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## **Life-Cycle Performance Framework for Building Sustainability: Integration Beyond Building Science**

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### **ABSTRACT**

In spite of the progress in the development of methods and tools to support sustainable building design, there is still a lack of a formal method to bridge the “no man’s land” gap between the traditional building engineering disciplines, and between these and the architecture, to achieve the level of building integration required for sustainability. The framework described in this paper is an attempt to develop such a method. The framework, grounded on building science, facilitates a comprehensive assessment of the life-cycle performance of buildings and building systems, by enabling multiple function-performance factors of a building to be addressed iteratively. Quantitative methods and test protocols can be incorporated into the framework for assessing the long-term viability of proposed solutions. The organization of the underlying principles of building life-cycle performance described in this paper will hopefully conduct to a more integrated treatment of buildings in research, education, and practice.

### **1. INTRODUCTION**

The “century of the environment” has brought new challenges for engineers to come up with creative approaches for minimizing the use of natural resources (i.e. doing more with less) and maximizing the use of renewable resources, while optimizing whole engineered system’s long-term functionalities (i.e. minimizing waste). These challenges are forcing engineers to leave their discipline silos and search for synergies with complementary disciplines with the common goal of sustainability. This paper addresses only the environmental aspect of sustainability.

The quest for sustainability has raised public awareness on the role of buildings as major direct and indirect stressors of the natural environment. A life-cycle view of buildings is now promoted, although far from formal practice, and project dimensions that were overlooked in the past are now relevant for the success of a project. As a result, project teams have become larger and project requirements have become broader and more difficult to fulfill due to a lack of robust connections between the traditional engineering disciplines. Such connections can only be established on a solid foundation that combines the principles of thermodynamics, the applied physics and interdisciplinary character of building science. Most of these connections already exist. However, they are not apparent to building researchers and practitioners. This paper aims at uncovering these connections to make them explicit, as well as the new connections that are emerging to support an integrated approach to building sustainability.

Frameworks are qualitative organizing principles for analyzing a system. The framework presented in this paper is a systems integration framework, as opposed to the integrated design process (IDP) framework developed by IEA

(2003) and iSBE (2007) that are process integration ones. Careful consideration has been given, however, to make the proposed framework compatible with process integration ones. The framework presented in Figure 1 describes three levels of integration: I) Strategic level, II) Systems level, and III) Natural environment level, that are required for achieving a fourth level of IV) Temporal life-cycle integration. The integration levels are coupled with the main tasks of a typical iterative synthesis-analysis-optimization (SAO) design process at the right of Figure 1: strategic level integration involves analysis and optimization of integrated solutions rather than individual components, and the systems and natural levels of integration involve synthesis and analysis. Expectedly, intensive simulation and optimization will also be conducted at the latter two integration levels. However, the results of these will be aggregated and evaluated within long-term performance assessment methodologies such as life-cycle assessment (LCA), and life-cycle cost analysis (LCC).

The SAO process indicates that the interactions between the different levels of integration are iterative rather than sequential to maintain the project focus, validate its strategies, and re-evaluate the performance targets. However, critical junctures at the transitions between the levels of integration need rigorous attention. The remainder of this paper will describe each integration level of the framework focusing on the building enclosure.

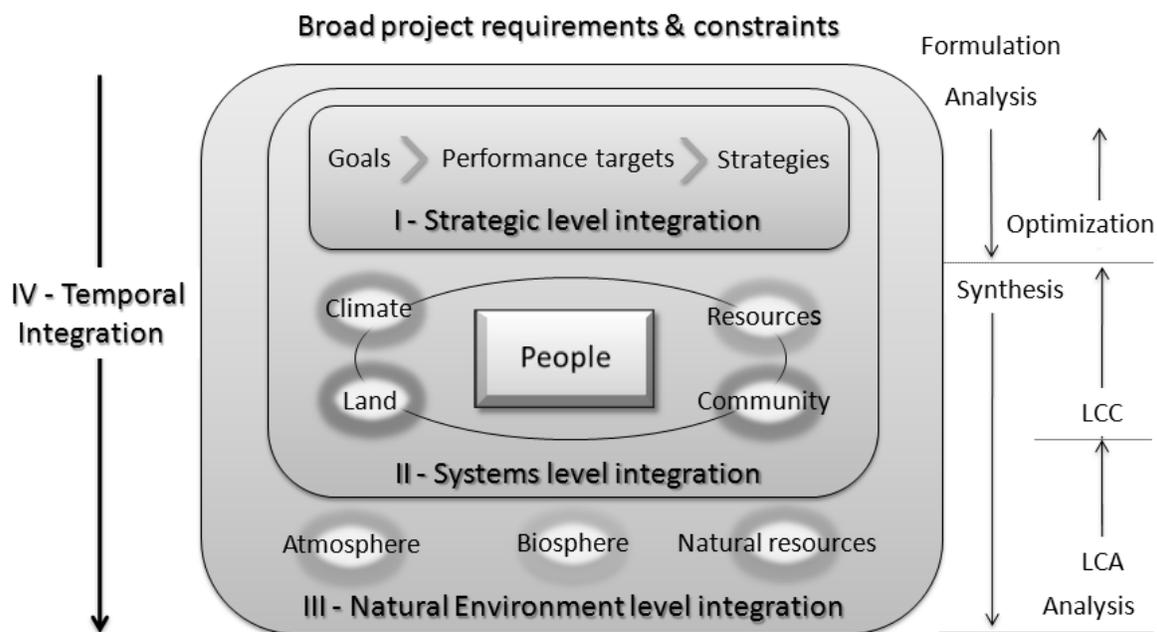


Figure 1: Building Integration Framework

## 2. PROJECT STRATEGIC LEVEL INTEGRATION (PSI)

Deru and Torcellini (2004) describe a performance-based design procedure in which the broad project requirements (e.g. sustainability, maintainability, convertability, economic viability, etc.) from the project vision are transformed into project goals under the particular constraints imposed. The project goals will drive the design process through the use of measurable performance targets (e.g. energy use intensity,  $\text{EUI} < 100 \text{ kWh/m}^2$ ). These will in turn be used to develop strategies (e.g. insulation, daylighting, thermal mass, etc.) to achieve the goals. The use of standard and available building performance metrics, e.g. EUI, is critical at this stage (Deru and Torcellini 2005).

In principle, strategic level integration is the easiest to achieve. However, it requires continuous feedback to validate its goals, assumptions, and strategies. Several methods have been developed to support the analysis and tracking of project goals during the design process at the strategic level. Most of these are decision support methods for assessing the level of sustainability of design alternatives that break-down the design problem hierarchically and use quantitative and qualitative criteria and a weighting methodology to compare each alternative against a benchmark: "...reduce annual source energy consumption by 70% compared to an energy code compliant building using ASHRAE 90.1 and a typical weather year" (Deru and Torcellini 2004).

The International Energy Agency Task 23 has developed a multicriteria decision making tool (MCDM'23) tool for whole building solar design (IEA 2000). The tool uses the analytical hierarchy process (AHP) described in ASTM standard E 1765-07 for evaluating design alternatives. The tool helps analyse and rank alternatives according to multiple criteria including, but not limited to: life-cycle cost, resource use, environmental loading, architectural quality and indoor quality. The tool shows results in graphical form, for example using the star multi-criteria building performance chart. Balcolmb and Curtner (2000) describe the use of this tool for pre-design and preliminary design.

Christensen et al. (2005) developed a tool called BEopt to identify optimal design on the path of zero net energy. The tool provides multi-criteria decision support and optimizes life-cycle costs. The tool includes a library of components grouped by categories that are used to build design alternatives. BEopt runs individual simulations for all the selected alternatives and searches for the most life-cycle cost-effective combination of alternatives. For energy simulations the tool calls DOE2 (LBL 2010) and TRNSYS (University of Winsconsin 2010) engines.

Green building rating and certification systems such as LEED (USGBC 2010) use fixed, i.e. pre-determined, performance criteria, categories, points, and weights to come up with a single performance indicator. GreenGlobes (GBI 2010) is a questionnaire-based, on-line tool for green building certification that uses fixed performance criteria and categories, but provides more flexibility to accommodate to the project's own context. Following a top-down approach, the questionnaire guides the user through the different stages of design. For an energy benchmark GreenGlobes calls Energy Star Target Finder tool (EPA 2010) that provides energy performance targets based on the CBECS database (DOE 2007) for commercial buildings. For life-cycle assessment (LCA) of materials, GreenGlobes calls ATHENA EcoCalculator for assemblies (ATHENA 2010).

Recently, interoperable commercial building information modeling (BIM) tools have become available to support sustainable designs. These tools permit the quick generation of design alternatives, which are used to run simulations and facilitate the comparison of simulation results among alternatives. In the background design models are transparently transferred between design applications, and from these to simulation engines for performance feedback. Currently, some of these tools focus on the energy and related CO<sub>2</sub> emissions aspects of sustainability, however software developers are working on supporting more sophisticated, and data intensive analyses such as embodied energy calculations and modeling natural ventilation (Autodesk 2010).

From the above discussion, it can be concluded that significant progress has been made to support integrated goal analysis, tracking, and decision-making at the strategic level. Feedback connections with the building systems (e.g. energy simulations) and natural environment (life-cycle assessments) levels have also been established. However, the critical junctures between the strategic, the systems and natural integration levels have not been addressed properly. Despite these integration efforts, to run the simulations many critical assumptions are made, and many unintended consequences from imposing ambitious performance targets are overlooked. As a consequence, green buildings often do not perform as expected (Turner and Frankel 2008). More importantly, commercial tools are becoming so easy to use that become dangerous in the hands of users lacking the proper background. This paper proposes a framework with explicit vertical connections between integration levels and horizontal ones between building systems to make systems' interactions more visible and uncover unintended consequences of alternatives.

### 3. BUILDING SYSTEMS LEVEL INTEGRATION (BSI)

Over the last forty years, the main driver for sustainability in buildings has been saving energy. Lessons from the past have revealed that the sole focus on energy savings has led to unintended health, comfort, and durability failures. These problems have been compounded by the use of modern, often untested for durability and health, resource and energy efficient construction materials. At the essence, these problems originate from a lack of understanding of the building science repercussions of energy "shifts" in a building. Building science (also called building physics or building dynamics) studies the dynamic interactions between occupants and building components and systems in response to the surrounding environment. Figure 2 illustrates these interactions.

Energy is at the core of every human activity. Building science is deeply rooted in the principles of thermodynamics: the study of energy, its transformations, and its relation to states of matter (ASHRAE 2009). In buildings, active systems (i.e. mechanical, electrical and plumbing) have become the means to supply this energy. Passive systems, on the other hand, improve microclimatic performance by relying on properties of the materials and construction combined with occupants' responses, and optimized use of renewable resources on site. In practice, an optimized operation of active and passive (i.e. hybrid) systems is required to meet to goals of sustainable building design.

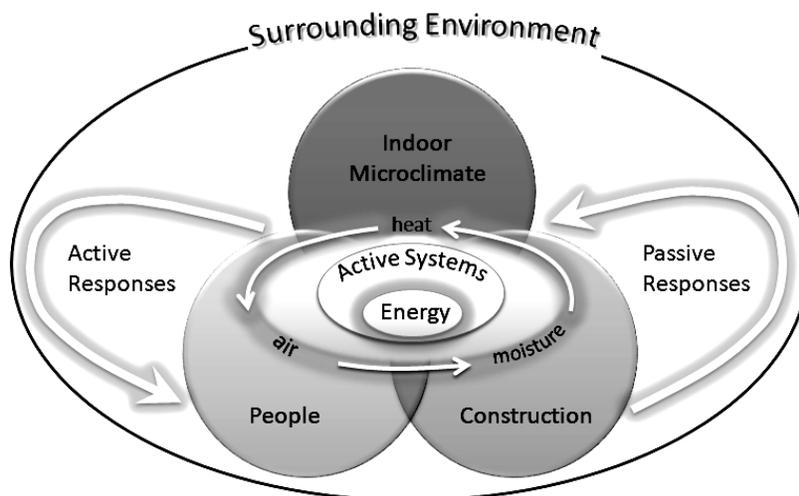


Figure 2: The Dynamics of the Built Environment

Therefore, the role of building science on building sustainability is two-fold: 1) to help understand and analyse the impacts of sustainability decisions driven by energy and low-impact materials on people and construction systems; and from this increased understanding, 2) to improve the building responses to the surrounding environmental loads and to the natural environment. Consequently, as shown in Figure 3, a systems' level of integration for building sustainability needs to be grounded in the physical principles of building science. Two intertwined levels of integration should in turn be contemplated: 1) the physical level (i.e. building science level), and 2) the technological level (i.e. the active building systems level), with the goal to maximize the synergetic interactions between building systems and between these and the surrounding environment.



Figure 3: Building Science: at the core of building sustainability

As the “skin” of the building, the enclosure plays a particularly critical role in controlling the dynamic building science interactions illustrated in Figure 2. Its primary function is to maintain a safe and stable indoor environment. However, as described by Straube and Burnett (2005) the enclosure performs multiple functions that are grouped in four main categories: control, support, finish, and distribute (i.e. services). In the light of sustainability, these functions are now extended with a “new” harvest function of: energy, natural light, rain water, and even plants.

Sustainability is not possible without durability because extending the life of a building makes it more resource efficient. The connections between sustainability, building science, and durability can be appreciated by the fact that maintaining a healthy and comfortable indoor environment (technological level) creates energy flows across enclosures (construction), caused by temperature, air, and vapor gradients. If not managed properly, these energy flows may deteriorate enclosure materials. For example, in hot-humid climates the air-conditioning sucks moisture into the house through the enclosure and draws any associated mold into the breathing zone (people). The problem can be compounded by the fact that modern sustainable materials are more mold and water sensitive (e.g. engineered wood) & therefore, designing with these materials needs careful consideration of the micro-climates these will be exposed to (Lstiburek 2009). The basic thermal balance equation of a building illustrates the above interactions between microclimates, occupants, and construction materials:

$$\eta q_{\text{supply}} + q_{\text{internal}} = q_{\text{transmission}} + q_{\text{ventilation}} + q_{\text{infiltration}} + q_{\text{synergies}} \quad (1)$$

In equation 1,  $q$  is the thermal flux in Watts,  $q_{\text{internal}}$  is heat produced by occupants, equipment, lights, and solar irradiation;  $q_{\text{transmission}}$  is heat transmitted through the enclosure materials;  $q_{\text{ventilation}}$  is heat in the fresh air supplied/extracted to meet the needs of the occupants;  $q_{\text{infiltration}}$  is the heat gain/loss through enclosure leaks;  $q_{\text{synergies}}$  is a new term that represents any heat supplied/removed not accounted for by the previous terms (e.g. thermal storage). From the above equation it can be appreciated that the energy flows in buildings are mainly governed by coupled heat, air, and moisture transport processes (HAM). These processes, driven by environmental and mechanical loads, are the base for the critical juncture between the technological level of integration and the physical (i.e. building science) as they affect the durability of construction materials, as well as the occupants' productivity and health. Acknowledging the critical role of HAM processes in building energy performance, the International Energy Agency (IEA) created ANNEX-24 to study the HAM transport through building enclosures, and ANNEX-41 to model the whole building heat, air, and moisture response (Woloszyn and Rode 2008). The dynamic interactions between microclimates and enclosure walls are now being modeled (Steeman et al. 2009a) for assessing the damage risk on materials (Steeman et al. 2009b) and details.

Building science also studies the interactions between the building and its surrounding environment (Figure 2) from a purely durability point of view, by considering the impacts of UV solar radiation, wind, and wind-driven rain on buildings. In particular, the impact of wind-driven rain on buildings has been extensively studied, and combined with hygrothermal models to predict the enclosure response (Blocken and Carmeliet 2004). Research on the critical role of moisture in building durability is now being applied in practice. The Canadian Institute for Research in Construction developed an integrated methodology of moisture management strategies for exterior wall systems (Kumaran et al. 2003) that relies on indicators of hygrothermal response to relate wall performance to wall system types, damage functions, construction deficiencies, and climate loads. The 2011 version of EnergyStar, the program developed by the US Environmental Protection Agency (EPA) to certify energy efficient buildings, includes a whole section on moisture management of the building enclosure (Energy Star 2010).

The enclosure support function establishes an explicit connection to the structural system that considers enclosure-structure load sharing/compatibilities, construction and differential movement tolerances, and anchoring of enclosure components for continuous load transfer. The enclosure's integrity is critical to maintain its structural function. Unintended rain water penetration and environment humidity will likely impair its structural and all other functions. For example, ventilated attics are often used in warm climates for solar heat dissipation. However, in storm and hurricane prone regions any enclosure penetration creates vulnerabilities for wind-driven rain penetration and increased internal wind pressure during hurricanes (Bitsuamlak et al. 2009). Extensive laboratory experiments and field studies have been conducted to validate/calibrate models, and analyze the different functional aspects of the enclosure. Field compliance and verification tests are now becoming commonplace for high-performance buildings for which enclosure commissioning is mandated. Enclosure performance monitoring has also been performed in case study projects. Horvat and Fazio (2005) developed a protocol for building enclosure performance assessment that considers various performance aspects and methods for evaluation at different project stages.

Synergies between the technological and the physical levels of integration have been implemented in practice, e.g. radiant floor systems; while others are evolving, e.g. building integrated photovoltaic systems. Researchers are also evaluating with positive results the synergistic use of the moisture buffering capacity of materials (e.g. wood), to help moderate the indoor relative humidity and reduce energy (Rode and Grau 2008). Another synergistic integration example is the use of phase-change materials to store solar energy and moderate indoor temperatures (Entrop et al. 2009). The above examples demonstrate higher levels of integration that transcend the building boundaries and seek better integration with the natural environment (see Figure 3).

#### 4. NATURAL ENVIRONMENT LEVEL INTEGRATION (NEI)

The natural level of integration (Figure 1) refers to the minimization of environmental impacts of buildings rather than the integration of a building to the surrounding environment (i.e. the site), which is addressed at the building systems' level (Section 3). From the existing methods developed to assess the environmental impacts of buildings, the most widely accepted one is the life-cycle assessment described by ISO-14000 (ISO 1999). The life-cycle assessment (LCA) of a product is its quantitative evaluation of the environmental impacts from "cradle to grave", including the three main stages of a product life: I- production: resources extraction, transport, fabrication, and installation, II- operation (service life): use, maintenance, and repair, and III- end-of-life: demolition/deconstruction, disposal, reuse, and recycling. So far, the LCA methodology has been applied to different kinds of products and businesses. However, there is a lack of clear methodology for the application of LCA by the building industry. To make the LCA problem more tractable and depending on the goal, its scope can be reduced in a) time: to one or part of one of the stages above; b) scale: to whole building, system, assembly, or component levels; and c) impacts: to study only the impact categories that are considered more relevant.

The functional unit (FU) is the reference metric used in LCA to evaluate products, and guarantee functional equivalence in the environmental comparisons. The environmental performance of a component is linked to its service life. Therefore, the environmental impacts from maintenance and repairs required to sustain the intended function-performance are also accounted for in the evaluations. For example, in comparing roof systems the FU would be: 1 m<sup>2</sup> of roof system with R-value "R", service life "Y", and in climate zone "Z". The comparison would then assume maintenance and repair/replacement levels for each roof system. Such an analysis is purely materials-based because it does not consider the effects of improved product performance on related systems. For example, the LCA of a roof system with improved thermal properties should consider the environmental benefits from improved energy performance. The FU provides the connection between the NEI and BSI integration levels. Two key issues need to be addressed methodically to strengthen this connection: 1) the accurate prediction of the service life of components, including maintenance and replacements, and 2) the impacts of improved performance of a component/system on related components/systems.

##### 4.1 Accurate service life predictions of components and systems

Buildings' service life is longer than that of most engineered products. On the one hand, for time-tested building products, service life performance predictions involve uncertainties from construction quality, as well as quality and timely maintenance and care (particularly for components and systems that are exposed to the elements and traffic and whose service life performance is dependent on proper care). On the other hand, for new products, predicting the service life performance involves greater uncertainties. Existing methodologies and standards for predicting the service life of building components (e.g. CSA 1995) need to be considered for accurate LCA evaluations. These methodologies help describe a product's service life with a stochastic distribution that can be obtained through accelerated testing, HAM-deterioration modeling, and experience. LCA can then be stochastically combined with Montecarlo simulations to associate a confidence level to the environmental impact predictions. A more difficult problem arises when the improved performance products/systems is detrimental to the performance of related ones. For example, a radiant barrier placed at the underside of a shingled roof reduces the inward heat flow and causes the temperature of the shingles to raise, with subsequent durability reductions. The opposite effect occurs in winter if more insulation is placed inside a building without regard to the external components that will be subjected to extreme cold temperatures and reduced drying potentials. This problem becomes particularly critical with novel synergistic building systems that have not been time-tested, like the ones described in sections 3 and 4.2. Building Science, that may include HAM modeling and testing, should be applied in these situations.

##### 4.2 Impacts of improved performance on related systems

Sustainability and its principle of "doing more with less" encourages the use of systems that perform multiple functions, which adds complexity to the LCA problem. The FU boundaries in LCA evaluations on inherently multi-function systems, such as the building enclosure, are often expanded to cover related systems, and end up blurred, which increase the uncertainty of the LCA outcome. For example, for environmental comparisons of green roofs versus standard ones the FU often involves the energy performance of an entire building (Saiz et al. 2006 and Kosareo et al. 2007), thereby including aspects such as the shape of the building, height, type, roof area, etc. By expanding the FU boundaries, those analyses sacrifice in rigor from experiments and modeling of roof system

function-performance variables (e.g. transient heat dissipation that considers seasonal plant growth scenarios), and assume these from the literature. A more appropriate approach is followed by Pulselli et al. (2009). In comparing the environmental performance of wall systems relative to climate zones they conduct detailed simulations to assess the performance of these systems. The results are used to calculate the heat dissipation through the enclosures under transient outdoor environmental conditions and steady-state indoor conditions. The thermal analyses are therefore limited to the enclosure. Citherlet et al. (2000) perform LCA on windows relative to climate and orientation. They separate the analyses in two: a purely materials-based that does not consider the energy performance of windows, and an energy performance-based on a small room with steady-state indoor conditions and adiabatic surfaces, except for the one with the window. In doing so, they demonstrate that the environmental benefits of more efficient windows depend on climate and orientation.

Therefore, for inherently multi-function systems the LCA can be divided in two steps. Step 1 – Conduct a comprehensive performance analysis of the system functions by considering the environmental impact for each function separately under relevant scenarios, while keeping the FU boundaries as narrow as possible to minimize uncertainties. For example, the LCA for windows can be broken down in three LCAs: a materials' based, a thermal performance based, and a light transmission performance based. Step 2 – Use the results from Step 1 to evaluate the effect of the studied product/system on environmental performance of a case study building.

In summary, a methodology for evaluating the environmental impacts of buildings using LCA should guide the selection of FU boundaries that better represent the system being studied, provide a method for predicting the service life of components and the whole system, assist in breaking down the analysis of multi-function systems to enable comprehensive function-performance analyses, and provide a method to aggregate the results for sensitivity analysis, and optimization as illustrated in Figure 1.

## 5. CONCLUSIONS AND FURTHER WORK

This paper lays down the principles to analyze the life-cycle performance of buildings. These principles are organized in various levels of vertical integration (i.e. temporal) and horizontal integration (i.e. building systems). The systems integration level is in turn broken down into a technological and a physical level. The central role of building science in achieving proper integration is emphasized. The next step in this project is to improve and formalize the framework mathematically, and implement relevant quantitative examples to demonstrate its potential to support a more integrated treatment of buildings in research, education, and practice.

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