The Benefit of Integrating Emergy Synthesis and LCA towards More Comprehensive Analysis of Advanced Building Systems

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ABSTRACT

Emergy analyses (EMA) of buildings and architectural designs account for the materials and energy flows that go into the construction, operational life and decommissioning of a building. Many literature sources exist that reflect the UEVs for more typical building materials. However, these UEVs are often site- and time-specific, and cannot be easily extrapolated, particularly when the transportation and labor factors are taken into consideration. Furthermore, in the process of analyzing new and novel building systems, which aim to remedy the carbon and energy balance of buildings during the operational stage of their life span, we realized that many UEVs do not exist for newer more complex material systems. A study of a building-integrated solar PV system highlighted these two points. Here, many values were taken from literature to estimate the appropriate UEVs, based on life cycle analysis (LCA) databases and various studies. This led us to a deeper reflection on the opportunity of integrating EMA within the LCA method in the first place, which would permit leveraging comprehensive LCA databases, while at the same time augmenting LCA with an assessment of the total work of the geo-biosphere that underpins the resources used, which conventional LCA fails to consider through its more utilitarian focus.

INTRODUCTION

In terms of architectural system design, a socio-ecological approach would address the concept that in order to achieve a comprehensive assessment of how certain design options effect our environment, both human and other living system effects, and their subsequent associations, must be taken into consideration. Thereby, the application of Emergy Analysis (EMA) during the architectural design process justifies investigation due to the association and links between social and ecological factors that are conceptually inherent to its methodology. Brown explains emergy’s system of value as “donor” based rather than “receiver” based (Brown and Herendeen, 1996) in that it values a product or service based on how much goes into it rather than how much it is worth in monetary terms. This paper focuses on the potential for much useful application of EMA within an architectural design context. Within this architectural context, it investigates the data available for the calculation of emergy. It explains our application of EMA in performing EMA of traditional building material systems versus more advanced building systems, as well as the limitations which arose with the accessibility to Unit Emergy Value
data for more advanced material systems. It explores the EMA method as a means to understand the environmental impacts of architectural design options during the schematic design stage by highlighting the development of a plugin for architectural design which aims to allow for EMA to occur within the architectural design environment. The plugin aims to provide provenance to the UEVs, therefore helping to characterize the uncertainty in the data. We discuss the potential for integrating more internally consistent databases, and question if integrating EMA and Life Cycle Analysis (LCA) databases is a logical next step. LCA’s more widespread application in the industry and material development globally results in the availability of internally consistent databases which provide much data on technosphere inputs. By integrating the geo-biosphere UEV data from emergy analysis both the work of the technosphere and geo-biosphere can be taken into consideration. By integrating the fundamental flows of the geo-biosphere to and the technosphere inputs leveraged from existing LCA databases, both LCA and EMA methodologies can benefit from a comprehensive dataset.

THE DEVELOPMENT OF A PLUGIN FOR ARCHITECTURAL DESIGN

Typically, environmental impact analysis as well as energy and material analyses of buildings are carried out in isolation of the building design process itself, and are left to the later stages of the whole architectural process. However, this often limits their effectiveness in providing practical guidance on how to reduce the impact of such buildings, given that by the time the analyses are done, most of the key design decisions have already been made and altering these would prove extremely difficult given the multiple stakeholders involved in the built environment process. To try and change this unfortunate state of matters and facilitate the integration of analyses in the architectural design workflow at the most advantageous and appropriate timeframe, we created a novel tool named “Clark’s Crow”\(^2\), which aims to incorporate a specific useful application of EMA during the early stages of architectural design.

In fact, within an architectural context EMA offers the potential for much useful application. Clark’s Crow was developed as a new plugin for the “Grasshopper for Rhinoceros” 3D modelling environment, an environment commonly used by architects and designers in the early stages of design. The premise was that such a new plugin would allow architects to perform an EMA within the confines of their conventional design environment, thereby providing greater potential for incorporating energy and material analysis as well as decision making in the early stages of design. Clark’s Crow has been described in more detail elsewhere (Keena, Raugei, Aly Etman, Ruan, & Dyson, 2018; Keena N. , Aly Etman, Diniz, Rempel, & Dyson, 2016; Keena N. , Aly Etman, Rempel, & Dyson, 2016; Aly Etman, Keena, Diniz, Rempel, & Dyson, 2016). Figure 1 shows the concept of the tool, where Clark’s Crow’s results are output in table format. This becomes a design feedback loop allowing decision making among building stakeholders towards environmental sound urban and built ecologies.

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\(^1\) Unit Emergy Value (UEVs): Are defined as the amount of exergy of one type (usually solar) directly and indirectly needed to generate a unit of product, and expressed in (seJ/unit). UEVs is the umbrella term for three main UEV types: 1) transformity, 2) specific emergy and 3) energy per unit money. Transformity is expressed in units of solar energy per Joule named solar emjoules per Joule (seJ/J). Specific emergy is the emergy per unit mass used to express the energy needed to concentrate materials. Emergy per unit money defines monetary values in terms of energy. (Srinivasan, Braham, Campbell, & Cucija, 2012). The International Society for the Advancement of Emergy Research (ISAER) has compiled a database of UEV values with links to the literature that developed these values (ISAER, 2015).

\(^2\) The Grasshopper for Rhino plugins are all named after living species. Clark’s crows are birds with exceptional spatial memory, and we considered this an apt name for a tool dealing with Emergy.
It was initially assumed that the plugin would be used for built environment related emergy analyses only. Hence, the database of materials that the user may choose from within the Clark’s Crow plugin currently includes EnergyPlus\(^3\) materials, which are leveraged from another pre-existing plugin named Honeybee\(^4\) (Roudsari, Mackey, Yeziro, Harriman, Chopson, & Ahuja, 2014). At its current stage of development, Clark’s Crow is built upon this library, which is adapted for use in the plugin by adding the respective UEVs, sourced from the ISAER database and from other literature sources. Each UEV in Clark’s Crow adapted material library has been referenced so that its provenance can be tracked. A ‘decompose’ component allows the user to understand some degree of break-down of the UEV. For example, a user may select a material with or without services information. We deemed it necessary to allow the user to at least be able to change the UEVs in terms of the associated services inputs, particularly transportation and labor. The Clark’s Crow tool is now available on “Food4Rhino” (Keena N., Aly Etman, Ruan, & Dyson, 2018), an open source environment which allows users to download the tool and integrate it into their design environments. It bears reiterating, though, that this first release is a still beta version that considers only conventional and traditional building materials typically following those listed in the EnergyPlus database.

**LIMITATIONS WHEN TRYING TO ANALYZE ADVANCED BUILDING SYSTEMS**

On analyzing novel building systems with this first version of Clark’s Crow, we experienced limitations. In particular, the question arose of how to estimate the UEVs of advanced materials that may be required for such less conventional buildings. The latter systems particularly warrant analysis as they strive to be

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\(^3\) The US Department of Energy’s building simulation software named EnergyPlus (EP), contains an extensive database of materials and construction types including their properties from ASHRAE and other sources as outlined in ASHRAE handbook 2009 (ASHRAE, 2009).

\(^4\) Honeybee (Roudsari et al., 2014) is “Grasshopper for Rhinoceros” plugin for building energy simulation and it has the potential to supply some of the required raw data needed for an emergy calculation of building materials (i.e. material density, material thickness) and operational energy (i.e. the data can be pulled from the results of the building energy simulation including the energy consumption to meet heating, cooling, lighting, and equipment loads).
at the cutting edge of the environmental performance of buildings. Specifically, on carrying out an
emergy investigation of an integrated concentrating solar PV system developed by the Center for
Architecture Science and Ecology (CASE) (Novelli, 2016; Dyson, Jensen, & Borton, 2010; Dyson,
Jensen, & Borton, 2007) we recognized that many UEVs had not already been calculated (Roudsari,
Mackey, Yezioro, Harriman, Chopson, & Ahuja, 2014) for particular components of the system.

We therefore looked to LCA databases and literature to obtain material breakdowns. In particular,
LCAs of triple-junction solar systems were referenced (Kim, Knight, Krishnan, & Fthenakis, 2008;
Fthenakis & Kim, 2013). However, the materials for the life cycle of these cells involve a complex
inventory of technology-specific inputs, including many primary elements and manufacturing
processing techniques such as the processing of wafers into cells. The emergy literature is still limited
in the evaluation of UEVs for such processes. Although there are UEVs on crustal elements, including
Gallium, Indium, Arsenic, and Phosphorus (Cohen, Sweeney, & Brown, 2007), much more information
is needed to calculate the UEVs of the metals in their use form, including all life cycle stages (i.e.,
mining, purification, and refining). In terms of the manufacturing processes, we therefore resorted to
expressing the energy invested in terms of average crude oil equivalents (Brown, Raugei, & Ulgiati,
2012). We then leveraged LCA databases and literature where useful information on the required
processes was available, and used oil based equivalents in order to calculate the UEV of the material
components and manufacturing processes.

APPLYING UEVs FROM LITERATURE IS SUBOPTIMAL

Using UEVs sourced from published literature as done in the current beta version of Clark’s Crow is
actually fairly common practice in most EMA. However, this can still be suboptimal for three reasons:
1. **UEVs sourced from the literature are not homogenous**
   Taking UEVs form the literature leads to inconsistent values being used where, for instance, some are with vs others are without labor and services. Added to this is the fact that literature-sourced UEVs are path-dependent and not necessarily directly transferable or applicable to other case studies. In some cases, the calculation methods in the literature are not always transparent and reproducible.

2. **UEVs sourced from the literature are prone to obsolescence**
   Unless a common database is used which is monitored and maintained in order to keep it up to date with changes in processes and materials, UEVs can quickly become obsolete.

3. **New UEVs may be required**
   UEVs for particular processes and materials may not yet be available anywhere (as discussed above, this was found to be especially the case when dealing with advanced building systems). In these cases, the onus is put on the emergy analyst to create new UEVs from scratch (as we did for the case study briefly described in Section 3). However, this requires a certain level of emergy expertise, while in the context of the Clark’s Crow tool the aim was to make it as accessible as possible, even for novice users. We wanted to create a user-friendly tool that would not be intimidating or discouraging towards using EMA but rather provide enough information for both novices and experts alike.

**NEXT STEPS: THE NEED FOR AN INTERNALLY CONSISTENT DATABASE**

From our experience of running an EMA of more complex building systems, we also started to question how could we improve the usefulness of the tool to cater for other disciplines such as engineering and systems development. We quickly came to realize that this tool and others would greatly benefit from having a full database of technological processes that is internally consistent, and from which all necessary UEVs could be calculated on a per-instance basis (rather than sourced from pre-existing sources featuring different and potentially inconsistent calculations). But how do we get there? In fact, such databases already exist, an example being the Ecoinvent database widely used in LCA. It therefore seems to naturally follow that the best course of action would be to integrate emergy into LCA, thereby leveraging the full potential of such databases. The potential benefits of integrating emergy synthesis and LCA have already been outlined elsewhere (Ingwesen, 2011; Bala Gala, Raugei, Ripa, & Ulgiati., 2015; Raugei, Rugani, Benetto, & Ingwersen, 2014; Raugei, et al., 2016; Raugei, Bargigli, & Ulgiati, 2006; Arbault, Rugani, Tiruta-Barna, & Benetto, 2014; Brown & Buranakarn, 2003). (Ingwesen, 2011) in particular, outlined the potential of integrating established UEVs of geo-biospheric flows with existing LCA databases of technological processes for calculating UEVs of all technosphere inputs, as illustrated in Figure 3. This approach would augment LCA with an assessment of the total work of the geo-biosphere that underpins the resources used, which conventional LCA fails to consider through its more utilitarian focus. And, importantly, it would also lead to a more robust set of UEVs, which would automatically benefit from the continuous updating effort that is already on-going for the LCA databases, complemented by the information on the work of the geo-biosphere for a limited number of fundamental flows such mineral ores, fossil fuels, ground water, topsoil, rainfall, wind etc., for which UEVs are less intrinsically variable.
Figure 3. The potential benefits of integrating emergy synthesis and LCA. By integrating established UEVs of the geo-biosphere with leveraged existing databases calculating UEVs of the technosphere inputs both analysis methods can advance one another. This figure is redrawn and modified from (Ingwesen, 2011).

It is also important to note that other tools and plugins already exist which integrate LCA into the building design process, most notably: 1) TALLY (BIM in Revit+LCA)\(^5\); 2) Tortuga\(^6\) (LCA in Grasshopper; uses two LCA databases: Quartz Project LCA Data (US/GaBi) and Ökobau.dat (DE)).

CONCLUSIONS AND APPEAL TO JOIN FORCES

Existing efforts are occurring which integrate LCA and EMA such as SCALEM (Software for CALculating EMergy based on life cycle inventories) (Marvuglia, Benetto, Rios, & Rugani, 2013). This software allows for a rigorous calculation of EMA associated with a product or service by implementing the Emergy algebra rules at the Lifecycle Inventory (LCI) modelling level. It then calculates the UEV of a product using UEVs of geo-biosphere or ‘fundamental’ inputs assembled from literature and the ISAER database. One potential next step for the Clark’s Crow tool is to leverage the SCALEM database

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\(^5\) Tally (KT Innovations, Thinkstep, & Autodesk, 2013), which aims to facilitate LCA analysis within building information modeling (BIM). This tool has proven useful in providing LCA on demand, during the time frame and within the environment in which buildings are created.

\(^6\) Tortuga (Moethu, 2013) is an open-source Grasshopper for Rhinoceros plugin which evaluates the Life Cycle Analysis and Global Warming Potential (CO2e) of a Grasshopper model. It allows the user to choose between two different LCA Material databases accessed within Grasshopper i.e. Quartz Project LCA Data (US/GaBi) and Ökobau.dat (DE).
for the calculation of EMA within the ‘Grasshopper for Rhino’ environment, especially for more complex and advanced material and building systems. Collaboration has the potential, to benefit the advancement of these multiple efforts in creating tools for the application of EMA. This could lead to a collaborative effort towards more frequent and far-reaching applications of EMA across multiple disciplines and for interdisciplinary research.

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