photo de couverture
Louise Blondel, Bologne, janvier 2022.

lieux**dits** *#21*

Juin 2022

lieux**dits** *#21*

Faculté d'architecture, d'ingénierie architecturale, d'urbanisme de l'Université catholique de Louvain
Louvain research institute for Landscape, Architecture, Built environment

Référence bibliographique :
Stephan, A. (2022). Digital models for life-cycle assessment and material-flow analysis of urban built stocks. An opinion piece. *Lieuxdits, 21*, 20–25. doi:10.14428/ld.vi21.67213

SEMESTRIEL

ISSN 2294-9046
e-ISSN 2565-6996

Éditeur responsable : Le comité éditorial, place du Levant, 1 - 1348 Louvain-la-Neuve (lieuxdits@uclouvain.be)

Conception graphique : Nicolas Lorent
Impression : CPRINTi

LOCI
Faculté d'architecture
d'ingénierie architecturale
d'urbanisme

LAB
Louvain research institute for
Landscape, Architecture,
Built environment

www.**uclouvain.be/loci**
www.**uclouvain.be/lab**

Digital models for life-cycle assessment and material-flow analysis of urban built stocks

An opinion piece

Author

André Stephan
International expert in the life-cycle assessment of buildings and the development of digital models
Professor of environmental performance and parametric design
Architecture&Climat, LOCI+LAB, UCLouvain
0000-0001-9538-3830

Abstract. *Buildings and infrastructure assets represent a significant share of human anthropogenic material stocks, energy use, and related environmental flows, including greenhouse gas emissions. Current methods for assessing built stocks at a city scale are neither detailed nor comprehensive enough, however. This piece provides and discusses requirements for digital models to quantify the combined life-cycle environmental performance and material-flow analysis of urban built stocks. It justifies why these models need to be bottom-up, parametric, multi-scale over the life cycle, and spatially explicit, and why they need to integrate uncertainty. The potential and limitations of such digital models are discussed.*

Keywords. *life-cycle assessment · urban metabolism · material flow analysis · buildings · environmental performance · environmental flows*

Résumé. *Les bâtiments et infrastructures représentent une grande partie du stock matériel anthropogénique, de l'utilisation d'énergie, et des flux environnementaux associés. Cependant, les méthodes actuelles d'évaluation des stocks bâtis à l'échelle urbaine ne sont pas assez détaillées et holistiques. Cet article présente et discute les exigences des modèles informatiques qui visent à quantifier à la fois la performance environnementale sur l'ensemble du cycle de vie et les flux de matière des stocks bâtis urbains. Ces modèles nécessitent des approches* bottom-up*, paramétriques, multi-échelle sur le cycle de vie. Ils doivent aussi être spatialisés et intégrer les incertitudes. Ces nécessités sont justifiées et discutées dans l'article, ainsi que les potentialités et les limites de ce type de modèles informatiques.*

Mots-clés. *évaluation de cycle de vie · métabolisme urbain · analyse des flux de matière · bâtiments · performance environnementale · flux environnementaux*

Introduction

Cities are responsible for more than half of all anthropogenic energy use (Grubler et al., 2012) and associated greenhouse gas emissions (IPCC, 2014). In addition, construction materials within urban buildings and infrastructure assets also represent more than 50% of all accumulated material stocks extracted by humans (Krausmann et al., 2017). The extraction, processing, transportation, maintenance, reuse, recycling, and ultimately decommissioning of these materials require significant amounts of embodied environmental flows, including energy and water. With the climate emergency upon us (IPCC, 2018) and dwindling finite resources (Wiedmann et al., 2015), it is critical to realistically quantify and map available materials in urban built stocks and the associated life-cycle environmental flows needed to produce construction materials, operate and maintain buildings, and reuse, replace, recycle, and decommission construction materials. 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 posed by climate change and finite resources.

While there has been significant research conducted on the life-cycle assessment of buildings (Chastas, Theodosiou, & Bikas, 2016; Chau, Leung, & Ng, 2015; Dixit, 2017, 2019; Vilches, Garcia-Martinez, & Sanchez-Montañes, 2017) and on the material stocks and flow analysis of cities (Lanau et al., 2019; Mastrucci, Marvuglia, Leopold, & Benetto, 2017; Mirabella, Allacker, & Sala, 2019; Petit-Boix et al., 2017), we do not yet have the necessary tools to provide a comprehensive analysis conducted at scale. Currently, we either have detailed and holistic analyses conducted at a building scale (e.g., Birge and Berger (2019), or generally rough analyses conducted at the neighbourhood or urban scale (e.g., Lausselet, Ellingsen, Strømman, and Brattebø (2019). While significant efforts have been deployed in recent years to combine a high level of detail with a high coverage of environmental flows (e.g., Stephan and Athanassiadis (2017), there is still a significant amount of research required to achieve both and thus enable a high environmental performance of built stocks.

This paper highlights the main features digital models would require to effectively quantify material stocks and flows and associated life-cycle environmental flows of urban built stocks. This paper is by no mean exhaustive and purposely does not focus on the details due to the lack of space. For more detailed information on the topic, readers are referred to Stephan, Crawford, Bunster, Warren-Myers, and Moosavi (2022).

Digital models for material-flow analysis and life-cycle environmental performance

In order to quantify environmental performance in a meaningful manner and ensure that environmental effects are not simply shifted across time or scales of the built environment, digital models need a significant level of sophistication and complexity. They need to move closer to what Rosnay (1975) called the 'macroscope', a tool that enables us to look into complex systems. The key features digital models for urban environmental performance need are detailed below.

Theoretical framework

Digital models that aim to replicate built stocks in cities need to adopt a 'nested systems' approach (Walloth, 2016) to represent the very nature of built stocks, i.e., construction materials (e.g., steel) manufactured into construction elements (e.g., steel rebar), joined into construction assemblies (e.g., reinforced concrete slab) placed into built assets (e.g., apartment building) situated in a neighbourhood (e.g., Soho) located in a city (e.g., London) within a region or country (e.g., the United Kingdom). This enables a model to represent material flows and quantify environmental performance at different scales while taking into account the interrelationships between these scales.

In addition, digital models need to be dynamic in order to be able to quantify the evolution of parameters over time, especially with modern society's fast rate of change and the upcoming decarbonisation of energy systems. Static modelling approaches over the long life-span of built assets simply do not enable a realistic assessment (Su, Zhang, Zuo, Li, & Yuan, 2021).

Combining a nested approach across the scales of the built environment with a dynamic temporal approach enables broad spatio-temporal coverage of built stocks which needs to be combined with a life-cycle approach (ISO, 2006) to account for life-cycle stages of nested components (e.g., a construction material) that occur outside the spatial system of the city (e.g., the extraction of iron ore from a mine in Western Australia). The resulting theoretical framework for effective digital models aimed at urban environmental performance is depicted in Figure 1.

Scope

In order to quantify the life-cycle material and environmental flows of urban built assets, a range of indicators need to be considered. Elementary flows of material quantities, energy use, water use, greenhouse gas emissions, and waste are considered the most critical environmental flows to consider. Together, these flows represent the dominant majority of all associated environmental effects, as demonstrate by Oregi, Hernandez, Gazulla, and Isasa (2015) for energy alone. The material stock in existing and future buildings and infrastructure assets needs to be quantified, alongside material flows associated with the replacement of materials. Embodied environmental flows associated with the production of construction elements and assemblies as well as the operational flows associated with the use of built assets (e.g., heating an office building or lighting a street) need to be considered. At the urban scale, the environmental flows associated with the mobility of residential buildings' occupants need to be considered to provide a more comprehensive approach (Bastos, Batterman, & Freire, 2015). This broad scope enables the capture of an extremely broad environmental profile of built assets and their occupants, consistent with the theoretical framework detailed above.

A bottom-up approach

A bottom-up approach to modelling built assets is critical in order to enable assessment that provides a sufficient level of detail. Questions such as, "where is this material located within a building?", "When was it installed?", "What is the power rating of the gas boilers in that train station main terminal?" are essential to allow a detailed assessment. Digital models at the urban scale that do not consider the smaller scales or simply use material intensities per surface area (e.g., Tanikawa and Hashimoto (2009) to characterise buildings fail to provide the information required either for robust modelling or for assessing the built stock for urban mining or other circular-economy approaches. This information includes, but is not limited to, the bill of quantities of materials, elements, and construction assemblies, specifications of building systems, construction systems used within the building, the basic geometry of the building, and the year of construction (and ideally of subsequent renovations).

Parametrisation

In addition to a bottom-up approach, digital models need to be parametric to enable the exploration of different urban designs and building designs and, most importantly, to test the sensitivity of environmental performance to a range of parameters (Hollberg & Ruth, 2016). Without parametrisation, digital models will be extremely costly to update and will not be flexible enough to represent a broad range of built assets (e.g., different types of streets, different types of buildings, different types of infrastructure assets).

Multi-scale life-cycle approach

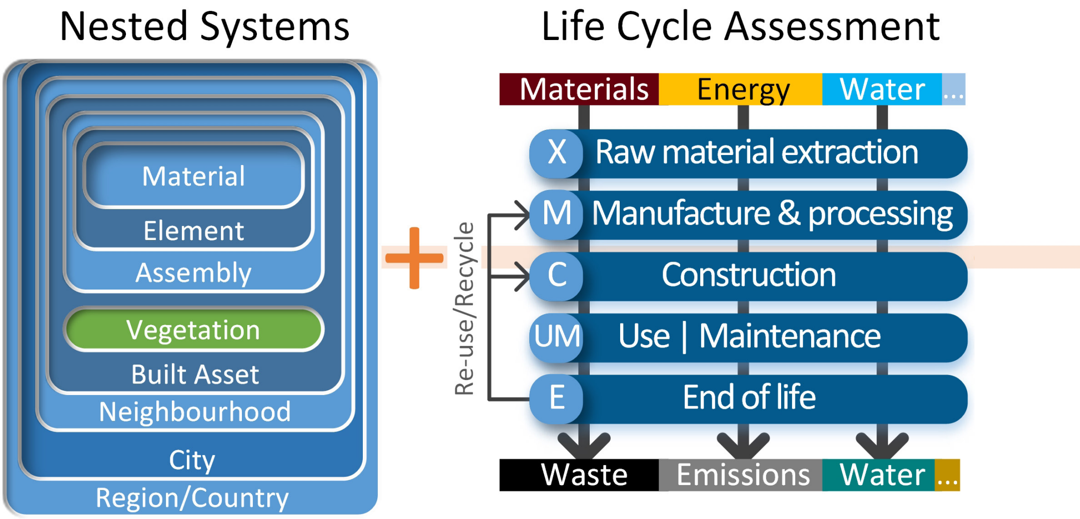
A bottom-up parametric approach needs to be adopted across the nested scales of the built environment and across the life cycle of each component at each scale. Failing to do so prevents digital models from accounting for flow-on effects between scales and/or between life-cycle stages. For example, Stephan, Crawford, and de Myttenaere (2013) demonstrate that when adopting this approach, passive houses, which focus on significantly reducing the space heating energy demand, tend to shift that energy use to other life-cycle stages and other scales of the built environment. In other terms, the additional embodied energy needed for the insulation of buildings is significant and does not necessarily yield net primary energy savings, depending on the energy source used (as also demonstrated by Gustavsson and Joelsson (2010). Furthermore, as most passive houses are located in suburban settings, this implies additional energy use for mobility, shifting energy use from the building scale to the urban scale. A multi-scale life-cycle approach is therefore essential.

Spatialisation

In addition to all the features above, spatialising the results is critical from a decision-making perspective. This enables digital models to answer such important question as where materials are located, which buildings need renovation, and what suburbs are the most energy-intensive in terms of cooling demand. The importance of spatialisation is highlighted by prominent researchers in the field, including Tanikawa, Fishman, Okuoka, and Sugimoto (2015), Kleemann, Lederer, Rechberger, and Fellner (2016), and Creutzig et al. (2019). Integrating digital models for urban environmental performance with geographic information systems (GIS) is therefore key to adding the spatial dimension of the assessment.

Uncertainty

A very important aspect of any digital model that tackles urban environmental performance is the integration of the significant underlying uncertainty. Since any model is only an attempt to represent reality (Le Moigne, 1999), there will always be a certain level of uncertainty to take into account. Because of the sheer number of variables associated with the digital models presented here, this accumulated uncertainty can be such that it hinders decision-making.



① Theoretical framework for digital models enabling a detailed and comprehensive material-flow analysis and life-cycle assessment of urban built stocks.

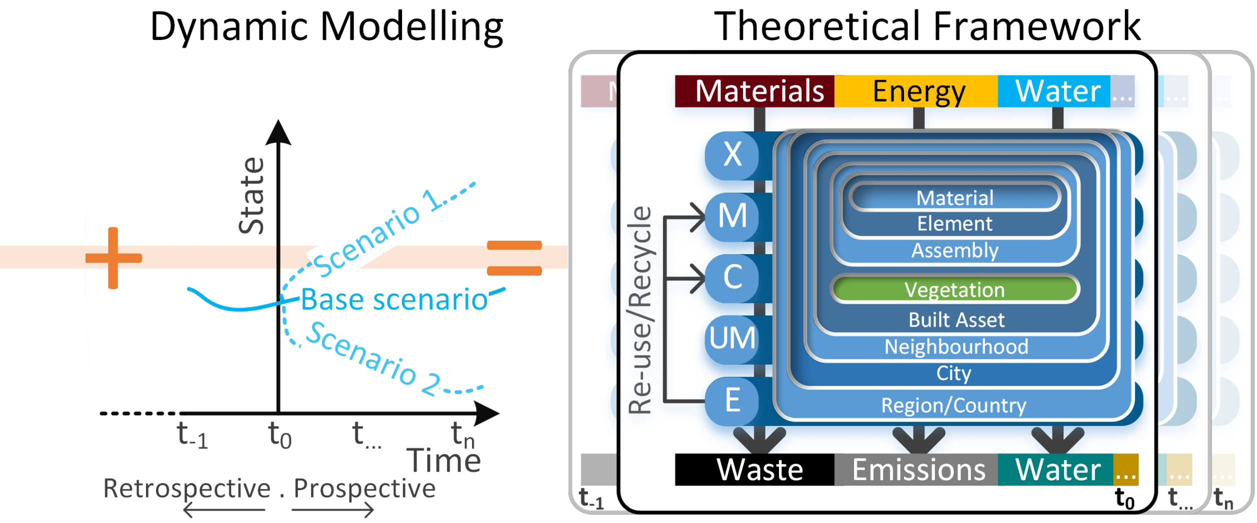
It is therefore critical to incorporate it. Uncertainty in digital models for urban environmental performance can be associated with the core data used (e.g., the embodied energy of one cubic metre of 25 MPa concrete), the algorithms used to derive indicators from such data (e.g., the outer walls surface area, derived from a plan-view of a building), the variability associated with parameters that are not directly modelled (e.g., variability in hot water usage between different occupants in a building), the lack of integration of certain parameters (e.g., the urban cooling effect of tree canopies on the cooling energy demand), the limited amount of information for certain variables, and the assumptions made to fill these data gaps (e.g., the on-site wastage coefficient associated with electrical cables), among others. In addition, the temporal evolution of parameters represents increased uncertainty in digital models for urban environmental performance, as predicting the future is speculative at best (Brown, 2004). Incorporating uncertainty in and propagating it through digital models for urban environmental performance is therefore essential.

Discussion and conclusion

This opinion paper has suggested what digital models would require for integrated material-flow analysis and life-cycle assessment of urban built stocks, including buildings and infrastructure assets. The theoretical framework of a dynamic nested-systems approach across the life cycle of built assets, combined with a bottom-up approach, parametrisation, the multi-scale life cycle approach, the need for spatialisation and the need to account for uncertainty demonstrate the significant sophistication and complexity of such digital models.

This results in a number of limitations. First, these digital models are extremely data-intensive, which hinders their applicability, as the lack of data implies the need for assumptions which result in additional uncertainty. Second, even if these models are developed and operational, they might not directly lead to decisions that result in net environmental-performance gains, because of the fragmentation of the construction industry. For instance, even if architects using the model understand that the mobility-related environmental flows are significant for the occupants of their buildings, they might not have the power to effect the choices to reduce that environmental flow. It is possible that an architect would not even quantify these mobility-related environmental flows. This has implications in terms of education and awareness that are discussed below. Third, the algorithms used to derive certain indicators are much less mature and tested than others. For example, while we can simulate, with a certain degree of confidence, the heating demand of a particular building, it is much harder to approximate the amount of construction materials in it based on available data (Lanau et al., 2019). Additional advances in such algorithms is needed to reach a higher and more uniform degree of precision.

Despite these limitations, digital tools for urban environmental performance that satisfy the requirements discussed in this paper would enable an unprece-



dented level of sophistication in guiding urban design decisions that result in net environmental gains. Such models are essential to devise robust policies for renovation and urban mining and a more circular economy. Results from applying such models to international case studies can also provide critical information about how to manage cities to yield better environmental outcomes (see inter alia Athanassiadis, Bouillard, Crawford, & Khan, 2016; Lederer et al., 2020; Stephan & Athanassiadis, 2017, 2018). The application of such digital models can also challenge current educational paradigms, emphasising the need to raise built-environment professionals' awareness of the interconnectedness of their disciplines and of environmental flows associated with their design and management decisions. The development of such digital models needs to be sustained and their application supported internationally. This will ultimately enable us to quantify the environmental performance of urban built stocks in a detailed yet comprehensive manner and help us mitigate climate change and improve environmental performance. ■

Additional information

Nested Phoenix, a digital model that adopts these requirements, is currently being implemented and will be made available on its dedicated website: www.nestedphoenix.com. Links to all publications and data sources will also be available on the website.

Acknowledgments

This research was funded by the Belgian Fund for Scientific Research (F.R.S.-FNRS) Mandat d'Impulsion Scientifique grant (F.4547.21).

Mediagraphy

Athanassiadis, A., Bouillard, P., Crawford, R. H., & Khan, A. Z. (2016). Towards a Dynamic Approach to Urban Metabolism : Tracing the Temporal Evolution of Brussels' Urban Metabolism from 1970 to 2010. *Journal of Industrial Ecology*. doi:10.1111/jiec.12451

Bastos, J., Batterman, S. A., & Freire, F. (2015). Significance of mobility in the life-cycle assessment of buildings. *Building Research & Information*, 1–19. doi: 10.1080/09613218.2016.1097407

Birge, D., & Berger, A. M. (2019). Transitioning to low-carbon suburbs in hot-arid regions : A case-study of Emirati villas in Abu Dhabi. *Building and Environment, 147*, 77–96. doi: 10.1016/j.buildenv.2018.09.013

Brown, J. D. (2004). Knowledge, uncertainty and physical geography : towards the development of methodologies for questioning belief. *Transactions of the Institute of British Geographers, 29*(3), 367–381. doi: 10.1111/j.0020-2754.2004.00342.x

Chastas, P., Theodosiou, T., & Bikas, D. (2016). Embodied energy in residential buildings-towards the nearly zero energy building : A literature review. *Building and Environment, 105*, 267–282. doi:10.1016/j.buildenv.2016.05.040

Chau, C. K., Leung, T. M., & Ng, W. Y. (2015). A review on life cycle assessment, life cycle energy assessment and life cycle carbon emissions assessment on buildings. *Applied Energy, 143*(0), 395–413. doi:10.1016/j.apenergy.2015.01.023

Creutzig, F., Lohrey, S., Bai, X., Baklanov, A., Dawson, R., Dhakal, S., . . . Walsh, B. (2019). Upscaling urban data science for global climate solutions. *Global Sustainability, 2*, e2. doi: 10.1017/sus.2018.16

Dixit, M. K. (2017). Life cycle embodied energy analysis of residential buildings : A review of literature to investigate embodied energy parameters. *Renewable and Sustainable Energy Reviews, 79*, 390–413. doi: 10.1016/j.rser.2017.05.051

Dixit, M. K. (2019). Life cycle recurrent embodied energy calculation of buildings : A review. *Journal of Cleaner Production, 209*, 731–754. doi: 10.1016/j.jclepro.2018.10.230

Grubler, A., Bai, X., Buettner, T., Dhakal, S., Fisk, D. J., Ichinose, T., . . . Weisz, H. (2012). Chapter 18 - Urban Energy Systems. In Global Energy Assessment - *Toward a Sustainable Future* (pp. 1307–1400). Cambridge University Press, Cambridge, UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria.

Gustavsson, L., & Joelsson, A. (2010). Life cycle primary energy analysis of residential buildings. *Energy and Buildings, 42*(2), 210–220. doi:10.1016/j.enbuild.2009.08.017

Hollberg, A., & Ruth, J. (2016). LCA in architectural design—a parametric approach. *The International Journal of Life Cycle Assessment, 21*(7), 943–960. doi:10.1007/s11367-016-1065-1

IPCC. (2014). *Climate change 2014 : mitigation of climate change. Contribution of working group III to the fifth assessment report of the intergovernmental panel on climate change*.

IPCC. (2018). *Global warming of 1.5 °C an IPCC special report on the impacts of global warming of 1.5 °C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty*. Retrieved from Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA : https ://ezp.lib.unimelb.edu.au/login?url=https :// search.ebscohost.com/login.aspx?direct=true&db=edszbw&AN=EDSZBW821893548&site=eds-live&scope=site

ISO. (2006). ISO 14040 :2006 In *Environmental Management - Life Cycle Assessment - Principles and Framework*. Switzerland : International Organization for Standardization.

Kleemann, F., Lederer, J., Rechberger, H., & Fellner, J. (2016). GIS — based Analysis of Vienna's Material Stock in Buildings. *Journal of Industrial Ecology*. doi: 10.1111/jiec.12446

Krausmann, F., Wiedenhofer, D., Lauk, C., Haas, W., Tanikawa, H., Fishman, T., Miatto, A., Schandl, H. & Haberl, H. (2017). Global socioeconomic material stocks rise 23-fold over the 20th century and require half of annual resource use. *Proceedings of the National Academy of Sciences, 114*(8), 1880–1885. doi: 10.1073/pnas.1613773114

Lanau, M., Liu, G., Kral, U., Wiedenhofer, D., Keijzer, E., Yu, C., & Ehlert, C. (2019). Taking Stock of Built Environment Stock Studies : Progress and Prospects. *Environmental Science & Technology, 53*(15), 8499-8515. doi: 10.1021/acs.est.8b06652

Lausselet, C., Ellingsen, L. A. W., Strømman, A. H., & Brattebø, H. (2019). A life — cycle assessment model for zero emission neighborhoods. *Journal of Industrial Ecology, 24*(3), 500–516. doi:10.1111/jiec.12960

Le Moigne, J.-L. (1999). *La modélisation des systèmes complexes* (Nouv. éd.). Paris : Dunod.

Lederer, J., Gassner, A., Keringer, F., Mollay, U., Schremmer, C., & Fellner, J. (2020). Material flows and stocks in the urban building sector : A case study from Vienna for the years 1990-2015. *Sustainability (Switzerland), 12*(1). doi:10.3390/SU12010300

Mastrucci, A., Marvuglia, A., Leopold, U., & Benetto, E. (2017). Life Cycle Assessment of building stocks from urban to transnational scales : A review. *Renewable and Sustainable Energy Reviews, 74*, 316-332. doi: 10.1016/j.rser.2017.02.060

Mirabella, N., Allacker, K., & Sala, S. (2019). Current trends and limitations of life cycle assessment applied to the urban scale : critical analysis and review of selected literature. *The International Journal of Life Cycle Assessment, 24*(7), 1174–1193. doi:10.1007/s11367-018-1467-3

Oregi, X., Hernandez, P., Gazulla, C., & Isasa, M. (2015). Integrating Simplified and Full Life Cycle Approaches in Decision Making for Building Energy Refurbishment : Benefits and Barriers. *Buildings, 5*(2), 354–380. Retrieved from http :// www.mdpi.com/2075-5309/5/2/354

Petit-Boix, A., Llorach-Massana, P., Sanjuan-Delmás, D., Sierra-Pérez, J., Vinyes, E., Gabarrell, X., Rieradevall, J. & Sanyé-Mengual, E. (2017). Application of life cycle thinking towards sustainable cities : A review. *Journal of Cleaner Production, 166*, 939–951. doi: 10.1016/j.jclepro.2017.08.030

Rosnay, J. d. (1975). *Le macroscope : vers une vision globale*. Paris : Éditions du Seuil.

Stephan, A., & Athanassiadis, A. (2017). Quantifying and mapping embodied environmental requirements of urban building stocks. *Building and Environment, 114*, 187–202. doi:10.1016/j.buildenv.2016.11.043

Stephan, A., & Athanassiadis, A. (2018). Towards a more circular construction sector : Estimating and spatialising current and future non-structural material replacement flows to maintain urban building stocks. *Resources, Conservation and Recycling, 129*, 248-262. doi: 10.1016/j.resconrec.2017.09.022

Stephan, A., Crawford, R. H., Bunster, V., Warren-Myers, G., & Moosavi, S. (2022). Towards a multi-scale framework for modelling and improving the life cycle environmental performance of built stocks. *Journal of Industrial Ecology*. doi: 10.1111/jiec.13254

Stephan, A., Crawford, R. H., & de Myttenaere, K. (2013). A comprehensive assessment of the life cycle energy demand of passive houses. *Applied Energy, 112*, 23–34. doi:10.1016/j.apenergy.2013.05.076

Su, S., Zhang, H., Zuo, J., Li, X., & Yuan, J. (2021). Assessment models and dynamic variables for dynamic life cycle assessment of buildings : a review. *Environmental Science and Pollution Research, 28*(21), 26199-26214. doi:10.1007/s11356-021-13614-1

Tanikawa, H., Fishman, T., Okuoka, K., & Sugimoto, K. (2015). The Weight of Society Over Time and Space : A Comprehensive Account of the Construction Material Stock of Japan, 1945–2010. *Journal of Industrial Ecology, 19*(5), 778–791. doi: 10.1111/jiec.12284

Tanikawa, H., & Hashimoto, S. (2009). Urban stock over time : spatial material stock analysis using 4d-GIS. *Building Research & Information, 37*(5-6), 483–502. doi: 10.1080/09613210903169394

Vilches, A., Garcia-Martinez, A., & Sanchez-Montañes, B. (2017). Life cycle assessment (LCA) of building refurbishment : A literature review. *Energy and Buildings, 135*, 286–301. doi: 10.1016/j.enbuild.2016.11.042

Walloth, C. (2016). *Emergent nested systems*. New York, NY : Springer Berlin Heidelberg.

Wiedmann, T. O., Schandl, H., Lenzen, M., Moran, D., Suh, S., West, J., & Kanemoto, K. (2015). The material footprint of nations. *Proc Natl Acad Sci U S A, 112*(20), 6271–6276. doi: 10.1073/pnas.1220362110