-transport flows associated with the mobility of residents is considered at a neighbourhood or city level, as advocated by a number of authors (Bastos et al., 2015; Lotteau et al., 2015; Rickwood, Glazebrook, & Searle, 2008; Steemers, 2003). Transport flows are quantified by multiplying the average annual travel distance per occupant by the environmental intensity of the relevant transport mode, for each occupant in the household and each transport mode they use, as per Equation 3.

Covering both direct and indirect transport environmental flows is essential to ensure a more holistic environmental assessment. Transport results in significant indirect environmental flows as demonstrated in a number of studies (Chester & Horvath, 2009; Jonson, 2007; M. Lenzen, 1999; Stephan & Crawford, 2016). Indirect transport environmental flows range from energy and water use for car manufacturing, registration, insurance and servicing, to embodied environmental flows associated with manufacturing tramways, train wagons, and bikes, as well as for the operation of public transport services (e.g. printing, advertising, etc.).

It is important to flag that user-transport environmental flows will be modelled dynamically, as detailed in Section 4.10. This means that the evolution of key parameters, *inter alia* distance travelled, modal split, technological efficiency, and electricity mix, will be modelled using scenario making, enabling the consideration of potential changes in mobility.

4.5. Carbon sequestration in vegetation and green infrastructure

Carbon sequestration in vegetation and green infrastructure is taken into account to ensure that the capacity of green infrastructures to act as carbon sinks (or potential emitters) in the built environment is considered when designing a neighbourhood (Strohbach et al., 2012). This is calculated based on the tree species, age, and the climate, using the method developed by the U.S. Department of Energy (1998). For instance, the carbon sequestrated in a park is equal to the sum of the carbon sequestrated in all its trees and its soil, as per Equation 4. At this stage, the modelling framework only accounts for carbon sequestration in the soil and in trees that are planted in public (i.e. in parks, alongside roads, in nature strips, etc.) and private properties (i.e. gardens), but this can be later extended to account for the carbon cycle associated with other types of plants such as understorey plants, land covers and shrubs. The benefits of trees for sequestrating carbon remain conditional upon a variety of contextual factors including irrigation sources and methods, water quality, and appropriateness of selected tree species (Birge, Mandhan, Qiu, & Berger, 2019). For example, depending on the context, there may be a conflict between the benefits of carbon sequestration and water-energy requirements for implementation and maintenance, which might counterbalance their greenhouse gas emissions reduction capacity. Similarly, the levels of carbon sequestration can be very different across types of soils and climates as demonstrated in Pouyat, Yesilonis, and Nowak (2006), Velasco, Roth, Norford, and Molina (2016) and Lindén, Riikonen, Setälä, and Yli-Pelkonen (2020). As such, land-use changes in urban developments can alter the carbon sequestration potential of soils (sometimes turning them into net emitters) and significantly affect the greenhouse gas emissions balance of a development. Accounting for such relationships is just one example of the holistic nature and potential of this proposed modelling framework.

The sequestrated carbon could also be converted to a negative global warming potential, expressed in kgCO_2e, that can be combined with the life cycle greenhouse gas emissions to obtain a net balance. Eventually, green infrastructure assets have the potential to contribute to 'climate positive' developments after a certain period of time, by sequestrating more carbon dioxide equivalent than embodied and operational greenhouse gas emissions. Recent tools such as the *Climate Positive Design Pathfinder* (https://climatepositivedesign.com/pathfinder/), are providing guidance for designers in this regard.

4.6. Life cycle cost

The life cycle cost associated with the construction, replacement of materials and operation of a building (including mobility costs) is included in the modelling framework (see Equation 5). This comprises a combination of one-off costs and ongoing annual costs. One-off costs are typically in the form of the construction costs at the development stage, and the occurrence of singular costs throughout the life of the built asset to replace its elements. Other one-off costs include the cost of private transport modes (e.g. car and bike), the cost of appliances (e.g. dishwasher, television, etc.) and their replacement over time. Ongoing costs are annual operational costs involved with running the building and include those associated with energy and water use, and management and maintenance of the built asset. In order to understand the financial magnitude of a project, a cash flow modelling framework is used to examine the built asset costs over its life-time. The cost of the built asset is then quantified using the net present value technique (Berk & DeMarzo, 2010) to provide a total cost in present day current terms (e.g. EUR2021). The modelling framework uses a bottom-up approach to costing by assigning individual costs for construction materials, elements, assemblies, appliances, trades, and private transport modes; then looks at the recurrent annual costs for fuel, electricity, management and maintenance, public transport and other relevant items. These costs are then inputted to a cash flow modelling framework over the life-period of the built asset on an annual basis; the costs are then summed on an annual basis and as they are initially calculated at current prices, an inflation factor is utilised to estimate future costs for each expenditure. These inflation figures will be based on data from World bank. To provide a current understanding of the actual life cycle cost of the building in today's euros, the cash flows are then discounted back to a Net Present value as per Equation 5. The net present value technique for life cycle costing has been widely used in the built environment and for financial modelling of building and infrastructure assets, for example see Robinson (1989), Pyhrr, Roulac, and Born (1999), Morrissey and Horne (2011), Leckner and Zmeureanu (2011), and French (2013).

Estimating life cycle cost into the future, as well as the current value of existing built assets, is a very uncertain exercise. In terms of prospective life cycle costing, there is significant uncertainty in the values of the inflation index, which can be different for the construction sector, and the discount rate. Similarly, the residual value of building elements that are being dismantled in the future is very hard to estimate. In Equation 5, we make the choice of considering the residual value as zero, as elements are replaced at the end of their service lives, as shown in Stephan and Stephan (2016). In practice, this is certainly not true, notably in a circular economy paradigm, where elements could be re-used, repurposed, or recycled (Adams, Osmani, Thorpe, & Thornback, 2017). This is however outside the scope of this work and constitutes future research. Similarly, the current value of existing built assets is very hard to quantify and is excluded for buildings with construction years that are too far in the past (e.g. more than 40 years, depending on the study). What is the value of a 500-year-old mill in a European city? From a heritage perspective, the value is often unquantifiable and is related to range of cultural aspects, including craftmanship (Kohler & Hassler, 2002), but purely from a material, perspective, it may not be very high. We acknowledge this as a limitation of the model, but also as a current frontier in our ability to ascertain the value of built stocks from different perspectives.

4.7. Value of the land

Apart from the cost of items themselves, the integrated modelling framework captures the value of the land through the residual land valuation approach. The calculation is highly dependent upon the current or proposed development type, for prospective greenfield or brownfield developments. For the purposes of the modelling framework, it uses the concepts of a static modified residual land valuation approach. This approach estimates the underlying present value of the land based on its future use which is integrated into the overall modelling framework.

The estimation of the residual value for the land is based on its productive capacity or its utility value. The use value of the site is dependent on present and future uses, physical characteristics and economic considerations, within the legal context and driven by the local market (Brigham, 1965). The residual land value is calculated by estimating the value of the project upon completion, deducting development costs and associated interest, land holding costs and interest charges, and the profit of developers (Harvard, 2008). While this is a simplified approach to land valuation, it is utilised and accepted by the valuation profession to assess the value of developable land, globally. The residual land value is calculated as per Equation 6 (Wyatt, 2013).

4.8. Neighbourhood and city level aggregation

Assessments at the neighbourhood and city level consist of summing the individual environmental and financial flows of all constituting buildings and infrastructure assets. This is what Mastrucci et al. (2017) define as the 'building-by-building' approach in their review.

4.9. Uncertainty

Uncertainty in the data is one of the major limitations of parametric models relying on multiple variables. This often stems from data gaps, which can be further exacerbated when compiling inventories for such a complex modelling framework, or from uncertainty in existing data. Yet, this uncertainty should be seen as an intrinsic component of any modelling framework (Le Moigne, 1999) rather than a limitation. This condition is therefore addressed by the modelling framework and propagated throughout all algorithms to allow more resilient decisions. Interval analysis (Moore, Kearfott, & Cloud, 2009) is used to model parameter uncertainty. This simple approach consists of specifying a minimum and maximum value to a parameter. In the absence of statistical data on the uncertainty distribution of every parameter considered, it is the preferred approach. For instance, the probability distribution associated with the embodied water of timber is currently unknown. A solution to this problem can be found in using interval analysis which accounts for known boundary values. One of the advantages of relying on interval analysis in an object-oriented modelling framework is the ability to modify how uncertainty is modelled in future iterations and to enrich the modelling framework as stochastic information on uncertainty becomes available. The use of interval analysis is already a significant improvement over most existing building-related life cycle assessment models, such as the one used in the Athena Institute Impact Estimator (ATHENA, 2019). This is complemented by the ability to override calculations or specific values in the modelling framework if these are known, for example when post-occupancy data is available. In this case, the modelling framework integrates measured and simulated data, reducing uncertainty when more reliable or relevant data is available.

Practically, and based on our previous experience in the life cycle assessment and material flow analysis of built stocks, the level of uncertainty will vary depending on the type of variables in the model and the level of information available to characterise them. Uncertainty on hybrid embodied environmental flow coefficients is around ±40%, as reported in Crawford (2011). Uncertainty on operational energy use at a household level can be extremely high, as demonstrated by Gram-Hanssen (2010). At a more aggregated scale, ranges of ±20% are usually adopted in existing studies, e.g. Pettersen (1994) and Stephan and Crawford (2014b). User-transport related flows can be assumed to suffer from a similar level of uncertainty (±20%) , although studies have demonstrated that the mobility patterns of individuals can be highly predictable (Gonzalez, Hidalgo, & Barabasi, 2008; Song, Qu, Blumm, & Barabási, 2010). The amount of materials in a given building or built asset can vary widely based on the archetypal resolution used to describe buildings or assets (Lanau et al., 2019). In the approach adopted here, where bills of material quantities are estimated dynamically, based on the geometry of the floorplan, previous research has found deviations of 5-35% for residential buildings on average, depending on the assembly type modelled (Stephan, 2013). Financial indicators, such as costs, inflation rates and discount rates suffer from a high level of uncertainty over time. Aggregating these high levels of uncertainty reveals that the absolute values of indicators calculated with the framework is very high (~>±40%). However, when comparing different scenarios using the model, and given that most scenarios suffer from the same sources of uncertainty, most of that uncertainty can be eliminated in the comparison, which enables the identification of building and infrastructure designs and planning that result in net environmental improvements.

4.10. Dynamic modelling

The dynamic nature of the modelling framework is one of its most advanced features. It enables the temporal evolution of parameters to be modelled over the period of analysis, while capturing the flow-on effects of this evolution across all linked parameters. This is done by using matrix calculations, which include the values of variables for each year. The evolution scenarios can be defined using either interpolation between set values of a parameter at particular years, or by manually specifying values over periods of time. This enables the modelling framework to answer multiple policy and 'what-if' questions, significantly improving its prospective assessment power. For example, the modelling framework is able to answer questions such as 'what are the life cycle implications of replacing all single-glazed windows in every building in a city with double glazing?'; 'what is the embodied energy versus operational energy savings trade-off of insulating all roofs of all buildings in the city to a specified level?'; 'what are the environmental effects associated with replacing a major artery in the city, compared to renovating it?;' or 'what are the life cycle environmental and cost implications of developing a greenfield site at the edge of the city compared to demolishing old low-rise buildings and building medium-rise apartments in the city?''

It is important to flag that at this stage of development, we propose to model dynamic evolutions as percentage variations of current data, rather than as variations to processes and technological evolutions within an integrated hybrid life cycle inventory as this would be out of scope of this project and would further induce uncertainty in the model regarding modelling assumptions. Where possible, we propose to use a more refined prospective modelling, for example by modelling specifically future greenhouse gas emissions associated with electricity production (see examples below on embodied environmental flows and transport modes). Equation 7 is a generic equation describing how a variable would be dynamically modelled.

For prospective assessments, life cycle embodied environmental flows will be modelled by varying the main inventory data, such as the electricity mix, over time. This is possible through the extremely disaggregated data from the EPiC database (Crawford et al., 2019), which conserves all the individual pathways for each material. An aggregated indicator for the electricity mix will be developed for each material and this will be varied over time to reflect some of the potential improvements to embodied environmental performance. The environmental flow intensity of input-output sectors will be modelled similarly, by modifying the environmental intensity of electricity-related sectors over time in the calculation of the input-output remainder. For example, modelling the dynamic evolution of the electric grid and its influence on the embodied environmental flow coefficient of a material *m* will be performed as per Equation 8.

For retrospective assessments, it is extremely hard to accurately model the embodied environmental flows of old materials in a built stock as inventory data is almost inexistent. If life cycle inventory data is available, embodied environmental flow coefficients for a year closer to the construction year could be used. However, given that older coefficients relied on data with a lower resolution and a higher uncertainty, it is unclear if using them would provide a more robust assessment. In this case, standardised scenarios will be developed, based on calculating embodied environmental flows as it would be today and modifying it by a factor (e.g. +20% for buildings up to 25 years old). Initial results from our longitudinal study of hybrid embodied environmental flows coefficient for construction materials in Australia (Crawford & Stephan, 2020; Lara Allande, Stephan, & Crawford, 2020) demonstrate a ~28% decrease in embodied energy intensities of covered construction materials, between 1996 and 2019. However, this figure is just indicative and a lot more research is needed in this area to be able to inform more robust modelling.

The evolution of future user-transport related variables will also be modelled prospectively using 'what-if' scenarios. These variables, such as the modal split, the direct energy intensity of a car per vehicle-kilometre, the direct energy intensity of a tramway per passenger-kilometre, the greenhouse gas emissions intensity of the electricity grid to power electric trains, and others, will be modelled using matrices with annual values, as described above (through interpolation or manual input). This will enable the model to consider potentially significant variations of these parameters over time. Equation 9 describes how tramway-related transport greenhouse gas emissions are calculated dynamically, for an occupant.

In addition, all datasets used will document the assumptions made, and will be made publicly accessible in order to improve data availability and transparency (Hertwich et al., 2018). Further discussion on the applicability and usefulness of the dynamic modelling approach is provided in Section 6.

4.11. Integration with geographic information systems

The model will be linked to geographic information systems (GIS) to enable both inputs from GIS databases and the visualisation of results on maps (e.g. Stephan and Athanassiadis (2017) or Lanau and Liu (2020)). This is a critical feature that tends to be systematically called for in recent reviews in the field of material stock modelling and life cycle assessment at the urban scale, *inter alia* Mastrucci et al. (2017) and Lanau et al. (2019).

Integration with GIS enables the model to capitalise on a myriad of information in terms of material stock modelling, notably building footprints shapefiles, potential three-dimensional geometry, building typologies, infrastructure length and layout, and other fundamental data that are the basis of modelling built stocks. Similarly, this integration can enable the representation of relevant indicators directly on the map, such as life cycle environmental flows, material stocks, and other relevant quantities.

4.12. Data availability

The modelling framework is currently being implemented and will be made available in the future on its dedicated website: www.nestedphoenix.com. Links to all publications and data sources will also be available on the website. Relevant parts of the code will also be made available through an open repository, linked to the website.

The data related to the proof-of-concept case study is available in open-access on Figshare[1].

5. Proof-of-concept case study

A proof of concept case-study located in Melbourne, Australia is used to demonstrate the feasibility of the proposed modelling framework. As its name suggests, the proof-of-concept does not encompass all the different facets of the modelling framework, but rather covers those indicated in Table 1.

Table 1: Aspects of the modelling framework covered in the proof-of-concept case study

Aspect of the modelling framework	Covered in proof-of-concept
Material stocks and flows	✓
Embodied environmental flows	✓
Operational environmental flows	✓
User-transport flows associated with the mobility of residents	✓

[1] https://www.doi.org/10.6084/m9.figshare.16899553

Carbon sequestration in vegetation in green infrastructure	✓
Life cycle cost	
Value of the land	
Neighbourhood and city level aggregation	✓
Uncertainty	
Dynamic modelling	✓
Integration with geographic information systems	

The proof-of-concept case study is a small residential neighbourhood (11 200 m² surface area) recently built on the fringes of Melbourne, Australia. It consists of a rectangular park of 3 600 m² surrounded by streets with 21 town houses, 3 detached houses, and an apartment building. In addition to the park, the lawns of the residential buildings represent 965 m². A total of 40 eucalyptus trees are planted in the park and the lawns, of which 36 survive at 50 years and are taken into account in the carbon sequestration calculations. The total impervious surface is 6 635 m². The neighbourhood houses 139 persons in total. The residents use electric cars and tramways for their mobility. All embodied environmental flows calculations are based on the EPiC database (Crawford et al., 2019). The general characteristics of the residential buildings are summarised in Table 2. In addition to the residential buildings, the neighbourhood comprises 340 m of paved roads (2 720 m² in total) alongside standard piping and cable infrastructure for water distribution, sewage and power. For the more information about the data used in the proof-of-concept case study and associated calculations, please download the supplementary information (see Section 4.12).

Table 2: Characteristics of the residential buildings composing the proof-of-concept neighbourhood

Characteristics	Detached houses	One-storey Row houses	Two-storeys Row houses	Apartment building
Period of analysis (years)	50 years			
Building useful life (years)	>50 years (no demolition)			
Number of houses in the neighbourhood	3	8	13	1
Number of storeys	1	1	2	7
Gross floor area (m²)	230	204	195	2268
Number of occupants	4	3	3	56
Structure	Timber-framed			Reinforced concrete
Façade	Brick veneer wall – 80 mm of fibreglass insulation - Double glazed aluminium framed windows			Precast concrete bearing walls – 80 mm of fibreglass insulation - Double glazed aluminium framed windows

Roof	Concrete tiles – 160 mm of fibreglass insulation	Flat concrete slab with 160 EPS insulation
Finishes	Medium standard finishes	
Average *U*-value ($W/(m^2K)$)	0.60	
Average air renewal rate (ach^{-1})	0.5	
Operational energy sources	Gas heating (eff. 0.7) and cooking (eff. 0.9); Electrical cooling (eff. 2.5); Solar domestic hot water (solar fraction 0.75) with gas auxiliary system (eff. 0.9).	
Primary energy conversion factors ($GJ^{PRIMARY}/GJ^{DELIVERED}$)	Electricity: 3.4[a] (Use of wet brown coal in Victoria, Australia) Gas: 1.4[a]	
Greenhouse gas emissions factor ($kgCO_2e/GJ^{PRIMARY}$)	93.11[b]	
Average annual car travel distance per capita (km/a)	9 949[c]	
Average occupancy rate of cars	1.6[d]	
Direct energy intensity of electric cars (MJ/pkm)	3.6[e]	
Indirect energy intensity of electric cars (MJ/pkm	1.406[f]	
Average annual tramway travel distance per capita (km/a)	2 218[c]	
Direct energy intensity of tramways (MJ/pkm	0.368[f]	
Indirect energy intensity of tramways (MJ/pkm)	0.67[f]	

Note: eff. represents the efficiency of the end-use system. The solar fraction represents the fraction of hot water energy demand supplied by the solar system. Delivered energy figures (converted to primary energy terms) are used for lighting and appliances because no information is available about the efficiency of the devices used. All average figures for operational energy consumption are derived from DEWHA (2008). Sources: [a] from Crawford, Bartak, Stephan, and Jensen (2016), [b] from Australian Energy Institute (2014), [c] based on figures for Melbourne from Department of Transport (2021), [d] from BITRE (2009), [e] assumed based on average efficiency of current electric cars, and [f] based on M. Lenzen (1999).

The life cycle material flows and greenhouse gas emissions over 50 years are presented in this paper. We take into account initial and recurrent embodied greenhouse gas emissions, operational greenhouse gas emissions, mobility-related greenhouse gas emissions, biogenic carbon sequestrated in timber products, biogenic carbon sequestrated in trees in the park and lawns, and greenhouse gas emissions associated to land-use changes from grassland to parkland, lawns and impervious surfaces. We also model a reduction of the primary energy conversion factor for electricity by 60% over 50 years (down to 1.36), of the GHG emissions factor for electricity by 80% over 50 years (18.6

$kgCO_2e/GJ^{PRIMARY}$) and a bulk reduction of embodied greenhouse gas emissions by 10% every 10 years, over 50 years.

Results of this proof-of-concept study are visualised in the dashboard presented in *Figure 4*, representing the distribution of total life cycle greenhouse gas emissions over 50 years with fixed values over time, the material stock distribution by material, and line plots representing the evolution of the life cycle greenhouse gas emissions when the primary energy conversion factor for electricity and its emissions factor are reduced over time, along with embodied greenhouse gas emissions intensities.

Figure 4 clearly demonstrates the breadth of the modelling framework and enables comparing indicators as varied as greenhouse gas emissions due to land-use changes, the recurrent embodied greenhouse gas emissions of paint, the cooking-related greenhouse gas emissions that are wasted due to inefficiencies in the energy supply chain and the contribution of a particular building to the total life cycle greenhouse gas emissions over 50 year. The material stock, e.g. the amount of glass available in the neighbourhood, and the dynamic evolution of greenhouse gas emissions following a scenario of climate change mitigation are also displayed. Within the proof-of-concept case study, it is important to note the significant greenhouse gas emissions that are wasted due to inefficiencies in energy conversion processes, such as electricity generation (14 Million $kgCO_2e$). This amount alone is more than 1.5 times the life cycle embodied greenhouse gas emissions. Importantly, greenhouse gas emissions associated to land-use changes, to biogenic carbon and to carbon sequestration were very small (<2% of the total). This is due to the significant greenhouse gas emissions intensity of the current economy, to the relatively small number of trees on site (40 in total) and to the limited amount of timber used in the buildings (~300 m^3). Due to the limitations in terms of space, the results of this proof-of-concept are not explored in further detail.

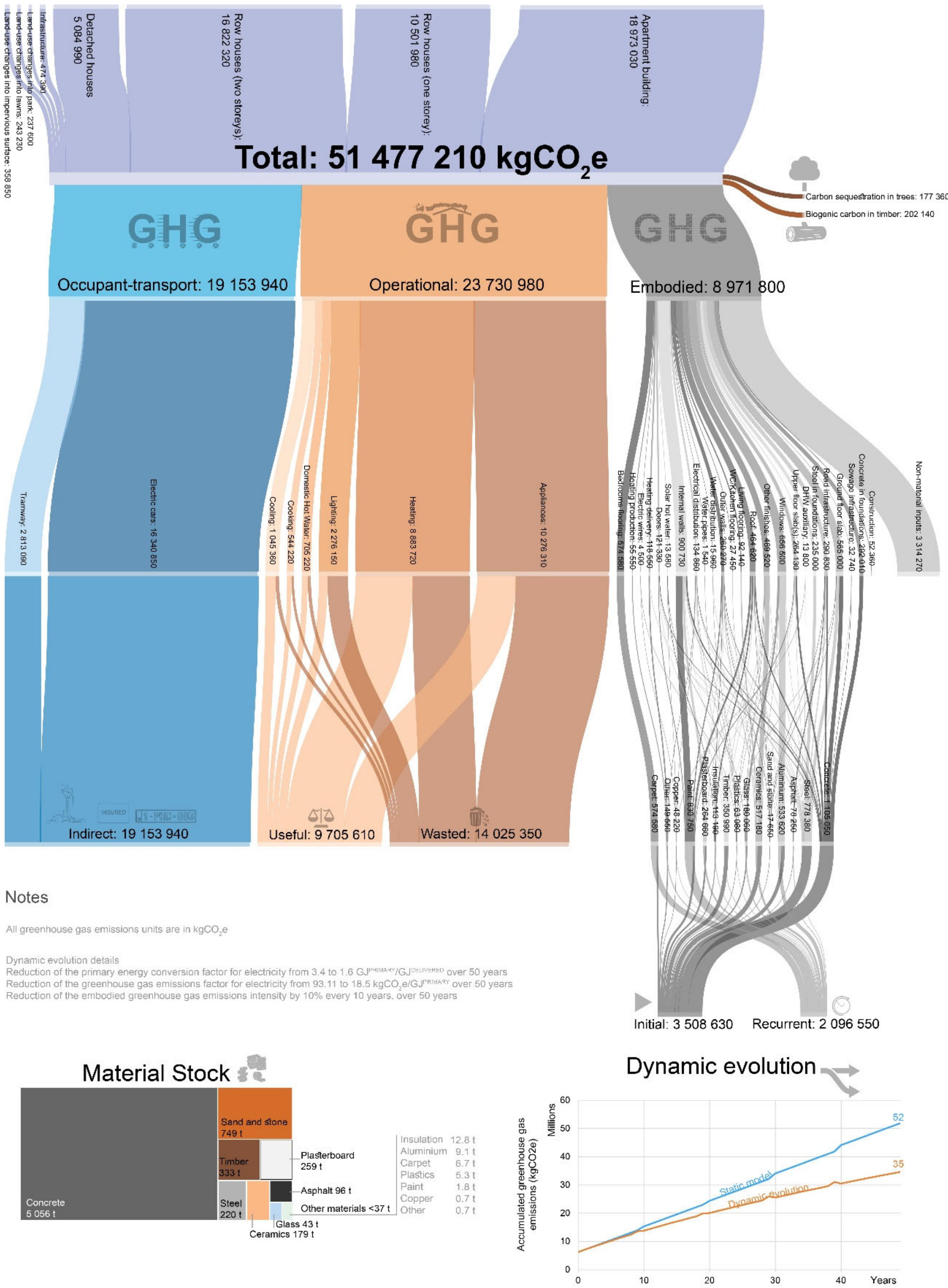

Figure 4: Dashboard summarising the life cycle greenhouse gas emissions breakdown of the proof-of-concept case study, its material stock and accumulated greenhouse gas emissions using a static model and a dynamic evolution. Underlying data for Figure 4 are available in the 'Results' sheet of the

supplementary information workbook, available on Figshare at https://www.doi.org/10.6084/m9.figshare.16899553.

6. Discussion

This paper proposes one of the most comprehensive and sophisticated life cycle environmental modelling frameworks for the built environment to date. It provides the theoretical and scientific foundations for the development of a modelling framework that enables more robust and holistic decision-making to improve the net environmental performance of built stocks at different scales of the built environment.

This modelling framework addresses the need for interdisciplinary and inter-scalar integration highlighted by researchers in many fields, such as material flow analysis (Muller et al., 2014), urban energy analysis (Allegrini et al., 2015), and life cycle assessment (Anderson, Wulfhorst, & Lang, 2015; Säynäjoki, Heinonen, Junnila, & Horvath, 2017). Ramaswami et al. (2018, p. 6) call specifically for '*developing the science to assess the sustainability outcomes nexus in urban systems, i.e., the co-benefits and trade-offs among multiple human and planetary well-being outcomes across spatial (local to global) and temporal scales*', which is largely addressed by this modelling framework. By providing a central modelling framework that can accommodate nested objects at different scales of the built environment, as required by different disciplines, this paper paves the way for a more integrated life cycle environmental assessment and improved environmental performance.

The proposed modelling approach does not pretend to provide a definitive quantification of every single environmental flow and cost indicator of built stocks. Instead, the aim is to propose a consolidated approach to integrate the multiple scales and dimensions associated with the life cycle environmental performance of built stocks. As such, the modelling framework acts as a container and can produce results as accurate as the underlying data being fed as inputs. Given that these data do suffer from significant uncertainty at present (see Section 4.9), the model would be best used to compare different development or retrofitting alternatives. Since these alternatives rely on the same base data, the uncertainty in their comparison is significantly reduced. The model is thus most suitable for planning and city-level decision-making, while enabling a high spatial and temporal resolution, down to the material scale. Importantly, the ability to conduct retrospective and prospective assessments will enable a thorough analysis of past and future urban developments or technological changes, respectively. From a practical perspective, the proposed modelling approach will capitalise on recent advances in centralising and mainstream urban data as highlighted by Creutzig et al. (2019), such as the Metabolism of Cities network (https://metabolismofcities.org/), to better characterise built stocks. This means that existing data will be used and completed where necessary and then shared again with the community, to avoid redundancy in data collection. The initiatives of multiple cities to share their data openly (e.g. City of Melbourne (2021)), also help obtain much of the base data required for the modelling framework. As more accurate data become available, existing datasets can be updated and improved. Notably, citizen science projects, such as colouring London (https://www.pages.colouring.london/), will potentially provide high resolution bottom-up data across multiple cities.

A broader system boundary requires a significant amount of additional data. This can hinder the use of the modelling framework in data-poor areas. The number of assumptions required to fill data gaps would increase uncertainty to levels that could potentially render the modelling framework unusable (Brown, 2004). While uncertainty modelling is integrated in the framework, additional efforts to develop international and consistent environmental databases are needed to provide high resolution data in multiple contexts. Recent global databases such as the multi-regional input-output database Eora (Manfred Lenzen, Moran, Kanemoto, & Geschke, 2013) or the global material flows database (Schandl et al., 2016), as well as local open data collated by city councils (City of Melbourne, 2021) are steps in the right direction. For instance, Pomponi and Stephan (2021) have used EORA to estimate the water, energy and carbon dioxide footprint of the construction sector in economies in Global North and South. However, more data is needed to better develop urban science in general (Ramaswami et al., 2018), notably in the Global South.

While this paper has presented a comprehensive modelling framework for environmental and financial assessment of the built environment, the implementation of the framework into a software has not been piloted yet at the time of writing. Only a proof-of-concept case study, relying mostly on Excel-based calculations and previous python code of the authors has been presented here. The software will need to be verified to ensure that all calculations are mathematically correct, validated to ensure that the outputs are representative of reality, within uncertainty ranges, and tested on varied built stocks internationally before being usable by relevant actors of the built environment. Using the proof-of-concept case study as a basis, it is easy to imagine the breadth of results that the fully developed software will provide, combining environmental analysis across multiple flows with financial performance, spatialization and uncertainty analysis.

7. Conclusion

This paper presents a modelling framework that provides a unique and innovative approach to quantifying and improving the environmental performance of the built environment. The breadth of the framework across environmental and financial performance of the built environment can provide a robust approach to the design, analysis and development of buildings, infrastructure assets, neighbourhoods and cities. Ultimately, the proposed modelling framework provides an opportunity for integrated actions across different built environment disciplines, enabling, to collectively respond to challenges presented by climate change and resource depletion. This modelling framework may be used to improve the performance of existing neighbourhoods or cities, and in the design and development of new urban areas.

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Author contributions

AS conceptualised, designed and developed the framework, wrote the paper and made all figures. **RC** contributed to the conceptualisation and development of the framework and structuring and editing of the paper. **VB** contributed to the development and parametrisation of the modelling framework, and to the review of the paper. **GWM** contributed to the conceptualisation, integrated the residual land modelling framework, provided guidance on life cycle costing and discounted cash flow considerations, and reviewed the paper. **SM** contributed to the conceptualisation, integrated carbon sequestration through green infrastructure in the modelling framework, provided guidance for the design of the figures and data visualisation, and reviewed the paper. **AS** revised the paper with the help of **SM**, **GWM**, **RC**, and **VB**.

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Figure Legends

Figure 1: Theoretical basis of the proposed environmental assessment framework, combing nested systems theory, life cycle assessment and dynamic modelling frameworks to enable a comprehensive coverage of environmental flows.

Figure 2: List of uses for the decision-making modelling framework, by scale and disciplinary stakeholders of the built environment

Figure 3: Scope of the decision-making modelling framework for multi-scale environmental assessment of the built environment

Figure 4: Dashboard summarising the life cycle greenhouse gas emissions breakdown of the proof-of-concept case study, its material stock and accumulated greenhouse gas emissions in static and dynamic scenarios

Appendix A: Mathematical formulation

Embodied environmental flows

$$LCEF_b = \sum_{a=1}^{A}\sum_{e=1}^{E}\sum_{m=1}^{M}\left(Q_{m,e,a,b} \times FC_m^{\mathrm{CY_b}}\right) + \left(TFBS_b^{\mathrm{CY_b}} - \sum_{m=1}^{M} TFR_m^{\mathrm{CY_b}}\right) \times C_b^{\mathrm{CY_b}}$$

$$+ \sum_{y=\mathrm{CY_b}}^{TH}\sum_{a=1}^{A}\sum_{e=1}^{E}\sum_{m=1}^{M} \delta_{m,e,a,b,y} \times \left(Q_{m,e,a,b} \times FC_{m,y}\right) + \left(TFBS_{b,y} - TFR_{m,y} - NATFR_{m,y}\right) \times C_{m,e,a,b,y}$$

$$\delta_{m,e,a,b,y} = \begin{cases} 1 \Leftrightarrow \dfrac{(y - CY_b)}{SL_{m,e,a}} \in \mathbb{Z}^+ \\ 0 \Leftrightarrow \dfrac{(y - CY_b)}{SL_{m,e,a}} \notin \mathbb{Z}^+ \end{cases} \qquad \forall\ CY_b < y \leq TH$$

$$(1)$$

Where: $LCEF_b$ is the life cycle embodied flow of the built asset b in flow unit (GJ for energy); A is the total number of assemblies in the built asset b; E is the total number of elements in the assembly a; M is the total number of materials in the element e or the assembly a; $Q_{m,e,a,b}$ is the quantity of material m in the element e in the assembly a in the built asset b (e.g. tons of steel); $FC^{CYb}{}_m$ is the hybrid flow coefficient of material m in flow unit per functional unit of material (GJ/tonne) at the year of construction of building b, CY_b, if available or at the year of assessment ya if not; $TFBS^{CYb}{}_b$ is the total flow requirement of the input-output sector associated with the built asset type of built asset b (e.g. residential building), in flow unit/currency unit (e.g. $kgCO_2e$/EUR for greenhouse gas emissions) at the year of construction of building b, CY_b; $TFR^{CYb}{}_m$ is the total flow requirement of the input-output pathway representing material m, in flow unit/currency unit (e.g. $kgCO_2e$/EUR for greenhouse gas emissions) at the year of construction of building b, CY_b; $C^{CYb}{}_b$ is the cost of the built asset b in currency unit (e.g. EUR) at the year of construction of building b, CY_b; TH is the time horizon of the analysis, e.g. 2050; CY_b is the construction year of built asset b, e.g. 2018; $\delta_{m,e,a,b,y}$ is a modified Dirac delta function; $NATFR_m$ is the total flow requirement of all input-output pathways not associated with the installation or production process of material m being replaced, in flow unit/currency unit (e.g. $kgCO_2e$/EUR for greenhouse gas emissions), e.g. pathways representing concrete production when replacing aluminium window frames; $C_{m,e,a,b}$ is the cost of the material m used in element e, in assembly a, in built asset b, in currency unit (e.g. EUR); and $SL_{m,e,a}$ is the service life of the material m as used in element e and assembly a, in years.

Life cycle operational environmental flows

$$LCOPF_b = \sum_{y=CY_b}^{TH} \sum_{e=1}^{E} \left(R_{e,y,b} \times S_{e,y,b} \times \frac{1}{\eta_{e,y,b}} \times ULF_{e,y,b}^{s} \right) \tag{2}$$

Where: $LCOPF_b$ is the life cycle primary operational energy or total water flow of built asset *b*, in GJ or kL; *y* is a year of the period of analysis of built asset *b*; *E* is the total number of end-uses *e*; $R_{e,y,b}$ is the power or water rating of the end-use *e* during year *y*, in GW or kL/s; $S_{e,y,b}$ is the operational schedule of end-use *e*, in seconds per year (it is a function of the built asset type, occupancy, etc.) during year *y*; $\eta_{e,y,b}$ is the efficiency of the end-use *e* (e.g. the efficiency of a water heater) during year *y*; and $ULF^{s}_{e,y,b}$ is the upstream losses factor associated with sources on which end-use *e* operates (e.g. electricity for a water heater) during year *y*. See Equation 1 for the definition of *TH* and CY_b.

Life cycle occupant transport environmental flows

$$LCTF_b = \sum_{y=CY_b}^{TH} \sum_{h=1}^{H} \sum_{o=1}^{O} \sum_{m=1}^{M} \left(DFI_{m,y} + IFI_{m,o,h,y} \right) \times ATD_{o,h,b,m,y} \tag{3}$$

Where: $LCTF_b$ is the life cycle transport flow of the occupants *O* of household *h* living in built asset *b*, in flow unit (e.g. GJ for energy); *y* is a the year; *M* is the total number of transport modes used by occupants *O* living in household *h,* in building *b*; DFI_m is the direct flow intensity of transport mode *m*, during year *y*, in flow unit/km; IFI_m is the indirect flow intensity of transport mode *m* during year *y*, in flow unit/km; and $ATD_{o,h,b,m,y}$ is the average annual travel distance of occupant *o,* of household *h,* living in built asset *b*, using transport mode *m*, during year *y*, in km. See Equation 1 for the definition of *TH* and CY_b.

Carbon sequestration in vegetation and soil

$$CS_{gi} = \sum_{t=1}^{T} \sum_{y=PY_{t,gi}}^{TH} SF_{t,y,gi} \times ACS_{t,y,gi} + \sum_{s=1}^{S} \sum_{y=LUCY_{s,gi}}^{TH} A_{s,gi} \times \Delta ACSLUC_{s,gi} \tag{4}$$

Where: CS_{gi} is the carbon sequestration of green infrastructure *gi* in kgC; *T* is the total number of trees in green infrastructure *gi*; $PY_{t,gi}$ is the plantation year of tree *t* in green infrastructure *gi*; $SF_{t,y,gi}$ is the survival factor of tree *t* at year *y* in green infrastructure *gi*, which is a function of its species, growth rate and age; A$CS_{t,y,gi}$ is the annual carbon sequestration rate of tree *t* for year *y* in green infrastructure *gi*, in kgC/annum; S is total number of soil areas; $LUCY_{s,gi}$ is the year during which the land-use change of soil *s* occurred in green infrastructure *gi;* See Equation 1 for the definition of *TH*; $A_{s,gi}$ is the area of soil *s* in green infrastructure *gi*, affected by land-use change, in m²; $\Delta ACSLUC_{s,gi}$ is the change in annual carbon sequestration rate for soil *s* in green infrastructure *gi* affected by land-use change, in kgC/(m²·a). See equation 1 for a definition of *TH*. Note: if there is no land-use change, the carbon sequestration of the existing soil is considered.

Life cycle cost

$$LCC_b = \sum_{y=CY_b}^{TH} \frac{\left(\sum_{a=1}^{A} Capex_{a,b,y} + \sum_{i=1}^{AI} Capex_{i,b,y} + \sum_{e=1}^{E} C_{e,b,y} + \sum_{w=1}^{W} C_{w,b,y} + \sum_{m=1}^{M} C_{m,b,y}\right) \times (1+CPI)^y}{(1+r)^y}$$

(5) Where: LCC_b is the life cycle cost of built asset *b* in currency units (e.g. AUD or EUR), in net present value terms; *A* is the total number of assemblies in building *b*; $Capex_{a,b,y}$ is the capital expenditure associated with assembly *a* in built asset *b* during year *y*; $Capex_{a,b,y}$ is the capital expenditure associated with item *i* (e.g. dishwasher, electric bike) related to built asset *b* during year *y; E* is the total number of energy sources used in built asset *b*, including fuel for cars; $C_{e,b,y}$ is the cost of the energy source *e* used in association with built asset *b* in year *y*; *W* is the total number of water source; $C_{w,b,y}$ is the cost of water source *w* used in association with built asset *b* in year *y*; *M* is the total number of public transport modes; $C_{m,b,y}$ is the potential cost of public transport mode *m* (e.g. tramway, train, taxi-boat, ferry) used by a household living built asset *b* in year *y*; *CPI* is the considered inflation rate; and *r* is the discount rate. See Equation 1 for the definition of *TH* and CY_b.

Value of the land

$$LV_{d,0} = (1+i)^t \times \left[\frac{V_{d,0}}{(1+p_d)} - C_{d,0} - (IC_d + IL_d)\right]$$

(6)

Where $LV_{d,0}$ is the residual net present land value of development *d*; *i* is the cost of finance and comprises the annual interest rate and discount factor; *t* is the development period; $V_{d,0}$ is the current estimate of development *d*'s value on completion; p_d is the developer's profit based on the current estimate of development *d*'s value (variations to this are profit based on the development costs, we have utilised the development value for our modelling framework); $C_{d,0}$ is the current estimate of development *d*'s costs including construction and costs associated with the land; and IC_d is the finance costs calculated for the construction costs of development *d* over the construction period, and IL_d is the land holding and acquisition costs of development *d* calculated over the entire development period.

Dynamic modelling of a generic variable

$$\boldsymbol{Q_b} = BV_b^{\mathrm{ya}} \times \boldsymbol{DEF_b} \tag{7}$$

Where: $\boldsymbol{Q_b}$ is a matrix of dimension ($TH\text{-}CY_b$, number of scenarios) representing the different values of a variable associated with built asset *b* over the years and the different scenarios; BV_b^{ya} is the base value of the variable associated with built asset *b* studied at the start year of assessment ya (e.g. conducting an assessment in 2022 with base data from 2020 would result in ya = 2020); and $\boldsymbol{DEF_b}$ is the dynamic evolution factors matrix of variable BV_b associated with built asset b, of dimension ($TH\text{-}CY_b$, number of scenarios), containing a scalar factor by which BV_b needs to be multiplied for each year (row) and scenario (column). See Equation 1 for the definition of *TH* and CY_b.

Dynamic modelling of the influence of changes in the electricity grid on the embodied environmental flow coefficient of a material

$$\boldsymbol{FC_m} = NEFC_m^{ya} \times \boldsymbol{I} + EFC_m^{ya} \times \boldsymbol{DEES_m} \times \boldsymbol{EFI} + EFC_m^{ya} \times (\boldsymbol{I} - \boldsymbol{DEES_m}) \times \boldsymbol{FEFI} \tag{8}$$

Where: $\boldsymbol{FC_m}$ is a matrix of dimension ($TH\text{-}CY_b$, number of scenarios) representing the different values of the embodied environmental flow coefficient of material *m* over the years and different scenarios (e.g. in GJ/FU of material for energy); $NEFC^{ya}_m$ is the non-energy-related part of the embodied environmental flow coefficient base value of the variable associated with built asset *b* studied at the start year of assessment ya (e.g. this will be zero when modelling embodied energy); $\boldsymbol{I}$ is the identity matrix of dimension ($TH\text{-}CY_b$, number of scenarios), EFC^{ya}_m is the energy-related part of the embodied environmental flow coefficient base value of the variable associated with built asset *b* studied at the start year of assessment ya (e.g. this will be FC_m (see Equation 1) when modelling embodied environmental flows); $\boldsymbol{DEES_m}$ is the matrix of dynamic evolution of the electricity share of energy, of dimension ($TH\text{-}CY_b$, number of scenarios) with values between 0 and 1; **EEFI** is the environmental flow intensity of electricity, of dimension (*TH-CY**b***, number of scenarios) (e.g. in GJ/FU of material for energy); and **FEFI** is the environmental flow intensity of fossil fuels, of dimension (*TH-CY**b***, number of scenarios) (e.g. in GJ/FU of material for energy). See Equation 1 for the definition of *TH* and CY_b.

Dynamic evolution of tramway-related occupant transport greenhouse gas emissions

$$\boldsymbol{ATRAMTGHG_{o,h,b}} = ATRAMTD_{o,h,b}^{\ ya} \times \boldsymbol{ATRAMTDE_{o,h,b}} \times \times (TRAMDE^{ya} \times \boldsymbol{TRAMDTECHE} \times \boldsymbol{PEFELECE} \times \boldsymbol{EFE} + TRAMIGHG^{ya} \times \boldsymbol{DE}) \quad (9)$$

Where: $\boldsymbol{ATRAMTGHG_{o,h,b}}$ is a matrix of dimension ($TH\text{-}CY_b$, number of scenarios) representing the different values of the annual tramway-related transport greenhouse gas emissions of occupant o, living in household h, in built asset b, in $kgCO_2e$; $ATRAMTD_{o,h,b}^{ya}$ is the annual tramway travel distance of occupant o, living in household h, in built asset b, for the start year of asssessment ya, in km $\boldsymbol{ATRAMTDE_{o,h,b}}$ is a matrix of dimensions ($TH\text{-}CY_b$, number of scenarios) representing the dynamic evolution of the annual tramway travel distance, with values as fractions of $ATRAMTD_{o,h,b}^{ya}$; $TRAMDE^{ya}$ is the base direct energy intensity of using a tramway at the start year of analysis ya, in $GJ^{Delivered}$/pkm; ***TRAMEDTECHE*** is a matrix of dimensions ($TH\text{-}CY_b$, number of scenarios) representing the dynamic evolution of the direct energy intensity of a tramway, with values as fractions of $TRAMDE^{ya}$; ***PEFELECE*** is a matrix of dimensions ($TH\text{-}CY_b$, number of scenarios) representing the dynamic evolution of the primary energy conversion factor for electricity used by the tramway, $GH^{Primary}/GJ^{Delivered}$; ***EFE*** is a matrix of dimensions ($TH\text{-}CY_b$, number of scenarios) representing the dynamic evolution of the greenhouse gas emissions factor for electricity, in $kgCO_2e/GJ^{Primary}$; $TRAMIGHG^{ya}$ is the base indirect greenhouse gas emissions intensity of a tramway at the start year of assessment ya, in $kgCO_2e$/pkm; and ***DE*** is a matrix of dimensions ($TH\text{-}CY_b$, number of scenarios) representing the dynamic evolution of the indirect greenhouse gas emissions factor tramways, with values as fractions of $TRAMIGHG^{ya}$. See Equation 1 for the definition of *TH* and CY_b..