Quantifying the Embodied Environmental Impact of Building Materials During Design:
A Building Information Modeling Based Methodology

Roderick Bates[1], Stephanie Carlisle[1], Billie Faircloth[1], Ryan Welch[1]

[1]KieranTimberlake, Philadelphia, USA

ABSTRACT: This paper will review the challenges associated with environmental impact analysis during the design process, and the authors' effort to answer those challenges by developing a tool that pairs environmental impact data with building information modeling (BIM). It will review the tool's ability to reconcile the deviation in material quantities found in a built project relative to the simplified forms represented in a building model, and to link the material quantity data with environmental impact information. This paper will also review the results produced by the tool as the environmental impact of each element and option in a building model becomes apparent to the designer in real time, throughout design iterations and project phases. Finally, the paper will review examples from the authors' own architectural projects, which demonstrate the use of the tool for reducing the embodied environmental impact of building materials.
Keywords: Life Cycle Assessment (LCA); Building Information Model (BIM); Building Materials; Embodied Environmental Impact

INTRODUCTION

During their manufacture, use, and disposal, building materials consume significant natural resources and energy, resulting in the generation of environmental impacts. The quantity of glass, concrete, steel, insulation, and other materials found in both contemporary and historic building stock makes these impacts sizable. Annually, 24% of the total materials extracted from the lithosphere flow into "building material and construction" activities [1].

In the field of architecture, the primary environmental impact assessed to date is carbon emissions attributed to energy consumption of building operations, which accounts for approximately 40% of US annual energy production, and 32% of global annual energy production [2,3]. The energy consumption attributed to a building material's life cycle may at present be comparatively far less than operations energy, with current figures indicating that building materials represent 2-38% of a building's lifetime energy consumption depending upon building type and location [4]. However, range has increased to 9-46% for high performance buildings as a result of voluntary standards and stringent energy codes [5].

Voluntary standards such as LEED, Passive House, the 2030 Challenge, and BREEAM are drivers for reducing the annual and lifetime energy consumption of buildings during operation. Meanwhile, energy codes have become more stringent—increasing by 14% in the case of the residential International Energy Conservation Code and by 29% in the case of ASHRAE Standard 90.1 between 1975 and 2005 [6].

But alongside this trend of addressing operations energy consumption via voluntary standards and increasingly stringent codes, no companion movement has appeared to address the environmental impacts of building materials. The logical outcome of this is that the environmental impacts associated with operations energy consumption will decrease, while the impacts attributed to the life cycle of building materials will continue to increase—quite possibly to a point where materials are the dominant source of building-related environmental impact. Given the recent emergence of voluntary building standards to address the environmental impact of building materials (most notably in the United States with the 2030 Challenge for Products and the LEED NC V4 pilot credit MRpc63: Whole Building LCA), the practice of assessing and minimizing the environmental impacts associated with building materials is expected to gain more attention from clients, practitioners, and facilities managers [7,8].

However, at present no efficient means exists for a designer to assess the environmental impact of building materials during the design process. The methods and tools that do exist fail to readily integrate with design tools, most notably BIM.

Supplying environmental impact information during design permits a material selection process in which environmental impact can be considered alongside and concurrently with performance, maintenance, cost, and aesthetics. This need for environmental impact data in "real time" compelled the authors to develop a tool that provides the relevant data to those making material selection decisions at the same pace at which they make those decisions, within the BIM workflow.

CHALLENGES OF TRADITIONAL ASSESSMENT METHODOLOGY

Buildings present a challenging context in which to calculate environmental impacts. Not only are they complex entities composed of thousands of materials, each with their own constituent material pathways, flows and life cycles, but they are also highly tailored, individual tectonic expressions, balancing a host of functional, aesthetic and performance demands while negotiating the complexity of site and program [9]. In the fields of engineering, industrial and architectural design there is emerging consensus that Life Cycle Assessment (LCA) is the most successful tool to assess environmental considerations during the design process [4,10]. However, there is little consensus about how such calculations ought to be conducted in terms of analysis scope and resolution. The majority of published LCAs and other environmental impact studies are either conducted on simplified building typologies—focusing on "typical" building construction and understanding the relative contribution of building elements [11]—or they are conducted as post-mortem assessments with high resolution of data but no readily available baselines or comparisons [12]. While both techniques represent interesting exercises, we see these methodologies as having minimal applicability to the building design process due to their limited ability to answer questions in design phases and readily extrapolate data to future design projects.

Whole building LCA requires a critical examination of material and systems relationships and begins with an examination of scope and resolution—a formalized way of focusing on the most impactful items and on critical and comparable relationships [13,14]. Often, the assembly abstractions and assumptions in whole building LCA are made on the basis of volume or weight, falling largely in line with an analytical part-to-whole understanding of buildings and post-mortem building assessment in which a design can be seen as fixed, or in which the unique aspects of a design have been neutralized in order to reflect a "typical" case. While it is sensible to focus on impact-intense elements such as core and shell materials, detailed contribution assessments of building materials and design elements are needed to further building performance and help designers make sustainable material decisions [15]. A methodology is needed that is both compatible with conducting assessments while material and systems decisions are still in flux and with helping designers track and evaluate multiple options and iterations.

Continuous feedback regarding environmental impacts of design decisions is important for the same reasons that it is challenging. Not only do architectural designs change in resolution across design stages (from schematic design to design development and construction documentation phases), but the methods by which they are evaluated shift continuously as well. Questions asked in each stage change as material and systems decisions are subject to a constant review and revision, and the design of the building is further tuned and articulated. Architects and engineers have begun to tackle the paradox of increasing analysis while operating in environments of uncertainty in other areas of building modeling and simulation (energy modeling, costing, structural assessments, etc.) and have begun to address the need for tools that pull high-quality data analysis closer to the design process while making use of a BIM workflow.

When conducting such assessments, the authors found two primary challenges to integrating LCA with architectural design: 1) managing complexity and specificity of model inputs over project stages and 2) limitations in existing packaged material databases. Currently, there is no consensus on the scope or resolution of what constitutes a "whole building," making comparisons across assessments difficult and creating data-interpretation challenges due to the lack of rigorous and meaningful baselines.

Most existing tools and calculation methods take advantage of industry data on clearly identifiable and simple materials such as steel, concrete, glass, and wood. They ignore necessary co-products such as adhesives or finishes and simplify complex assemblies such as multi-layered or active curtainwalls, high performance membranes, and mechanical equipment—strategies that lie at the forefront of reducing operations energy [16]. While professional LCA tools such as SimaPro and GaBi allow for an exceptional level of detail regarding life cycle processes, material attributes, and assembly specificity, manual inputting of data and nuanced building up of custom entries is tedious and error prone for designers untrained in LCA methodology. Additionally, these tools do not connect readily to the BIM workflow [10].

While publicly and third-party verified data on building materials and products has increased in recent years, along with a push for greater transparency in the building material industry, such data remains out of reach for most designers due to its cost, complexity, or format. In practice, unless environmental impact information is understandable and accessible, it is very difficult to integrate into design decisions. A key limitation in present LCA methodology lies in the translation between the distant languages of LCA (calculated in weight and volume of discrete materials and chemical inputs and outputs) and the grammar of building construction and CAD drawings or BIM models (expressed through building assemblies measured in linear feet or square footage or through performance specs and loads). While industry data for materials such as steel, concrete, and ceramics are readily available, the number of processed construction material entries for products and assemblies such as structural members, door and window assemblies, flooring assemblies, or discreet finishes, coatings, adhesives, and fasteners is woefully inadequate. It is our understanding that to meet these challenges, new tools and assessment methods are required, ones that can meet the needs of designers and address the growing aspirations of the architecture, engineering, and construction industries to lower the environmental impacts of building and construction.

BIM-INTEGRATED TOOL DEVELOPMENT

In order to create an environmental impact assessment workflow that is compatible with the design process and capable of informing design decisions, environmental impact assessment tools must create data that are relevant (ask questions that are important to the architect), intelligible (make sense to designers) and transferable (operate on the same scale of resolution and decision making as the designer). Building on these ambitions, the authors developed the Real-Time Environmental Impact Tool (RTEI™) as a plug-in to Autodesk's Revit platform that allows users to associate BIM elements with environmental impact data from an external database (Fig. 1). Through a series of dialog boxes, a user builds take-off definitions, which express mathematical relationships between the abstract representation of assemblies in a Revit model and their physical counterparts in real construction so that RTEI™ can produce an accurate inventory of materials. Through this process, the user also identifies entries in an external database appropriate to each material, allowing RTEI™ to quantify environmental impact totals. Finally, the user can generate a set of reports that examines the contribution of each material or assembly to the total environmental impact across multiple impact categories. These reports may also be used to compare the cumulative environmental impact of alternative design options throughout the design process.

By working directly within a Revit model, RTEI™ presents several immediate advantages over conventional workflows for generating material inventories [17]. The take-off definitions and material associations one builds are not simply

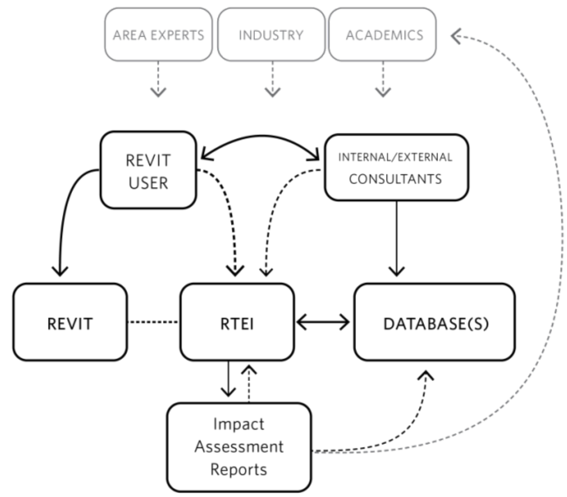

Figure 1: The role of RTEI™ in an environmental impact assessment workflow.

static calculations; they are dynamic formulas that are saved within each BIM element type definition, and they generate updates automatically with any changes to the model. Thus, any modifications to particular elements or additions of predefined element types will be reflected in new totals. Likewise, additions of previously undefined element types will be flagged, prompting the user to make incremental updates in RTEI™ as the model evolves. These definitions also permit the seamless transfer of information between Revit projects. If a wall type has been defined in one model, it can be imported into another, and all of its associated RTEI™ definitions will be transferred automatically. This transferability can have enormous value for architecture and engineering firms that maintain a library of standard BIM elements or new project templates. Once RTEI™ definitions are built for these elements; all projects that incorporate them will be able to take advantage of their embedded content without having to duplicate efforts. Only those element types that are custom to a given project would require modification.

While integrating environmental impact assessment into BIM offered advantages over other workflows, several challenges remained to address during the development of the RTEI™. These challenges included:

1. Scope: Defining the system boundary for a particular assessment.
2. Quantification: Accounting for the actual material represented by a Revit model at a level of detail appropriate to each phase of design.
3. Representation: Maintaining a database of materials that adequately represent the assemblies for a given project.
4. Relevance: Presenting results to the user in a manner that informs decision-making and captures embedded assumptions.

SCOPE

The scope of environmental impact assessments vary significantly depending on the context of the design objective. The comparison of two flooring finishes, the comparison of multiple design options, and the benchmarking of a whole building all require careful consideration of what building materials and life cycle stages are to be included in each assessment [14]. RTEI™ provides an interface for defining a system boundary that leverages several features intrinsic to Revit: Categories, Worksets, and Design Options. Revit contains several built-in Categories, such as floors, walls, ceilings, and doors, allowing users to easily isolate particular features of the model that are salient to a given question. However, Categories do not necessarily distinguish between other features of interest, such as a building's core and shell exclusive of interior partitions. We have therefore adopted Revit's Worksets feature as another selection filter, which allows users to partition model elements into bins based on their function or location. Finally, Revit's Design Options partition a model into commensurable sets of mutually exclusive elements, providing a natural framework for comparative studies.

Once the scope of assessment has been established, RTEI™ displays a project browser containing all of the BIM elements that meet the selection criteria (Fig. 2). These elements are organized in a tree containing Design Options at the top-level, followed by Categories, Family Types, and their constituent Revit materials. This structure allows users to easily navigate between similar assemblies, while allowing them to define the same material differently depending on its use in a given assembly. As the project browser provides a complete list of BIM elements falling within the system boundary, it provides a natural context for gauging completeness of the definitions. Hence, we chose to incorporate color-coding for each node in the tree so that the user can readily track which items remain to be defined.

In most cases, the Revit materials defined for a given assembly do not constitute a complete inventory of actual architectural materials. Caulks, paints, adhesives, and sealants are but a few of the accessories and co-products that are not typically modelled in BIM practice but nonetheless may be substantial contributors to the building's environmental impact, particularly with regard to indoor air quality, and should therefore be included in the system boundary [18]. We have identified two ways in which these more elusive materials may be accounted for in RTEI™. In cases where a co-product's use is readily predicted by the presence of a given substrate, we have attempted to bundle these materials together into a single entry and provide remarks on the system boundary (e.g. gypsum wallboard, inclusive of waterborne painted finish). In other cases, where a co-product is normally required whose quantity is not readily predicted by the quantity of substrate, we have used these remarks to inform the user to add an accessory material manually.

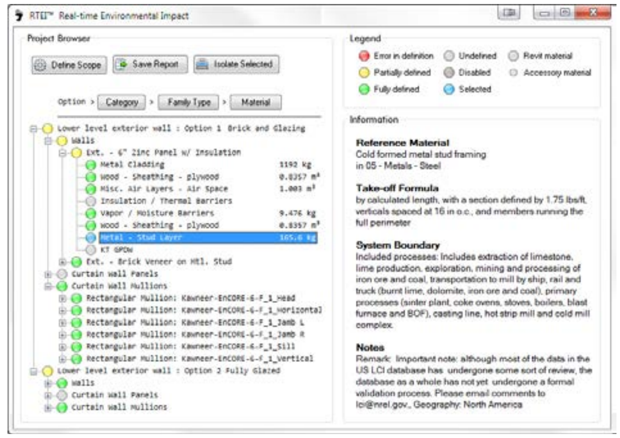

Figure 2: RTEI™ Project Browser dialog with remarks shown for a "Metal – Stud layer" entry.

QUANTIFICATION AND REPRESENTATION

In addition to accounting for materials that are not modelled explicitly, RTEI™ must resolve the discrepancies encountered between the abstract BIM representation of materials and the actual material volume of their physical counterparts. Depending on the context, a material may be accounted for most accurately by its modeled volume (e.g. concrete and masonry); modeled surface area (e.g. sheet goods and membranes); or modeled length and referenced cross-sectional area (structural framing and mullions) (Fig. 3).

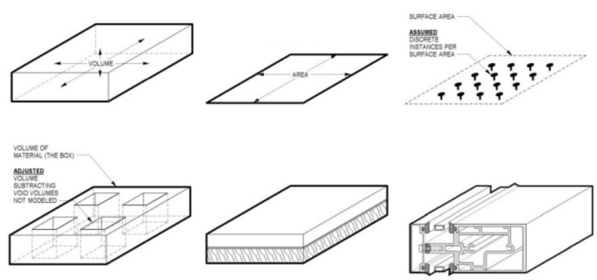

Figure 3: Various representations of material assemblies.

The RTEI™ material definition dialog attempts to resolve this by guiding users to develop a take-off formula that is consistent with both the Revit family and the chosen reference material (Fig. 4). For instance, after the user assigns the reference material "cold formed metal stud framing" to a metal stud layer, the material definition dialog prompts the user to select "by calculated length" as the take-off method because stud framing is not typically modelled explicitly in Revit. The user is subsequently prompted to load a standard

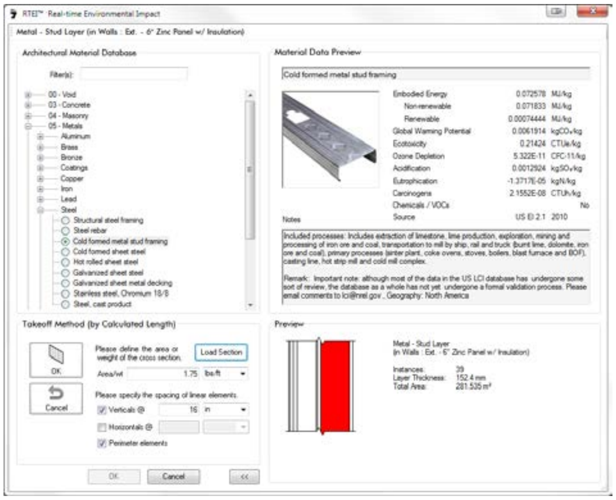

Figure 4: RTEI™ material definition dialog.

stud section and specify a typical spacing. Through this process, the user is effectively defining a take-off formula that is saved back to the Revit model. The total quantity of material and the take-off formula are displayed for reference alongside each completed entry in the project browser so that the user can easily double-check prior work. Implicit in the grouping of co-products into a single entry is the capacity to extend bundling to address the various levels of detail encountered across design phases. While the previous example presumes that the building design has evolved to a point at which the Revit model contains wall types with well-defined layers, it is not unreasonable to assume that a project team may work with more generic model elements in pre-schematic and schematic design phases. Thus, bundling entire systems together into common sets of flooring, structure, envelope, and fit-out types could serve as a useful means of applying RTEI™ to a model in which only the generic building mass and floor areas are defined. One could thereby assign the envelope to be 60% "R-20 insulated metal panel" and 40% "standard curtainwall glazing" and the floor structure to be "lightweight concrete on steel deck and steel framing (typical office loading)."

The paucity of regionally-specific and product-specific data appropriate to the building industry presents a significant challenge to development of environmental impact assessment tools intended for designers [1,4,10,14]. We must therefore ensure that users are provided with reference materials that not only reflect the system boundaries appropriate to their chosen scope (in terms of life cycle stages and required co-products) but also capture the broad diversity of global manufacturing and construction practices. To that end, the authors developed a proof-of-concept database consisting of approximately 400 architectural materials and assemblies common to several of our projects. These entries draw from EcoInvent v2 [19], US LCI [20], and US-EI 2.2 [21] LCI databases and have been processed in SimaPro to account for cradle-to-gate life-cycle stages. Processing of LCI information is a necessary step required to build up a robust data set of architecturally specific materials and related LCIA results according to accepted characterization schemes TRACI2, IMPACT, BEES, etc. While our present database is functional for development, it is our intent for the commercial version to be managed and maintained by a professional LCA database provider.

RELEVANCE

While architects may use the tool to access individual entries in a casual manner through the project browser, the RTEI™ tool facilitates the production of customizable impact assessment reports for more formal analysis. Output reports can be generated to answer specific design questions, with a corresponding scope and boundary clearly articulated. For example, the tool can generate output reports on the material quantities and corresponding impacts for the entire building (allowing users to interrogate contributions of individual groups or assemblies) or compare multiple Design Options. Users may specify characterization schemes and impact categories that fit with their project's goals and priorities. Assembly contribution assessments may be broken down in a number of ways (according to Revit Family Types, Categories, MasterSpec division, material entity, Workset) to facilitate targeted question asking and produce actionable data. RTEI™ maintains a complete itemized breakdown of these associations for each BIM element, so there is great flexibility in tailoring such output charts to the given research goal.

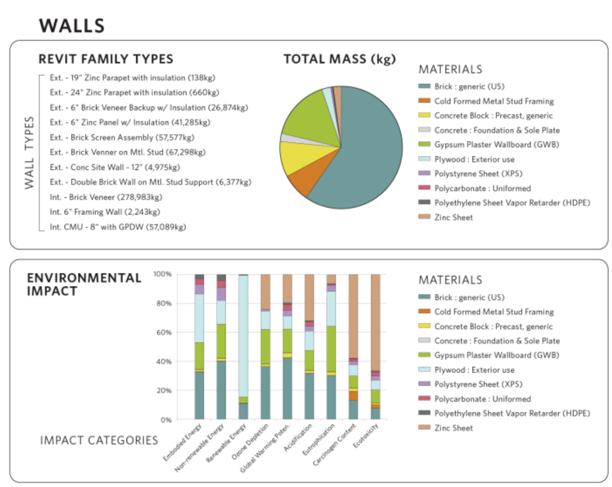

Figure 5: This assessment of wall types in the design of Building 7R shows the relationship between Revit family types, material breakdowns by weight, and environmental impacts.

For instance, an examination of wall assemblies in the authors' design for Building 7R demonstrated that zinc sheet goods were the majority contributor to carcinogens and ecotoxicity despite accounting for less than 3% of the weight of all wall materials (Fig. 5). The balance of detailed, quantifiable outputs with ease of data interpretation allowed for a close evaluation of material selection at the resolution of design decisions.

While this example illustrates the potential value of BIM-integrated environmental impact assessment, further development of output reporting is needed before RTEI™ can be used effectively by a designer untrained in LCA practice. In particular, the authors recognize the importance of communicating the limitations in data availability, resolution of database entries, and uncertainty factors along with remarks on system boundaries. Output reports presently produce results in numerical and graphical form, performing calculations and reporting data in compliance with ISO specifications (ISO 14040 and 14044).

CONCLUSION

Through the development of the Revit-integrated RTEI™ tool, the authors developed a means by which building designers can account for the environmental impact of building materials during the design and project delivery process at a pace commensurate with design optioning and iteration. Through BIM integration, the tool effectively makes the environmental impact of materials apparent at the time of their selection. This significant shift from current practice may permit the project team and project stake holders to consider environmental impact information concurrently with other material selection decisions such as performance, cost, maintenance regimes and aesthetics. It is anticipated that the widespread use of this tool by the architecture community would allow the decrease in building operation energy consumption to be matched by a similar decrease in the embodied environmental impact of buildings.

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REFERENCES

1. Bribián, I.Z., Capilla, A. and A. Uson, (2011). Life cycle assessment of building materials: Comparative analysis of energy and environmental impacts and evaluation of the eco-efficiency improvement potential. *Building and Environment*, 46(5): p. 1133-1140.
2. United States Department of Energy (2012). Building Energy Data Book: 1.1 Buildings Sector Energy Consumption. Washington, DC: US DOE ERRE.
3. International Energy Agency. FAQs: Energy Efficiency. [Online], Available: http://www.iea.org/aboutus/faqs/energyefficiency/ [8 May 2013]
4. Bribian, I.Z., Aranda A., and S. Scarpellini, (2009). Life cycle assessment in buildings: State of the art and simplified LCA methodology as a compliment for building certification. *Building and Environment*, 44(12): p. 2510-2520.
5. Sartori, I., Hestnes, AG., (2007). Energy use in the life cycle of conventional and low energy buildings: a review article. *Energy and Buildings*, 39(3): p. 249-257.
6. United States Department of Energy (2008) Energy Efficiency Trends in Residential and Commercial Buildings. Washington, DC: US DOE EERE.
7. Architecture 2030. 2030 Challenge for Products. [Online], Available at: http://architecture2030.org/2030_challenge/products [08 May 2013]
8. United States Green Building Council. MRpc63 documentation and questions. [Online], Available: http://www.usgbc.org/credits/mrpc63-aq [8 May 2012]
9. Quale, J., Eckelman, M.J., Williams, K.W., Sloditskie G. and J. Zimmerman, (2012). Construction Matters: Comparing environmental impacts of building modular and conventional homes in the United States. *Journal of Industrial Ecology,* 16(2): p. 243-253.
10. Millet, D., Bistagnino, L., Lanzavecchia, C., Camous, R., and T. Poldma, (2007). Does the Potential of the use of LCA match the design team needs? *Journal of Cleaner Production*, 15(4): p. 335-346.
11. Ortiz, O., Castells, F. and G. Sonnemann, (2009). Sustainability in the construction industry: A review of recent developments based on LCA. *Construction and Building Materials,* 23(1): p. 28-39.
12. Verbeeck, G. and H. Hens, (2010). Life cycle inventory of buildings: a contribution assessment. *Building and Environment,* 45(4): p. 964-967.
13. Tillman, A., Ekvall, T., Bauman, H. and Thomas Rydberg, (1994). Choice of system boundaries in life cycle assessment. *Journal of Cleaner Production*, 2(1): p. 21-29.
14. Crawford, R., (2011). *Life Cycle Assessment in the Built Environment.* London: Spon Press, p.43.
15. Blengini, G.A. and T.D. Carlo, (2010). The changing role of life cycle phases, subsystems and materials in the LCA of low energy buildings. *Energy and Buildings,* 42(6): p. 869-880.
16. Kellenberger, D. and H.J. Althaus, (2009). Relevance of simplifications in LCA of building components. *Building and Environment,* 44(4): p. 818-825.
17. Scheuer, C., Keoleian, G.A., and P. Reppe, (2003). Life cycle energy and environmental performance of a new university building: modeling challenges and design implications. *Energy and Buildings*, 35(10): p. 1049-1964.
18. Yu, C. and J. Kim, (2011). Building Environmental Assessment Schemes for Rating of IAQ in Sustainable Buildings. *Indoor and Built Environment,* 20(1): p. 5-15.
19. Frischknecht, R., et al., (2005). The ecoinvent database: Overview and methodological framework. *International Journal of Life Cycle Assessment*, 10(1): p. 3-9.
20. Trusty, W. and M. Deru, (2005). The US LCI database project and its role in life cycle assessment. *Building Design and Construction,* 5: p. 26-29.
21. EarthShift, US-EI database. [Online] Available: http://www.earthshift.com/downloads/US-EI_database.pdf [08 May 2013]