

## URBAN ENERGY LIFECYCLE: AN ANALYTICAL FRAMEWORK TO EVALUATE THE EMBODIED ENERGY USE OF URBAN DEVELOPMENTS

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### ABSTRACT

Given the dominating impact of the built environment on global carbon emissions, reducing operational energy use in buildings has long been considered a key strategy towards more sustainable urban development. In contrast, building energy use related to material production, construction, and demolition has been considered to be significantly less important. However, given the proliferation of low and even net zero energy buildings, more holistic life cycle assessment (LCA) of buildings becomes necessary. This paper hence proposes an analytical framework and a new CAD tool for Rhino3d to estimate the cumulative embodied energy content of an urban design proposal or retrofit scenario based on a simple design 3D massing model combined with an interactive online material database. The tool can be linked with traditional, EnergyPlus based operational energy assessments in order to predict the overall environmental impact of a proposed urban design.

### INTRODUCTION

Energy consumption based on fossil fuels and related carbon emissions to the atmosphere have become a widely accepted metric to quantify the environmental impact of the built environment. Given the recent exponential urban growth in developing countries, both the International Panel for Climate Change (IPCC, 2007) and United Nations Environment Program (UNEP, 2009) reports on Climate Change have identified the building sector as a main contributor responsible for more than 30% of those emissions. Both organizations have called for dramatic short and long term improvements in the building sector urging especially architecture and urban designers to facilitate this change. Governments have responded with overall carbon reduction plans such as the US Department of Energy's energy efficiency initiatives, and the European Union 2010/31 and 2012/27 Directives (European Commission, 2012). The latter promotes nearly zero-energy buildings and set a goal for a reduction of 80% emissions levels by 2050. These governmental energy reduction frameworks have triggered new goals for municipalities and professional organizations such as the New York City 2030 Plan or the AIA 2030 Commitment.

Over the past twenty years most efficiency efforts have focused on fuel consumption associated with the operation of buildings whereas energy use and carbon emissions stemming from life cycle phases such as production of materials, transport, and maintenance have been largely neglected. The reason for this omission is that those emissions tended to represent less than a 5% of the total impact in an assumed lifespan of 50 to 70 years (Hannon et al., 1978). The existing work on the relation between the so called embodied energy of materials and operation energy have suggested that even in very efficient buildings the latter is responsible for 80-90% of the building's overall energy use for assumed lifespans of 50 to 60 years (Ramesh et al., 2010). Sartori and Hestnes reached the same conclusion in a literature review of 60 cases and found an overall directly proportional relation between Operation energy increase and total Lifecycle energy increase (Sartori and Hestnes, 2007).

However the current trend towards long term sustainability goals combined with the appearance of nearly zero energy standards such as Passivhaus (1996), Minergie-P (2001) or Net-Zero Energy, and increasingly restrictive energy codes, have led to a reconsideration of the embodied energy (or carbon) of materials in buildings. In this context, embodied energy can make a difference when comparing design options, and even become the main contribution in the total lifecycle energy. Thormark reported that embodied energy could reach a 40% of the total energy in very low energy housing (Thormark, 2002), and a critique of the process approach to embodied energy calculation for materials of Stephan, Crawford and Myttenaere referred vales of 60-70% of the total for embodied energy in an analysis of urban density studies (Stephan et al., 2011).

The evaluation of these additional energy inputs through Lifecycle Assessment (LCA) methodologies allows for a more holistic reduction of the impact of buildings for both new construction and retrofit scenarios. While energy use occurring during building operation is strongly dependant on occupant behaviour and energy systems management, embodied energy choices are (with the constraints of economic realities) nearly exclusively a consequence of architectural design and material selection.

Consciously or not, architects and urban planners are making key LCA related decisions during schematic design and design development. A number of LCA tools for buildings have been proposed in the past, such as Envest2 (UK), Eco-Quantum (Holland) Athena (Canada), or LEGEP (Germany). Envest2, Eco-Quantum and Athena are LCA only tools in which buildings are defined by components in a spreadsheet-based format, while LEGEP is an integrated assessment tool, which also performs other building analysis such as operation or costs. Erlandsson and Borg compared their performance identifying weaknesses in their time handling and user feedback aspects (Erlandsson and Borg, 2003), while Kohler described them not effective as design tools especially during the fast paced the early stages of a project (Kohler et al., 2010). According to the authors the main limitations can be summarized as follows:

- Modelling geometry becomes a slow and restricted, 'add-on' process, which does not allow for connections with the CAD tools commonly used throughout design.
- Analysis bases on a unique random lifespan, and is not able to take into account time dependence and handle scenario analysis.
- The scope of analysis is always limited to one building, without allowing for the analysis of urban planning proposals in which design decisions have an extensive effect, by setting the rules for a whole development.
- Their connection with material databases is not accessible to modellers who have to rely on general data of existing collections included in the tools.

In an attempt to tackle these limitations, this paper proposes a first parametric CAD-based LCA design tool. The tool has been developed as a plug-in for RHINOCEROS, a widely used CAD environment. It facilitates the fast analysis of standard urban massing models by automatically extracting material quantities and linking them to a custom online material database to assess the overall carbon impact of a design. Being RHINOCEROS based, the tool can be used for rapid parametric model generation and analysis. The tool is described in detail in this work followed by two example applications.

## METHODOLOGY

### Lifecycle energy analysis for buildings

LCA is the process in which material and energy inputs of a system are being quantified and evaluated in terms of their environmental impact in different categories, including global warming, water pollution or resource depletion. Usually these inputs are analysed in the phases of extraction and manufacture of materials, use, and disposal of the product. LCA

studies, regulated by ISO 14040 (2007), generally include four main phases: Goal and scope definition, lifecycle inventory (LCI), impact assessment and interpretation of results, and are widely used in industrial design. When applied to buildings in the construction sector, the diversity of materials, assemblies and systems generates numerous difficulties for its application, especially in scope definition, accounting and inventory phases.

With energy use and carbon emissions being the main current metrics in sustainable building design, the focus of the tool developed in this paper is Lifecycle Energy Analysis (LCEA), initially presented as a method for full energy building accounting (Adalberth, 1997) (Ramesh et al., 2010) which does not consider other impact categories. This particular methodology distinguishes between Operation (OE) and Embodied Energy (EE) inputs and establishes three boundary levels (Figure 1): Manufacturing, Use and Demolition.

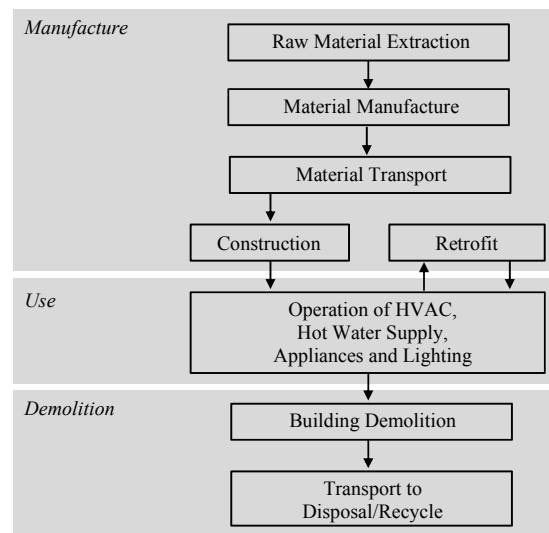


Figure 1 LCEA building phases diagram

While assuming the second place in importance of embodied energy in building design, the progressive reduction of operation energy as well as the need for time based specific scenarios for long term evaluation require tools for its evaluation. LCEA methodology is employed as a base framework for the new CAD tool, presented in this paper to address those needs.

### Lifecycle embodied energy estimation method

The Embodied energy inputs happen in the three previously defined phases of the lifecycle, and they are divided in three independent values: Initial EE ( $EE_I$ ), Recurrent EE ( $EE_R$ ) and Demolition EE ( $EE_D$ ). The first includes the extraction and manufacture of materials, their transportation to the site and the construction energy, and its value is calculated using Equation 1:

$$EE_I = \sum(m_i M_i + d_i T_i v_i) + C a_b \quad (1)$$

Where  $M_i$  is the content of energy of manufacture per unit of material  $i$ ,  $T_i$  the content of energy per unit of distance and volume of material  $i$ , and  $C$  the energy used in the construction of the building. In the current state of the tool and in this paper Transportation energy ( $T$ ) and construction energy ( $C$ ), with a very small contribution to total EE, are not yet considered.  $EE_R$  refers to those specific material inputs for maintenance and eventual retrofit of the building and is obtained with Equation 2, while  $EE_D$  considers the energy used in the disassemble process by built area as shown in Equation 3:

$$EE_{R,y} = \sum(m_i M_i + d_i T_i v_i) R_y \quad (2)$$

$$EE_D = D a_b \quad (3)$$

Where  $R_y$  is the rate of maintenance of the material for the year  $y$  considered, and  $D$  the energy spent in demolition per unit of built area. The total EE of the building for a specific year  $y$  is obtained through Equation 4 (plus the value of  $EE_D$  if  $y$  is the last year of the expected lifespan):

$$EE_y = EE_I + \sum_0^y EE_{R,y} \quad (4)$$

Given this LCEA infrastructure, the CAD tool makes possible the connection of a 3d geometric model (From which  $m$ ,  $v$  and  $a$  are obtained) with a materials and construction database (which contains  $M$ ,  $T$ ,  $d$ ,  $R$ ,  $C$  and  $D$  values).

### CAD tool modelling framework

The LCEA CAD application developed for this work provides a tool set for the calculation of embodied energy by year values of a building, given a general massing, such as those used in an early stage of architectural or urban design. It is built on the CAD environment of Rhino3d and its parametric modelling application Grasshopper (McNeel, 2010). It employs an external open material database and allows for visualization and export of results. Figure 2 diagram represents the components in the tool set:

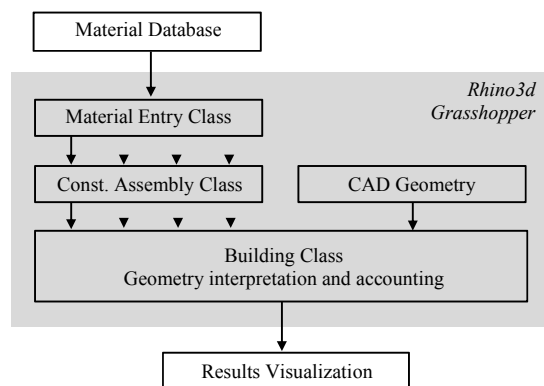


Figure 2 Modelling workflow diagram

The application is written in C#, and it fundamentally uses three object classes, (Material Entry, Construction Assembly, and Building Object) which

form a simplified BIM structure for the accounting of the geometry with separate properties for each level of information in the building (Table 1).

Table 1  
Building Modelling Components

CLASS	PROPERTIES
Material Entry	- Thickness and Density - Material Energy Content - Material Maintenance Rate
Construction Assembly	- List of Material Entries - Material Energy Content - Material Maintenance Rate
Building Object	- List of Construction Assemblies - Floor Height - Window to Wall Ratio (WWR) - Structural Density Ratio (STR) - Partition Density Ratio (PTR)

Building Object connects the geometry of one or more massing with the information of materials, by simplifying and accounting its components. The types of available Construction Assemblies required to define a Building Object are defined in two groups: Those also present in Energy+ operation energy simulations (Ground floor, Internal floor, External floor, Roof, Façade and Glazing) and those only necessary for EE calculations (Vertical Structure and Partitions). The process is equivalent to that of the existing Athena Spread sheet calculator, using CAD geometry as a source for accounting.

Annual results for one or more Building Objects are obtained as an array of energy values and can be introduced in the visualization component to obtain graphic three-dimensional analysis in Grasshopper. Values can be extracted for any lifespan by Building or by Area Unit, for the Building or any of the Construction Assemblies.

### Geometry simplification and accounting

The interpretation of the massing volumes represents the maximum simplification step of the tool, because requires the translation of simple volumes into floors, facades, etc. granting that way the capability of dealing with parametric models in short times. Similar techniques for volume interpretations have been used for LCA analysis of the built stock of cities often combined with GIS sources at a wider urban scale. David Quinn used simplified interpretation of urban 3d massing to identify clusters of building typologies based on Plot Ratio, Green Space Ratio, Built Area Ratio and Average Height in London (Quinn et al., 2011). In this case the structure and internal partition system density is defined by the user using the previously referred ratios (WWR, STR, PTR).

The translation happens in the creation of a building object in four steps: (1) Generation of Assembly objects from surfaces depending on their orientation (Figure 3), (2) Generation of glazing based on WWR, (3) Generation of Interior floors based on given Height, and (4) Quantification of vertical structure and partitions per floor based on provided ratios.

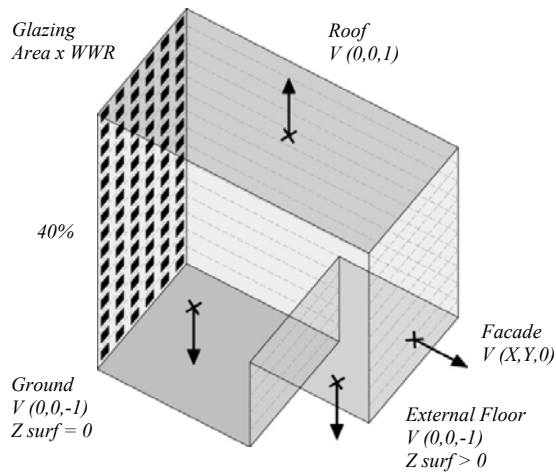


Figure 3 Geometry interpretation diagram

### Proposed material data online sourcing

The material database for LCEA proposed in this framework requires not only the Cradle to Gate Embodied Energy (CtG) values available in the existing databases for construction, but also specific Maintenance or Substitution Rates for each construction assembly. Both types of information present difficulties in terms of lack of reliable data especially for long-term predictions, and in terms of specificity in time and place for each project.

Embodied energy and carbon CtG values are present as aggregated average values in several international databases such as EcoInvent from Switzerland, (Frischknecht et al., 2007), Athena from Canada (Athena SMI, 2002), CES from UK (GRANTA, 2012) or ICE from University of Bath (Hammond and Jones, 2008). Their specific national scope questions their precision.

In the case of lifespan of construction materials and assemblies, the uncertainty is even larger requiring the prediction of use and maintenance scenarios. Filchakova used an adaptation of Lachat's Swiss reference data for the average lifetime of specific building components, for the analysis of Swiss built stock (Filchakova et al., 2009). For German buildings, Kohler proposes the use of the Appendix 6 of 'Leitfaden Nachhaltiges Bauen' in his LCA methodology studies (Kohler et al., 2010). Another source for service life information comes from insurance companies databases, such as the study for residential buildings developed by BLP for the UK National Audit Office in 2005.

The CAD tool uses a Text or CSV file as a material database which includes the name, density, CtG embodied energy and a maintenance Ratio from 0 to 1 for 1 to 100 years, following the format:

*Name, d (kg/m<sup>3</sup>), 0, EE<sub>y=0</sub> (MJ/kg), [...], n, EE<sub>y=n</sub> ;*

Being *n* the number of the year considered. It is an open and project specific database which can be defined by the user based on any of the others.

However, the fast exploration of options also in material solutions happening at the schematic phase of a project requires flexibility and the possibility of exploring local materials or particular retrofit scenarios. For that reason part of the development of the CAD tool included the creation of an Online Material Database (Still in a prototype state) which allows for the introduction and extraction of specific materials directly into the modeling space. Such a data infrastructure, allowing for specificity in each project will be a prerequisite for any LCA modeling tool, and is presented here as an area of future development.

### Testing of methodology in parametric model

In order to evaluate the use for design of the CAD tool for LCA Embodied Energy calculations, a parametric 3d model of a massing for a complex of apartment blocks (Based on Peabody terrace Apt. in Cambridge, MA) was built in Rhino3d, and defined both in terms of Embodied and Operation energy. Each building is formed by a lower longitudinal block and a tower and follows an interior distribution with access corridors in every two floors and secondary stairs, with a general floor height of 3m (Figure 4).

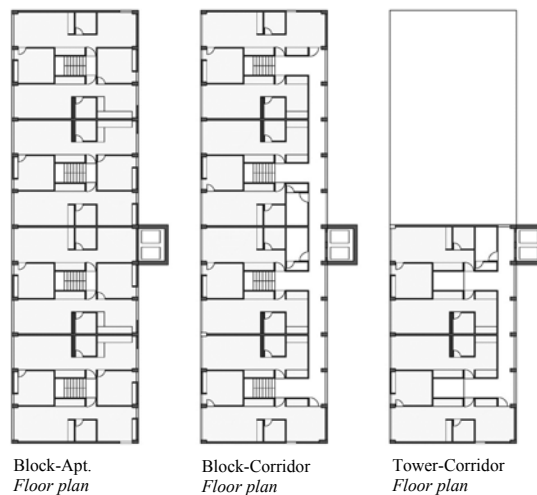


Figure 4 Floor plans of model building

The typology uses a reinforced concrete porticos system, with a double pane heavy construction façade, exposed concrete in interior ceilings, and wood framed partitions. Windows are double-glazed and the average WWR is 30%. The vertical structure ratio (STR) expressed in number of supports per m<sup>2</sup> is 0.05, and the density of partitions (PTR) in metres per m<sup>2</sup> in 0.50. Table 2 summarizes the composition of the assemblies built in the analysis parametric model. ICE database was used as a source for Embodied Energy data while maintenance rates were extracted from BLP materials durability study for residential construction.

Table 2  
Base model construction assemblies

ASSEMBLY	COMPOSITION
Façade	6 cm Prefab Concrete 8 cm Rock Wool 8 cm Brick Masonry
Roof	Waterproof 8 cm XPS insulation 4 cm Cement Mortar 30 cm Reinforced Concrete
Ground Floor	70 cm Reinforced Concrete 8 cm XPS Insulation 2 cm Cement Mortar 3 cm Terrazzo Flooring
Internal Floor	30 cm Reinforced Concrete 2 cm Cement Mortar 3 cm Terrazzo Flooring
Glazing	Double Glazing Clear Air filled Aluminium Frame
Partition	2x1.5 cm Plaster Board 2x4 Timber Studs every 70 cm
Vertical St	Reinforced Concrete 40x70 cm

Three different analyses were developed as part of this paper in order to test the CAD tool embodied energy calculation capabilities:

1. Single Building Geometry Test: The base case of the building model was evaluated by both a manual and a simulated geometry accounting process, in order to evaluate the tool error in geometry simplification.
2. Urban Parametric Geometry analysis: A multiple building urban parametric model was built in Grasshopper, which allowed for the variation of block dimensions. The tool was used for evaluating the Embodied Energy for different urban densities.

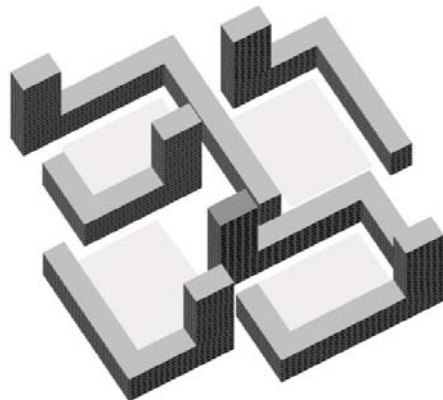


Figure 5 Parametric Urban Model Base

3. Urban LCEA Analysis: Based on the urban base parametric model the total energy lifecycle (Embodied and Operation) was calculated for scenarios of improvement of the building envelope, comparing their relative of total lifecycle energy.

For test 2, the parametric urban geometry model (Figure 5) was analysed for EE in three cases (A,B,C) with different construction materials for the

façade assembly. Within each case, three different urban density scenarios (Figure 6) (Defined by their site occupation ratio (SOR)) were modelled in order to establish the relative importance of the geometry against the material composition for EE, resulting in nine scenarios (Table 3).

Table 3  
Geometry parametric cases and scenarios

CASE	PARAMETERS	SCENARIOS
A. HEAVY	Heavy masonry façade Variable density	1. SOR 0.22 2. SOR 0.07 3. SOR 0.48
B. STEEL	Steel framing façade Variable density	1. SOR 0.22 2. SOR 0.07 3. SOR 0.48
C. WOOD	Wood framing facade Variable density	1. SOR 0.22 2. SOR 0.07 3. SOR 0.48

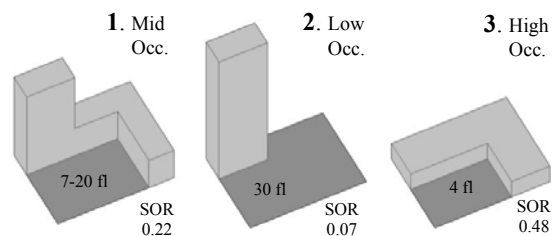


Figure 6 Urban density parametric scenarios.

For test 3, the parametric urban geometry model was analysed for EE and OE in an additional case (D) with a fixed geometry and three envelope performance scenarios (Table 4). Both forms of energy were added for a LCEA in order to evaluate the relative importance of the envelope improvement EE compared to the performance improvement achieved in OE.

Table 4  
Embodied/Operation LCEA cases

CASE	PARAMETERS	SCENARIOS
D. INSUL	Insulation Depth + Glazing Type	1. Insul. 2 cm 2. Insul. 10 cm 3. Insul. 18 cm

Operation energy simulation was developed for each scenario for Boston, using Energy+ (DOE, 2007) as simulation engine. Values for equipment, lighting and hot water energy intensity were obtained from average values for the state of MA. (RBECS Database, 2009)

The assumed fuel for Space Heating is Natural Gas while every other energy consumption including Space Cooling is based on Grid electricity. The conversion factors employed for the translation of End Use energy into Primary energy are specific for the energy mixture of Massachusetts. It is assumed a factor of 1.05 for Natural Gas and 3.34 for electricity (NSTAR, 2012).

## RESULTS

### Geometry test case: Single building model

The process of accounting for assembly quantities in the model building was developed both manually (with the exact sizes of partitions, supports and glazing) and in simulation with the tool (Using simplified ratios for the specific project). Both the quantity of m<sup>2</sup> and embodied energy per assembly have been compared, presenting negligible differences of 4% and 3%, respectively (Figure 7).

Façade, partitions and glazing seem to generate the principal error. Such analysis validates the use of the tool for this specific typology justifying further parametric analysis.

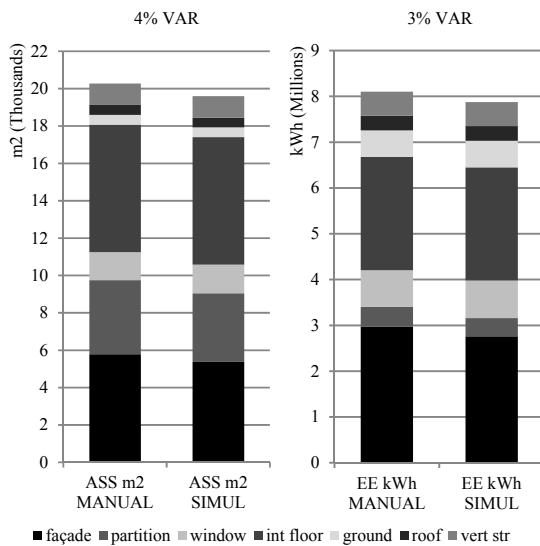


Figure 7 Manual vs. Simulated accounting comparison for assemblies (m<sup>2</sup>) and energy (kWh)

### Urban parametric model Embodied Energy

Three urban densities of SOR0.22 (Base block), 0.07 (Isolated towers), and 0.48 (Low rise) were modelled for cases A, B and C of façade construction. Embodied energy values for 50 and 100 years were obtained by building and by urban proposal. When analysing the results in kWh/m<sup>2</sup> for the three cases the following conclusions can be extracted from the comparison (Figure 8):

- The scenario with lowest occupation ratio (2) presents the lowest EE value at 50 years in every case. The highest value at 50 years corresponds to the highest occupation (3).
- The relative difference between density scenarios is more relevant the lower the EE of the façade case. In case C the difference between extreme densities is a 15% of the maximum.
- However, for high EE constructions the shape of the buildings in terms of density becomes irrelevant. In case B the difference between extreme densities is only of a 1%.

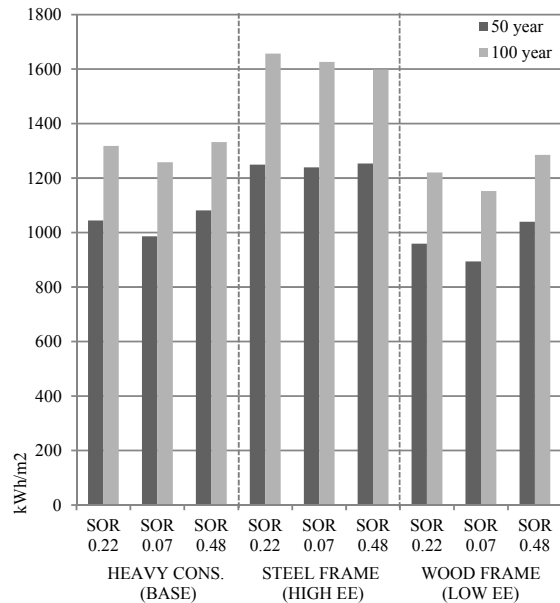


Figure 8 Embodied Energy in kWh/m<sup>2</sup> 50-100 year. Cases of Heavy Cons, Steel Frame and Wood Frame.

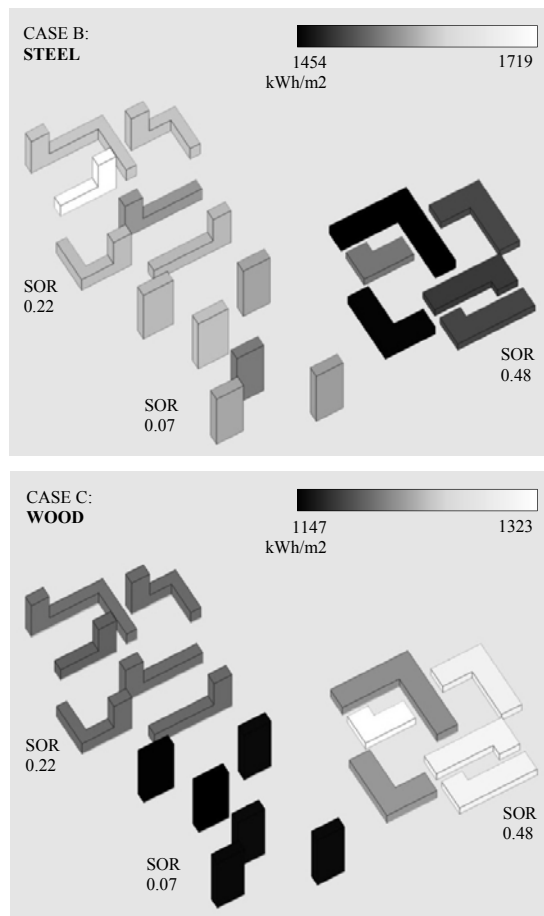


Figure 9 Parametric analysis caption from the tool. Embodied Energy in kWh/m<sup>2</sup> per building 100 year. Case B (Steel frame) and Case C (Wood frame)

While the previous conclusions were true for the general urban density models, the building-by-building analysis produced with the tool (Figure 9) showed how specific structures contradict the general trend. The tool test proves that the relevance of urban density and form on the EE content depends strongly on the energy intensity of the construction assemblies.

### Urban parametric model Total Energy LCEA

The existing model EE was analysed considering one geometry (SOR 0.22) and three envelope performance scenarios with increasing levels of insulation from 2 cm, to 10 cm (ASHRAE code compliance) and to 18 cm (Figure 10).

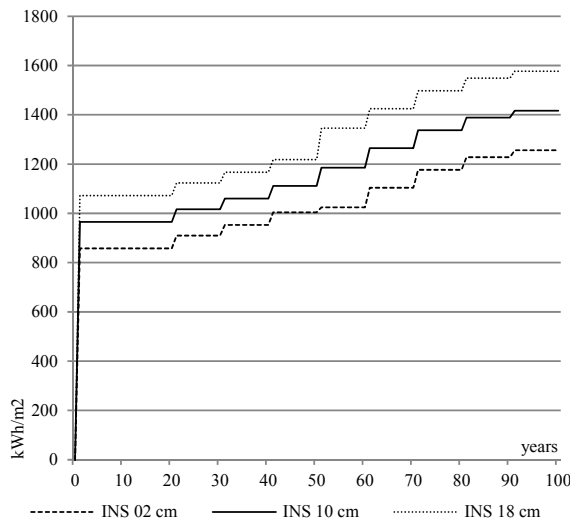


Figure 10 Embodied Energy by year in kWh/m2. ENVELOPE scenarios (2-10-18 cm insul.).

The addition to the yearly embodied and operation primary energy I the total LCEA (Figure 11) shows that the first scenario (2 cm ins. Lowest EE) becomes accumulates more energy consumed than scenarios 2 and 3 only after 6 and 8 years, respectively. However, between cases 2 and 3 the initial embodied energy difference of the additional insulation gives case 3 (Lowest Operation) a higher accumulated total energy for the first 48 years, cancelling the improvement in performance of the insulation.

Figure 11 confirms the hypothesis on which this third test was founded, namely that for rather inefficient buildings (very low insulation levels) operational energy is more relevant than embodied energy whereas beyond a certain insulation level the EE of the chosen insulation becomes the determining factor. Although not considered in this OE simulation, climate change future weather scenarios will significantly change the yearly operation consumption, requiring the use of morphed weather files based on predictions which could potentially reduce the relative relevance of OE in the complete LCEA.

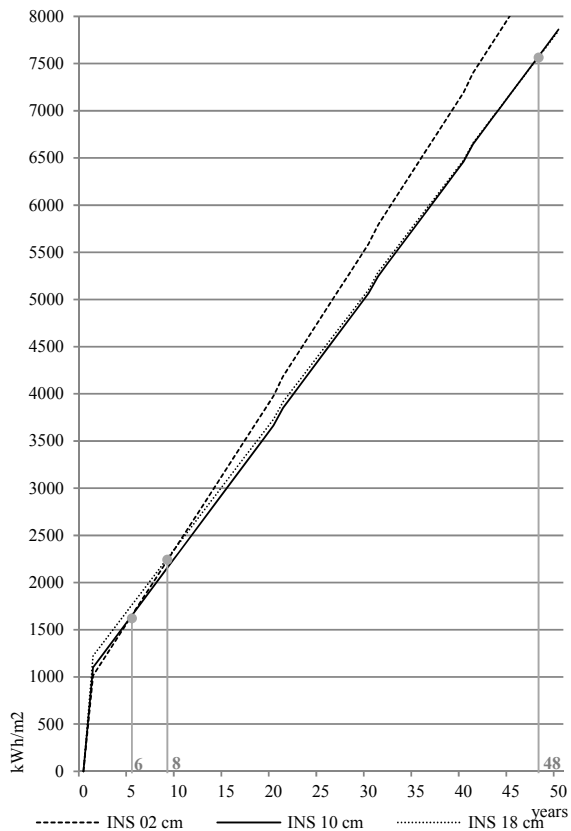


Figure 11 Total LCEA energy by year in kWh/m2. ENVELOPE scenarios (2-10-18 cm ins.).

## DISCUSSION

### Modelling and parametric design in LCA

The use of LCA provides a holistic way for analysing the environmental impact of a building through time, either in terms of energy, carbon emissions or other impact categories. Given society's increased emphasis on effectively reducing carbon emissions in the long run, LCA can help of governments and institutions to track their performances. However in order to introduce LCA based analysis a part of contemporary architecture and urban design, workflows have to be developed that facilitate this type of analysis within existing design workflows. This paper hence demonstrated an effective way to integrate LCA analysis within a widely used CAD environment plus parametric design editor. A user of the tool may base material sections for a building on detailed parametric studies. A remaining question is whether this type of analysis oversimplifies the problem and gives the designer a false sense of security. In other words, is the information provided by an LCA tool during schematic design, when many design decisions are still unrefined, reliable enough to provide meaning feedback? While this question deserved further investigations, the authors hypnotize 'yes' since the simulation input provided by Rhino to the LCA model is identical to what the ATHENA software requires in its EXCEL spreadsheet tool.

### Does it matter?

The LCEA developed in the paper has proven how the relative improvement of the thermal performance of the building envelope in an urban proposal became secondary after a certain insulation level is maintained. The question is how likely those admittedly small changes, that might happen over a decade from today, are to trigger any change in today's design practice. This question is of course identical to how well we – as a species – will be able to deal with climate change and to implement very long mitigation efforts. Effectively reducing carbon emission is a long-term project but so is any building that we construct and any neighbourhood that we plan.

### The need for a different database structure

The most serious caveat of this work is that even with the optimized LCA design workflow presented in this paper, how good are the underlying databases? Unfortunately, the current state of environmental databases for materials provides only rather general information and thus requires further improvement. While this paper does not *per se* address the question of how to improve the quality of existing material databases, the authors' vision for the online material database used by the tool presented is to provide an infrastructure that can be regionally organized, managed and controlled. The nature of the organization responsible for these database remains to be resolved going forward.

### CONCLUSION

This paper has explored the combination of existing LCA methodologies and databases for buildings with a parametric CAD environment. The resulting design tool allows architects and urban planners to consider question of LCA from the earliest design phases onward.

### NOMENCLATURE

$EE_y$  = Total emb. energy for year  $y$  (kWh)  
 $EE_I$  = Initial emb. energy (kWh)  
 $EE_{R,y}$  = Recurring emb. energy for year  $y$  (kWh)  
 $EE_D$  = Demolition emb. energy (kWh)  
 $m$  = Material mass (kg)  
 $M$  = Manufacture emb. energy (MJ/kg)  
 $d$  = Material density (kg/m<sup>3</sup>)  
 $T$  = Transport emb. energy (MJ/kg)  
 $v$  = Material volume (m<sup>3</sup>)  
 $C$  = Construction emb. energy (MJ/kg)  
 $a_b$  = Built area  
 $D$  = Demolition emb. energy (MJ/kg)

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