Modeling the Built Environment Element by Element: Uncovering Greenhouse Gas Intensive Policies and Structures with a New Visualization Tool

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ABSTRACT

Future population growth is estimated to be concentrated in urban areas of the developing world. This growth and demographic shift will require a large amount of construction materials and generate Greenhouse Gas emissions. The present study is motivated by the lack of a holistic approach to understand how urbanization affects resources and the environment. A framework is established, which links population increase and the associated material flows devoted to construction of additional housing units as well as densification of the existing building stock. Different political scenarios as well as alternative construction techniques and building materials are used to explore the potential for reducing material requirements and embodied GHG related to urban growth in Johannesburg, South Africa. Stock dynamics modeling techniques are applied with the use of building typologies and uncertainty quantification. The bottom-up approach allows identifying appropriate solutions for decarbonization by localizing embodied GHG with a revisited Sankey diagram. The results of the dynamic model over time indicates that only a combination of densification of the building stock with multi-story buildings and the use of alternative construction materials and techniques shows a real potential to decelerate embodied GHG while aiming to provide adequate and sustainable housing.

Keywords: *urban metabolism, scenario analysis, embodied energy*

1. INTRODUCTION

Countries of the developing world are facing an increase in population and accelerated urbanization. 60% of the built environment required to accommodate the earth's urban population by 2050 remains to be built (UNEP, 2013). While construction materials are already the single biggest form of material flows (Schandl and West, 2010), the coming urbanization wave will increase even more the pressure on resource extraction and its deleterious environmental impact. The objective of this paper is therefore to explore potentials to reduce material requirements and Greenhouse Gas (GHG) emissions caused by urban growth.

To do so, Urban Metabolism (UM) is used as it is a common method to understand how human and economic development affects the natural environment (Pauliuk et al., 2015). Studies on UM are subject to quality and amount of accessible data. This issue is raised in standard literature reviews (Broto et al., 2012; Zhang et al., 2015). Furthermore, studies at the urban scale in developed countries are data intense and go into great detail. In cities of developing and emerging countries, where this type of information does not exist, data mining remains a big challenge and data on the national level is used. Recent urbanization in most African cities has been largely informal (Cobbinah et al., 2015). In consequence, national or city data are of little help to grasp the material flows of these new settlements. There is a need for a finer granularity analysis whilst keeping a large-scale approach in order to extract sound and relevant data in a time-effective way.

The present paper wants to combine bottom-up accounting and demand-driven modelling of the building stock. By applying a combined approach, the advantages of the different modeling techniques can be employed for the specific situation in an emerging country: data scarcity can be overcome, information on the city scale can be modeled dynamically over time and the influences of socioeconomic indicators are taken into account. Different scenarios for the identified determinants of the building stock's embodied GHG emissions are proposed. The scenario compares and combines these potentials to minimize future impacts.

2. DATA AND METHODS

2.1 Typologically driven stock dynamics model

The framework for the model was adapted from a current stock dynamic approach developed by Hu and colleagues (2010). The method makes use of building typologies to model a whole urban residential building stock by simply using averages. The relevant service unit of the present study is floor area in use. This process is determined by the population size and per capita floor area (PCFA). PCFA is dependent on the dwelling type, it is one parameter considered to define building typologies. Actually, for each building typology, the household size is modeled. This includes people per household and habitable space per household. These characteristics are then translated to the PCFA as an expression of the population's lifestyle.

The floor area in use of the residential building stock is described with a state variable (in m^2) and a derivative, which represents the net stock accumulation. A density of materials is defined (in kg/ m^2), which depends on building type, the volume of its elements and the density of used construction material. The material density controls the input of materials by linking it to the floor area. Equivalent to floor area, materials in use have a state variable (in tons of material) and derivative. The output of floor area and materials is determined by lifetime of dwellings and material respectively. Inflows are controlled by simple balance relations as a sum of in stock and outflow of mass and floor area.

The environmental impact of the production of each building material is defined as an embodied GHG intensity. The combination of this embodied GHG intensity with the input of materials in use allows to calculate the additional embodied GHG required for the additional floor area. Equivalent to the processes floor area and materials, embodied GHG in use is also modeled with a state variable (in tons of CO_2 equivalents), and a derivative.

2.2 New visualization tool

To visualize the allocation of the resources in the building stock, a diagram resembling a Sankey flow diagram is developed. The diagram helps to easily track the embodied GHG when modelling in a data scarce environment. It is a vital way of disentangling the building stock since the incorporation of typologies in the model makes it more complex to grasp and interpret. Furthermore, it allows comparing different technological and political options to decarbonize urban areas.

Often a huge number of line and bar charts are used to show the contribution of different types of infrastructure elements and their characteristics regarding material and energy intensity. These ways of presenting material stocks and flows make it difficult to grasp the entire information because results are shown in various tables and charts. The proposed revisited Sankey diagram makes it easier to see the link between different composites and processes and to visually identify the main drivers of material and energy consumption. The diagram highlights optimization potential, mainly from a structural engineering point of view. The proposed visualization does not show continuous flows like a classic Sankey diagram does. It is revisited so that the width of links indicates the proportion from one node to the next, but the illustrated flows change in terms of units from one step to the next.

2.3 The city of Johannesburg

The City of Johannesburg Metropolitan Municipality (referred to as Johannesburg in this article) is chosen as a case study. Johannesburg is a sprawling city composed of dispersed residential, industrial and office developments (Economist Intelligence Unit, 2011). As a result, it is less dense compared to other major African cities, leading to a particular interest of examining the challenges that arise from urbanization. The present study used national censuses for 1996, 2001 and 2011 (Statistics South Africa, 2011).

Building typologies

The building typologies are based on definitions of dwelling types from the South African census in 2011 and were gathered in 5 dwelling typologies: (1) house on a separate stand, (2) flat in a block of flats, (3) house/ flat/ room in backyard, (4) informal dwelling in backyard, and (5) informal dwelling in settlement. These 5 dwelling types represent around 87.5% of the residential building stock in Johannesburg (Statistics South Africa, 2011). The model is run for a period from 1975 to 2040. Starting in 1975 allows creating reasonable initial conditions as the service life of buildings is relatively low and a large part of the urbanization linked with population growth happened at that period.

Material sets of building typologies

For each building typology a specific material set in kg per floor area and kg per building element is defined. Building elements considered are load bearing walls, roof, slabs and the foundation. The inventory is based on floor plans and images of representative buildings that can be allocated to each typology.

As it can be seen from Table 1, the two informal dwelling types (4 and 5) are identical in terms of material requirement but they were modeled separately in order to implement changes in the share of dwellings from political decision.

Element	Type (1)	Type (2)	Type (3)	Type (4)	Type (5)	Other
Walls	12,505	21,780	7,441	218	218	15,597
Foundation	16,432	18,751	2,548	-	-	17,205
Ceiling	-	17,120	-	-	-	5,707
Roof Trusses	310	1,117	268	-	-	579
Roof Tiles	1,905	6,222	1,163	71	71	3,344
Amount	31,152	64,990	11,419	289	289	42,431

Table 8: Amount of material in kg per building element for building typologies

GHG intensity of building materials

The current study focuses on GHG emissions related to the production of the different building materials. The maintenance can be neglected as we focused on structural elements (Hoxha et al., 2014) and the demolition and landfill phase of the life cycle are not the main responsible of the climate change related impact compared to the production phase of building materials (Lasvaux, 2012).

Future scenarios

Finally, future scenarios for the evolution of the building stock are considered. Engineering and policy measures were considered. For the engineering side, changes in the structural design as well as changes in the type of materials are considered. For the policy aspects, the focus lies on a change in building typologies.

Two structural design options are considered: a conventional structure of reinforced concrete slabs for multi-story buildings and an optimized one where a vaulting system is used allowing to drastically reduce the amount of materials for slabs (Block et al., 2010; Hebel, 2015). This innovative system was implemented by Hebel (2015) in Ethiopia in the “SUDU - Sustainable Urban Dwelling Unit” project.

For the alternative construction materials, the building materials low carbon concrete and earth are considered. Low carbon concrete is a concrete made with a cement containing a low proportion of clinker and therefore associated with smaller GHG emissions. This is the current trend in the cement industry where at the global level the clinker substitution is currently around 20% and the extreme scenario considered in the present study assumes that the substitution could reach 50%, which is a technical limit from the cement chemistry (Habert and Roussel, 2009). Concerning earth materials, earth based construction has been used for more than 10,000 years and a revival of this material can be observed in recent years (Landrou et al., 2016; Scrivener et al., 2016). The environmental impact associated with this material is extremely low and, if not stabilized, can be reduced to the impact associated with extraction and transport of the raw material. However, a stabilization of the material would lead to higher emissions per m^3 and per MPa compared to traditional concrete.

Three different policy scenarios are considered. One scenario represents an elimination of informal settlements, which is in line with UNEP’s recommendation to eliminate existing housing backlog in South Africa. The second scenario considers a densification of the city through an increased share of apartment buildings in the building typologies. This is strongly encouraged by UNEP who considers that the existing urban density of 15-20 dwelling units/ hectare should be increased to a minimum of 35-45 dwelling units/ hectare via smaller plot sizes and multi-story buildings (UNEP, 2011).

3. RESULTS

3.1 Total embodied GHG emissions for political and technological scenarios

The different scenarios considering alternative structures and materials are combined with the policy scenarios to examine the potential impact of each respective scenario and are compared to the current situation (2011 data) and the Business as Usual (BAU) trend scenario in 2040.

The bar chart in Figure 1 shows how a change in policy, indicated by pattern, and different combinations of material and technology, as shown as groups on the x-axis, affect the embodied GHG intensity of Johannesburg in 2040. The diagram indicates that the different political scenarios alone do not have a primary importance in the future of GHG emission reductions. The same goes for singular improvements in technology. When considering low-carbon-concrete and optimized ceiling structure, the difference between the technical scenarios is small for the single policy scenarios (BAU or no informal settlements). However, the promotion of flats allows to increase the leverage effect of the optimized ceiling structure compared to the technical solutions where only low carbon concrete is used. Finally, it is also clear that the use of radical alternative materials and smart structure shows the potential for significantly reducing embodied GHG of the residential building stock by 2040. If these radical technical shifts are additionally combined with policy making which promotes a denser building stock by moving people from freestanding houses into apartment buildings, then the GWP linked with construction materials could stay within range of the 2011 value in in 2040.

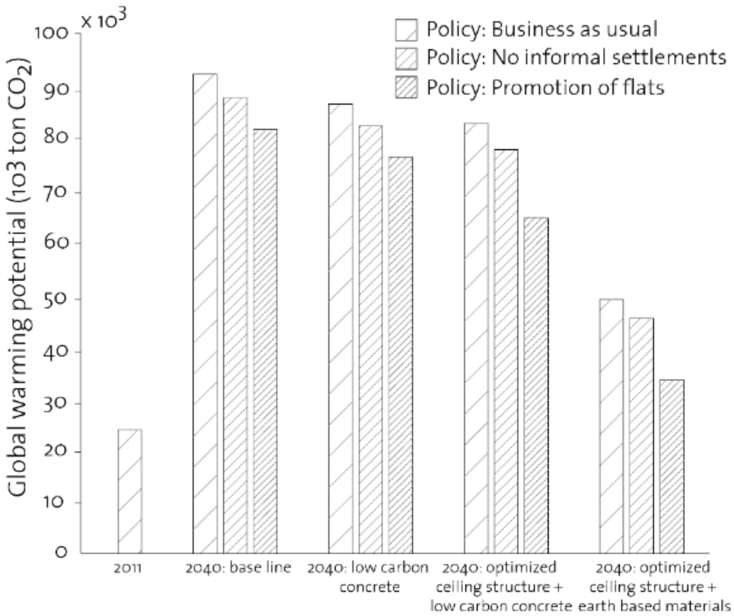

Figure 1: Total embodied GHG released in 2040

3.2 Visualization of building stock in 2040: comparison best and worst case

The proposed representation method helps to localize and track embodied GHG by breaking down the building stock into its components and small scale elements. It is important to note that the modified Sankey diagram developed in Figure 2 does not show one consistent unit but that from the first node to the second number of people per building typology are shown. From the second to the third node the links indicate mass of material per building element. This unit remains the same for the next step, a translation to type of construction material. The last links show amount of embodied GHG.

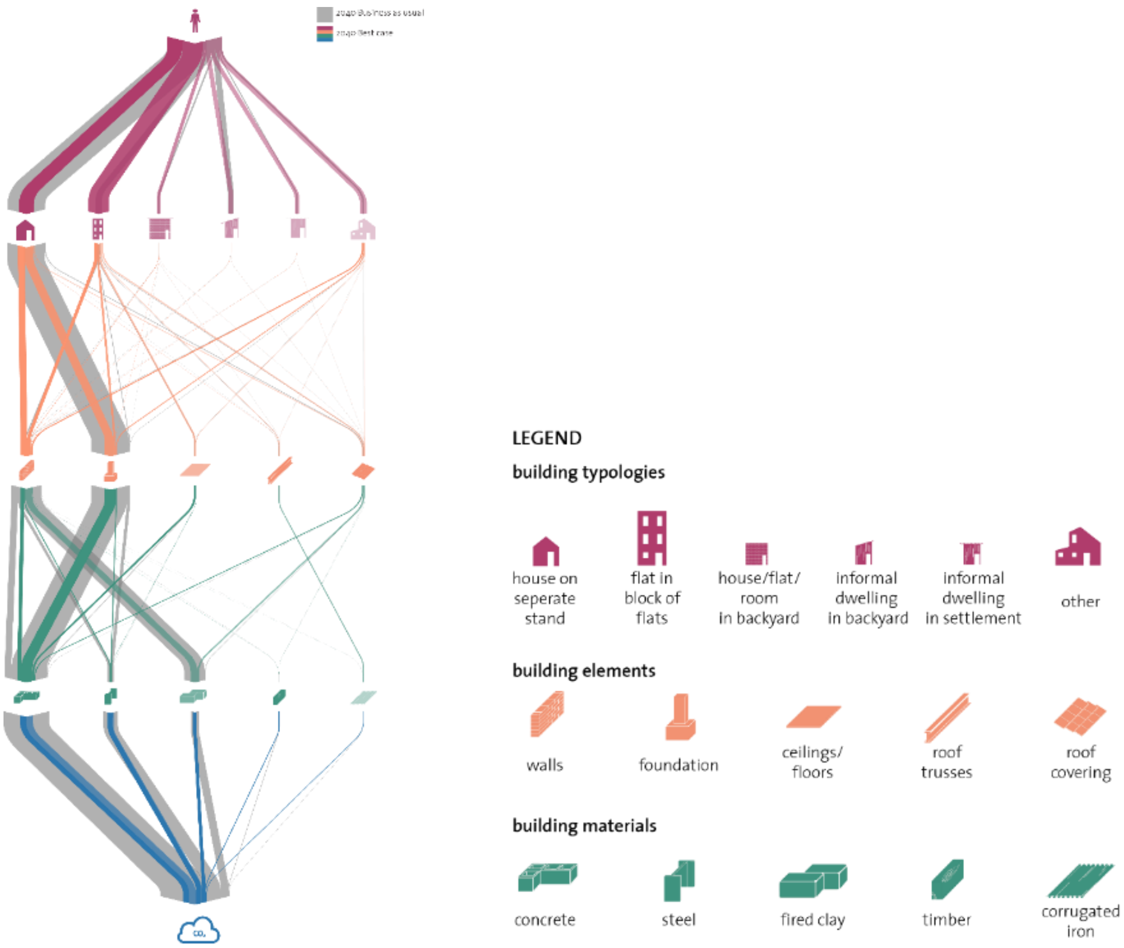

Figure 2: Revisited Sankey for the best (combination of promotion of flats with optimized floor structures and alternative building materials) and worst (BAU) case in 2040

Figure 2 shows the structure of the building stock for two extreme scenarios: the BAU and the one where optimized radical change in structure and materials are used as well as a shift towards multi-story buildings. The enormous amount of saving potential is clearly visible in the final GHG quantification. At the same time it can also be clearly explained that this is mainly due to the drastic reduction of the concrete for the foundation due to the shift from single houses to apartment. This is linked with two components. The first one is that there is less requirement of foundation per m^2 built in an apartment than in a freestanding single family house, and the second is that much less multi-story buildings need to be built to accommodate the growth of the population compared to when accommodated in single houses. This double effect induces that embodied GHG of the residential building stock could be reduced to one third compared with the BAU trend of current building techniques and housing habits.

4. DISCUSSION

The revisited Sankey diagram visually tracks construction material and associated embodied GHG of the built environment. There could be other types of visualization if we want to improve and understand, for example waste management or the potential for refurbishment. In that case, the focus would probably lie on the quality of construction and the age of buildings. However, these issues seem to be more relevant in developed countries where the current policy often wants to enable closed-loop material systems in the construction sector due to the fact that their cities are already built. Wiedenhofer and colleagues (2015) state that large share of material inputs are required for maintenance of existing stocks in the European Union and recommends that proper management of already built infrastructure will be crucial for future resource use. The Sankey-like diagram proposed in this study could help to understand the potential for refurbishments in such a context by linking age of the building, quality of construction and need for renovation with required amount of materials and energy.

5. CONCLUSION

The main purpose of this study was to propose a simple representation of the building stock and its drivers (population, building types, and materials) to be able to clearly understand the consequences of different potential actions. These actions being at the technical levels (type of materials, type of structure) as well as at the policy or urban planning level (building typologies). It is possible to use this representation and the results for transdisciplinary discussions and co-construction of pathways for decarbonization with all stakeholders involved in the production of the built environment.

Furthermore, the initial results show that urban planning actions will not have a significant impact if they are not combined with technical changes (materials and structure). Also, focusing on technological changes alone can only result in little action. It is the combination of both that can potentially stabilize greenhouse gas emissions related with the construction of the built environment in a context of a dramatically fast increase of the floor area demand in cities.

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