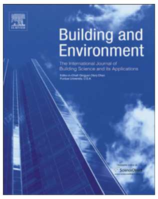
Building and Environment 79 (2014) 138–151

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv



Comparison of energy-based indicators used in life cycle assessment tools for buildings

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ARTICLE INFO

Article history:
Received 25 February 2014
Received in revised form
25 April 2014
Accepted 10 May 2014
Available online 20 May 2014

Keywords:
EIO-LCA
ATHENA® Impact Estimator
Eco-LCA
Emergy
Life cycle assessment tools
Environmental building design

ABSTRACT

Traditionally, building rating systems focused on, among others, energy used during operational stage. Recently, there is a strong push by these rating systems to include the life cycle energy use of buildings, particularly using Life Cycle Assessment (LCA), by offering credits that can be used to achieve higher certification levels. As LCA-based tools are evolving to meet this growing demand, it is important to include methods that also quantify the impact of energy being used by ecosystems that indirectly contribute to building life cycle energy use. Using a case-study building, this paper provides an up-to-date comparison of energy-based indicators in tools for building assessment, including those that report both conventional life cycle energy and those that also include a wider systems boundary that captures energy use even further upstream. This paper applies two existing LCA tools, namely, an economic input–output based model, Economic Input–Output LCA, and a process-based model, ATHENA® Impact Estimator, to estimate life cycle energy use in an example building. In order to extend the assessment to address energy use further upstream, this paper also tests the Ecologically based LCA tool and an application of the emergy methodology. All of these tools are applied to the full service life of the building, i.e., all stages, namely, raw material formation, product, construction, use, and end-of-life; and their results are compared. Besides contrasting the use of energy-based indicators in building life cycle tools, this paper uncovered major challenges that confront stakeholders in evaluating the built environments using LCA and similar approaches.

1. 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 sparked 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 (e.g., conduction, convection and radiation across the building envelope; airflow prediction using Computational Fluid Dynamics, etc.), from chemistry to develop new building material compositions (e.g., polymer technologies used for roof coatings that turn black during winter months and white in summer months, etc.), and from biology for bio-organism-based technologies (e.g., Living Machines™ for waste water recovery onsite, etc.).

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 methods have been developed to support environmental decision-making, Fig. 1. The first level category includes the Assessment Frameworks. These are integrated and structured assessment models that aid in the comparison of various alternatives for projects and policies. Examples include Environmental Impact Assessment and Strategic Environmental Accounting. The second first level category is composed of analytical evaluation tools that assist in decision-making or in finding potential solutions to specific problems within the framework [1]. These tools are discussed under 2 s level sub-categories - reductionist and non-reductionist tools. While reductionist tools such as Cost Benefit Analysis, evaluate performance by reducing a complex system to a smaller set of variables and integrating its

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http://dx.doi.org/10.1016/j.buildenv.2014.05.006
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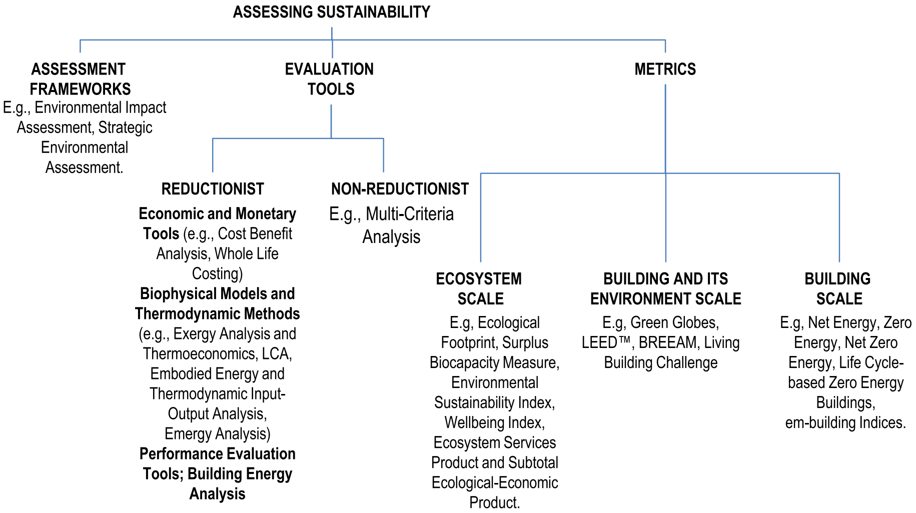

Fig. 1. Assessment methods to support environmental decision-making.

measurable characteristics, non-reductionist tools such as Multi-Criteria Analysis incorporate methodological choices that are partly subjective. Finally, metrics measure the achievement of a project in sustainability terms.

To elaborate, reductionist tools use a single measurable indicator, a single dimension, a single objective, a single scale of analysis or a single time horizon [2]. There are several types of reductionist tools such as economic and monetary tools which are distinct from biophysical models, thermodynamic methods, and energy performance tools. Economic and biophysical tools are both reductionist, but have dissimilar orientations. While the former uses market currencies as a metric, the latter uses physical units. In other words, economic models rely on an anthropocentric perspective, while biophysical tools use an eco-centric perspective [1]. Economic tools such as Cost Benefit Analysis and Whole Life Costing oversimplify environmental problems by collapsing them into a monetary dimension and since environmental costs are only partly represented by market valuations, these tools are not suitable for environmental evaluation of envelope systems. Biophysical models and thermodynamic methods for the analysis of goods and services provide a direct accounting of resource costs. The critical factors are physical measures of the "natural capital" invested in the production of the good or service. Examples of biophysical models include thermo-economics, Life Cycle Assessment (LCA), embodied energy analysis, thermodynamic input–output analysis, exergy analysis, and emergy analysis. Most biophysical models allow substitution within the same form of natural capital or resource but not between different kinds or qualities. Emergy modeling is the exception, since the normalization of quality between different resource types is performed when converting resource quantities into emergy.

Three second level sub-categories are used to categorize the metrics at varied scales or measurement boundaries. They are the ecosystem, building - environment, and building scales. Examples of ecosystem scale metrics include Ecological Footprint, Surplus Biocapacity Measure, Environmental Sustainability Index, Wellbeing Index, etc. Examples of building - environment metrics, i.e., rating systems typically used in the USA are Green Building Initiative's Green Globes [3] and Leadership in Energy and Environmental Design or LEED™ [4]. Finally, the building scale metrics include concepts such as net energy, zero energy, net zero energy, etc.

Two of the most commonly adopted rating systems in the USA are Green Globes and LEED™. Both these rating systems utilize existing standards and procedures to rate buildings. Among others, energy estimation of new or major renovation of existing buildings is an important credit component of the rating systems that employs building energy simulation tools; see for example, Green Globes' Energy category [5]. Recently, there is a strong push by these building rating systems to include life cycle-based environmental impacts, of which life cycle energy use is one of the primary indicators. The most recent versions of Green Globes and LEED™ offer credits to go beyond typical energy estimation and to encourage study of building energy use and environmental impacts from a life cycle perspective. As LCA-based tools to quantify building energy use are evolving to meet this growing demand, it is important to include methods that also quantify the impact of energy being used by ecosystems that indirectly contribute to building life cycle energy use. Our objective is to provide an up-to-date comparison of energy-based indicators in tools for building assessment, including those that report both conventional life cycle energy and those that also include a wider systems boundary that captures energy use even further upstream. This paper applies two existing LCA tools namely, an economic input–output based model, Economic Input–Output LCA (EIO-LCA), and a process-based model, ATHENA$^{®}$ Impact Estimator, to estimate life cycle energy use in an example building. In order to extend the assessment to address energy use further upstream, this paper also tests the Ecologically based LCA (Eco-LCA) tool and an application of the emergy methodology. By expanding the boundary within which building life cycle energy is accounted for, these latter two tools are able to incorporate an approximation of building impacts on ecosystem goods and services. The incorporation of ecosystem goods and services into LCAs will improve decision making in the design, construction, operation, and decommissioning of buildings in order to minimize environmental impacts and utilize natural resources in a sustainable and efficient matter. Preliminary work related to incorporation of ecosystem services in LCA is discussed in Srinivasan et al. [6,7].

1.1. Economic input–ouput and process-based LCA

Assessing the environmental impacts and raw material consumption associated with various approaches to the built environment is currently achieved using Life Cycle Assessments. LCA emerged as a defining framework during the last two decades, largely due to the increasing awareness of environmental issues associated with the manufacturing sector, along with the waste generated by manufacturing processes. LCA was formalized by the International Standards Organization (ISO) to examine industrial systems' performance, from the point of extraction of raw materials, through the manufacturing process and finally to product disposal. According to an International Standards Organization (ISO) document [8], which refers to principles and framework for environmental management, LCA considers the entire life cycle of a product, in terms of energy and materials used in its manufacture, as well as the end of life of that product. LCA consists of four major steps: definition of goal and scope, life cycle inventory (LCI), Life Cycle Impact Assessment (LCIA) assessment, and interpretation of results. The definition of goal and scope describes the purpose as well as the functional unit and system boundaries of the LCA. In the LCI phase, data are collected and analyzed to determine quantities of material and energy inputs and outputs of the LCA. The LCIA determines potential damage caused by the system as defined by the quantities of inputs and outputs, and finally, in the interpretation phase, the inventory and impact assessment results are reviewed and conclusions are reached and recommendations made about the environmental performance of one product relative to one or more others [8].

Economic Input–Output (EIO) and process-based are two major approaches to developing LCI. Detailed tracking of each of the diverse processes used in the system boundary is essential for developing a process-based LCI [9]. Depending on the goal and scope, this can be a lengthy and detail-intensive procedure that may lead to high cost, time, and issues related to data confidentiality and verifiability. Whereas, a top-down approach such as EIO-LCA uses available sectoral economic data and, therefore, typically the whole economy of a country is the boundary of the analysis [10]. Although robust and easy-to-use, the EIO-LCA approach has several drawbacks: (i) it uses aggregate data, and aggregate industry sectors may not provide information on the particular processes used in the manufacturing of the product under investigation; (ii) the data for the 1997 input–output benchmark model is based on the 1997 US economy, thus adding uncertainty to results from different years, although correction coefficients exist to minimize industry data variation; and (iii) data used in the EIO model are incomplete, with inherent uncertainties, thus, potentially, underestimating results such as environmental impacts [9]. Henrickson et al. provides a detailed comparison of EIO-LCA with process-based models [11]. Many studies have demonstrated the usefulness of LCA in the assessment of the life cycle energy use of manufacturing processes [12–14]. The boundaries associated with the traditional LCA starts from the extraction of raw materials, expand to the manufacturing of a product, and continue up until the end of the product's life [15]. Other researchers have taken a more holistic approach by going beyond the initial embodied energy of materials and including a more detailed accounting of processes and environmental impacts throughout the life cycle of the building. Two such inclusions are the energy used in construction and operation of the building [16,17]. In another study, a process-based hybrid life cycle indicator model was used to calculate the embodied energy and emissions of a high-rise education building [18]. In this study, specific data on transportation and construction activities were included in the Input–Output model used for building materials manufacturing.

Some researchers have developed approaches to utilize LCA in the built environment [19–21]. Cole [22] took an LCA approach to analyze and determine carbon dioxide emissions and the embodied energy used by the construction process at the job-site for three different types of small building structural materials. Although great efforts have been made to quantify energy expenditures as well as environmental impacts within the built environment, few studies have used a complete holistic LCA approach that considered the whole cycle from the manufacturing of building materials through demolition of the building at the end of its useful life. Such an approach quantifies the life of the building, along with its associated environmental impacts. One such study was conducted where the authors determined the energy and mass needed for a 7300 m^2 six story building with a life span of 75 years [23]. This study also measured environmental impacts caused by the production of primary energy used throughout the life cycle of the building (petroleum, coal, natural gas, and nuclear energy), and their contributions to global warming, ozone depletion, acidification and nitrification of soils and water, and solid waste generation. Ramesh et al. [24] demonstrated, through a compilation of studies, that the most energy used throughout the lifecycle of a typical building is during its operation. Bilec and team [25] developed temporal- and spatial- based dynamic process modeling, i.e., Dynamic LCA and applied it to assess building use phase energies with wireless sensor networks [26] and integrating Indoor Environmental Quality metrics within this dynamic framework [27].

Yet, the use of LCA for buildings has not been as ubiquitous as in the manufacturing sector, mostly due to the fact that the design and approach used for each building are often unique. Further, the life cycle approach has raised awareness of potential impacts to the services provided by ecosystems, i.e., the ecosystem goods and services directly and indirectly responsible for the creation and support of the natural systems that support the processes and economic sectors of society. It has been argued that ecosystem services are the backbone of any economy, since all raw materials come, one way or another, from biogeochemical cycles associated with a given ecosystem, both the biotic and abiotic system components [28,29]. Yet impacts to ecosystem services are not captured with conventional LCA methodologies.

There are several needs for improved assessment of buildings that are currently being pursued. For one, the LCA boundaries for buildings need to be standardized to develop a consistent assessment protocol, and to compare among several life cycle building strategies. Also, ecosystem goods and services need to be incorporated into the LCA of the built environment to account for resource depletion, particularly since buildings consume vast amounts of natural resources and energy, most of which are non-renewable. As cities expand to meet the need of growing populations, the goods and services that ecosystems provide, inevitably, may be threatened by unsustainable practices. It is imperative that those concerned with the built environment start implementing strategies that minimize the disruption of ecosystem goods and services, as these are the foundational support for economies.

1.2. Ecosystem services in LCA

Ecosystem services are the benefits that humans are provided directly and indirectly by ecosystems, and embody the very tangible dependencies of the human population on the biosphere [30]. Ecosystem services may be provisional (e.g., harvested crops), supporting (e.g., purification of water), regulating (e.g., climate), or cultural (e.g. outdoor recreational activities) [31].

In Life Cycle Assessments, industrial-environmental systems are represented as a series of interconnected processes with inputs and outputs of materials and energy, enveloped in the larger environmental system. An ecosystem may be modeled as a system of inputs and outputs in the context of the biosphere, which is the approach often taken in systems ecology [32]. The outputs of ecosystems that are directly or indirectly supportive of human populations in these models may be considered analogous to ecosystem services [33].

Tracking the inputs and outputs of ecosystems may then be one form of modeling ecosystem services. In the field of systems ecology, an environmental accounting methodology using emergy has been developed to account for all of the inputs of ecosystems and transform them to a common energy-based unit, the solar emjoule (sej). The sum of the required available energies may be assigned to an ecosystem service as a way of approximating the total available energy supporting the provision of that service. This methodology can be equally applied to technical systems such as a building or the built environment if the processes of energy transformation underlying the materials and energy used by the system are known. If the uses of ecosystem services as inputs to technical systems can be approximated, then using emergy, it is possible to estimate the available energy from those ecosystem services that is being used in products.

The initial concept, which eventually became emergy, was first introduced by H.T. Odum in the 1960s. Emergy is based on the laws of thermodynamics, general systems theory, and ecology [34–36]. It evaluates the dependency of a product on its upstream environmental and resource energy flows using a common unit of measurement, which is the solar emjoule. Emergy is the solar emjoules embodied in a defined material or system. Non-renewable resources are considered to be more energy intensive than renewable resources. For instance, the amount of solar emjoules needed to generate a given amount of energy embodied in fossil fuel is much greater than an equivalent amount of embodied energy in biomass, e.g., wood [36].

Emergy has been viewed as a useful method for environmental evaluation of production systems [37]. One of the first efforts to integrate emergy analysis and LCA is the Emergy-based LCA (EmLCA) approach, which integrated the impact of emissions into the emergy analysis [38,39]. In this approach, materials (as input) and emissions (as output) were obtained from existing databases used in LCA. An Ecological Cumulative Exergy Consumption (ECEC) indicator was later developed to determine the exergy consumed by the ecological processes required to produce the raw materials, to dissipate the emissions, and to sustain the operation of the industrial processes [40,41]. Eco-indicator 99 [42] was used to study, among others, the impact of the construction of a building on human health.

As the need to consider impacts on ecosystem services became more widely acknowledged in the field of product sustainability and LCA, Zhang et al. [43,44] described how emergy can be used to provide an approximation of ecosystem services, and further proposed the ECEC indicator in the Eco-LCA model to capture them in an LCA.

Eco-LCA provides the framework to account for ecosystem goods and services using the ECEC indicator. This approach uses the 1997 US EIO model. In addition to estimating emissions associated with the 1997 US economy, the results of Eco-LCA can provide an idea of how much of a particular ecosystem good or service was used, or consumed to create a given product. The Eco-LCA framework was designed to show data outputs in several units, namely, mass (measured in kilograms), energy (measured in joules), Industrial Cumulative Exergy Consumption or ICEC (measured in joules), and ECEC (measured in solar equivalent joules or seJ), where ECEC is closely related to emergy [36,40].

Since Eco-LCA uses the 1997 US EIO model, it poses similar problems to those inherent in EIO-LCA. For instance, a particular sector (e.g., Iron and Steel Mills) may be composed of several industries associated with the manufacturing of a specific product (e.g., structural steel beams of a building), but the environmental impact results depict the average of all industry's emissions within the sector.

Moreover, there were a few attempts to implement Unit Emergy Values (UEVs) in LCA software; for instance, Raugei applied UEVs to LCI results in SimaPro [45]; and Rugani et al. [46] developed the Life Cycle Impact Assessment (LCIA) indicator based on an emergy-like quantity or Solar Energy Demand (SED), which was integrated with EcoInvent processes. Methods to determine the uncertainty of UEVs have been presented by Ingwersen [47]. Besides, Ingwersen [48] also applied to emergy concepts in EcoInvent for assessing gold mining production. Recently, Rugani et al. [49] describe potential improvements to emergy evaluations that can be gained by using LCA, and Raugei et al. [50] have expounded on the added value to LCA of including emergy as an indicator. Although the Eco-LCA and other emergy-LCA synthesis models have been applied to analyze certain sectors of the economy, they have not been extensively used in assessing the built environment.

2. Methods

In order to compare the use of energy-based indicators for buildings, common tools used to calculate these indicators for buildings were selected and applied to a case study building.

2.1. Case study building

Rinker Hall in the University of Florida campus was selected as a case study for this comparison. Rinker Hall is home to the University of Florida's School of Construction Management. This three-story building has a floor area of about 4394 m^2 and a footprint of about 1622 m^2. The building contains primarily classrooms and construction and teaching laboratories on the first two floors, and offices on the third floor. The building was designed to maximize natural light by using skylights and louvers. It has lighting controls in the form of motion sensors and dimmers to reduce energy use. Furthermore, water use is reduced by the use of low-flow plumbing fixtures, waterless urinals, and a rainwater harvesting system. Rinker Hall's building materials consist of bricks recovered from demolition, recycled cellulose insulation material, local and regional assembly of parts, certified wood, and renewable flooring material. Cooling and heating for the building is supplied by chilled water and steam, from central plants.

2.2. Model selection

Two LCA tool that report conventional life cycle energy use, i.e., EIO-LCA and ATHENA® Impact Estimator were selected for application alongside two tools that include an energy-based emergy indicator, the Eco-LCA tool and the emergy methodology. EIO-LCA is a freely available online tool (http://www.eiolca.net) and is maintained by the Carnegie Mellon University's Green Design Institute [9]. We used EIO-LCA to estimate life cycle energy use, reported in terajoules (TJ). ATHENA® Impact Estimator [51] is a decision support tool that provides a cradle-to-grave process-based LCA incorporating regional data such as appropriate electricity grid data (energy mix), transportation modes and distances to estimate life cycle energy use in TJ. Eco-LCA is an alternative tool for Economic Input–Output LCA that can also be used to estimate the appropriation of specific ecosystem goods and services by production processes. Eco-LCA is also a freely available online tool (http://resilience.eng.ohio-state.edu/eco-lca/) [52]. Here, we used Eco-LCA to estimate ECEC in solar equivalent joules as well as conventional life cycle energy use (TJ). To perform the emergy analysis, we used a conventional table-form emergy evaluation [36] where all inputs to the building life cycle are listed along with their associated UEVs (sej per physical unit of input, typically energy or mass). The inputs were multiplied by the unit emergy values to estimate emergy per item, and emergy of all items are summed to estimate total building life cycle emergy in sej.

2.3. System boundaries

There are implicit differences in the system boundaries of EIO-LCA, ATHENA® Impact Estimator, Eco-LCA, and emergy methods in relation to the entire life cycle of a building (cradle-to-grave); therefore, a modified version of the Building Research Establishment's (BRE) building life cycle stage analysis was used to describe these differences [53], Fig. 2. A new Raw Material Formation stage was included preceding the Product Stage to introduce the energy expenditure related to the formation of raw materials from Earth's geobiosphere, which is addressed by both the Eco-LCA and emergy models. For this research, only the Operational Energy Use and Maintenance phases belonging to the Use stage were used owing to data availability. While the Operational Energy Use phase relates to energy consumption, i.e., electricity, chilled water, steam, natural gas, etc., used during the useful life of the building, the Maintenance phase covers all actions for maintaining the product or the building, as a whole, during its useful life. The other phases in the Use stage are Repair (covers all actions for maintaining through repair works for continued usage during useful life), Replacement (covers all actions for replacing the product at the end of the product's service life), and Refurbishment (covers all actions for restoring the product in a building to its former good condition), and Operational Water Use (covers all potable and non-potable water use over the building's service life). The End-of-life stage is composed of Demolition, Transport, Waste Processing, Disposal (to landfill), Reuse/Recovery/Recycle. All assessment models were applied with an analysis boundary of the building's life cycle that includes all stages namely, Raw Material Formation, Product, Construction, Use, and End-of-life.

2.4. Data collection and preparation

Using a bill of materials alone would not reflect the entire life cycle of Rinker Hall; therefore, it was necessary to extend the analysis boundary to incorporate the Operational Energy Use (starting from the day the building was occupied and continuing until the end of its useful life), Maintenance, and Decommissioning (including deconstruction, recycle and reuse, and energy used for transporting materials to the materials' final destination). In order to incorporate these latter stages, we include operational energy data on the replacement of building components necessary for building maintenance, and estimate energy for demolition, some deconstruction, disposal, and recycling of materials. Technical documents such as construction drawings, finish schedules, and commissioning reports were used to generate an inventory of inputs. These include a list of materials used and their mass quantities. For this analysis, a few assumptions were used, namely land use was assumed to be a renewable resource as the site was previously a parking lot and not virgin land; and demolition, site pavement, and human services (used in construction stage) were excluded.

To calculate the energy use and related emissions due to the transportation of materials from the manufacturing site to the construction site, diesel fuel was assumed to be the primary fuel used. The monetary cost of diesel fuel was estimated based on material quantities used, truck capacity and type, and distance traveled from the manufacturing to the construction site, Table 1. The distances from manufacturer to the building site for most of the structural components and facades, as well as some interior components were obtained from the LEED™ report [54]. Transportation energy used in construction and construction waste disposal was also estimated based on local recycling and landfill facilities, as well as material quantities designated for reuse, recycling or the landfill. Travel distances for electrical, plumbing, and mechanical equipment were not available; therefore, they were not included in the calculations.

Since data for the energy consumed during the construction of Rinker Hall was not available, estimates from other studies were used [20,23,55]. The energy used was assumed to have come primarily from diesel fuel used by construction equipment. Based on the above mentioned studies, 4.75% of the initial embodied energy of materials was used for the construction of structural and interior components. Because embodied energy was measured in Joules, a conversion factor was used to obtain gallons of diesel fuel used in the construction process (i.e., 1 gallon of diesel = 135.8 MJ). The cost of one gallon ($1.50) of diesel fuel during the time of Rinker Hall's construction was used in EIO-LCA and Eco-LCA.

Within the Use stage, Maintenance phase was assumed that if a given component's (e.g., curtain wall glazing, doors, etc.) expected useful lifespan was less than that of the building, it was entirely replaced i.e., all glass for curtain walls, all doors, paint on all interior walls, etc. To obtain maintenance energy, the monetary value from the Guaranteed Maximum Price (GMP) estimate report was used for each particular component being replaced. GMP, presented under the Construction Specification Institute (CSI) MasterFormat®, reflects every component of the building design in terms of total

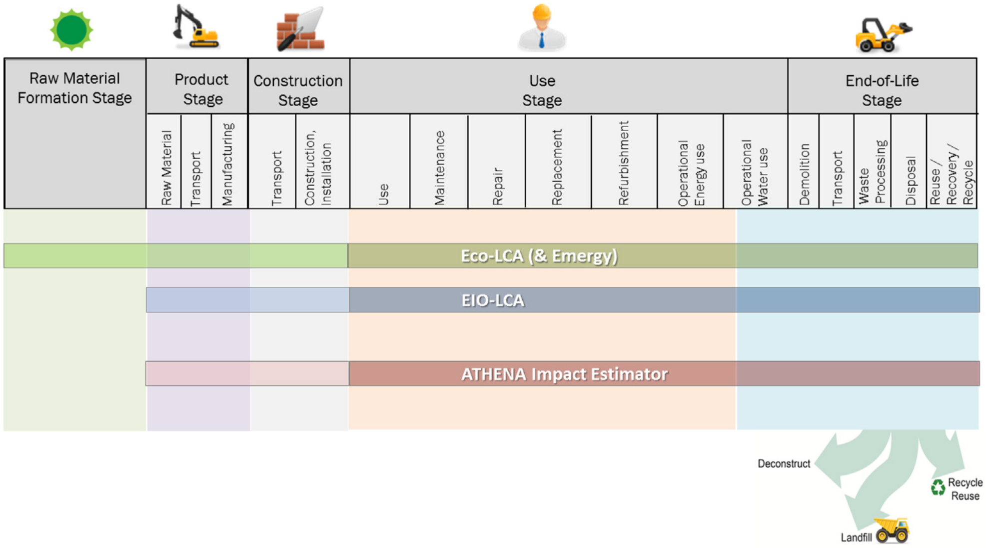

Fig. 2. System boundaries for the life cycle inventory and impact assessment methods used to evaluate the built environment. Adopted from BRE [52] and modified to include a new phase "Raw Material Formation" preceding the Product Stage.

Table 1
Transportation energy: to construction site (Construction Stage), during construction (Maintenance phase) and deconstruction (End-of-Life Stage). CY = cubic yards, SF = square feet, Tons = metric tons.

Material transported	Material quantity	Vehicle	Truck capacity	MPG	No. of trips	Distance to facility (miles)	Fuel type	Fuel used (Gal)
Transportation of material to construction site								
Recycled concrete	3333 CY	Class 8 truck	27 CY	5	123	1.5	Diesel	37
Concrete	1329 CY	Ready-Mix	8 CY	3.83	166	5.3	Diesel	230
Rebar (concrete)	69 tons	Class 8 truck	18 tons	5	4	92.6	Diesel	74
Structural steel	308 tons	Class 8 truck	18 tons	5	17	55.8	Diesel	191
Drywall	133 tons	Class 8 truck	18 tons	5	8	145	Diesel	232
Metal wall panels	16300 SF	Class 8 truck	3000 SF	5	5	369	Diesel	401
Aluminum storefront	9995 SF	Class 8 truck	2000 SF	5	5	71.6	Diesel	72
ACTs	28 tons	Class 8 truck	18 tons	5	2	344	Diesel	107
Total					**330**	**1085**		**1344**
Transportation of material waste during construction								
Asphalt	230 tons	Class 7 truck	8.4 tons	5	27	11	Diesel	60.2
Concrete	157 CY	Class 8 truck	27 CY	5	6	11	Diesel	12.8
Limerock	274 tons	Class 7 truck	8.4 tons	5	32	2.6	Diesel	17.0
Land debris	75 tons	Class 7 truck	4 tons	7	20	11	Diesel	31.4
Gypsum board	14 tons	Class 8 truck	18 tons	5	1	290	Diesel	58.0
Steel	2 tons	Class 6 truck	5 tons	12	1	9.2	Diesel	0.8
Cardboard	1 ton	Class 6 truck	5 tons	12	1	7.4	Diesel	0.6
Total					**88**	**342.2**		**181**
Transportation of materials during deconstruction								
Reused								
Structural steel	308 tons	Class 8 truck	18 tons	5	17	2	Diesel	6.8
Metal wall panels	16300 SF	Class 8 truck	3000 SF	5	5	2	Diesel	2.2
Aluminum storefront	9995 SF	Class 8 truck	2000 SF	5	5	2	Diesel	2.0
Metal/wood doors	48 tons	Class 7 truck	8.4 tons	5	6	2	Diesel	2.3
Red bricks	218 tons	Class 7 truck	8.4 tons	5	26	2	Diesel	10.4
Recycled								
Concrete	1329 CY	Class 8 truck	27 CY	5	49	5.5	Diesel	54.1
Drywall	133 tons	Class 8 truck	18 tons	5	8	145	Diesel	232.0
ACTs	14 tons	Class 8 truck	18 tons	5	1	5.5	Diesel	0.9
Misc. metals	14 tons	Class 7 truck	8.4 tons	5	1	5.5	Diesel	1.1
Interior glass	11 tons	Class 7 truck	8.4 tons	5	2	5.5	Diesel	2.2
Metal studs	30 tons	Class 7 truck	8.4 tons	5	4	4.6	Diesel	3.3
Metal deck	34 tons	Class 7 truck	8.4 tons	5	4	4.6	Diesel	3.7
Metal stairs	171 tons	Class 8 truck	18 tons	5	10	4.6	Diesel	8.8
Landfill								
Carpet	3 tons	Class 7 truck	8.4 tons	5	1	35.2	Diesel	7.0
Linoleum	3 tons	Class 7 truck	8.4 tons	5	1	35.2	Diesel	7.0
Door frames	36 tons	Class 7 truck	8.4 tons	5	4	35.2	Diesel	30.3
Tile	10 tons	Class 7 truck	8.4 tons	5	1	35.2	Diesel	8.2
Wood	165 tons	Class 7 truck	8.4 tons	5	20	35.2	Diesel	138.3
Drainage system	522 tons	Class 7 truck	8.4 tons	5	62	35.2	Diesel	438.0
Total					**227**	**402**		**959**

material quantities and dollar amount. This approach does not reflect future changes in material cost throughout the lifespan of the building. The lifespan of building components, in number of years, were adapted from Scheuer et al. [23].

The operational energy use data of the building was obtained from the University of Florida's Physical Plant Division. A summary record depicting monthly energy consumption and cost for seven consecutive years for cooling, heating, and operations of the building were used to calculate annual average energy consumption data, i.e., since the building became operational. This, then, was extrapolated to obtain cumulative energy consumption for the 75-year lifespan of the building. It is to be noted that this approach neither accounts for changes in energy prices nor includes renewable energy sources in future years (e.g., photovoltaic systems that might provide future energy needs for the building). The total energy consumption of the building was expressed in US dollar amounts so it could be entered into the LCA models. For this study, energy inflation and energy cost fluctuation were not included.

Assumptions for the End-of-life stage energy included deconstruction of structural steel, façade, and some interior components, the demolition of components that could not be dismantled, and transportation of deconstructed, demolished, and recyclable materials to appropriate locations. The deconstruction and demolition energy was estimated from an Athena study done in Toronto, Canada [56]. In this study, the energy required to deconstruct the structural steel of an office building of similar size to Rinker Hall was determined to be 130 MJ/m^2. The deconstruction energy was assumed to be 260 MJ/m^2 to account for both deconstruction and demolition energy. Diesel fuel was designated as the primary source of energy used in the deconstruction and demolition process.

Because one of the features of Rinker Hall's design was for its structural components and façade to be easily deconstructed, this study made the assumption that most of the structural components and façade would be reused in future construction within the campus. Also, it was assumed that the remaining miscellaneous metals, glass, concrete, gypsum board, and non-structural metal would be transported to recycling facilities within city or county limits. Therefore, the transportation energy to such facilities was estimated and included.

Since EIO-LCA and Eco-LCA are based on economic input–output data for the US economy, the monetary values for all materials were gathered from the bill of materials and matched with appropriate US economic sectors. The costs of the materials were obtained from Rinker Hall's GMP estimates prepared by the construction company responsible for constructing the building. Some of the costs in the GMP estimates had a lump sum for labor, equipment cost and overhead, and profit to subcontractors. For those instances, RS Means, a US construction industry reference guide for construction cost estimation, was used to determine the cost breakdown into labor, materials, equipment, overhead, and profit using a similar material and job description [56]. This method was evaluated using known labor, material, equipment, overhead, and profit found in the GMP. The difference between the actual material cost and the RS Means was calculated to be between 5% and 10%, which was determined to be negligible, i.e., within the overall expected accuracy of our estimates. Also, all costs were converted to 1997 US dollars by discounting cost back to 1997 using annual inflation rates between 2003 and 1997 to remove effects related to currency inflation. Because the emergy of material replacement was unknown, the ratio of replacement energy to material production energy from Eco-LCA was multiplied by the emergy of the production energy.

In the case of ATHENA® Impact Estimator, input data was gathered from Rinker's construction documents and GMP. The operational energy data was calculated as described above, and input into the model as a yearly value. Since the software did not allow input of Gainesville for project location, the city of Orlando in Florida was selected.

3. Model results

The application of the EIO-LCA, ATHENA® Impact Estimator (life cycle energy use in TJ in both models), Eco-LCA (life cycle energy use in TJ, and ECEC in sej), and emergy (life cycle emergy in sej) each present different energy-based perspectives of Rinker Hall's life cycle. Appendix A lists the building components organized by CSI division numbers in the GMP and their energy expenditures along with their respective life cycle stages. In addition, this table provides in depth results from the assessment methodologies for the life cycle phases; EIO sector numbers; and replacement years (for maintenance) used for this analysis. However, in the case of the ATHENA® Impact Estimator, input data is not available by CSI divisions and, therefore, it is tabulated at the bottom of the table for comparison purposes.

The life cycle energy use is not directly comparable with the emergy-based metrics from the other two models, i.e., Eco-LCA and emergy, but all four offer alternatives for measuring building resource use are shown in Table 2. The emergy based-methods, Eco-LCA (in terms of ECEC, unit sej) and emergy, include the energy supporting ecosystem goods and services involved in the formation of raw materials. Rinker Hall's life cycle energy distribution using ATHENA® Impact Estimator is roughly similar to EIO-LCA, where operational energy use accounts, respectively, for 98.4% and 89.5% of the total use. Even though these proportions are similar, the operational energy value itself using the ATHENA® Impact Estimator is about twice as much as EIO-LCA (1373 TJ and 643.4 TJ respectively). Differences in Product and Maintenance stages using EIO-LCA and ATHENA® Impact Estimator can be attributed to the limited materials and building components included in the ATHENA® life cycle database. In the latter model, the building material database is restricted to the structural and envelope systems that are most commonly used. On the contrary, since EIO-LCA is a sector-based approach, it is not limited to the components of the building that can be included in the analysis, as long as a particular material is covered under a specific industrial sector. Therefore, EIO-LCA can provide a more thorough assessment, since components such as mechanical, electrical, and plumbing can be input in the analysis, yet suffer uncertainties related to typical sector-based LCA methods.

Fig. 3a–d shows the breakdown of building life cycle stages using Eco-LCA, EIO-LCA, and emergy models. Approximately 56% of total energy use was allocated to the Product Stage of Eco-LCA, Fig. 3a, unlike EIO-LCA, Fig. 3b, where operational and maintenance energies represent more than 90% of total energy. The dominant energy expenditure (in TJ) of Eco-LCA model, Fig. 3a, is driven by the Raw Material Formation stage. This, again, can be explained by the amount of primary solar-based energy that entered the economy via the forestry and agricultural sectors. One of the major contributors to energy expenditures for the Product and Maintenance stages are electrical systems, mechanical equipment, and finishes, where these products are not captured by the ATHENA® Impact Estimator for the same reasons discussed earlier. Transportation energy expenditure within Construction stage was better assessed by the ATHENA® Impact Estimator using specific project location data. However, EIO-LCA and Eco-LCA models may not be accurately modeled unless specific material transport (to construction site) data is available. In the case of this project, LEED™ submittal documents were used to gather relevant transportation information.

Eco-LCA analysis shows greater emphasis in the operational energy use phase, as this model captures the higher energy quality of, for instance, non-renewable sources of energy, i.e., solar energy required to make resources such as coal, natural gas, etc., used for

Table 2
Built Environment Stages and Assessment Methodologies: EIO-LCA, ATHENA® Impact Estimator, Eco-LCA, and emergy.

Stage	Sub-stages	EIO-LCA[a] (TJ)	ATHENA® impact estimator[b] (TJ)	Eco-LCA (TJ)	Eco-LCA (sej)	Emergy (sej)
Product Stage	Raw Material Formation, Extraction, Transport & Manufacturing	57.16	14.02	13021	2.8 e19	1.86 e20
Construction Stage	Material Transport to site	0.05	0.46	1.3	5.3 e15	1.2 e16
	Construction & Installation	2.86	0.32	651	1.4 e18	9.3 e18
	Construction Waste Transport	0.01	n/a	0.2	7.1 e14	1.6 e15
Use Stage	Operational Energy Use	643.5	1373	5450	4.71 e19	2.0 e19
	Maintenance	15.26	4.38	4020	5.7 e18	2.8 e19
End-of-life stage	Demolition	0.56	0.32	2.2	6.0 e16	2.9 e17
	Transport	0.04	0.11	15	3.8 e15	8.6 e15
Total		719.4	1392.61	23160	8.23 e19	2.44 e20

[a] EIO-LCA and Athena Impact Estimator does not include the energy of raw material formation.

[b] ATHENA® Impact Estimator does not include replacement of mechanical or electrical equipment.

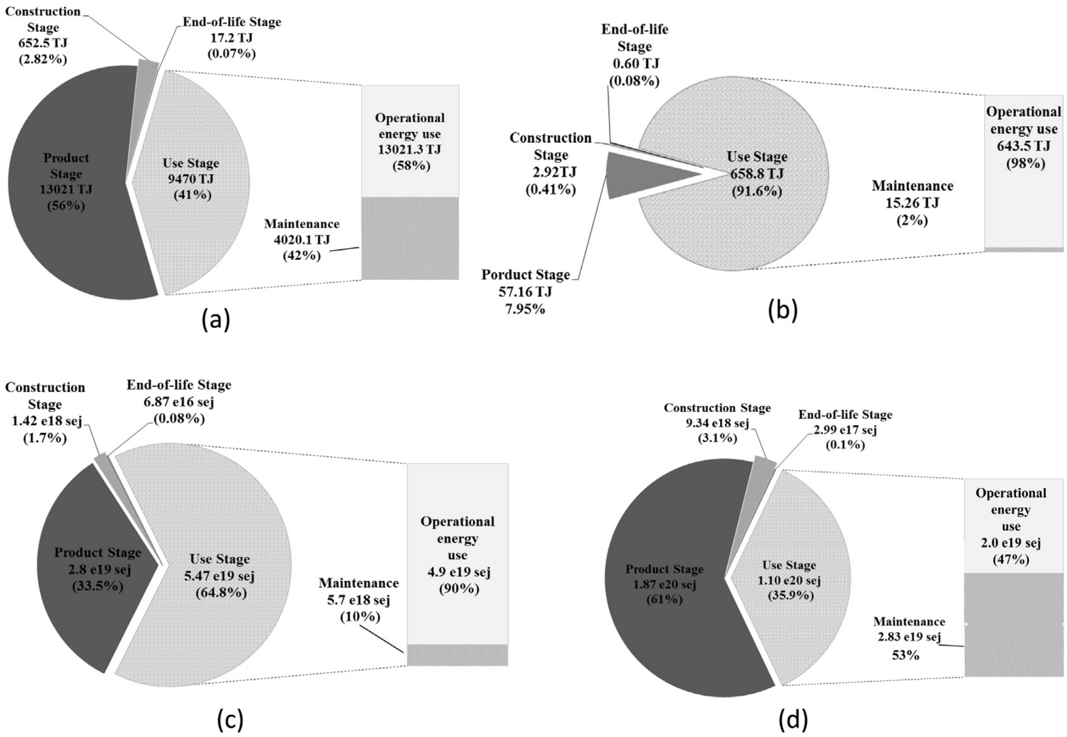

Fig. 3. a. Life Cycle energy use in TJ using Eco-LCA. Operational energy use is 58% of Use Stage, but is only 41% of total energy use. b. Life Cycle energy use in TJ using EIO-LCA. Operational energy is 98% of the Use Stage, which is 91.6% of total energy use. c. Life Cycle emergy use in sej using Eco-LCA. Operational energy use is 90% of the Use Stage, which is 64.8% of total emergy use. d. Life Cycle emergy use in sej using emergy analysis. Operational energy is 74% of the Use Stage, which is 35.9% of total emergy use.

electricity and heat generation, Fig. 2c. Whereas the Eco-LCA model used monetary values as inputs, emergy analysis used material quantities and unit emergy values making the emergy analysis of greater detail in terms of accounting for specific materials that make a particular component of the building. For instance, curtain walls' metal frame and glass, as well as resources consumed or lost on the site during the building's lifetime are used to develop emergy quantities. In addition, the transformity values used in the emergy analysis could differ from those in Eco-LCA for the same material, e.g. operational energy use and maintenance. Furthermore, emergy uses a co-product allocation rule for products of multi-output processes (e.g., co-generation of electricity and steam) whereby all the incoming energy is assigned to each product [57], whereas Eco-LCA uses the conventional economic allocation, splitting the incoming energy based on the relative price. These differences in methodology and material transformity values contributed to the large differences in sej values between Eco-LCA and emergy, specifically, in the Product and Use stages, see Table 2 and Fig. 3c–d.

Table 3

Comparison of the operation portion of Rinker Hall's life cycle using Athena, Eco-LCA and EIO-LCA. Eco-LCA includes nonrenewables and renewable sources of energy entering the economy through the power generation and supply industry.

[a]Sector ID	Classification	Ecosystem goods and services	ATHENA® impact Estimator (TJ)	Eco-LCA (TJ)	EIO-LCA (TJ)
221100 Power Generation and Supply	Lithosphere	Crude Oil	112.8	25.60	7.57
		Coal	439	425	496
		Natural Gas	669	116	120
		Nuclear	137	0.686	n/a
		[b]Non-fossil fuel sources	15.2	n/a	19.80
	Biosphere	Detrital Matter	n/a	0.17	n/a
		Wood (Dry)	n/a	1.37	n/a
		Grass	n/a	0.06	n/a
		Fish	n/a	0.01	n/a
	Atmosphere	Non used	n/a	0.00	n/a
	Hydrosphere	Non used	n/a	0.00	n/a
	Ecological service	Soil erosion (farm)	n/a	0.0301	n/a
		Soil erosion (construction)	n/a	0.000870	n/a
		Sunlight (farm)	n/a	344	n/a
		Sunlight (forest)	n/a	3990	n/a
		Sunlight (ranch)	n/a	546	n/a
		Hydropotential	n/a	0.3880	n/a
		Geothermal	n/a	0.0161	n/a
		Wind	n/a	0.00358	n/a
Total			1373	5449.34	643.37

[a] Sector ID is only relevant to Eco-LCA and EIO-LCA .

[b] EIO-LCA groups all non-fossil fuel sources of energy (nuclear, hydropower, etc.) under "non-fossil fuel sources."

Table 4
Differences between Eco-LCA and emergy for the three components of the operation phase of Rinker Hall’s life cycle.

Operational energy type	Energy (J)	Energy (kWh)	Cost per Unit energy ($/kWh)	Eco LCA (sej)	Emergy (sej)	Sector ID
Steam	5.89e13	16,360,797	$180,450	1.45e18	3.02e18	221,300
Chilled water	3.02e14	84,315,018	$2,314,725	1.64e19	1.21e19	221,100
Electricity	1.23e14	34,143,482	$2,814,750	2.92e19	4.29e18	
Total	4.83 e14	1.35 e08	$5,309,925	4.71e19	2.00e19	

In the case of the operational energy use phase, a large difference exists among ATHENA® Impact Estimator, EIO-LCA, and Eco-LCA. Table 3 compares power generation and supply attributed by each of these three methodologies within a classification system for specific ecosystem goods and services' and their origin, such as lithosphere, biosphere, atmosphere, hydrosphere, and ecological service. Eco-LCA accounts for renewable sources of primary energy that enters the economy through the power generation and supply industry. The largest contributor is the sunlight energy entering the economy through the agricultural, farming, and forestry sectors, where it accounts for 73% of the operational energy use of Rinker’s life cycle. Sunlight is lower quality energy than fossil fuel for the production of electrical energy; therefore, the aggregation method used to produce the Eco-LCA results in energy (TJ) can be, in some instances, misleading [47].

A similar disagreement between Eco-LCA and emergy may be observed in the operational energy use phase, i.e., the energy expenditure (sej) for Eco-LCA is over two times greater than for emergy, Fig. 3c–d. To examine the difference between these two values, operational energy use was further broken down into its energy components: electricity (used for lighting, computers, etc.), chilled water (for cooling the building), and steam (for heating the building), see Table 4. In order to maintain consistency, emergy values were calculated using the same fuel mix of the sector IDs used in Eco-LCA, see Table 5, and transformity values obtained from the literature. The prominent differences may be observed in the emergy value of steam (six times larger than Eco-LCA) and the emergy value of chilled water (two times larger than Eco-LCA), Fig. 4. In the case of Eco-LCA, the ECEC is determined by estimating the exergy consumed by the ecological processes required to produce the raw materials, dissipate the emissions, and sustain the operation of the industrial processes. In the case of emergy estimation, material transformities are employed. The EIO sector ID (221300: water sewage and other systems) is the closest representation to centralized steam generation for heating purposes. This sector ID is mainly composed of industries responsible for water treatment and water distribution facilities. The fuel mix given by this particular sector ID may not be representative of a centralized steam generation facility, potentially, underestimating the use of fossil fuels for steam generation. Also, as mentioned above, the transformity values [58,59] used in the emergy calculations may not be the same values used in the Eco-LCA analysis, and the use of the co-product rule in emergy results in all of the incoming energy for co-generation being attributed to each co-product.

Table 5
Fuel distribution and emergy values for steam, chilled water and electricity for Rinker’s operational life cycle phase.

Fuel mix of operational energy components	Fuel mix[a] (%)	Energy (J)	Transformities (Sej/J)	Emergy (sej)
Steam				
Coal	19%	1.12e13	37,800[b]	4.23e17
Natural Gas	41%	2.41e13	43,500[b]	1.05e18
Oil	40%	2.36e13	65,800[c]	1.55e18
Total	100%	5.89e13		3.02e18
Chilled water				
Coal	77%	2.34e14	37,800[b]	8.85e18
Natural Gas	19%	5.64e13	43,500[b]	2.45e18
Oil	4%	1.19e13	65,800[c]	7.83e17
Total	100%	3.02e14		1.21e19
Electricity				
Coal	77%	9.47e13	37,800[b]	3.58e18
Natural gas	19%	2.34e13	43,500[b]	1.02e18
Oil	4%	4.92e12	65,800[c]	3.24e17
Total	100%	1.23e14		4.29e19

[a] Fuel mix for steam, chilled water and electricity are based on the sector IDs of the 1997 Economic Input–Output model associated with this operations. Sector ID 221300_Water, sewage and other systems corresponds to steam, and Sector ID 221100_Power generation and supply corresponds to chilled water and electricity. It is to be noted that the primary fuel mix percentages were selected from Eco-LCA. For example, Coal is predominantly used primary fuel for production of electricity and chilled water. For emergy calculation, the fuel mix percentages derived from Eco-LCA were used along with the fuel transformities, i.e., the primary fuel mix percentages does not necessarily reflect the actual primary fuel mix percentages of the power plant that supplies energy to UF campus.

[b] Campbell and Ohrt, 2009 [58].

[c] Bastianoni et al., 2009 [60]. Specific emergy of total distillate (diesel) is 65,800 sej/J based on calorific value (43 kJ/g) and specific emergy (2.83e9 sej/g).

It is to be noted that Eco-LCA uses the transformities developed in Zhang et al. [43,44] which are based on mixed baselines. Zhang et al. used transformity based on mixed emergy baselines. Besides, it was found that the assumptions about the mineral elements are that they are all the same transformity. For the comparison study between Eco-LCA and emergy to be valid, the calculations done by Eco-LCA, i.e., the database that consists of the transformities used for calculating the ECEC values, need to be redone to ensure that it uses transformities on the same baseline (emergy transformities used in this paper uses 9.26e24 sej/Y baseline).

To capture ecosystem goods and services within the building’s life cycle, an aggregation scheme such as ECEC (via Eco-LCA model, as in the case of this paper) is more appropriate. ECEC, being closely related to emergy, accounts for the energy (e.g. sunlight, tide, crustal heat) used in the formation of raw materials (fossil fuel, wood, limestone, iron ore, etc.), and expresses that energy in terms of solar equivalent joules (i.e. the amount of solar energy necessary

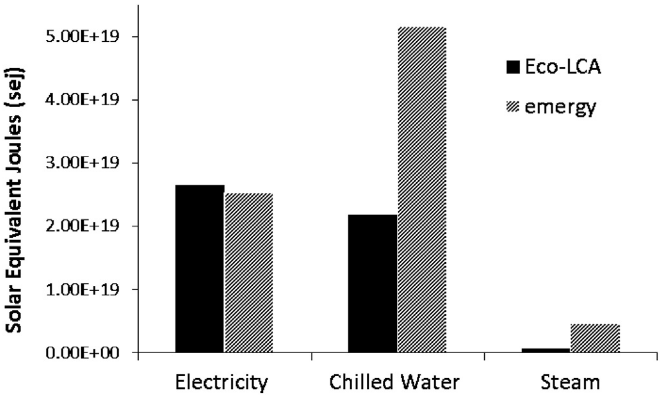

Fig. 4. Comparison between Eco-LCA and emergy for electricity, chilled water, and steam use (Operational Energy Use phase) of Rinker Hall's life cycle.

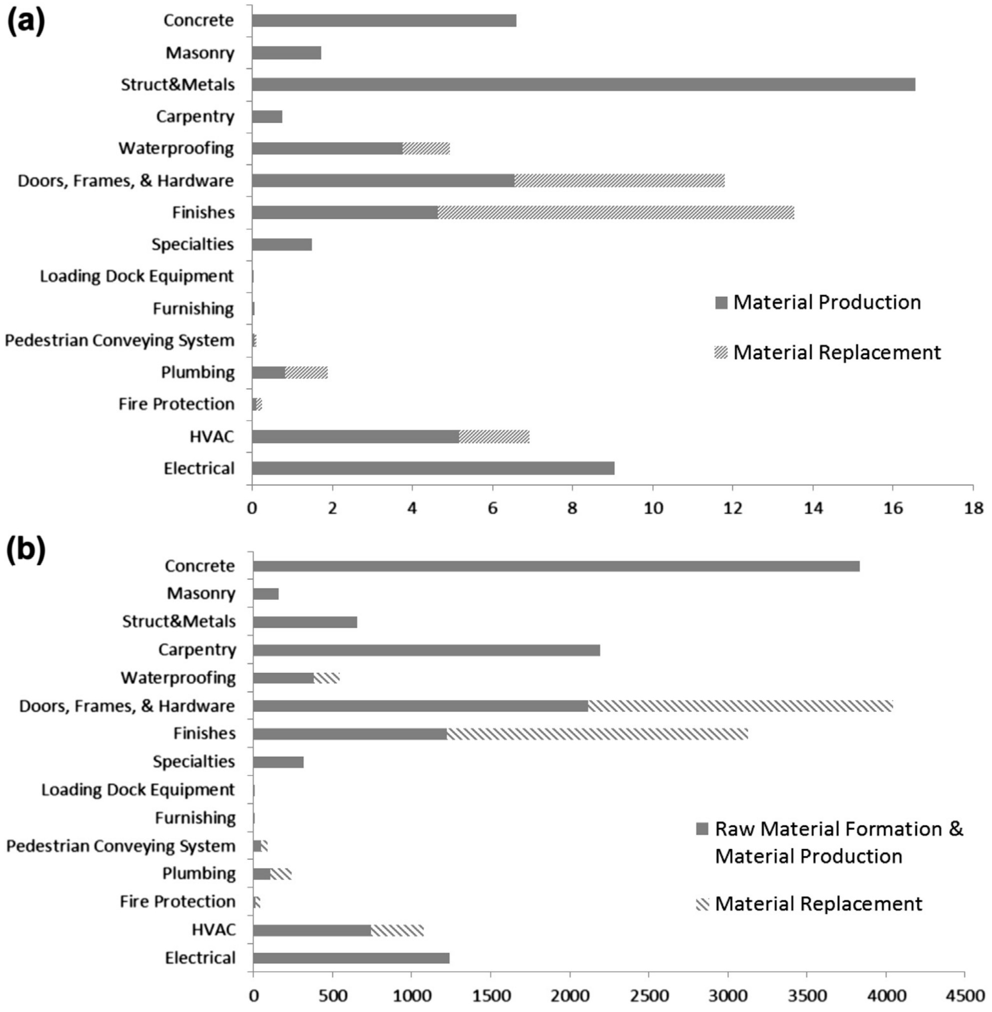

Fig. 5. a. Energy expenditure of building components using EIO-LCA (in TJ). b. Energy expenditure of building components using Eco-LCA (in TJ).

to produce a given amount of raw material). This approach captures the energy quality of different natural resources (e.g. 1 J of fossil fuel can generate more electrical energy than 1 J of plain sunlight), and provides a common unit of measurement for comparisons [52]. Building material selection is an important step toward building sustainability. Fig. 5a and b shows significant increase in energy expenditure of building components before and after considering maintenance. In the first scenario (EIO-LCA), the top four components in terms of energy expenditure are, in this order: Structural Systems & Metals; Finishes; and Doors, Frames & Hardware. However, in the second scenario (Eco-LCA), the top four includes, in this order: Doors, Frames & Hardware; Concrete; Finishes; and Carpentry. Fig. 6 shows the percentages of energy for Concrete; Structural Steel; Finishes; and Doors, Frames & Hardware, when analyzed with the four models discussed in this paper.

4. Summary of energy-based indicators in building environmental assessment tools

4.1Modeling challenges

This study uncovered two major challenges that confront building stakeholders in evaluating the built environment using LCA and similar approaches, namely (a) establishing consistent system boundaries and (b) the data collection methodology and data integrity. As noted above, the system boundaries in relation to a building's life cycle had to be extended to account for the entire life cycle of the building under investigation (cradle-to-grave). One of the major challenges for evaluating buildings is consistency in the choice of system boundaries. For instance, in conducting LCA of buildings, in spite of several research attempts, there are only a handful of studies that considered the entire life cycle of the building, notable among them is Scheuer et al. [23]. As sustainable building construction practices advance, the incorporation of LCA

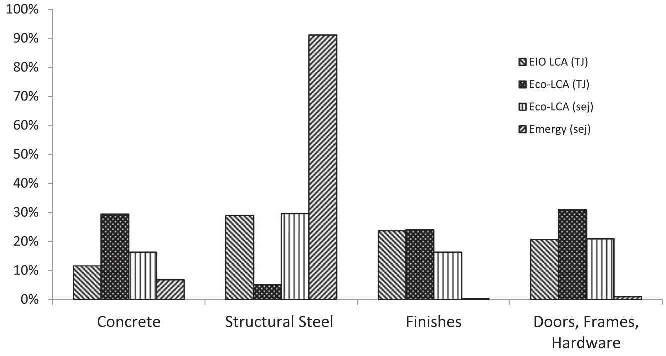

Fig. 6. Percent of embodied energy by CSI division (including maintenance energy for finishes and Doors, Frames and Hardware).

Table 6
Summary table depicting advantages (with a "+" sign) and disadvantages (with a "−" sign) associated with existing methods for analyzing the built environment (table adapted from Ref. [4], with additional information from Refs. [2,31,42].

	ATHENA® impact Estimator	EIO-LCA	Eco-LCA	Emergy
General	+ Easy to use; reproducible −LCI is limited to materials for the structure and envelope of the building − Building materials and assemblies may not be representative of actual design	+ Data for EIO model comprise a good representation of US manufacturing industry (steel, roofing material, paints, cement, etc.) + Provides information on every commodity in the economy + Easy to use; reproducible	+ Data for EIO model comprise a good representation of US manufacturing industry (steel, roofing material, paints, cement, etc.) + Provides information on every commodity in the economy + Easy to use; reproducible	+ Treats all products and services in terms of a common exergetic basis − Limited set of values to match with building materials − Difficult to explain; requires training to use ± Easy to use; reproducible provided transformities of the same baseline are used.
Data requirements	+ Construction Documents	+ Cost data only	+ Cost data only	− Bill of materials and matching unit emergy values from the literature
Boundaries	− Includes all life cycle stages except upstream of extraction	− Includes all life cycle stages except upstream of extraction	+ All life cycle stages including upstream of extraction	+ All life cycle stages including upstream of extraction
Geographical location	+ Impacts results even at regional level, if data available.	− Impacts results only at the national level depending on country EIO data.	− Impacts results only at the national level depending on country EIO data.	+ Impacts can be calculated using transportation-related energies.
Results	− Does not include ecosystem service impacts + Includes specific impact results on air, water, and human health	± Results are based on US economy + Uses publicly available data, reproducible results − Does not include ecosystem service impacts + Includes specific impact results on air, water, and human health − Uncertainty inherent in original EIO model data (EIO LCA model data comes from surveys and forms from industry)	± Results are based on US economy + Uses publicly available, reproducible results + Includes ecosystem services + Includes specific impact results on air, water, and human health − Uncertainty inherent in original EIO model data (EIO LCA model data comes from surveys and forms from industry)	+ Results more robust than input–output results if based on high quality life cycle inventory + Includes ecosystem services − Does not include indicators of environmental impact, impacts to specific resources, or ecosystem service impacts − Uncertainty in use of emergy conversion factors extracted from the literature
Needs improvement	Electrical systems, mechanical equipment, finishes, etc. should be included.	Currently, 2002 IO data are available, which is still a decade old.	Transformities of the same baseline should be used in Eco-LCA software to develop valid comparison with emergy.	A comprehensive building materials' transformity database.

for the built environment has become a tool to help stakeholders evaluate building components and buildings as a whole. Although tools such as ATHENA® Impact Estimator and EcoCalculator used for complying with building rating systems account for the whole life cycle of the building, they do not account for ecosystem goods and services, nor do they account for all components of the building (e.g. HVAC equipment, electrical and plumbing components). In order to evaluate the building's energy, environmental, and ecological impacts, establishing a consistent system boundary that represents the entire building life cycle as well as including all components of the building is crucial.

The second modeling challenge is discussed in two parts, a) data collection methodology, and b) data integrity. For this particular research, the input data for the economic based models and emergy analysis was based on the GMP provided by the contractor. Therefore, the input as well as output data for the LCA was organized by the CSI master format which continues to be the dominating format used in the construction industry. This master format makes it difficult to assign a dollar amount and material quantities to specific materials involved in a particular building assembly (e.g. shell, roof, interior), therefore, restricting the ability to analyze different options for building assemblies for a particular building. Furthermore, data aggregation using CSI master format hinders the possibility of obtaining results for different sub-stages of the building's life cycle. For instance, within the Use stage, all data was under Maintenance due to the difficulty of categorizing the data to resemble the other sub categories. More importantly, in order to develop a full and complete LCA for holistic assessment that includes ecosystem goods and services, it is vital that, if not all, most of the cells in Appendix A should be complete with values derived from documents. It is to be noted that there is a lack of research work in the End of Life stage, particularly, how to develop assessments for decommissioning, disposal, and reuse/recovery/recycle phases of buildings.

In terms of data integrity, selecting accurate LCA data to apply to the building life cycle, in the case of EIO-LCA and Eco-LCA models, can be problematic. Because, both EIO-LCA and Eco-LCA use a country's economy as the boundary of the analysis, this approach makes it difficult to select an appropriate sector to a particular building process, or material. For example, the steel used in the building belongs to the EIO sectors (IDs 33111, 332322, 332323, 332313). The most suitable sector was selected based on professional expertise and listed in Appendix A.

Similarly, the transformity values used in emergy analysis require considerable enhancement for use in buildings and the built environment. A comprehensive building materials emergy database with renewable resource use and non-renewable contents is fundamental for applying this method to a wide variety of buildings. Currently, for the same material, several transformities exist. This is due to the inclusion of the location of the manufacturing process as well as variations in the manufacturing methods [61].

There are software tools that are available for use by the building community to evaluate buildings, at a system or whole building level. Some of the tools require expertise in modeling, for instance, SimaPro [30]. Others that do not require a great deal of modeling expertise include ATHENA® Impact Estimator, EcoCalculator, etc.

4.2. *Summary of energy-based indicators from selected tools for use in building evaluation*

Based on this study, in the context of building evaluation, EIO-LCA does not include the evaluation of ecosystem goods and services when reporting life cycle energy. However, Eco-LCA (sej) and emergy evaluation capture information related to impact on ecosystem services by including upstream energy used by ecosystems to form the resources indirectly used by building. Yet, employing each of these tools to evaluate life cycle energy use for mainstream applications may not be simple owing to their inherent limitations, i.e., data uncertainties and related shortcomings, and modeling challenges as discussed above.

Nevertheless, the evaluation methods overwhelmingly highlight the energies used up in building material manufacture in addition to operational energy and, thus, lead to different conclusions than EIO-LCA results. The incorporation of impacts on ecosystem goods and services into LCAs will enrich sustainability-related decision making in the design, construction, operation, and decommissioning of buildings, but the current methods used in this paper have limitations and require further development. Based on this study, it is expected that users employing such methods for mainstream applications, in this context, must exhibit caution in the development of data inputs and analyzing results. The capabilities of the selected building environmental assessment tools, in terms of their advantages and disadvantages, are discussed in Table 6. The advantages and disadvantages listed are in the context of use for building evaluation, although many implications are more widely applicable, since the models could be used to analyze a wide arrange of products and services.

5. Conclusions

This paper provides an up-to-date comparison of selected life cycle-based tools for evaluating the built environment from the perspective of life cycle energy use, particularly EIO-LCA, Eco-LCA, ATHENA® Impact Estimator, and emergy. Using a case study building in a university campus setting, this paper compared these tools to identify their strengths and weaknesses. Additionally, the detailed analysis conducted using building materials and energy data brought to light challenges related to modeling life cycle energy use in buildings, particularly, consistent system boundaries and data collection. While typical life cycle tools such as EIO-LCA and ATHENA® Impact Estimator provided valuable information, the tools that incorporated the upstream energy used to support ecosystem goods and services in the measure of life cycle energy use, i.e., Eco-LCA and emergy, will enrich sustainability-related decision making in the design, construction, operation, and decommissioning of buildings. The latter tools, namely Eco-LCA and emergy evaluation, each capture information related to impact on ecosystem services that is not captured by the conventional LCA tools, and as applied here, they have a more thorough consideration of life cycle stages. Nevertheless, all of the tools studied in this paper have limitations with respect to full building evaluation and require further development. Based on this study, it is expected that users employing such methods for mainstream applications, in this context, must exhibit caution in the development of data inputs and analyzing results. More importantly, effort should be placed in tracking data of all stages of building life cycle including End-of-Life stage which currently lacks adequate research work.

Disclaimer

Although EPA contributed to this article, the research presented was not performed by or funded by EPA and was not subject to EPA's quality system requirements. Consequently, the views, interpretations, and conclusions expressed in this article are solely those of the authors and do not necessarily reflect or represent EPA's views or policies.

Acknowledgments

The authors would like to thank Dr. Bhavik Bakshi, Jayasubha Lakshmanan and Paulina Acosta.

Appendix A

Appendix A.

CSI Division #	Building Component		Environmental Assessment Methodology	Product Stage				Construction Stage		Use Stage							End-of-Life Stage				Benefits & Loads Beyond the System Boundary	Replacement Years
				Raw Material Formation	Raw Material	Transport	Manufacturing	Transport	Construction, Installation	Use	Maintenance	Repair	Replacement	Refurbishment	Operational Energy Use	Operational Water Use	Demolition	Transport	Waste Processing	Disposal	Reuse / Recovery / Recycling Potential	
1	Sitework		Emergy (sej)					1.0854E+15														75
			Eco-LCA (sej)					4.78943E+14														
			Eco-LCA (TJ)					0.11931904														
			EIO-LCA (TJ)					0.00472														
2	Earthwork		Emergy (sej)																			75
			Eco-LCA (sej)																			
			Eco-LCA (TJ)																			
			EIO-LCA (TJ)																			
			ATHENA Impact Estimator (TJ)																			
3	Concrete		Emergy (sej)	1.27934E+19				3.04837E+15	6.3967E+17									4.84036E+14				75
			Eco-LCA (sej)	4.61595E+18				1.34366E+15	2.30798E+17									2.1358E+14				
			Eco-LCA (TJ)	3835				0.335176542	191.7387045									0.053				
			EIO-LCA (TJ)		6.588			1.30E-02	0.3294									0.002				
4	Masonry		Emergy (sej)	1.00848E+18				b	5.04241E+16									9.30206E+13				75
			Eco-LCA (sej)	1.30486E+18				b	6.52429E+16									4.10446E+13				
			Eco-LCA (TJ)	158				b	7.875364703									0.010226934				
			EIO-LCA (TJ)		1.711			b	0.08555									0.000746				
5	Structural & Misc. Metals		Emergy (sej)	1.69928E+20				1.70702E+15	8.4964E+18									1.72584E+14				75
			Eco-LCA (sej)	8.37432E+18				7.53428E+14	4.18716E+17									7.52355E+13				
			Eco-LCA (TJ)	657				0.187354049	32.83810393									0.0187				
			EIO-LCA (TJ)		16.549			0.007	0.82745									0.001361				
6	Rough Carpentry		Emergy (sej)	3.2904E+15				b	1.6452E+14									1.23623E+15				75
			Eco-LCA (sej)	1.5905E+17				b	7.95252E+15									5.45627E+14				
			Eco-LCA (TJ)	2192				b	109.5829845									0.1359				
			EIO-LCA (TJ)		0.74			b	0.037									0.005				
7	Waterproofing		Emergy (sej)	3.53376E+14				3.58443E+15	1.76688E+13		5.63235E+15							1.94278E+13				35 roof membrane & insulation
			Eco-LCA (sej)	1.1504E+18				1.58171E+15	5.752E+16		1.49E+17							8.28292E+12				
			Eco-LCA (TJ)	382				0.394091676	19.09602382		160.3							0.0021				
			EIO-LCA (TJ)		3.749			0.015	0.18745		1.19							0.000147				
8	Doors, Frames & Hardware		Emergy (sej)	1.84739E+18				6.39725E+14	9.23695E+16		2.9445E+19							3.2873E+14				50 Doors; 40 Exterior glass
			Eco-LCA (sej)	3.26892E+18				2.82111E+14	1.63446E+17		1.07201E+18							1.48814E+14				
			Eco-LCA (TJ)	2116				0.070332306	105.8126649		1409.0							0.0371				
			EIO-LCA (TJ)		6.539			0.003	0.32695		2.2							0.001443				
9	Finishes		Emergy (sej)	3.95445E+17				3.03058E+15	1.97723E+16		6.30288E+18							2.32028E+15				10 Paint; 12 Carpet; 18 Lenolium floor; 20 ACT
			Eco-LCA (sej)	2.23876E+18				1.3371E+15	1.11938E+17		2.37199E+18							1.01434E+15				
			Eco-LCA (TJ)	1220				0.333093362	60.98276342		1907.9							0.253				
			EIO-LCA (TJ)		4.622			0.013	0.2311		8.9							0.010923				
10	Equipment		Emergy (sej)	a																		75
			Eco-LCA (sej)	2.74345E+14				b	1.37172E+13													
			Eco-LCA (TJ)	0.1902				b	0.009509889													
			EIO-LCA (TJ)		0.002			b	0.0001													
11	Furnishings		Emergy (sej)	a																		75
			Eco-LCA (sej)	1.32783E+16				b	6.63917E+14													
			Eco-LCA (TJ)	3				b	0.128491022													
			EIO-LCA (TJ)		0.036			b	0.0018													
12	Pedestrian Conveying System		Emergy (sej)	a							a											40
			Eco-LCA (sej)	1.72151E+17				b	8.60755E+15		1.72151E+17											
			Eco-LCA (TJ)	44				b	2.199379545		44.0											
			EIO-LCA (TJ)		0.042			b	0.0021		0.042											
13	Plumbing		Emergy (sej)	9.88394E+16				b	4.94197E+15		1.57537E+18							3.91564E+15				20
			Eco-LCA (sej)	6.6043E+17				b	3.30215E+16		1.07732E+18							1.72914E+15				
			Eco-LCA (TJ)	107				b	5.361602843		134.0							0.4308				
			EIO-LCA (TJ)		0.82			b	0.041		1.044							0.016				
14	Fire Protection		Emergy (sej)	a							a											25 Sprinkler heads
			Eco-LCA (sej)	4.57304E+16				b	2.28652E+15		9.14608E+16											
			Eco-LCA (TJ)	14				b	0.71985692		28.8											
			EIO-LCA (TJ)		0.094			b	0.0047		0.14											
15	HVAC		Emergy (sej)	a							a											20
			Eco-LCA (sej)	2.00535E+18				b	1.00268E+17		7.59177E+17											
			Eco-LCA (TJ)	741				b	37.05954399		336.2											
			EIO-LCA (TJ)		5.146			b	0.2573		1.77											
16	Electrical		Emergy (sej)	a																		75
			Eco-LCA (sej)	3.59E+18				b	1.795E+17													
			Eco-LCA (TJ)	1239				b	61.94722087													
			EIO-LCA (TJ)		9.04			b	0.452													
	Operational Energy		Emergy (sej)												8.16E+19							
			Eco-LCA (sej)												4.9E+19							
			Eco-LCA (TJ)												5450.3							
			EIO-LCA (TJ)												643.5							
			ATHENA Impact Estimator (TJ)												1373.7							
	Total		Emergy (sej)	**1.87E+20**				**1.30955E+16**	**9.30376E+18**		**3.73E+19**				**8.16E+19**			**8.57E+15**				
			Eco-LCA (sej)	**2.83E+19**				**5.77696E+15**	**1.37997E+18**		**5.69E+18**				**4.9E+19**			**3.78E+15**				
			Eco-LCA (TJ)	**13021**				**1.44**	**635.35**		**4020.1**				**5450.3**			**0.9408**				
			EIO-LCA (TJ)		**57.2**			**0.056**	**2.784**		**15.3**				**643.5**			**0.0376**				
			ATHENA Impact Estimator (TJ)		**14.02**			**0.46**	**0.32**		**4.38**				**1373.7**			**0.11**				

a Emergy did not include any materials from this CSI division

b Data on transportation was not available

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