Available online at www.sciencedirect.com
ScienceDirect
Procedia Engineering 118 (2015) 507 – 514
Procedia Engineering
www.elsevier.com/locate/procedia

International Conference on Sustainable Design, Engineering and Construction

A framework to understand effect of building systems deterioration on life cycle energy

Albert Thomas[a,*], Carol C. Menassa[a], and Vineet R. Kamat[a]

[a] *Dept. of Civil and Environmental Engineering, Univ. of Michigan, 2350 Hayward Street, G.G. Brown building, Ann Arbor, MI 48109, USA.*

Abstract

The building sector accounts for nearly 41% of U.S. primary energy use. Various tools have been developed for estimating the embodied energy during the design and construction phase of a building. However, there is a lack of a comprehensive mechanism which can measure and control the energy flow occurring during the operation phase of a building. Loss of efficiency of building systems and deterioration of various building components can collectively reduce the performance of a building, which eventually results in more energy flow into a building in the form of more maintenance and replacement requirements, as well as, increased operational energy demand. This research analyses a building's deterioration mechanism and presents a system dynamics simulation based "Life Cycle Energy Framework" that couples material performance and energy simulation to arrive at an optimal maintenance and replacement cycle for major materials over the entire operation period of a building. The case study results indicate that the proposed framework can help various building stakeholders in understanding and limiting the energy usage of the building from the design phase until the end of life phase.

Peer-review under responsibility of organizing committee of the International Conference on Sustainable Design, Engineering and Construction 2015

Keywords: Service life; Building systems and deterioration; Operational energy; Recurrent embodied energy; System dynamics.

1. Introduction

A typical building requires different forms of energy during its life cycle- spanning from raw material production till demolition, with the energy requirements for all these stages heavily dependent on fossil based fuel reserves. The

* Corresponding author. Tel.: +1 734 548 1342; fax: +1 734 764 4292.
E-mail address: albertth@umich.edu

Peer-review under responsibility of organizing committee of the International Conference on Sustainable Design, Engineering and Construction 2015
doi:10.1016/j.proeng.2015.08.469

demand for providing better living facilities is on a surge and also the world population is expected to grow up to 9.6 billion by 2050 [1] which is nearly a 36 % increase from now. Thus, providing comfortable and sustainable living conditions to mankind is going to be a big challenge in the future for architects, the building construction industry, and facility managers.

Construction and operation of buildings requires energy, and currently, the building sector accounts for nearly 41% of U.S. primary energy usage [2]. The introduction of energy efficient equipment and technologies has increased the opportunities to reduce operating energy in buildings and now there is an increased focus towards reducing the embodied energy associated with building materials and their production processes [3]. Previous studies have shown the significance of embodied energy requirements in a building [4,5,6,7]. However, very few studies have dealt with a building's use phase, particularly focusing on the energy requirements for maintenance and material replacements. The primary aim of this study is to remedy this situation and develop a system dynamics framework to analyze various components constituting the total energy requirements in a building over its lifetime by analysing various material maintenance and replacement scenarios.

3. Background

The total energy requirements in a building consist mainly of operating energy and embodied energy. Operating energy is the energy expended in maintaining the internal environment of a building in liveable conditions. Embodied energy is the energy sequestered in building materials during production, construction, demolition and disposal [3]. Initial embodied energy (IEE) is the energy required to construct a building initially and recurrent embodied energy (REE) is the energy required to carry out the necessary material maintenance and replacements over the building's life time.

There are various country specific databases available for obtaining the embodied energy of various construction materials [2,4,8,9,10] and these have been extensively used to determine the embodied energy estimate of buildings during the initial design phase [11,12,13]. Embodied energy requirements during the construction phase [17] and during the end of life phase [5,18,19] were also investigated by various studies. Overall, the principles behind the calculation of embodied energy during the design phase are well understood. Various studies have been done in the past comparing REE with IEE [6,7,23], and the maximum of the recurrent embodied energy projected is about 7.3 times of initial embodied energy for a building lifespan of 100 years. Even though the results obtained across these studies varied, all of them established the fact that recurrent embodied energy value can be significant; and especially for high performance buildings where the operational energy is continuously brought down by means of energy saving measures, any measure for optimizing the embodied energy during the use phase thus becomes very important.

3.1. Deterioration of Materials

Deterioration of materials is the major factor which demands incurring recurrent embodied energy. In addition, ignoring required regular maintenance and material replacement can decrease the performance of a building, thereby resulting in an increased operating energy requirement. Research studies assessing the deterioration patterns of building materials and the service life of materials are very limited. For a material assembly consisting of more than two materials, concept of differential durability advocated that different materials in a material assembly will be possessing different durability which will result in an underutilized or wasted durability (embodied energy) during replacement [25]. Another work analysed various cementitious, synthetic and ceramic mosaic cladding materials used in buildings and found out that they primarily follow a linear or exponential deterioration pattern and also suggested a method to predict the service life based on the deterioration pattern [26]. A material's thermal performance is usually expressed in terms of R-Value and when a material deteriorates its R-value will decrease

[28]. ASHRAE 90.1-2013 defines the R-Value as the "reciprocal of the time rate of heat flow through a unit area induced by a unit temperature difference between two defined surfaces of the material or construction under steady state conditions" [27]. Regular maintenance and replacement of the materials play a key role in ensuring required R-Value for the materials and also to provide comfortable living conditions to the users.

The recurrent embodied energy incurred during the use phase of a building depends mainly upon the service life of the building materials used [21,25]. Deterioration due to various agents can bring down the service life gradually and also the performance of the material assembly made of specific materials. Based on the function, a building assembly can be classified into four major components which are structures, envelopes, finishes and building services**.** Different building assemblies can have different effects on the thermal performance of a building. For example, external walls were found to have the maximum impact on the thermal performance (increase in operating energy) of the building [29]. However, the impact of a maintenance and replacement schedule to the operating energy usage in a building is still unclear. In other words, can the recurrent embodied energy being spent on doing maintenance and replacement bring a benefit to the building owner in terms of the reduction in the annual operation energy of a building? And, If yes, by how much? The main goal of this research is to study this aspect and develop a framework which can help various building stakeholders in evaluating different scenarios to determine an optimum maintenance and replacement schedule.

4. Research methodology

In spite of the development of various tools for material selection for an environmentally sustainable design, there lacks an integration framework which can monitor the maintenance and replacement pattern of materials and its impact on the total life cycle energy requirements over a building's life time. The overall research methodology adopted for this research is presented in Fig 1 below.

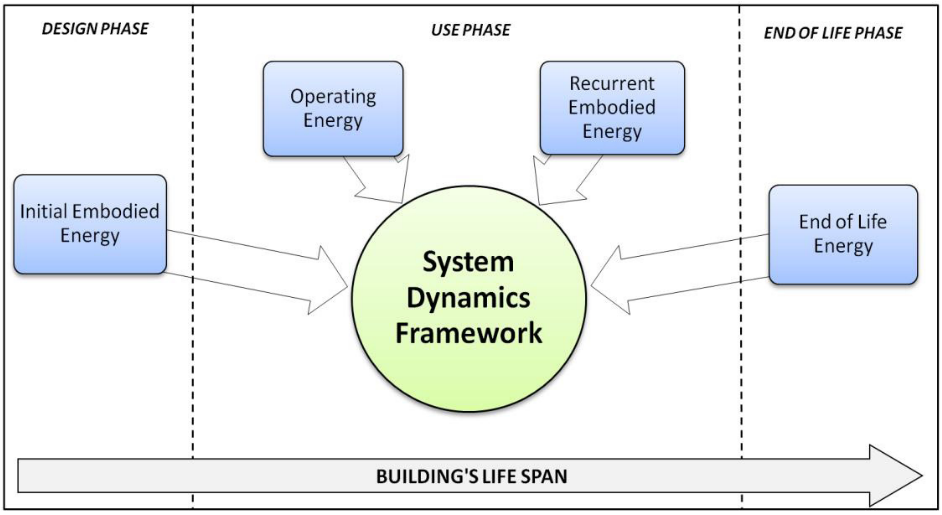

Fig. 1. Research Thematic Diagram

A building's typical lifecycle encounters incurring IEE, OE, REE and energy associated with the end of life phase. Energy analysis programs which are currently in use are mainly focused on analysing annual operating energy requirements in a building. But as observed from the literature, the embodied energy requirements in a building also need to be monitored continuously to achieve maximum savings; however, currently there lacks a framework which can monitor this embodied energy flow during the use phase of a building's life cycle. In addition, in a practical scenario, energy spent on maintaining a building component can increase the building's performance which can possibly result in decreasing the annual operating energy. In addition to this, during the demolition phase, recycling of materials can provide energy back into the system. Hence, computing a building's life cycle energy ideally demands a framework with a highly coupled approach analysing various feedbacks, cause and effect relationships and more importantly by bringing all components in the same environment to facilitate decision making. A system dynamics approach offers an ideal paradigm to analyse a complex system like this and is therefore adopted for this research. The simulation analyses are conducted using the Anylogic 7.0.0 software package.

4.1. System dynamics simulation

Fig 2 below depicts the system dynamics framework which simulates the entire life time period of a building assimilating the various energy requirements at each phase as mentioned in the earlier section.

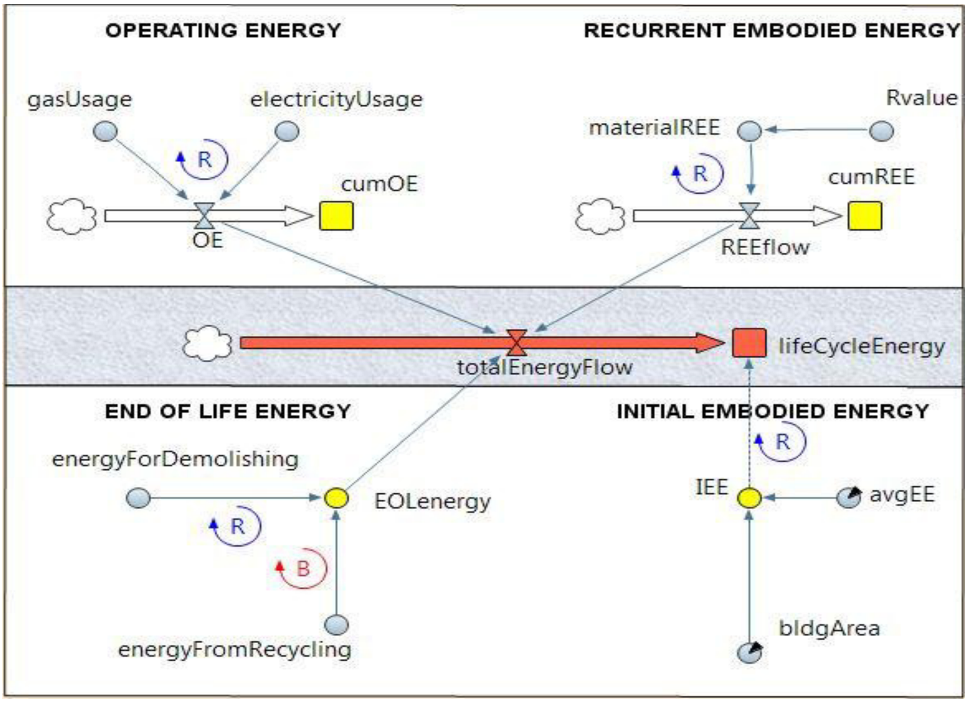

Fig. 2. System Dynamics Simulation

A typical simulation starts with the design phase of a building wherein IEE will be calculated and added to the life cycle energy stock as the initial value. As simulation advances, OE and REE will be required during the use phase. The OE section includes electricity usage and gas usage simulated over the life time. Energy Plus V 7-2-0, an open source energy simulation software provided by the U.S Department of Energy (DOE) is used for simulating the annual operating energy requirements of the building model. REE depends upon the material maintenance and replacement schedules for the building. The EOL section includes energy coming back to the grid through recycling the materials- which is represented as a balancing feedback and also the energy required for demolishing the building. During the course of simulation, all energy requirements get added to the lifecycle energy stock and completion of one full simulation period provides the complete energy requirements for a building in its entire life cycle.

4.2. Case study

An office building located in Chicago is selected as a case study model. The building has 12 stories with a basement and a gross area of 46,320 m^2 and is one of the EnergyPlus compatible models provided by DOE across different climate zones in the US. A period of 50 years is adopted as the lifetime for the analysis based on various similar studies [6,21,23,29]. An external wall assembly consisting of external stucco cladding, wall insulation, concrete wall material, interior gypsum finishing and windows is selected for illustrating the framework. The deterioration patterns of the building materials are adopted based on the typical patterns observed from the literature [24,25,26]. IEE, REE and EOL energy for the various materials and the model are calculated based on the various LCA related studies [2,5,30,31,33]. Two scenarios are considered for testing the developed framework. Scenario 1 considers only the replacement of materials over the life time, while Scenario 2 considers regular maintenance of the material along with replacement options.

4.2.1. Scenario 1:- Replacement of materials with no maintenance

In this scenario, no regular maintenance is assumed for the external wall assembly materials over the entire life time. But after a material reaches its service life, it is assumed to be replaced. At time of replacement, the performance of the material is assumed to reset to the initial installed performance level. Replacement rates of the materials are adopted from various literatures [26,29,32,34] and are summarised in Table 1 below. Wall concrete and insulation are projected to have a lifetime of more than 50 years and hence no replacement is assumed for these materials over the analysis period.

Table 1. Replacement pattern- Scenario 1

Material	SCENARIO 1: REPLACEMENT PATTERN OF MATERIALS																																																	
Stucco													■													■													■											
Insulation																																																		
Concrete																																																		
Gypsum																									■																									■
Windows																														■																				
YEARS	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50

■ - Replacement of material

4.2.2. Scenario 2- Replacement + Maintenance

For this scenario, in addition to the regular replacement pattern adopted in scenario 1, maintenance is also carried out for the windows every 10 years. The replacement and maintenance frequencies adopted for scenario 2 are indicated in Table 2 below.

Table 2. Replacement / Maintenance pattern- Scenario 2

Material	SCENARIO 2: REPLACEMENT AND MAINTENANCE PATTERN OF MATERIALS																																																	
Stucco													■													■													■											
Insulation																																																		
Concrete																																																		
Gypsum																									■																									
Windows										▓										▓										■										▓										▓
YEARS	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50

■-Replacement of material

▓-Maintenance of material

5. Results and discussion

This research analysed impact of two different replacement and maintenance scenarios on the operating energy over a building's life time. The results obtained are plotted in Fig 3 below.

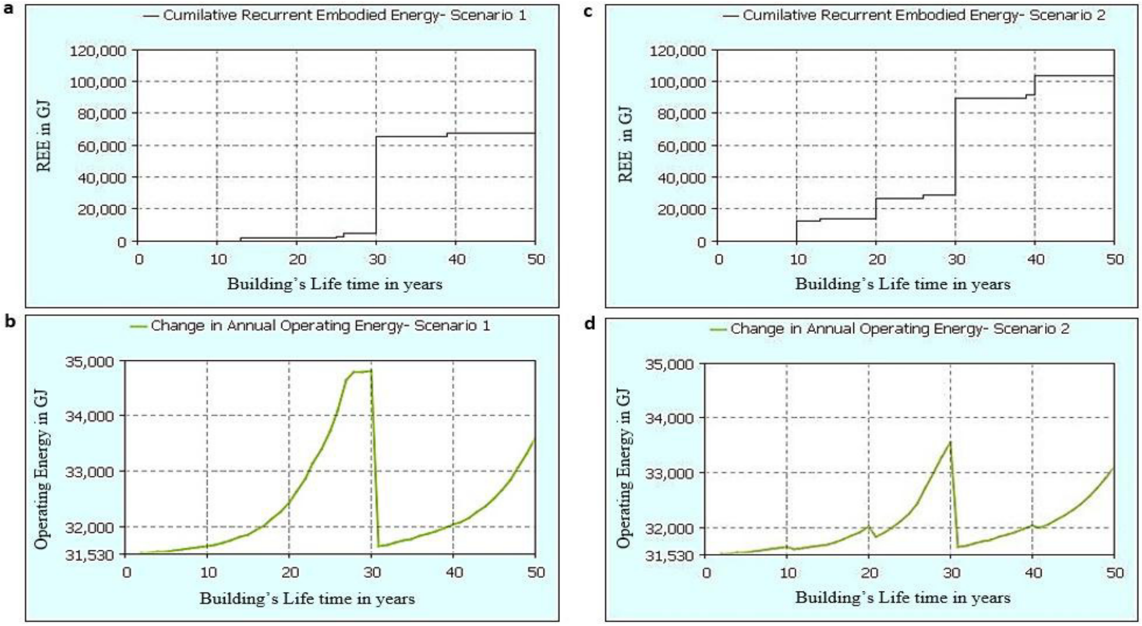

Fig. 3. (a) Cum REE increase-Scenario 1; (b) Yearly Annual OE change- Scenario 1; (c) Cum REE increase-Scenario 2; (d) Yearly Annual OE change- Scenario 2

Two graphs are plotted for each scenario. The REE values are plotted on a cumulative basis in the first graph and the corresponding year on year change in annual operating energy is plotted in the second graph. Both scenario1 and scenario 2 give a steady increase in the annual operating energy values over the life-time of the building until 30 years. Clearly, replacement of windows at 30 years incurs a high REE and has a big impact on the annual operational energy requirements in both scenarios. Also in scenario 2, frequent reductions in operating energy usage are observed whenever maintenance on windows is carried out at every 10 years. In addition, the peak operating energy value in scenario 2 is lesser compared to scenario 1. These initial results indicates that as the building elements deteriorate, the yearly operating energy requirement increases, which in turn can increase the total energy requirement over the building's life-time. It can also be observed that regular maintenance of building materials can bring down the operating energy requirements in a building. Performing various scenarios like this can result in an optimum replacement and maintenance schedule which can help realize substantial reductions in the operating energy.

6. Conclusions and future work

A building located at Chicago was selected as a case study in this research. Energy plus V 7-2-0 was used for energy simulations and Anylogic 7.0.0 was used for carrying out the system dynamics analyses. Operating energy usage for two scenarios based on different replacement and maintenance scenarios were explored. It is observed that performing regular maintenance and replacement can bring reduction to the annual operating energy in any building and quantifying this savings for different materials can be a big motivation for future studies in this domain especially for high performance building where the embodied energy is comparatively higher. However, the presented approach also has some current limitations. This work selected only external wall assembly for the analysis and in scenario 2, maintenance was considered only for windows. In reality, the performance of all materials in a building can affect the operational energy requirement and also maintenance is to be carried out on all materials of a building assembly. In addition, there are many other factors such as occupant behaviour, weather effects, and efficiency of equipment which can affect the energy use in a building which are currently being incorporated into the model by the authors. Cost associated with maintenance also is an important parameter to be considered in tandem with incurring an extra recurrent embodied energy. In the future, the authors will extend the scope of this research initiative by including the aforementioned factors to result in a fully developed building life cycle energy analysis tool.

7. Acknowledgments

The authors would like to acknowledge the financial support for this research received from the U.S. National Science Foundation (NSF) through the grant NSF-141855. Any opinions and findings in this paper are those of the authors and do not necessarily represent those of NSF.

8. References

[1] United Nations, World Population Prospects The 2012 Revision Volume I: Comprehensive Tables, (2013) pp 17-18
[2] United States Department of Energy (DOE), Building Energy Data Book. 1.1 Buildings Sector Energy Consumption. (2012) Washington, DC: US DOE ERRE.
[3] M. K. Dixit, J. L. Fernández-Solís , S. Lavy, C. H. Culp. Identification of parameters for embodied energy measurement: A literature review. Energy and Buildings, 42(8), 1238-1247.
[4] G. P. Hammond, C. I. Jones, Embodied energy and carbon in construction materials. Proceedings of the Institution of Civil Engineers-Energy,161(2) (2010) 87-98.
[5] C. Thormark. A low energy building in a life cycle-its embodied energy, energy need for operation and recycling potential. Building and environment,37(4), (2002) 429-435.
[6] R. J. Cole, P. C. Kernan, Life-cycle energy use in office buildings. Building and Environment, 31(4), (1996), 307-317.
[7] G. Treloar, R. Fay, P. E. D. Love, U. Iyer-Raniga, Analyzing the life-cycle energy of an Australian residential building and its householders. Building Research & Information, 28(3), (2000) 184-195.
[8] A. M. Moncaster, K. E. Symons, A method and tool for 'cradle to grave' embodied carbon and energy impacts of UK buildings in compliance with the new TC350 standards. Energy and Buildings, 66, (2013) 514-523.
[9] Athena Impact Estimator version 5, (computer software), Athena Sustainable Materials Institute, Ontario, Canada
[10] BEES, (Web Application), National Institute of Standards and Technology, (2010), Gaithersburg, USA.
[11] G. Capper, J. Matthews, S. Lockley, Incorporating embodied energy in the BIM process. CIBSE ASHRAE Tech Symp, (2012) 18 - 19 April, Imperial College, London, UK.
[12] G. Rossit, M. Lawson, Material LIFE: The Embodied Energy of Building Materials, <http://media.cannondesign.com/uploads/files/2012-09-21_Material_LIFE.pdf> (June 20, 2014)
[13] R. Shiftehfar, M. Golparvar-Fard, F. Peña-Mora, K. G. Karahalios, Z. Aziz, The Application of Visualization for Construction Emission Monitoring In Construction Research Congress (2010) pp. 1396-1405.
[14] Z. Alwan, P. Jones, The importance of embodied energy in carbon footprint assessment. Structural Survey, 32(1), (2014) 49-60.
[15] M. Asif, A. Davidson, T. Muneer, Life Cycle of Window Materials-A Comparative Assessment. Millenium Fellow School of Engineering, Napier University, Edinburgh <http://ohv.parks.ca.gov/pages/1054/files/uk%20window%20frame%20lca.pdf> (July. 1,2014)
[16] G. Weir, T. Muneer, Energy and environmental impact analysis of double-glazed windows. Energy Conversion and Management, 39(3), (1998) 243-256.
[17] M. Memarzadeh, M. Golparvar-Fard, Monitoring and visualization of building construction embodied carbon footprint using DnAR-N-dimensional augmented reality models. Construction Research Congress, (2012) 1330-1339
[18] S. Kara, S. Ibbotson, Embodied energy of manufacturing supply chains. CIRP Journal of Manufacturing Science and Technology, 4(3), (2011) 317-323.

[19] P. S. Vieira, A. Horvath, Assessing the end-of-life impacts of buildings. Environmental science & technology, 42(13), (2008) 4663-4669.

[20] S. Junnila, A. Horvath, A. A. Guggemos, Life-cycle assessment of office buildings in Europe and the United States. Journal of Infrastructure Systems, 12(1), (2006) 10-17.

[21] A. Rauf, R. H. Crawford. The Effect of Material Service Life on the Life Cycle Embodied Energy of Multi-Unit Residential Buildings. World SB14, (2014) October 28-30, Barcelona.

[22] R. Mora, G. Bitsuamlak, M. Horvat, Integrated life-cycle design of building enclosures. Building and Environment, 46(7), (2011) 1469-1479.

[23] R. Fay, G. Treloar, U. Iyer-Raniga, Life-cycle energy analysis of buildings: a case study. Building Research & Information", 28(1), (2000) 31-41.

[24] S. Y. Harris, Building pathology: deterioration, diagnostics, and intervention. (2001) John Wiley & Sons.

[25] T. Kesik, I. Saleff, Differential Durability, Building Life Cycle and Sustainability.In 10th Canadian Building Science & Technology Conference, (2005) Ottawa ON.

[26] I. M. Shohet, M. Puterman, E. Gilboa, Deterioration patterns of building cladding components for maintenance management. Construction Management & Economics, 20(4), (2002) 305-314.

[27] Standard, A. Standard 90.1-2013. IP Edition)—Energy Standard for buildings Except Low-rise residential buildings.

[28] Y. Ham, M. Golparvar-Fard, 3D Visualization of thermal resistance and condensation problems using infrared thermography for building energy diagnostics. Visualization in Engineering, 2(1), (2014) 1-15.

[29] R. H. Crawford , Isabella Czerniakowski, Robert J. Fuller, A comprehensive framework for assessing the life-cycle energy of building construction assemblies, Architectural Science Review, 53:3, (2010) 288-296

[30] Cannon Design. Material Life, Embodied Energy of Building Materials., < http://media.cannondesign.com/uploads/files/MaterialLife-9-6.pdf >(Jan. 1st, 2015).

[31] Athena Sustainable Institute, Cradle to Gate life cycle inventory for exterior stucco finishes, Ottawa, Canada October 2001.

[32] National Renewable Energy Laboratory, LCI Database < http://www.nrel.gov/lci/>(Jan. 1st, 2015).

[33] M. Jackson, Embodied Energy and Historic Preservation: A needed Reassessment. APT Bulletin, Vol 36, No. 4 (2005), pp. 47-52

[34] RS Means Company. Building construction cost data. RS Means Company (2014)