Available online at www.sciencedirect.com
ScienceDirect
Procedia CIRP 69 (2018) 78 – 82
www.elsevier.com/locate/procedia

25th CIRP Life-cycle Engineering (LCE) Conference, 30 April – 2 May 2018, Copenhagen, Denmark

A proposal to integrate system dynamics and carbon metabolism for urban planning

Thomas Elliot[a,b,*], Benedetto Rugani[a], Javier Babí Almenar[a], Samuel Niza[b]

[a]*Luxembourg Institute of Science and Technology, 41 rue du Brill, Belvaux L-4422, Luxembourg*
[b]*Instituto Superior Técnico, Universidade de Lisboa, Av. Prof. Dr. Aníbal Cavaco Silva 13, Porto Salvo, 2744-016, Portugal*

* Corresponding author. Tel.: +352-275-888-5039. *E-mail address:* thomas.elliot@list.lu

Abstract

Coupling of life-cycle thinking with urban metabolism (UM) has the potential to improve sustainable urban planning. Current urban metabolism models are largely ‘black-box’ methods which do not reveal the non-linearity of feedback loops and complex internal dynamics of urban systems. The integration of system dynamics (SD) with UM based on a life-cycle thinking approach can provide built environment professionals (e.g. town planners, civil engineers, architects) with a ‘transparent-box’ solution for assessing the potential of urban projects, plans, and their implementation. This paper describes the development of a method that integrates input-output (IO) table flows with SD modelling to improve the completeness of UM assessments. This modelling framework can also allow for a ‘nested’ multi-region assessment which takes into account sustainability burdens consequent to urban system changes occurring elsewhere in the national and/or global economy. Pros and cons of this proposal are showcased by the illustration of a model for Lisbon.

Keywords: Life-cycle thinking, system dynamics, urban metabolism, urban planning

1. Introduction

Urbanisation is now an important focus for climate research. As populations grow and accumulate in urban clusters there is a need to understand the associated global warming impacts. Consequent to the growth of urban populations and the complexification of the urban energy system, urban planning and development must understand the quantitative impacts of energy management practices within urban boundaries [1, 2]. Climate impacts associated with urban processes can be understood linearly using a life-cycle thinking approach to UM [1]. The use phase of these processes - which occurs in cities - is the focus of traditional black-box UM methods, while the environmental impacts associated with resource extraction, manufacturing, and disposal phases often occur exogenous to the UM boundary. The problem remains to understand how the impacts associated with urban development processes interact with one-another over time [1, 2, 3, 4]. Urban dynamics has a long history of evolution beginning in the 1970s, for example [5, 6], leading to modern modelling concepts [7] such as [8]. This paper reviews and addresses weaknesses of existing urban impact assessment methods and proposes an integrated transdisciplinary modelling framework applied to energy flows. A hypothetical example of Lisbon is used to illustrate the proposed modelling methodology and its potential application to urban planning and development.

2. Methods

This section explains three state-of-the-art methods [1] for modelling energy and carbon nexus, and their potential

doi:10.1016/j.procir.2017.10.003

contributions to an integrated method. Exploring these methods allowed us to design an improved carbon modelling solution for future applications to urban planning and development.

2.1. UM and life-cycle thinking

A valuable example for the collective modelling of urban processes required to capture the full life-cycle impacts has been proposed by Goldstein et al [9]. This is represented by a hybrid model (UM-LCA) built on traditional UM methods to enable life-cycle concepts such as life-cycle inventories and their indicators, hotspot analysis, and embodied environmental impact assessments [9]. UM-LCA could be used to estimate the global warming potential of a city. Despite being based on a holistic and pragmatic modelling system this UM-LCA framework remains limited in illuminating the 'black-box' of internal dynamic urban relationships [1].

2.2. Life-cycle thinking and SD

The state of the urban system depends on the causal relationships between the system elements [1]. As events occur, the state of the system changes. Onat [10, 11] proposed the integration of systems thinking with life-cycle sustainability assessment (LCSA). Onat and colleagues showed the need for interconnectedness in the modelling of sustainability impacts using causal loop diagrams to reveal dynamic relationships. In accordance with this rationale, we propose a method to link the UM-LCA approach with an urban sustainability model that considers complex internal dynamics, based on SD.

2.3. SD and UM

Studies [1, 3, 12, 13, 14, 15] identified this limitation of traditional black-box UM methods and proposed the integration of dynamic mathematical models for policy analysis to better understand the dynamic network of urban metabolic processes. In particular, Pincetl et al [3] proposed a 'second generation' UM method coupled with SD.

Each of these modelling frameworks offers advantages to illuminate the UM black-box. The advantages we promote are the consideration of dynamic causal feedback loops and embodied impacts associated with extended energy streams. By combining these features a better understanding of the carbon flows resulting from planning interventions and development policies may be achieved [1, 3]. Modelling the relationships between multiple elements which along multiple impact pathways and the network of causal links between them will reveal unanticipated trends. The proposed hybrid method is described below with reference to Lisbon's specific energy streams.

2.4. Scope and boundary

The urban system is defined by the municipal administrative boundary, including the relevant endogenous elements to represent the carbon metabolism of Lisbon. The administrative boundary is chosen to reduce modelling complexity. Historical Lisbon UM studies have also used fixed administrative boundaries [16, 17]. This boundary definition presents a philosophical limitation because natural systems do not have political borders. In its favour an administrative boundary is more readily transferable between cities and allows for easier data collection. This is discussed in section 4.2.

The temporal scale considers the long-term perspective. A long-term perspective is necessary in order to reveal the complexity with the black-box which is the research objective. The number of years, however, is left open for discussion.

Three mid-point impact categories are chosen: global warming potential, particulate matter, and fossil resource use. These are chosen on the basis of the authors' perceived relevance to urban energy use. Similarly, impacts associated with the end of life of capital goods such as transport infrastructure are not included. This is because of these goods are assumed to outlive the temporal urban planning horizon.

3. Results and Discussion

3.1. Simile software

The SD model was built using the software Simile v6.8p2 enterprise. Simile is a product of Simulistics and the basis of the Multi-scale Integrated Model of Ecosystem Services (MIMES) [18]. The model is composed of several sub-models which are system elements between which relationships exist, and it is these iterative relations which make the system dynamic.

The model developed for this study is comprised of a Lisbon boundary model which contains the sub-models called Economic sectors, Energy types, Population classes, Age groups, Transport modes, and Carbon stores. Each sub-model is an array of instances which account for the multi-scales specific to each state variable.

3.2. Economic sectors

The Economic sectors sub-model consists of 1 state variable (Gross Domestic Product, GDP) and the corresponding Production flow. The number of sub-model instances is equal to the number of economic sectors. These sectors should align with the World Input-Output Database (WIOD) [19] from which the import data of fossil fuels are obtained. The Energy types sub-model is nested within the Economic sectors sub-model in order to assess the energy dynamics at a sectoral level. The Energy types sub-model consists of 1 state variable (energy used). There are 6 energy types (6 instances): petroleum, diesel, LPG, natural gas, electricity, and biomass (including biofuels).

3.3. Population classes

This sub-model deals with the relationships the day-time population has on urban land use and energy demand. There are 4 class instances according to income brackets: high, medium-high, medium-low, and low. These are defined by the

World Bank using Gross National Income (GNI) per capita. The Age group sub-model is nested within the population classes and contains one state variable (Population). There are 4 age group instances: 0-14 years, 15-44 years, 45-64 years and over 65 years. A 4-by-4 matrix of population is created accordingly to allow for the population dynamics to more realistically influence economic production and workforce. Only the 2nd and 3rd age classes make up the economic workforce, while the 2nd, 3rd and 4th make up the potential vehicle driving population.

3.4. Carbon stores

There are 3 carbon storage instances: trees, buildings, and fossil fuels. Influences are defined between tree carbon and carbon emissions to air. Similarly, specific fossil fuel stores are influenced by transport modes using those respective fuels, and these fuels are substituted as mode shares change. Simile is easily adapted to include more types of carbon stores such as soil and food biomass but for the sake of illustration these are not pictured.

3.5. Transport modes

This sub-model deals with urban passenger and freight movements. It does not include aeroplane transport, ferries or shipping. There are 7 transport modes, 6 of which are passenger modes: human powered, light private passenger vehicles, taxies, buses, metro (underground rail), trains (including trams), and freight trucks. It is assumed that mode 1 uses no energy, modes 2, 3, 4 and 7 use refined fuels (such as petroleum, diesel or LPG), and modes 5 and 6 use electricity.

Trans-boundary car movements require detailed information in order correctly allocate their associated emissions to the urban system. Therefore, care should be taken to avoid the risk of over or under counting for commuter journeys.

3.6. Land uses

This Lisbon system has 20 land use instances, each of which has a carbon sequestration profile based on tree-cover. The urban system has a land use profile determined by the weighted average of land uses, which change according to influences from tree growth and urban population [19]. Land uses that do not have tree-cover are assumed to not sequester carbon from air and those land uses that do have tree-cover sequester carbon from air based on tree biomass per m^2.

3.7. Import flows

Data from the Environmentally Extended Input-Output tables of the WIOD are used to account for the pre-use life-cycle phases [19]. There are 44 country instances including Portugal, which in this model is treated like an exogenous trading relationship to Lisbon. Lisbon is subtracted from the rest of Portugal using Lisbon weighted GDP by sector [17]. The IO tables inform the import of energies which are used by the economic sectors and transport modes as it is assumed the no energy resources are extracted within the city.

3.8. Impact flows

The Impact flows module may contains a diverse number of mid-point and endpoint life-cycle impact categories required to characterise the resources and emissions associated with the use of energy and fuels in the model, e.g. global warming potential (kg CO_2-eq to air), particulate matter (kg $PM_{2.5}$ to air), and fossil resources (kg oil-eq). These are the variables used to assess and inform the potential urban planning decisions.

3.9. Model infrastructure

Fig. 1 shows, by way of recognisable icons, the relationships and the major elements which make up the proposed model. Fossil fuels and electricity enter the urban system from the left. The Lisbon municipal boundary encloses the internal energy dynamics which are represented by transport modes, industry and carbon stores, and their relationships with the urban population. Red arrows indicate positive influence and blue arrows indicate negative influences. The right side of Fig. 1 shows the elementary flows exiting the urban system into the natural environment, namely carbon dioxide to air.

The Simile software allows for the flexibility necessary for building and re-building system dynamic urban models, which is an ongoing and iterative research enquiry by its interdisciplinary and transdisciplinary nature.

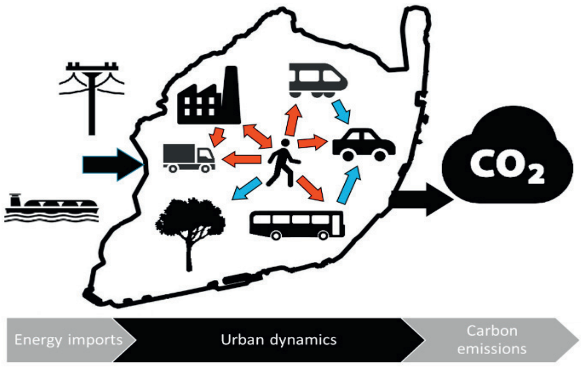

Fig. 1. Key relationships of Lisbon's energy dynamics.

4. Conclusions

The integration of SD, UM, and life-cycle thinking may provide more realistic impact assessment results to aid the urban planning process.

Aspects of novel planning concepts such as nature-based solutions, biomimicry and vegetecture, which provide co-benefits, may utilise the integration of SD modelling to capture the feedback relationships between the elements under their influence.

4.1. Future research

This proposed framework may advance the understanding of cities' complex internal energy dynamics, and stimulate future research on the integration of computational methods for sustainable urban planning. In particular, there is a need to incorporate a more complete urban system which is not limited to the elements pertaining to energy and carbon. Dynamic systems have been developed to model urban water [21], housing [22], and these could be adopted by the proposed method. Including those elements would allow for a broader range of impact categories to be modelled. Furthermore, there is interest from planners to make such a model spatially-explicit whereby land uses not only influence the dynamics but do so with the inclusion of geographic information systems maps. Tree-coverage was used to inform the carbon sequestration flow, but it also influences the urban heat island effect and social impacts [23, 24, 25] which can reduce the urban energy demand for cooling, and therefore is potential to expand the model to link other urban systems with causal feedbacks between energy and other urban system elements [26].

4.2. Limitations

The boundary definition is necessary for identifying which elements to model. However, the urban system is an open system, causally related to exogenous activities and therefore is limited by a fixed administrative model boundary. For example, transport flows transcending the administrative boundary are difficult to accurately allocate. An option to overcome this limitation is to make the system boundary spatially dynamic, whereby the perimeter is defined by an intensity of activities occurring within it, and as the intensity of those activities change over the execution of the model run, the perimeter responds by expanding or shrinking. An example of this is the Functional Urban Audit, which defines urban areas by connectedness of the built environment and commuter movements [27].

The model goes some way to illuminate the standard 'black-box' UM, but does not inform the urban planner about spatially-specific local hotspots. Including spatially-explicit information would further complicate the modelling process while adding to the uncertainty of results.

The impact categories are limited in their explanation of socio-economic factors. Not all three pillars of sustainability are considered. This risks shifting burdens to impact categories that are not assessed. Some social well-being factors may be loosely inferred from energy poverty and exposure to poor air quality. However, we see future research adding value by expanding the modelling scope to include an extensive profile of impact categories by introducing urban systems such as hydrological dynamics, housing dynamics with the afore-mentioned land use change dynamics.

Acknowledgements

This study was supported by the National Research Fund (FNR) of Luxembourg (CORE project "ESTIMUM" - C16/SR/11311935; www.list.lu/en/project/estimum/) and by the European Commission (H2020 project "Nature4Cities" - Grant No: 730468; www.nature4cities.eu).

References

[1] Beloin-Saint-Pierre, D., Rugani, B., Lasvaux, S., Mailhac, A., Popovici, E., Sibiude, G., . . . Schiopu, N. (2016). A review of urban metabolism studies to identify key methodological choices for future harmonization and implementation. Journal of Cleaner Production. doi:10.1016/j.jclepro.2016.09.014

[2] Kennedy, C., Pincetl, S., & Bunje, P. (2011). The study of urban metabolism and its applications to urban planning and design. Environ Pollut, 159(8-9), 1965-1973. doi:10.1016/j.envpol.2010.10.022

[3] Pincetl, S., Bunje, P., & Holmes, T. (2012). An expanded urban metabolism method: Toward a systems approach for assessing urban energy processes and causes. Landscape and Urban Planning, 107(3), 193-202. doi:10.1016/j.landurbplan.2012.06.006

[4] Zhang, Y., Li, Y., & Zheng, H. (2017). Ecological network analysis of energy metabolism in the Beijing-Tianjin-Hebei (Jing-Jin-Ji) urban agglomeration. Ecological Modelling, 351, 51-62. doi:10.1016/j.ecolmodel.2017.02.015

[5] Forrester, J., Urban Dynamics. Pegasus Communication Inc. (1969)

[6] Batty, M.: Modelling cities as dynamic systems. Nature **231**, 425–428 (1971)

[7] Batty M., Marshall S. (2012) The Origins of Complexity Theory in Cities and Planning. In: Portugali J., Meyer H., Stolk E., Tan E. (eds) Complexity Theories of Cities Have Come of Age. Springer, Berlin, Heidelberg

[8] Batty, M. (2009). Cities as Complex Systems: Scaling, Interaction, Networks, Dynamics and Urban Morphologies. In R. A. Meyers (Ed.), Encyclopedia of Complexity and Systems Science (pp. 1041-1071). New York, NY: Springer New York.

[9] Goldstein, B., Birkved, M., Quitzau, M.-B., & Hauschild, M. (2013). Quantification of urban metabolism through coupling with the life-cycle assessment framework: concept development and case study. Environmental Research Letters, 8(3), 035024. doi:10.1088/1748-9326/8/3/035024

[10] Onat, N. C., Kucukvar, M., Tatari, O., & Egilmez, G. (2016). Integration of system dynamics approach toward deepening and broadening the life-cycle sustainability assessment framework: a case for electric vehicles. The International Journal of Life-cycle Assessment, 21(7), 1009-1034. doi:10.1007/s11367-016-1070-4

[11] Onat, N., Kucukvar, M., Halog, A., & Cloutier, S. (2017). Systems Thinking for Life-cycle Sustainability Assessment: A Review of Recent Developments, Applications, and Future Perspectives. Sustainability, 9(5), 706. doi:10.3390/su9050706

[12] Kennedy, C., Stewart, I. D., Ibrahim, N., Facchini, A., & Mele, R. (2014). Developing a multi-layered indicator set for urban metabolism studies in megacities. Ecological Indicators, 47, 7-15. doi:10.1016/j.ecolind.2014.07.039

[13] Pincetl, S. (2012). Nature, urban development and sustainability – What new elements are needed for a more comprehensive understanding? Cities, 29, S32-S37. doi:10.1016/j.cities.2012.06.009

[14] H.Liu, & Zhang, Y. (2012). Ecological network analysis of urban metabolism based on input-output table. Procedia Environmental Sciences, 13, 1616-1623. doi:10.1016/j.proenv.2012.01.154

[15] Zhang, Y. (2013). Urban metabolism: a review of research methodologies. Environ Pollut, 178, 463-473. doi:10.1016/j.envpol.2013.03.052

[16] Niza, S., Rosado, L., & Ferrão, P. (2009). Urban Metabolism. Journal of Industrial Ecology, 13(3), 384-405. doi:10.1111/j.1530-9290.2009.00130.x

[17] Rosado, L., Niza, S., & Ferrão, P. (2014). A Material Flow Accounting Case Study of the Lisbon Metropolitan Area using the Urban Metabolism Analyst Model. Journal of Industrial Ecology, 18(1), 84-101. doi:10.1111/jiec.12083

[18] Boumans, R., Roman, J., Altman, I., & Kaufman, L. (2015). The Multiscale Integrated Model of Ecosystem Services (MIMES): Simulating the interactions of coupled human and natural systems. Ecosystem Services, 12, 30-41. doi:10.1016/j.ecoser.2015.01.004

[19] Timmer, M. P., Dietzenbacher, E., Los, B., Stehrer, R. and de Vries, G. J. (2015), "An Illustrated User Guide to the World Input–Output Database: the Case of Global Automotive Production", Review of International Economics., 23: 575–605

[20] Lauf, S., Haase, D., Hostert, P., Lakes, T., & Kleinschmit, B. (2012). Uncovering land-use dynamics driven by human decision-making – A combined model approach using cellular automata and system dynamics.

Environmental Modelling & Software, 27-28, 71-82. doi:10.1016/j.envsoft.2011.09.005

[21] Zarghami, M., & Akbariyeh, S. (2012). System dynamics modeling for complex urban water systems: Application to the city of Tabriz, Iran. Resources, Conservation and Recycling, 60, 99-106. doi:10.1016/j.resconrec.2011.11.008

[22] Ho, Y- F., Wang, H-L., Liu C-C., 2012. System Dynamics and Genetic Artificial Neural Network Models for the Monitoring and Early Warning of Urban Housing Market. Available at: <https://www.systemdynamics.org/conferences/2012/proceed/papers/P1234.pdf>.

[23] Baro, F., Chaparro, L., Gomez-Baggethun, E., Langemeyer, J., Nowak, D. J., & Terradas, J. (2014). Contribution of ecosystem services to air quality and climate change mitigation policies: the case of urban forests in Barcelona, Spain. Ambio, 43(4), 466-479. doi:10.1007/s13280-014-0507-x

[24] Soares, A. L., Rego, F. C., McPherson, E. G., Simpson, J. R., Peper, P. J., & Xiao, Q. (2011). Benefits and costs of street trees in Lisbon, Portugal. Urban Forestry & Urban Greening, 10(2), 69-78. doi:10.1016/j.ufug.2010.12.001

[25] Oliveira, S., Andrade, H., & Vaz, T. (2011). The cooling effect of green spaces as a contribution to the mitigation of urban heat: A case study in Lisbon. Building and Environment, 46(11), 2186-2194. doi:10.1016/j.buildenv.2011.04.034

[26] Zhang, Y., Zheng, H., Yang, Z., Li, Y., Liu, G., Su, M., & Yin, X. (2016). Urban energy flow processes in the Beijing–Tianjin–Hebei (Jing-Jin-Ji) urban agglomeration: combining multi-regional input–output tables with ecological network analysis. Journal of Cleaner Production, 114, 243-256. doi:10.1016/j.jclepro.2015.06.093

[27] Feldmann, B. 2008. "The Urban Audit—Measuring the Quality of Life in European Cities." Eurostat, Statistics in Focus. Available at: www.epp.eurostat.ec.europa.eu/ cache/ITY_OFFPUB/KS-SF-08-082/EN/KS-SF-08-082-EN.PDF