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BUILDING ENVELOPE OPTIMIZATION USING EMERGY ANALYSIS

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ABSTRACT

Energy analysis is an integral component of sustainable building practices. Energy analysis coupled with optimization techniques may offer solutions for greater energy efficiency over the life-time of the building. However, all such computations employ the energy used for operations to benchmark and develop optimal solutions. This paper used emergy analysis to develop a method to identify the optimal solution for a building envelope system so that it will perform to its maximum potential given the mix of energy sources used for heating and cooling. The proposed method aids in the selection of building envelope materials and designs based on the total environmental impact for a particular building project.

INTRODUCTION

Because of the increased emissions of wastes and the depletion of fossil fuels, research and development in building technologies and integrated design processes have attained greater and renewed interest among stakeholders worldwide. Current research and development goes beyond the boundaries of building design and construction, and utilizes scientific knowledge from other fields to examine building performance, from physics to understand building thermodynamics and beyond.

To achieve sustainability, it is necessary to assess the performance of a building and its sub-components before they are built. Many kinds of building assessment tools have been developed to support environmental decision-making, and such tools may be broadly classified as reductionists or non-reductionists tools. Reductionist tools use a single measureable indicator, a single dimension, a single objective, a single scale of analysis or a single time horizon (Munda, 2006). There are several types of reductionist tools such as economic and monetary tools, thermodynamic methods, and energy performance tools. Economic models rely on an anthropocentric perspective, while biophysical tools use an eco-centric perspective (Gasparatos, 2010). Energy performance tools is part of biophysical tools. Examples of such tools, DOE-2 and ENERGYPLUS aid designers in analyzing various components of a building in relation to the internal and external environments. Although most of these tools have undergone mandatory validation protocols set by US Department of Energy, they still do not encompass routines for all possible design strategies (Crawley et al., 2005).

One of the critical components of energy analysis tools that call for further improvement is thermal envelope computation. For building energy efficiency, optimal envelope thermal performance is significant. The building envelope acts as a filter between the interior and the exterior, and it is a regulator of energy flow. An accurate assessment of envelope thermal performance will aid optimal sizing of systems for comfort and efficiency. Thermal envelope computation is classified based on material composition in a single-dimension (e.g., ASHRAE-based U-factor calculation methods such as parallel-path, isothermal planes, etc.) and spatial heat transfer in two- and three-dimensions (e.g., methods that utilize Finite Element Methods, etc.). The hourly building energy simulation programs cannot accurately represent the multi-dimensional effects of envelope heat transfer. Experiments carried out to evaluate multi-dimensional heat transfer using a one-dimensional approach show up to 44% errors in the R-value (thermal resistivity) calculations for metal-framed envelopes (Kosny and Kossecka, 2002). Since heat flow is three-dimensional, it may not be simplified to one-dimensional investigation as discussed in ASHRAE (2009), i.e., parallel-path or zonal methods, without introducing considerable error. Several studies confirm the inaccuracies in the one-dimensional approach over the two-, and three-dimensional analyses in the actual testing of envelope assemblies (Kosny and Kossecka, 2000). Two-and three- dimensional heat flow analysis solves issues related to thermal bridging in walls, windows and other envelope components unlike one-dimensional analysis.

Computing heat flow for two- or three-dimensions spatially is achieved by using auxiliary programs. THERM is a finite-element two- dimensional heat transfer analysis tool using a steady-state conduction algorithm, CONRAD (Curcija et al., 1995). THERM’s calculation routine evaluates conduction and radiation from first principles (Huizenga et al., 1999). Additionally, three-dimensional heat transfer analysis using Partial Differential Equations (PDE)-solvers can accurately address thermal bridge problems (Bloomberg, 1996; Posey and Dalgliesh, 2005).

Yet, the energy analysis tools employed for building and component analysis typically only account for the operating energies used to heat, cool, and power the building. They cannot provide a total environmental analysis since they do not account for the resources used during formation, extraction, manufacturing and maintenance of building components. While LCA methods do include explicit manufacturing and maintenance energies or costs, they exclude much of the environmental work provided by the biosphere in the formation and concentration of resources. What is needed is an ecological accounting model in which to contextualize and evaluate the results of current analysis tools.

The one comprehensive ecological accounting model available at present is based on emergy, a unit developed to systematically include all the work involved in the preparation and delivery of resources and services (Odum, 1996). A building is supported by a variety of inputs and outputs, some purchased and others provided without explicit cost by the environment. Inputs include embodied energies of all kinds and qualities, from the sun shining in the window to the ancient sunlight expended in the formation of the fossil fuels used to prepare the glass through which it is shining. By translating all inputs into a common energy unit, meaningful comparisons can be established between renewable and non-renewable resources, and between natural and man-made energies, refining the assessment of real costs over time. Outputs include the work products of that particular building, in this case, the provision of comfortable conditions for human occupancy. In emergy analysis the ratio of outputs to inputs is called transformity or specific emergy, and describes the environmental intensity of that output.

Emergy Analysis

Emergy analysis is an environmental accounting procedure through which a consideration of the entire lifespan of a building from formation-extraction-manufacturing to maintenance and operation cycles may be achieved. Solar and other energies that have been drawn upon for the formation-extraction-manufacturing of materials, the energy and material inflow necessary to resist degradation, and the resources required for operational use of the building constitute the available energy-emergy measure of what is required for the structure and function of a building. Energy Systems Theory and Emergy Analysis (Odum, 1983; 1996) through the development of integrated environmental accounting methods can offer a holistic solution for such an analysis.

Solar emergy is the available solar energy previously used-up, both directly and indirectly, to make a service or a product (Odum, 1971; 1983; 1996). Solar energy is used as the common denominator to express all resources, services and goods in terms of their relative ability to do work in a system. Thus, any product or service uses a common unit, "solar emergy joule" (semJ), as the unit of emergy. There are three main types of unit emergy intensity values namely, "transformity," "specific emergy," and "emergy per unit money." Transformity is the solar emergy required to make 1 unit of available energy of a quantity (e.g., a Joule of a product or service). Its units are solar emjoules per Joule (semJ/J). Specific emergy is the emergy value per unit mass of material (e.g., semJ/kg). In other words, specific emergy provides the energy that is required to concentrate materials. Emergy per unit money is used to convert monetary benefits into emergy values.

The emergy of a product can be calculated by multiplying a quantity of available energy (J) by its transformity. Available energy is energy with the capacity to do work, (i.e., it has an energy potential relative to its environment). Transformities are measured relative to a baseline. The baseline is developed using the three primary energy sources to the planet, i.e., solar radiation, deep heat generated from residual heat and radioactive decay within the earth, and the gravitational attraction of the sun and moon (Odum, 1996; Campbell, 2000). Transformities used in this paper use 9.44E+24 sej/yr baseline from Odum (1996). Several research projects have been conducted to develop transformity values, most notably Buranakarn (1998) for building materials, who used this baseline in his work.

Emergy analysis uses thermodynamic principles for environmentally conscious decision-making. In other words, emergy analysis provides a "total environmental analysis" that goes beyond typical thermodynamics and includes all environmental energies involved in the system under investigation. Based on the above, emergy analysis is chosen for this paper as a tool to evaluate environmental building design.

Only a handful of research efforts have focused on assessing buildings using emergy analysis: evaluation of recycling and reuse of building materials (Buranakarn, 1998); emergy associated with the operation of a Building (Meillaud et al., 2005); building manufacturing, maintenance and use – development of Em-building indices (Pulselli et al., 2007); energy and emergy based cost-benefit evaluation of building envelopes relative to geographical location and climate (Pulselli et a., 2009); emergy evaluation of a green façade (Price and Tilley, 2010); and energy balance framework for NZE buildings (Srinivasan et al., 2011a). A portion of the non-renewable resources may be substituted by renewable resources, also referred to as "Renewable Substitutability" (Srinivasan et al., 2011b; 2011c).

Such an approach will shift a building toward the highest order of sustainability in renewable emergy terms or toward a “Renewable Emergy Balance” or REB (Srinivasan et al., 2011b; 2011c). Thermodynamically, an REB building preserves a balanced Renewable Substitutability.

Although these studies focused on the use of emergy as a tool to evaluate building materials and buildings as a whole, and to develop performance indices for further exploration, there is not yet a comprehensive method to identify the optimal solution for a building envelope system that performs to its maximum potential to attain a desired level of comfort for the least emergy use by envelope-heating-cooling.

This paper uses emergy analysis to develop a method for identifying the optimal configuration of a building envelope system, which accounts for both the operating energies involved in heating and cooling, and the resources required in the formation and assembly of the envelope itself. It is a method that draws on embodied energy methods and life-cycle analysis, translating both into the units of a comprehensive ecological analysis.

BUILDING ENVELOPE EMERGY OPTIMIZATION

The Building Envelope Emergy Optimization structure consists of four modules: (1) Sub-System Identification (SSI), (2) Energy-Emergy Evaluation (EEE), (3) Thermodynamic Minimum Computation (TMC), and (4) System Performance Analysis (SPA). Building systems are split into sub-systems in the SSI module. This is followed by net emergy analysis of the building (EEE Module) that involves in-depth assessment of materials and energy-emergy inflow from material manufacturing to maintenance and operation of the building.

For energy used in building operation, the interior conditions are maintained at thermal comfort conditions complying with ASHRAE 55 Standard thermal criteria (ASHRAE, 2005). The largest contributor to overall system performance through achieving the desired thermal comfort is identified in the TMC module to allow for the calculation of a thermodynamic minimum transformity. Using building energy-emergy performance indices, system performances are assessed in the SPA module.

The core of this optimization component is the recognition of the occurrence of a thermodynamic minimum transformity that exists for the generation of any product or service dependent on a building system and its sub-systems. This thermodynamic minimum for generation of the desired product or service is used to identify optimal insulation to achieve the desired thermal performance. As the performance allows the product to approach a thermodynamic minimum transformity, systems and sub-systems attain the most efficient formation possible for maximum empower.

The Sub-System Identification module identifies the sub-systems that comprise the building envelope system. This is followed by Energy-Emergy Evaluation analysis that determines the energy-emergy data for all three phases of a system namely manufacture, maintenance, and operation. For the sub-system that contributes the largest amount to the operational energy-emergy quantities, the thermodynamic minimum transformity is identified. Using the already computed emergy flow values and the minimum transformity, system performance is analyzed for further improvement. Figure 1 shows the envelope emergy analysis to maximize renewable resource use to move toward a Renewable Emergy Balance.

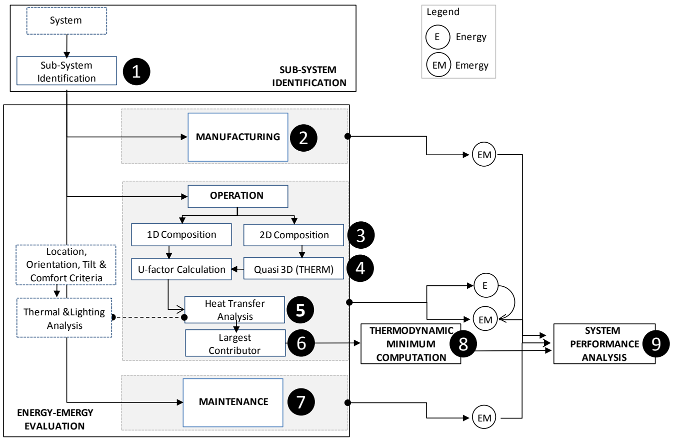

Figure 2. Building envelope emergy optimization flowchart.

Building envelope heat and light transport includes surface conductance measurements for opaque and transparent surfaces, surface radiation modeling for transparent surfaces, condensation effects, sol-air characteristics for detailed envelope heat flow analysis, and related light penetration for transparent surfaces.

Sub-system Identification Module

The building envelope is an enabler of energy-emergy flow. An envelope system may be comprised of several sub-systems (or layers). In this module, the various sub-systems that constitute the envelope system are identified (STEP 1).

STEP 1: Energy-emergy analysis in “Identification of Sub-Systems.” In this step, sub-systems of the envelope are identified.

Energy-emergy evaluation module

For every sub-system, the manufacturing emergy quantity (STEP 2), emergy of operational energy consumption (STEPS 3 to 5), and related maintenance data and emergy requirements (STEP 7) are computed in this module. This process is performed in several steps and it uses an iterative approach until all sub-system energy-emergy data are obtained (energy data are converted to related emergy quantities using appropriate transformities or specific emergies). The initial step (STEP 3) in evaluating the building envelope involves the determination of sub-system material composition in terms of dimensionality: "one-dimensional," if the sub-system uses a single material type such as wall cladding, etc. The sub-system material composition may be "two-dimensional" if the sub-system is comprised of two or more materials such as envelopes with cavity zones filled with insulation. This is followed by determination of sub-system U-factors (STEP 4). Once U-factors are established, sub-system operational energy consumption is computed (STEP 5) using whole building simulation. Thus, for each envelope sub-system, the available energy or mass flows in the envelope are computed. These energy flows are converted to emergy. In this paper, this accounting method of computing energy flow and converting to emergy quantities is referred to as "energy-emergy" accounting. It is to be noted that every energy source (fuel type) possess a transformity value. This transformity and the quantity of energy used is then used to compute emergy content of the energy source. Thus, emergy content varies by fuel types (electricity, natural gas, oil, etc). Such an accounting is performed for three stages, formation-extraction-manufacturing, maintenance and operation.

STEP 2: Energy-emergy analysis in "Manufacturing." For each envelope sub-system, the data for formation-extraction-manufacturing are collected and emergy is calculated.

STEP 3: Energy-emergy analysis in "Operation: Identification of Material Composition." In this step, the operational energy flows related to the envelope sub-system are computed.

STEP 4: Energy-emergy analysis in "Operation: Determination of U-factors." In this step, the sub-system U-factor is calculated. If the composition is one-dimensional, the U-factor computation is determined (as the reciprocal of thermal resistance, if available, or from the thermal conductivity supplied by the manufacturer. If the composition is two-dimensional (for example, a wood- or steel- framed envelope structure that includes cavity zones with multiple material configurations such as the frame and insulation material), then a quasi 3D U-factor computation methodology is used. The quasi-3D method uses the modeling of a detailed section of the sub-system in a 2D Finite-Element-Method (FEM) environment to closely replicate 3D heat transfer spatially to determine the U-factor of an "equivalent wall." This step employs THERM software for computing U-factors of a two-dimensional sub-system.

STEP 5: Energy-emergy analysis in "Operation: Heat Transfer Analysis." In this step, the sub-system is then analyzed for heat transfer using a whole building energy analysis. Annual envelope heat transfer is computed. While exterior conditions are location specific, interior conditions are maintained at thermal comfort conditions complying with ASHRAE 55 thermal criteria, particularly temperature. The heat portion of the radiation spectrum is taken into consideration during the heat transfer computation for both opaque and transparent surfaces. The contribution of the visible portion (380~780nm) is determined by introducing necessary daylight sensors which are integrated as part of the whole building energy simulation engine, for evaluation of the additional energy consumption required. This step utilizes the DOE-2 engine for computing the annual envelope heat transfer, which includes the additional energy requirement for supporting light levels for task illumination.

STEP 6: Energy-emergy analysis during "Operation: Largest Contributor." For each envelope sub-system, the "largest contributor" to system performance, in terms of energy-emergy quantity, is identified in this step.

STEP 7: Energy-emergy analysis in "Maintenance." For each envelope sub-system, the emergy required for maintenance is calculated.

Thermodynamic minimum computation module

As the performance (i.e., emergy required for the desired thermal comfort) approaches a thermodynamic minimum transformity through optimal selection of insulation, sub-systems attain the most efficient product formation possible for maximum empower. Using parametric analysis, the "largest contributor" sub-system is evaluated to determine maximum empower (or minimum transformity).

STEP 8: Energy-emergy analysis in "Thermodynamic Minimum Computation." For the "largest contributor," the emergy to available energy ratio provides its transformity. In order to identify the minimum (thermodynamic minimum transformity) to attain maximum empower, a parametric assessment (e.g., changing the thickness of the insulation) is performed until a thermodynamic minimum is realized. Using parametric analysis, the minimum transformity associated with the "largest contributor" to the emergy of the envelope is identified. Material transformity is the ratio of emergy to available energy or the potential to do work. While the emergy of the material can be calculated using all direct and indirect energy forms to make the product, the available energy is the internal kinetic energy, in this case made up of envelope heat transfer through one or more modes – conduction, convection and radiation. Every system and sub-system configuration attains the most efficient formation possible for maximum empower. Thus, for the largest contributor material, the transformity reaches a minimum following either of these two conditions – (a) material life-time is longer (consistent with the goals of sustainability as frequent replacements of a material cumulatively may possess larger emergy value) and (b) higher potential energy of the material (again, in line with sustainability objectives as the system and/or subsystem is less active in transporting heat based on the exterior-interior conditions). All energy-emergy calculations are carried out over one life-time of the building and, therefore, the transformity will approach a minimum as the potential energy maintained in the building over its life time maximizes. In other words, through improvement in envelope insulation, i.e., an increase in envelope emergy and its characteristics of thermal resistivity permits significant improvement in the maintenance of available (potential) energy within the building by the envelope configuration, thereby leading to the least possible transformity value.

System performance analysis module

In this module, the sub-system minimum transformity is used to evaluate current sub-system performance.

STEP 9: Energy-emergy analysis in "System Performance Analysis." The current sub-system performance is evaluated (as a potential for improvement) to the thermodynamic minimum derived from STEP 8. For each sub-system evaluated for a location and orientation (tilt included), only one thermodynamic minimum exists. This data can be used to develop "Building Emergy Spectrum of Envelope Systems" which is unique for a particular envelope system (or sub-system). By virtue of generalizing the location characteristics, the envelope systems' performance can be mapped for climatic zones and orientations. Thus, the emergy optimization method for envelope design offers a procedure for mapping envelope systems and their performances.

CASE STUDY OF AN EXISTING FACILITY

The US EPA, Office of Research and Development, National Health and Environmental Effects Research Laboratory (NHEERL), Atlantic Ecology Division at Narragansett, RI conducts sediment, water quality and ecosystem research in a variety of environments ranging from freshwater through marsh and estuarine to near shore marine environments along the Atlantic coast of the United States from Florida to Maine. The Main Office building, Wet Lab and Wet Lab Addition comprise the main facility buildings at the center of the site. The Wet Lab Addition was constructed in 1975 as an add-on to the Main Office and Wet Lab buildings constructed in 1963. An Office Addition is an expansion constructed in 1999.

Results

NHEERL's AED building structure was used as a case study to optimize the envelope using emergy analysis. The envelope system is comprised of spandrel glazing, masonry wall and windows. As part of the opaque wall system, the spandrel glazing and the masonry wall were analyzed in detail. The performance evaluation follows the four-step process given above– Sub-System Identification, Energy-Emergy Evaluation, Thermodynamic Minimum Computation and System Performance Analysis. Among all the sub-systems that constitute the envelope, the insulation used in the masonry wall was identified as the largest contributor to building energy flow. In order to iteratively seek the best performing insulation using emergy analysis, a set of insulation values were identified. They ranged from R-11 to R-35 in increments of R-3 (approximately 1" thickness). In the Energy-Emergy Evaluation module, an emergy calculation was performed for the envelope system. This corresponds to the formation-extraction-manufacturing portions of the envelope system. In the Thermodynamic Minimum Computation module, the envelope system was analyzed using THERM. The masonry wall with new insulation (R-value) was simulated using THERM to determine the U-factor of the envelope configuration. Additionally, the spandrel glazing portion was analyzed to compute the U-factor using THERM, see Figure 2. This procedure was performed for all R-value options for the masonry wall. Using both the masonry and spandrel glazing units' U-factors, the weighted U-factor data were obtained. The purpose of this exercise was to determine the weighted average U-factors to input in the energy analysis program.

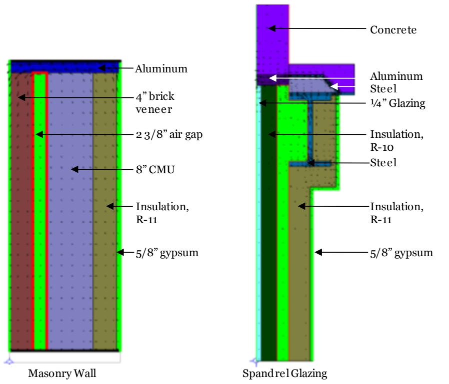

Figure 2. Building envelope system model using THERM.

Table 1 lists the weighted average u-factor that corresponds to the R-value of the material. A THERM simulation was performed after removing the insulation. This represents the wall with R-0 type which was used as a baseline to compute energy savings due to the inclusion of insulation in the wall. The goal was to identify the optimal level of insulation that would allow the envelope system to perform best in emergy terms, i.e., through maximizing its available energy. As discussed earlier, the optimal envelope configuration in emergy terms would offer maximum empower to achieve the desired thermal comfort with the least emergy use.

Table 1. Insulation values and U-factors of masonry wall and weighted average for entire opaque wall assembly.

Insulation R-value	U-factor		
	Masonry Wall	Spandrel Glazing	Overall Envelope
0	0.2881	0.3033	0.2914
11	0.1856	0.3033	0.2111
14	0.1612	0.3033	0.1920
17	0.1509	0.3033	0.1839
20	0.1355	0.3033	0.1718
23	0.1238	0.3033	0.1626
26	0.1158	0.3033	0.1564
29	0.1097	0.3033	0.1516
32	0.1050	0.3033	0.1479
35	0.1017	0.3033	0.1453

Two scenarios were considered for evaluation of an opaque envelope system –performance of the opaque envelope system, using electricity for cooling and natural gas for heating and performance of opaque envelope system, using electricity for cooling and heating, and Scenarios #1 and #2 focus on the opaque envelope system without varying window properties. However, they used different fuel types. The purpose of these scenarios is to determine performance changes due to change in fuel types. Both scenarios #1 and #2 ignored the lighting energy savings owing to daylighting sensors. In order to conduct integrated thermal and daylighting analyses, the existing facility was modeled using the DOE-2 program. This model was then used to simulate various scenarios such as changes to U-factors of envelope systems to evaluate the changes to loads (BTUs), energy use (kWh), etc. A detailed discussion of the model is available in Srinivasan (2010).

Model Setup and Assumptions

NHEERL's AED building structure that is comprised of four buildings was modeled with a DOE-2 program. The model used several assumptions. For model integrity, these assumptions were maintained as a constant for all variations of the base-model. The lighting power was introduced in spaces based on electrical drawings. The equipment power for spaces was input based on ASHRAE 90.1-2007 User Manual requirements (ASHRAE-UM, 2007). The value used for equipment power for spaces is 0.75 w/ft^2. For occupancy, a value (275 ft^2/person) consistent with the User Manual was used. The indoor temperature was maintained per ASHRAE 55-2005 Standard. Cooling and heating setpoint temperatures are 70°F and 76°F respectively. The building operation schedule is based on actual operating hours. All other equipment efficiencies were maintained as a constant.

Scenario #1: *Opaque envelope structure – using electricity for cooling and natural gas for heating.*

In this scenario, for every change in the R-value of the insulation (or the weighted average U-factor of the opaque envelope assembly), corresponding envelope heating and cooling loads (BTUs), and heating and cooling energy use (kWh) were computed. Using the transformity of the fuels (electricity and natural gas), the emergy content of fuels was computed. Similarly, the emergy content of the envelope system was computed based on its material structure.

It is crucial to extend all computed values to the life-time of the building. For example, energy analysis provides annual consumption data. This, then, is extended to the entire life-time of the building as the emergy content pertains to the useful life of the system. Wherever the systems' useful life-time is shorter than the life-time of the building, replacement of the system is undertaken. Similarly the heating and cooling envelope loads were extended to the life-time of the building. For the purposes of this case-study, a 2.5 factor has been used for material emergy. This factor may be understood as the total number of replacements of building materials, on average, that may happen during the lifetime of the building. In order to determine the optimum insulation for a given envelope system type, the ratio of the total emergy used (material and fuel usage) to total energy savings from the baseline configuration without insulation was calculated. These were evaluated to determine the option that achieves the minimum transformity for maintaining the designated comfort zone over the lifetime of the building.

Figure 3 shows that the rate of energy saved (represented as a continuous line) by improving insulation, is significantly higher than the rate of energy-use (represented by a dashed line). Energy saved represents the additional BTUs saved from a baseline rate of use. This rate-of-change in savings is a critical factor for determining the optimal insulation criteria for the envelope system, in emergy terms.

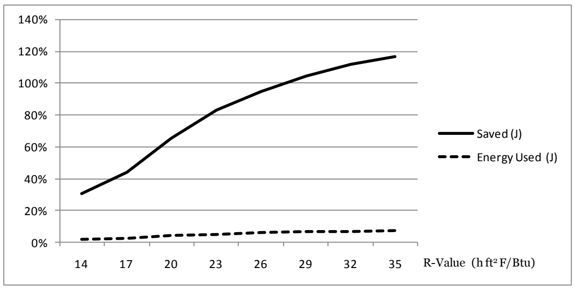

Figure 3. Rate of energy saved and rate of energy used plotted for insulation R-values.

Figure 4 shows the relationships of a change in insulation of the opaque envelope system tothe material emergy content and the emergy use (fuel consumption). Although the material emergy and the fuel use emergy are approximately the same magnitude, the change in their values due to increased insulation is significant. While the emergy of fuel use (represented as a continuous line) decreased at a slow pace in response to increases in insulation, the emergy of envelope materials increased at a rapid pace (shown as a dotted line) in response to increased insulation. For example, when the insulation value is R-11, the building's fuel use emergy is higher than the material emergy value. Recall that these values correspond to the entire useful life-time of the buildings. However, these two quantities intersect near insulation option R-23. Beyond this insulation value, the emergy content of material surpasses the fuel use emergy.

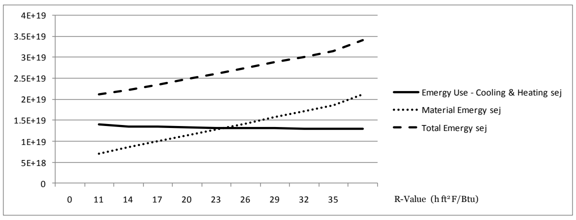

Figure 4. Material and fuel use emergy plotted for insulation R-values, scenario #1.

The overall envelope emergy to available energy ratios are plotted against insulation R-values, see Figure 5. The thermodynamic minimum transformity occurs at insulation R-23 (transformity is 9.95E+05 semJ/J). As shown in Figure 4, this is the point of intersection between the material emergy content of the envelope and the fuel use emergy needed to maintain the designated comfort zone. However, further research may be needed to confirm the behavior of material and fuel use emergy, and the occurrence of minimum transformity. Thus, at an insulation of R-23 for the opaque envelope system, the best performance is exhibited through achieving the desired thermal comfort levels with least emergy. Within an energy framework, a different insulation option may be selected (based on the lowest fuel use in kWh). However, using a total environmental assessment approach, the insulation selected may vary as discussed in this paper.

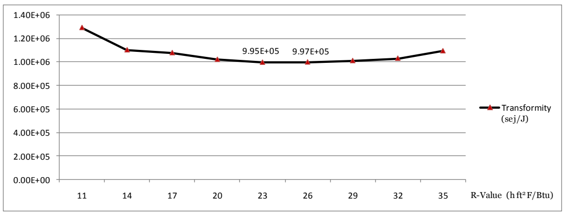

Figure 5. Transformity values calculated for insulation R-values, scenario #1.

Scenario #2: *Opaque envelope structure – using electricity for cooling and heating.*

In this scenario, the fuel type for both heating and cooling is maintained as electricity. The objective of this exercise is to find the correlation of fuel type (and its emergy content) to transformity. Figures 6 and 7 correspond to scenario #2. Since only electricity is used for heating and cooling in this scenario, the material emergy content of the envelope increased from scenario #2. This is due to the fact that the transformity of electricity used for this experiment is 1.60E+05 semJ/J (Odum, 1996) as compared to natural gas which posses a lower transformity, 4.39E+04 sej/J (Odum, 1996; Campbell and Ohrt, 2009). The minimum transformity occurs at insulation value R-26 (transformity 1.03E+06 semJ/J). The fuel source plays a major role in the total environmental analysis of the envelope as one might notice. Changing the fuel source offers an altogether different optimal solution, in this case study. However, in a conventional energy study, the optimal solution is purely determined either through energy cost or energy use quantity (BTUs) only.

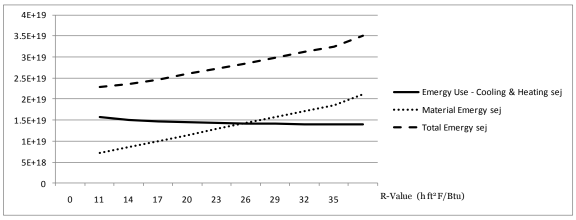

Figure 6. Material and fuel use emergy plotted for insulation R-values, scenario #2.

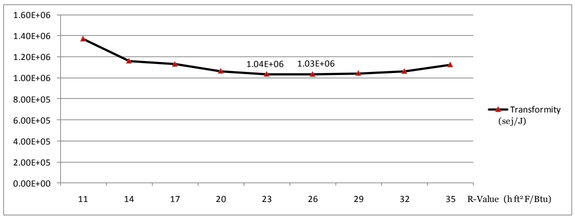

Figure 7. Transformity values calculated for insulation R-values, scenario #2.

CONCLUSION

We used emergy analysis to develop a method for identifying the optimal solution for a building envelope system so that it will be able to perform at its maximum potential given the mix of energy sources used for heating and cooling. Current methods focusing on energy flows aid building operational energy use but they do not include overall environmental analysis. Evaluating building components using emergy enabled us to perform optimization at the highest level of sustainability by taking into account all environmental contributions to the building envelope system. Using this method, optimal insulation levels were identified for various combinations of heating and cooling energy sources. The selection enhances the ability of the envelope system to achieve the desired degree of thermal comfort with the least environmental cost as measured through emergy use. The proposed method can aid in the selection of building envelope systems based on the total environmental impact for particular building projects. Additionally, we discuss the preliminary mapping of energy and emergy flows of building envelope systems in an easy-to-use tool for system selection. For the purposes of this paper, the system boundary included the built environment, and its components, specifically those that enabled thermal conditioning of the environment; however, it did not include the building occupants, which is higher order level of analysis.

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