

A comprehensive model for quantifying the environmental and financial performance of cities

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Abstract: Current models to quantify environmental performance in the built environment are flawed as they typically focus either on one scale of the built environment (e.g. buildings), on a limited range of environmental flows (e.g. energy), or a particular life cycle stage (typically building use). There is a need to develop a more comprehensive model to assess and improve the environmental performance of cities. This paper proposes a multi-scale, bottom-up, dynamic life cycle assessment model for the built environment. The model combines nested systems theory with life cycle assessment and dynamic modelling. It covers all scales of the built environment, from materials to cities. In particular, it considers material, energy, greenhouse gas emissions, water and financial flows required to produce construction materials and replace them (embodied flows); operate buildings and infrastructure assets (operational flows); and for the mobility of building users (transport flows). Furthermore, the model evaluates the value created by a particular real estate development. The paper describes how the model operates and the methods used to quantify each flow. By covering spatial and temporal boundaries across multiple environmental and financial flows, this model will significantly improve environmental assessment and decision-making for actors of the built environment.

Keywords: Life cycle assessment; life cycle cost; environmental performance; Python.

1. INTRODUCTION

Cities are and will continue to be the epicentre of human activity, representing 80% of global gross domestic product (World Bank, 2018) and accommodating the majority of the expected global population increase of ~3 billion people by 2050 (United Nations, 2015). Cities also represent ~60% of global final energy use and more than 70% of associated greenhouse gas emissions (World Bank, 2018), most of which are caused by the construction, maintenance, and operation of buildings and infrastructure. The maintenance and expansion of this built stock are the main drivers of resource extraction (UNEP, 2016) and associated environmental effects, such as climate change and resource depletion. Substantial and urgent improvements to the environmental performance of cities are needed to avoid devastating disruptions to ecosystems and human society. The window of action is closing rapidly as extreme weather events are becoming more frequent with climate change, resources are dwindling at the fastest rate ever, and freshwater is becoming increasingly scarce and polluted.

Tackling the environmental effects of cities and their built stocks can be achieved by empowering actors of the built environment, i.e. *inter alia* architects, engineers, town planners, landscape architects, construction managers, with evidence-based knowledge and models. These models can be used to quantify the environmental performance of cities and built stocks in order to compare alternatives and identify solutions with improved performance. Measuring the environmental performance of built stocks at the city level entails understanding their constituting components, i.e. buildings and infrastructure, and in turn, assemblies, elements and materials. Capturing spatial linkages across time is essential for a comprehensive quantification of the environmental performance of built stocks. Actors of the built environment rely on such models to provide the evidence needed for decision-making.

However, existing models for quantifying the life cycle environmental performance of built stocks are not sophisticated enough to provide sufficient information for decision-making. Most existing models focus either on one scale of the built

environment, e.g. a building, on one flow, e.g. energy, or on one life cycle stage, e.g. operation. Even studies that use a more holistic life cycle approach often underestimate embodied requirements (Crawford *et al.*, 2018) and are typically a one-off attempt, requiring a significant amount of time and resources to conduct (Crawford, 2011). Existing models to quantify the environmental performance of buildings and the built environment can paradoxically lead to buildings with poorer environmental performance, e.g. more energy-intensive (Stephan *et al.*, 2012). Furthermore, bottom-up models that capture linkages between scales are rare, incomplete and usually static (see Section 2). The need for more comprehensive models has been highlighted by researchers across the fields of urban energy analysis (Allegrini *et al.*, 2015), material flow analysis (Muller *et al.*, 2014), life cycle assessment (Anderson *et al.*, 2015; Säynäjoki *et al.*, 2017), as well as by international agencies such as UN-Habitat (2017). Means for comprehensively assessing life cycle environmental performance of the built environment, including embodied, operational and transport flows, across spatial and temporal boundaries, are urgently needed. This will help minimise poor-performing buildings and infrastructures, and the resultant effects on human society and the natural environment.

1.1 Aim and scope

The aim of this paper is to propose a bottom-up, dynamic, and multi-scale model to comprehensively quantify and improve the life cycle environmental and financial performance of cities and built stocks.

The model includes life cycle environmental flows, namely, energy, greenhouse gas emissions, water and materials, as well as cost. It considers embodied flows (associated with raw material extraction, production, construction, replacement of materials, and demolition), operational flows (associated with running a building/infrastructure) and user-transport flows (associated with the mobility of city dwellers).

2. EXISTING MODELS FOR ASSESSING ENVIRONMENTAL PERFORMANCE OF THE BUILT ENVIRONMENT

Environmental assessment of built stocks is typically conducted either at the building scale or at the neighbourhood/city scale. These two approaches are described below and the knowledge gaps in current assessments are highlighted.

In their review of building environmental assessment models, Haapio and Viitaniemi (2008) do not find any model that is capable of measuring a range of building types (e.g. office and residential), building categories (i.e. new, existing, refurbishment) and building components. Moreover, the models reviewed exclude infrastructure and cannot combine different buildings and infrastructures to evaluate the environmental performance of built stocks. While other models have been developed since this review, e.g. Huang *et al.* (2017), they still suffer from a range of limitations, including focusing on a one or two flows at most (in this example energy and greenhouse emissions only), and significantly underestimating embodied flows, i.e. the environmental flows associated with raw material extraction, material manufacture, processing and transport, construction, replacement of materials over time, and demolition. The overall conclusions of Haapio and Viitaniemi (2008) still hold: at the building level, there is no model that can comprehensively quantify life cycle environmental performance in order to provide decision-makers with sufficient information.

When evaluating the environmental performance of building stocks at a neighbourhood or city level, a large number of studies focus on the material stock and use top-down approaches (Muller *et al.* 2014). These top-down approaches do not allow assessors to spatialise the stock, to understand where materials are located or to model potential scenarios, such as retrofitting, housing form, or others, as these aspects are not parametrised in top-down models. If bottom-up approaches are used, the material stock in buildings is typically calculated using average material intensities per m² (e.g. see Tanikawa and Hashimoto (2009)). This means that the geometric characteristics of each building are ignored. Planners, consultants and city councils using such models do not always obtain an accurate representation of the stock and cannot disaggregate stocks by geometric element, e.g. northern façades.

When it comes to urban energy analysis models, a recent review by Allegrini *et al.* (2015) revealed that existing models largely ignore embodied energy, focusing on operational energy only. This is a clear shortcoming of such models as trade-offs between operational energy improvements and their embodied energy premium is not captured. In their review of life cycle assessment studies on neighbourhoods, Lotteau *et al.* (2015) identify only 21 studies conducted from 1980 to 2015.

Regardless of the scale of assessment, the other significant shortcoming of all existing models is their reliance on process analysis which can underestimate embodied flows by a factor of up to 4 at a whole building level (Crawford and Stephan, 2013). This is because process analysis captures only a certain number of processes upstream in the supply chain, failing to capture the entire supply chain.

Stephan (2013) has developed one of the most comprehensive models for the life cycle energy analysis of residential buildings and has applied it to a range of buildings in Australia, Belgium, and Lebanon. Recently, Stephan modified this model to apply it to non-residential buildings within the City of Melbourne and quantified embodied energy, water, greenhouse gas emissions and the material stock of 13,075 buildings (Stephan and Athanassiadis, 2017; 2018), demonstrating that such

models can be up-scaled to the city level. However, this was a one-off application as the original model is not designed for non-residential buildings. This paper builds upon the work of Stephan and incorporates new embodied flows data and quantification algorithms (see Section 3.3).

3. A MULTI-SCALE LIFE CYCLE MODEL FOR ENVIRONMENTAL AND FINANCIAL PERFORMANCE

3.1 Conceptual framework

This project combines the theory of nested systems, life cycle assessment and dynamic modelling in its conceptual framework, as depicted in Figure 1.

Nested systems theory (Walloth, 2016) focuses on the interactions between systems that are enclosing other systems (e.g. a city encloses neighbourhoods) or systems enclosed by larger systems (e.g. a window is an assembly enclosed by the building system). This theory has been developed for urban systems which are nested by nature, and is therefore ideal to model built stocks. It is by replicating the nested structure of urban systems that their interactions can be realistically modelled, better understood, and quantified. The nested systems theory provides the grounding for the model architecture.

Life cycle assessment is an internationally established and standardised method to quantify the environmental flows associated with any good or service, in this case built stocks in cities. It uses a life cycle inventory that compiles all the resource inputs and outputs of waste and pollutants for a product, across the different stages of the product's life cycle. The life cycle assessment method applied to buildings (European Standard 15978, 2011) provides the quantification approach used to comprehensively model a broad range of environmental flows across different scales and life cycle stages.

Dynamic modelling focuses on the temporal evolution of nested systems and their environmental flows across time. Since built stocks have very long lifespans compared to other products, lasting decades or hundreds of years, their environmental performance will evolve through time and depends on a myriad of parameters. The dominant majority of existing life cycle assessment studies are static, assuming a constant technological performance over time. The use of dynamic modelling in this research will enable a prospective assessment that tests a broad range of scenarios and temporal evolution of parameters. This, coupled with the capacity to conduct retrospective assessment in order to monitor past performance, will enable decision makers to devise solutions that are resilient to the inevitable change in context. This is a major improvement over existing models.

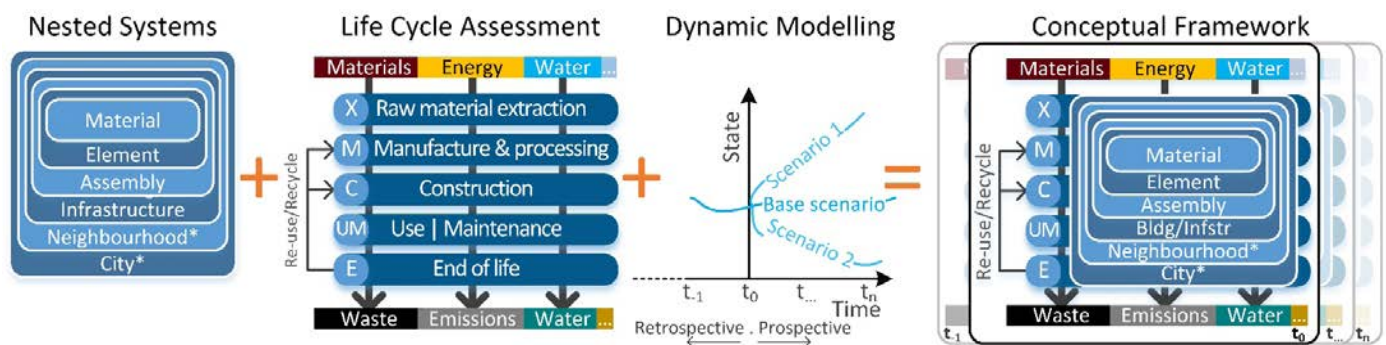


Figure 1: Conceptual framework of the research.

Note: * = modelled as a stock of buildings and infrastructures and includes user-transport flows.

3.2 Nested modelling

Developing the nested model is an iterative process. Individual models for materials, elements, assemblies, buildings (including new construction and retrofit), infrastructure, and built stocks for neighbourhoods and cities have been developed using Python programming language. But these models are prone to modifications over time as the model is used. Python is chosen for its flexibility, open source nature, multiple scientific computing models that are freely available for use (e.g. Pandas, Scientific Python, Numeric Python), and the fact that previous models developed by the authors rely on Python. The overall architecture of the model is presented in Figure 2. Object-oriented programming is used, and this results in three main advantages.

Firstly, each object is characterised as a separate entity with its own properties. For example, the model comprises 'window frame', 'lighting fixture' and 'sewage pipe' as objects. The 'window frame' object can have a 'material' property which is 'aluminium' and a 'number of glazing panes' property which can be '2'. This level of detail allows superior

modelling capabilities. Decision-makers will be able to investigate the effect of a broad parametric analysis on environmental performance ranging from the type of paint, lighting fixtures or roof insulation thickness, to the efficiency of the heating system, the installation of photovoltaic panels, the width of roads, the water efficiency of taps, the modal split of user-transport, or waste generation for on-site construction. Secondly, the algorithms are separated from the databases that feed them. This allows the model to be applied across international boundaries as long as data exist. In turn, this will enable the comparison of environmental profiles of different buildings or infrastructures internationally, while using the same model. This separation of data and algorithms also allows updates of each object to be undertaken seamlessly. The third advantage lies in the flexibility of the model. Because each object is a separate entity, it is easy to include new objects such as 'parks' as a new infrastructure type. This significantly improves the usefulness of the model in the future as it can be adapted and upgraded based on future research directions or user needs.

As indicated in Figure 1, the neighbourhood and city scales are modelled as built stocks. This means that interactions between buildings due to shading, wind tunnels, etc. are not captured in the model at this stage, but can be integrated at a later stage.

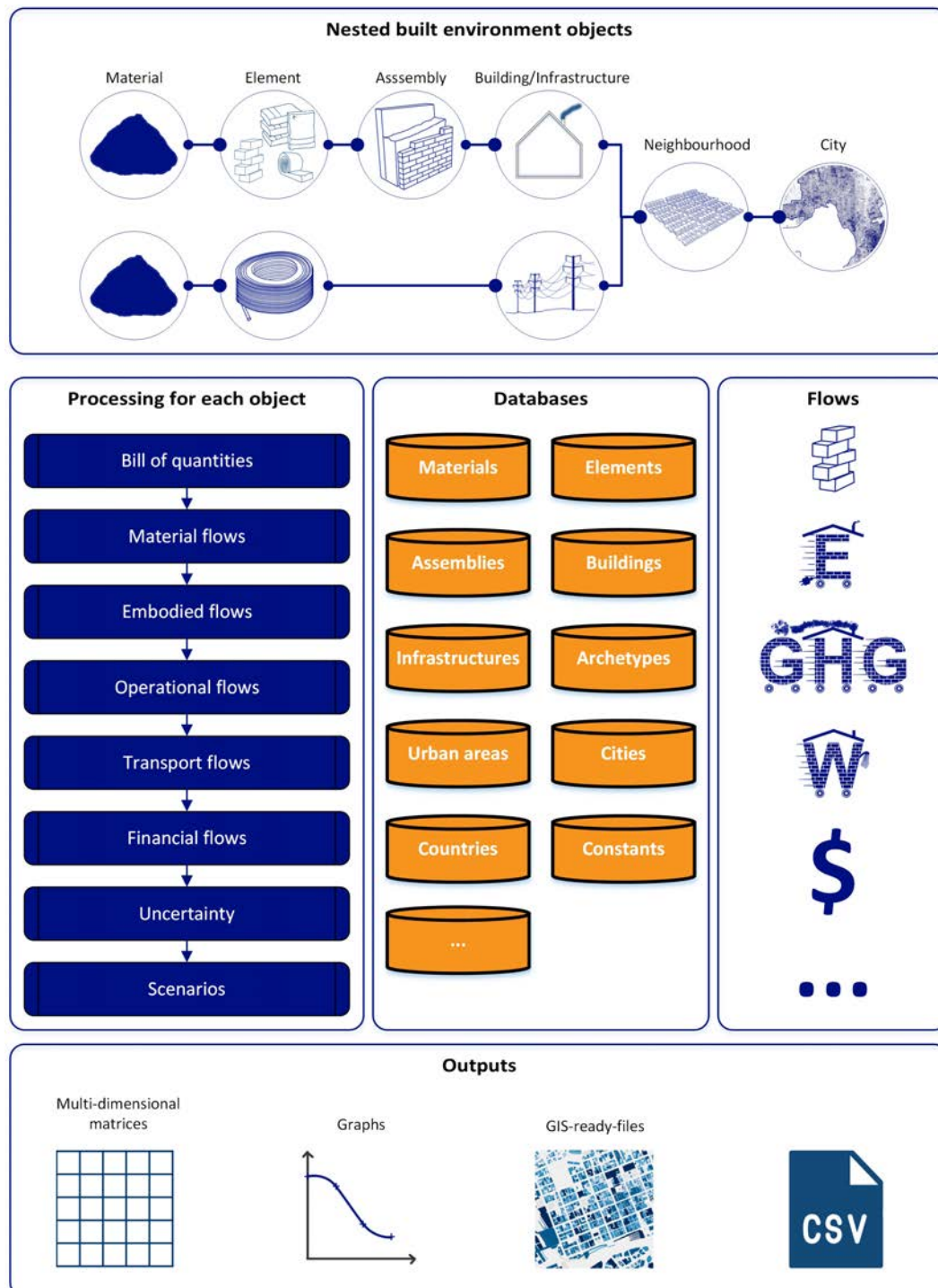


Figure 2: Diagram of the model

3.3 Modelling material flows

Material stocks and flows are modelled based on the geometric properties of a building or infrastructure and their constituting assemblies. Each assembly contains a number of elements and/or materials and specific quantities of these, e.g. one square metre of slab contains 0.2 m³ of concrete. Based on the geometry of a building, a bill of quantities of assemblies is generated and used to estimate the quantities of assemblies, elements and materials within a building or infrastructure (i.e. their inventory or stock). Elements and assemblies are replaced using average useful lives or material survival curves and result in a material flow for replacement. This approach has been successfully trialled in Stephan and Athanassiadis (2017; 2018). Material flows resulting from the demolition and construction of buildings and infrastructure at the neighbourhood and city scales are also calculated using the geometry and constituting assemblies. Construction and demolition activities are usually set based on previous trends but alternative scenarios can be modelled. The potential re-use and recycling of materials and elements in new buildings are modelled based on the material type (e.g. aluminium) and its remaining years of life.

3.4 Modelling embodied environmental flows

Embodied flows are quantified using the Path Exchange hybrid analysis (PXC) technique developed by Treloar (1997) and validated by Crawford (2008). This technique combines bottom-up industrial data with top-down economic data to capture all inputs and outputs across the entire supply chain of a product. The most recent hybrid embodied flow data are used in this model and are compiled into embodied flows coefficients. These are being compiled as this paper is being written and are based on semi-automated algorithms, as described in Stephan *et al.* (2018). Both initial (accounting for the original construction of a building or infrastructure) and recurrent (associated with material replacement over time) embodied flows are quantified. The material replacement flow (see above) is converted to a recurrent embodied flow. This allows the detailed evaluation of future embodied energy, water and material inputs as well as GHG emissions.

Embodied flows associated with a building are calculated as per Equation 1 below. Substituting the building with an infrastructure in the equation produces the associated life cycle embodied flows.

$$LCEF_b = \sum_{m=1}^M (Q_{m,b} \times FC_m) + \left(TFRBS_b - \sum_{m=1}^M TER_m \right) \times C_b$$

$$+ \sum_{m=1}^M \left[\left[\frac{(TH - CY_b)}{SL_m} - 1 \right] \times \left[(Q_{m,b} \times FC_m) + (TFRBS_b - TFR_m - NATFR_m) \times C_{m,b} \right] \right] \quad (1)$$

Where: $LCEF_b$ is the life cycle embodied flow of the building in flow unit (e.g. GJ for energy); M is the total number of materials in the building; $Q_{m,b}$ is the quantity of material m in the building b (e.g. tons of steel); FC_m is the hybrid flow coefficient of material m in flow unit per functional unit of material (e.g. GJ/ton); $TFRBS$ is the total flow requirement of the building sector associated with the building type of building b , in flow unit/AUD; TFR_m is the total flow requirement of the input-output pathway representing material m , in flow unit/AUD; and C_b is the cost of the building b in AUD; TH is the time horizon of the analysis, e.g. 2050; CY_b is the construction year of building b , e.g. 1987 or 2018; SL_m is the service life of the material m , in years; $NATFR_m$ 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/AUD, e.g. pathways representing concrete production when replacing aluminium frames; and $C_{m,b}$ is the cost of the material m in AUD in building b .

3.5 Modelling operational environmental flows

Operational energy and GHG emissions associated with heating, cooling, ventilation, hot water, lighting, appliances and cooking are considered in the model. These are calculated based on the building type, its occupancy pattern, number of appliances and systems (including solar energy generation) and power ratings. Heating and cooling are calculated by connecting the model to existing and verified models, such as Energy Plus. The heating and cooling demands are calculated for each individual buildings and summed for neighbourhoods and cities. The parametric disaggregation of operational energy and GHG emissions allows future users of the model to control individual parameters and evaluate their effect. All operational energy is expressed in final, delivered and primary energy terms. Primary energy figures capture all losses in the energy supply chain and are therefore critical in determining GHG emissions. These are calculated using conversion factors based on the energy sources used. A long term climatic model evaluates the impact of GHG emissions in terms of global warming potential based on the date of their emission, as illustrated by Kendall (2009). Operational water is modelled based on the building type, occupancy pattern, number of water fixtures and systems.

It is important to flag that the modelling of operational flows differs depending on the scale assessed. At a building level, more detailed energy modelling is appropriate to make decisions. At the neighbourhood and city levels, built stocks can be modelled using static thermodynamic equations to significantly improve the runtime of the model. This approach works well in heating-dominated climates (Reinhart and Cerezo Davila, 2016).

The life cycle operational energy or water flows of a building are obtained as per Equation 2.

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

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

3.6 Modelling transport environmental flows

The user-transport flows associated with mobility of residents is also taken into account at a neighbourhood or city level. This is done by multiplying the average travel distance per person by the environmental intensity of the relevant transport mode, as per Equation 3.

$$LCTF_{O,b} = (TH - CY_b) \times \sum_{o=1}^O \sum_{m=1}^M (DFI_m + IFI_m) \times ATD_{o,b,m} \quad (3)$$

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

Considering both direct and indirect environmental flows is critical to ensure a comprehensive environmental assessment. The significance of indirect environmental flows associated with transport has been demonstrated by a number of studies (Lenzen, 1999; Chester and Horvath, 2009; Stephan and Crawford, 2016).

3.7 Modelling life cycle cost and valuation

Life cycle cost is modelled using the net present value technique (Berk and DeMarzo, 2010). It uses bottom-up costs associated with individual construction material, elements, assemblies, trades, fuel prices, public transport fees and other relevant cost databases. These critical costs are summed and calculated at current prices, projected into the future with assumed inflation rates dependent on product, and are discounted back to a net present value as per Equation 4.

$$NPV_b = \sum_{y=CY_b}^{TH} \frac{\left(\sum_{a=1}^A Capex_{a,b,y} + \sum_{e=1}^E C_{e,b,y} + \sum_{w=1}^W C_{w,b,y} \right) \times (1 + CPI)^y}{(1 + r)^y} \quad (4)$$

Where: NPV_b is the net present value of building b in AUD; A is the total number of assemblies in building b ; $Capex_{a,b,y}$ is the capital expenditure associated with assembly a in building b during year y ; E is the total number of energy vectors used in building b , including fuel for cars; $C_{e,b,y}$ is the cost of energy vector e used in association with building b in year y ; W is the total number of water vectors; $C_{w,b,y}$ is the cost of water vector w used in association with building 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 .

Another important characteristic of the model is its ability to capture the value of the land based upon the proposed development type. It utilises the concepts of a modified residual land valuation model which estimates the underlying present value of the land based on the future utilisation of the land. As this analysis examines broader concepts and considerations, the variations in time horizons means a discounted approach would be beneficial.

The estimation of value for the land is based on value ascertained through the future use of the site on completion of the development. The value of the land is determined by its utility value, the use value of the site; which is dependent upon accessibility to economic activity, present and future uses, physical characteristics and other historical factors that might

affect the use of the land for a purpose (Brigham, 1965). To calculate this, the residual land value is determined through the estimation of the value of the project on completion, minus development costs and associated interest, land holding costs and interest charges and the developers' profit, usually a percentage of the development costs (Harvard, 2008). This can be calculated and reduced to a net present value as per equation 5 (Wyatt, 2013).

$$LV_{d,0} = (1+i)^t \times \left[\frac{V_{d,0}}{(1+p_d)} - C_{d,0} - (IC_d + IL_d) \right] \quad (5)$$

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 model); $C_{d,0}$ 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.

Although a simplified approach, the detail required in estimating with accuracy the residual land value lies within the calculations of construction costs and the estimation and assessment of the project on completion. Both of which can change with property and economic market conditions, yet this approach provides an assessment based on the conditions known at the time, and is utilised and accepted by the valuation profession to assess the value of developable land globally.

3.8 Dynamic Modelling and uncertainty

The dynamic nature of the model is another important feature. The model enables modelling the temporal evolution of parameters and quantification of their flow-on effects across the model. This is done by specifying certain evolution scenarios using either interpolation between set values at particular years or by manually specifying values over periods of time. This will enable users to evaluate the effect of changes to objects and/or flows across time.

Uncertainty in the data is one of the major drawbacks of quantifying the environmental performance of complex nested systems. However, this uncertainty should be seen as an intrinsic component of any model rather than a burden. It is taken into account to allow more resilient decisions. Interval analysis (Moore et al., 2009) is used to model parameter uncertainty. This simple approach, which consists of attributing minimum and maximum values to a parameter is chosen due to the lack of statistical data on the sheer amount of variables considered. For example, the probability distribution associated with the embodied energy of steel is not currently available. The advantage of implementing interval analysis is the ability to modify how uncertainty is modelled in the future and to gradually enrich the model. This is already a significant improvement over most existing building life cycle assessment models, e.g. Athena Institute Impact Estimator. Another feature is the ability to override computed figures as well as adding entries to databases. This is particularly useful when measured post-occupancy data is available (e.g. electricity bills). In this case, the model integrates measured and simulated data, reducing uncertainty.

The model is currently under development. It will be made available on its dedicated website: www.nestedphoenix.com. Links to all publications and data sources are also available on the website.

4. DISCUSSION AND CONCLUSION

This paper has presented a comprehensive life cycle assessment model for quantifying the environmental and financial performance of cities, covering multiple scales of the built environment, across different environmental flows, and including life cycle cost and valuation. It is one of the most advanced environmental performance models to date and endeavours to overcome flaws in existing models.

However, this comprehensiveness comes at the price of significant data requirements and complexity. In order to be able to cover such a broad range of environmental flows across space and time, a significant amount of data is required. This restricts the use of the model to where data are available to reliably model flows. The complexity of the model is another limitation. As it currently stands, the model requires significant expertise in environmental modelling, the built environment and computer programming. Future steps include developing user-friendly interfaces to facilitate decision-making and streamline the use of the model. This will help improve the environmental performance of cities.

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