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# Integration of Emergy Analysis with Building Information Modeling

Suman Paneru [1,*], Forough Foroutan Jahromi [2], Mohsen Hatami [1], Wilfred Roudebush [3] and Idris Jeelani [1]

[1] M. E. Rinker Sr. School of Construction Management, University of Florida, P.O. Box 115703, Gainesville, FL 32611, USA; mohsen.hatami@ufl.edu (M.H.); idris.jeelani@ufl.edu (I.J.)
[2] School of Architecture, College of Design, Construction and Planning, University of Florida, P.O. Box 115702, Gainesville, FL 32611, USA; forough.foroutan@ufl.edu
[3] School of Built Environment, Bowling Green State University, Bowling Green, OH 43403, USA; wroudeb@bgsu.edu
* Correspondence: spaneru@ufl.edu; Tel.: +1-515-724-1981

**Abstract:** Traditional energy analysis in Building Information Modeling (BIM) only accounts for the energy requirements of building operations during a portion of the occupancy phase of the building's life cycle and as such is unable to quantify the true impact of buildings on the environment. Specifically, the typical energy analysis in BIM does not account for the energy associated with resource formation, recycling, and demolition. Therefore, a comprehensive method is required to analyze the true environmental impact of buildings. Emergy analysis can offer a holistic approach to account for the environmental cost of activities involved in building construction and operation in all its life cycle phases from resource formation to demolition. As such, the integration of emergy analysis with BIM can result in the development of a holistic sustainability performance tool. Therefore, this study aimed at developing a comprehensive framework for the integration of emergy analysis with existing Building Information Modeling tools. The proposed framework was validated using a case study involving a test building element of 8′ × 8′ composite wall. The case study demonstrated the successful integration of emergy analysis with Revit®2021 using the inbuilt features of Revit and external tools such as MS Excel. The framework developed in this study will help in accurately determining the environmental cost of the buildings, which will help in selecting environment-friendly building materials and systems. In addition, the integration of emergy into BIM will allow a comparison of various built environment alternatives enabling designers to make sustainable decisions during the design phase.

**Keywords:** emergy; sustainability; environment; building information model; energy

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## 1. Introduction

The pursuit of sustainable development is a critical endeavor to save our planet, especially as the effects of climate change have become more serious in recent years resulting in extreme weather events, a rise in ocean levels, and unprecedented melting of the polar ice [1]. There is a growing concern about energy consumption in buildings and its implications for the environment [2]. Buildings are one of the largest consumers of energy, projected to consume approximately 48% of global energy by 2040 for their construction, operation, maintenance, and deconstruction [3]. According to the United States Green Building Council (USGBC), buildings alone emit 39% of $CO_2$ emissions [4] further exacerbating the challenges of the greenhouse effect. It is estimated that $CO_2$ emissions from buildings will grow at a rate of 1.8% per year through 2030 [5]. This emission rate contributes heavily to climate change, which poses one of the most urgent challenges of present times [1,6]. To respond to this environmental issue, the construction industry has taken several steps to ensure that sustainability is one of the primary design objectives in design and construction [7]. This includes the development of green building standards such as LEED, BREEAM, Green Globes among others. These green building standards incentivize eco-friendly design and construction. For example, nearly 80,000 projects across 162 countries have been LEED-certified [8]. As the environment is considered to be the fourth dimension of design and construction, construction professionals are striving to improve environmental accountability and reduce the negative impact of buildings on the environment [9]. To effectively achieve this objective, the Architecture, Engineering, and Construction (AEC) industry needs quantifiable metrics and analytical methodologies that consider the environmental impact in all life cycle phases of the infrastructure. Current methodologies for assessing the environmental impact of buildings such as energy modeling and analysis [10], life cycle cost analysis [11], value engineering [9], embodied energy (EE) analysis only account for energy consumption associated with extraction, production, construction, and building operation [9,12]. Often these methods do not consider the energy consumption in resource formation, demolition, recycling, and disposal phases [13,14]. Ignoring the energy consumed in these lifecycle phases results in an inaccurate assessment of the sustainability performance of buildings [15]. This subsequently limits our understanding and evaluation of the true environmental impact of building materials and processes [16].

The reason for this insufficient accounting of environmental impact is that the current assessment methodology of energy analysis only accounts for available energy. However, to create a product (such as bricks, concrete, woods, steel) a significant amount of energy is consumed in the transformation of products from raw material to the final form. This energy, being unavailable, is difficult and often impossible to account for, using traditional methods. Therefore, a novel approach to a holistic energy assessment is required. One of the potential solutions is an energy analysis methodology based on "*Emergy*". Emergy is the total amount of energy that is used in transformations, directly and indirectly, to make a product or provide a service [16]. It is the measure of the energy that has been used up (degraded during transformations) to make the goods or services [17,18]. As such, emergy helps to put raw materials, commodities, goods, and services on a common basis, by expressing these in terms of a common unit of emergy—Emjoules (i.e., amount of energy used to produce a good or service) [10,16]. Since emergy is the true value of energy consumed in producing a product or a service, an energy accounting method based on emergy can help us in determining the true environmental impact of buildings.

This holistic assessment would benefit the decision-makers in choosing eco-friendly materials and building systems, which is key to sustainable development. Environmental Value Engineering (EVE) combines the concept of emergy analysis and traditional value engineering [15] and accounts for emergy requirements in all life cycle phases of a building. While traditional value engineering is aimed at determining the most economical alternative for a specified number of years, EVE extends this analysis to include the environmental costs associated with the alternative throughout its life cycle (e.g., formation, demolition, recycling, and disposal). While EVE can theoretically be an enhanced alternative to current energy analysis methodologies, it is challenging to implement in practice. AEC industry usually uses Building Information Modeling (BIM) tools for the analysis of energy to improve sustainability performance in their design and construction. Although BIM provides opportunities to incorporate sustainable building features during the design phase, a lack of holistic assessment methodology hinders the true assessment needed for efficient sustainable design [19]. The integration of emergy analysis in BIM can, therefore, help designers to consider the true environmental cost of building materials and services. This can help designers select eco-friendly building materials and services that have minimal environmental impacts. Environmentally conscious decision making in design will subsequently help in reducing the impact of building on the environment and climate change.

The typical energy analysis in BIM only accounts for the energy requirement of building operations during a portion of the occupancy phase of its life cycle. This includes energy consumed in heating, cooling, lighting, and running mechanical and electrical appliances, but does not explicitly include energy requirement for raw material extraction and demolition phases of a building's lifecycle. Therefore, BIM-based energy analysis tools result in an incomplete assessment of energy requirements and subsequently fail to determine the true environmental cost of the buildings. Thus, a new approach to building energy evaluation is required that overcomes the limitations of existing BIM-based energy analysis tools. This can be achieved by incorporating emergy analysis to traditional energy analysis methods and developing a holistic approach of energy accounting that work seamlessly with existing BIM tools. The objective of this study is to develop and test a framework for the integration of Emergy analysis into existing BIM platforms. The study aims at investigating the limitations of current energy analysis methods and proposing an alternative method incorporating emergy in the building information models. The study develops an end to end pipeline for this integration and uses a case study to demonstrate and test the proposed method. This integration will help in accurately determining the environmental cost of the buildings, which will help in selecting environment friendly (based on emergy values) building materials and systems. In addition, the integration of emergy into BIM will allow a comparison of various built environment alternatives enabling designers to make sustainable decisions during the design phase. The proposed framework is evaluated in Autodesk Revit®2021 using a sample wall as a case study.

## 2. Background

Energy analysis principles utilize a thermodynamically process to determine the energy required directly and indirectly to a system to produce a specific good or service [20]. Though it is commonly used during the design phase of building construction, the operational aspects of building energy requirements are not fully considered during design decisions [11]. This results in poor environmental performance. Different types of energy analysis include mainly life cycle-based energy analysis and embodied energy analysis. Life cycle analysis (LCA) is an approach that accounts for energy inputs into the building in the production, operation, and demolition phases of the building lifecycle [21]. LCA provides a tool to serve the purpose of evaluating the influence of buildings on the environment by quantifying the environmental impacts and identifying the practical reduction measures to assess the sustainability performance of buildings [22,23]. LCA quantifies the potential environmental impact of a product or a service and is defined in the ISO 14040:2006 and ISO 14044:2006 standards [11]. On the other hand, embodied energy analysis considers energy used during production, installations, erection, and renovation of the building [21]. The sum of primary energies consumed in constructing a building through the use of construction materials, products, and processes, along with the energy consumed in transportation, administration, and services is collectively known as embodied energy [24]. Initial embodied energy refers to energy utilized and incurred for the initial construction of the building whereas recurring embodied energy is energy utilization due to regular maintenance, energy usage on the building during its operation phase, and remodeling of the building [9]. Embodied energy values vary and the parameters that cause variation in embodied energy are methodological (system boundary, embodied energy calculation method, and energy units) and data quality issues (incompleteness, inaccuracy, and non-representativeness) [25–27].

The advancement of Building Information Modelling (BIM) in recent years has expedited its use in a growing number of AEC projects and practical tasks [28]. Almost 70% of Architectural and Engineering (A/E) firms use BIM to simulate energy performance, 65% of firms use BIM to analyze total building performance [29]. Several AEC practitioners use BIM for modeling and analyses. Extending the use of BIM-based working and the needs for BIM-based interoperability with specialized AEC tools in various building construction subdomains has revealed that (i) a global all-encompassing model for all data in a construction project is neither realistic nor a practical target and that (ii) BIM data typically needs to be combined with other construction data to efficiently apply in real-world AEC tasks [21]. General Service Administration [30] defined BIM as the development and use of a multi-faceted computer software data model to not only document a building design but to simulate the construction and operation of a new capital facility or a recapitalized (modernized) facility. The resulting BIM is a data-rich, object-based, intelligent, and parametric digital representation of the facility, from which views appropriate to various users' needs can be extracted and analyzed to generate feedback and improvement of the facility design [30]. The US National BIM Standard 2007 defines BIM in three dimensions: (1) The Building Information Model (a product), which is a structured dataset describing a building; (2) Building Information Modeling (a process), which is the act of creating a Building Information Model; and (3) Building Information Management (a system), which comprises the business work and communication structure that increases quality and efficiency. BIM includes the geometry, spatial relations, geographic information, quantities, and properties of building elements, cost estimates, material inventories, and project schedules [31].

The integration of energy analysis with BIM requires complex computations that vary with the parameters of the building such as thermal properties, orientation, geometries, etc. [32]. Traditionally, energy analysis calculations were done by architects and engineers who use some complex computations to quantify and assess building performance in the design stage [33]. The building system analysis includes several functional aspects of a building such as circulation, lighting, energy distribution, ventilation, and consumption, thereby providing an excellent opportunity for the sustainability measures and performance analysis to be integrated with the BIM model [34]. In addition, BIM provides data related to the building geometry that allows the computation of several parameters (e.g., volume and related energy, orientation, and location of building, etc.) [35]. BIM can aid in sustainability decision making such as building orientation, building massing, daylighting analysis, water harvesting, energy modeling [36]. However, research also indicates that there are significant discrepancies between simulation results and the measured energy consumption of a building [37]. One of the reasons for this discrepancy is that the current energy analysis method does not account for the corresponding embodied energy, which several studies have emphasized and indicated that it may account for up to 60% of a building's total energy use [38]. In addition, while the integration of energy analysis with BIM provides an opportunity for designers to analyze the energy consumption from the early phases of the design process, such an approach has been confronted by the challenges of interoperability between various BIM tools and energy simulation tools [39]. Therefore, substantial improvements are needed to enhance the reliability of building energy use evaluation as a decision-making tool in the design process [40].

Environmental Value Engineering (EVE) is a life cycle analysis methodology based on emergy analysis techniques that evaluates the environmental impact and contribution of built alternatives (in terms of solar emergy) through various life cycle phases of a project. It enables one to select alternatives that minimize environmental impact towards a sustainable society [41,42]. As seen in Figure 1 below, EVE is an analysis system that combines emergy analysis with value engineering [15]. Emergy analysis uses emergy basis, emergy diagrams, and environmental value and is predominantly used in the large ecological decision process [16] whereas traditional value engineering is carried out to find the most economical alternative for a specified amount of years. EVE extends to include all factors associated with the alternative through its total life cycle phases of design and construction.

EVE compares built environment alternatives through 10 different phases, which are: (i) natural resource formation, (ii) natural resource exploration and extraction, (iii) material production, (iv) design, (v) component production, (vi) construction, (vii) use, (viii) demolition, (ix) natural resource recycling, and (x) disposal. The phases near the two extremes of the life cycle indicate the all-encompassing nature of the methodology. For example, the natural resource formation phase is intended to account for the value of environmental inputs during the formation of resources on Earth. For these phases, accounting of the environment, fuel energy, goods, and services is carried out using the transformity except for the natural resource formation phase which includes only environmental inputs [15].

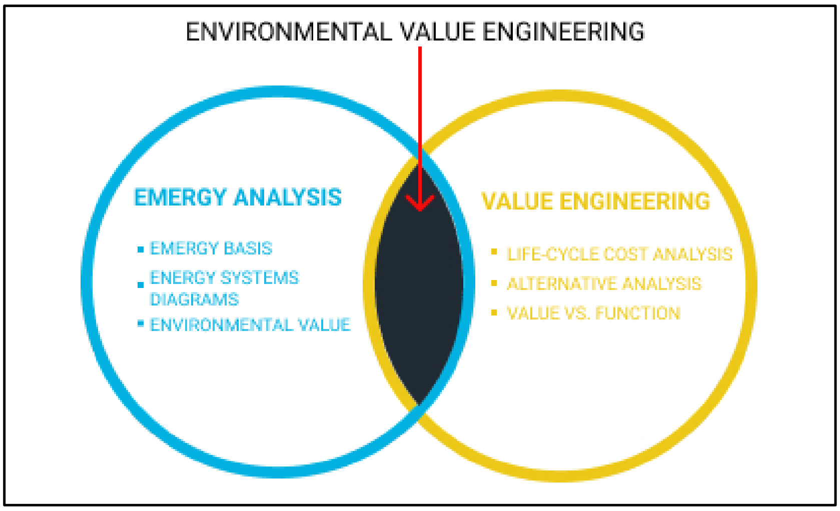



**Figure 1.** Definition of environmental value engineering.

After a review of the existing literature, journals, and publications, we concluded to the best of our knowledge, there is currently, no study that focuses on the integration of emergy analysis with BIM. This integration of emergy with the existing BIM system will add a new paradigm on selecting the alternatives and making built environment decisions for designers and engineers. In addition, this can also help designers select alternative material by comparing the emergy value of alternative material, and make comparisons on emergy and energy values.

## 3. Framework Development

The framework development included the following steps. First the existing energy analysis methods were studied to identify their limitations and subsequently the functional requirements of the proposed framework. These helped in designing the novel conceptual framework for emergy analysis which included identification of input parameters, data sources, computation methods as discussed in detail in the next section. This was followed by testing the developed framework using a case study discussed in Section 4. The case study involved testing the proposed framework to integrate emergy analysis with existing BIM platform and identifying the challenges that affected the smooth integration. Finally, recommendations for addressing the identified challenges are discussed in Section 5.

An extensive review of past studies focusing on energy analysis, building information modeling, and environmental value engineering was conducted to investigate the limitations of existing energy evaluation methods. It included a thorough review of conventional energy analysis in BIM-based simulation tools to investigate its limitations that the current framework needs to overcome in order to account for the true environmental costs of the built environment. The objective of the review was to identify the functional requirements of the framework to meet the desired goal of ensuring a holistic evaluation of the environmental impact of the built environment. Section 3.1 lists the identified limitations of traditional BIM-based energy analysis that emergy analysis can potentially overcome.

### *3.1. Limitations of BIM-Based Energy Analysis and EmA a Potential Alternative*

Both emergy analysis (EmA) and energy analysis (EA) are measures for evaluating the sustainability of building design and construction. EmA has a broader purview as it establishes a direct connection between environmental impact and economics [43] by including energy requirements from the formation of material to its demolition/recycling. BIM-based energy analysis has some limitations as it does not include energy consumed in some phases of the building life cycle (e.g., extraction, formation, demolition). In addition, the price of energy accounted for in BIM is market dependent and neglects the environmental dependencies. Moreover, EA also considers renewable energy as free even though harnessing renewable energy has an associated emergy cost, therefore not truly "free. The limitations of Energy analysis when compared to emergy analysis are shown in Table 1. This comparison confirms the key narratives that demonstrate the potential for EmA to emerge as an efficient tool for the overall sustainability assessment. Therefore, the proposed framework utilizes the concept of emergy and offers an efficient alternative to traditional energy analysis.

**Table 1.** Comparison table between EmA and EA [10,43].

| Category | Limitations of Energy Analysis (EA) | EMERGY Analysis (EmA) as a Potential Alternative |
|---|---|---|
| Definition | Energy analysis in BIM is mainly based on R-value (material's ability to resist the heat) of building envelope materials, heating loads, cooling loads, appliances, and lighting loads of the building. Limitation: does not include the energy requirements in all phases | Emergy analysis expresses all energies in the form of solar emergy |
| Application | Operational energy analysis, import-export balances | Net energy analysis, import–export balances |
| Connection to economics | Mostly conventional: combine EA results with "right" prices (market prices). Limitation: Market dependent and neglects environmental dependencies | Strong connection through the conversion of EMERGY to monetary equivalents. |
| Transformity | Embodied energy = the direct and indirect energy required to produce a good, service, or entity. Limitation: EA quantifies indirect energy, but it does not account for energy of different types. | The EMERGY required to produce a good or service divided by the energy of the good or service equals its transformity |
| Inclusion of human labor | It does not include energy cost of human labor. It only considers the market value of energy cost. Limitation: No direct human labor cost is only considered | Account for the labor as labor produces goods and services |
| Inclusion of renewable energy | EA was originally developed for fossil and hydro energy, but renewable energy can easily be included if needed Limitation: Energy analysis considers renewable energy as free | Because renewable energy accounts for roughly half the total energy driving the combined system of humanity and nature, EMA routinely includes it |

### 3.2. *Emergy Integration with BIM- A Conceptual Framework*

A novel conceptual framework for emergy analysis shown in Figure 2 is proposed in this study based on Emergy as a potential alternative with current energy analysis. The framework comprises of the following stages:

i. Identification of the input properties
ii. Computation of the transformity
iii. Calculation of emergy values for different life-cycle phases
iv. Computation of total emergy

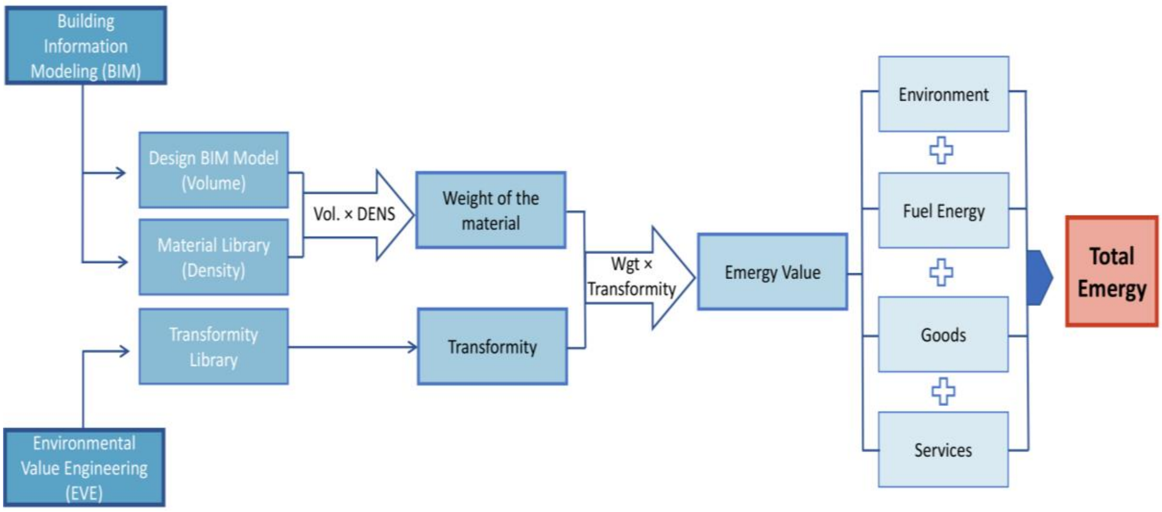



**Figure 2.** Conceptual Framework Integration of Emergy into BIM.

These stages are explained in detail below. As most building alternative systems are composed of different materials, the framework is applicable for each material component and the final value of emergy for the building is the summation of emergy values of individual components.

(i) *Identification of the input properties*

This stage identifies the input properties that are subsequently used to determine the emergy value of each material. First, it is important to calculate the weight of the material used in the building. The weight can be obtained from the density of a material and the volume of the material used in the building. The densities of different materials can be obtained from material libraries. The BIM application may include a pre-loaded database of material densities. It is important to follow a consistent unit system (metric or imperial) throughout the process. Thereafter, the volume of material of the building component can be obtained from the BIM tool by simple extraction of building component dimensions. Finally, we can obtain the weight of the material using the values of volume and density. For example, the weight of concrete masonry exterior wall can be calculated by obtaining densities of concrete and steel used in the wall and computing the volume of each used in the wall from the dimension information stored in BIM.

(ii) *Identification of the Transformity*

The next step is to obtain a value of transformity. The transformity is defined as the quantitative variable equal to the emergy (in emjoules) of one kind of available energy required directly and indirectly to make one joule of the energy of another type. It is used to compute the emergy of material given its weight. The units of transformity are solar emjoules/Jule, solar emjoules/gram, or solar emjoules/US Dollars. The Transformity values for different materials can be obtained from the transformity library developed by Odum [15,17]. Emergy is calculated as the product of the transformity and the weight of the material. Mathematically:

$$\text{Emergy (Em)} = \text{Transformity (T)} * \text{Weight of the material (W)} \quad (1)$$

The Table 2 below shows some materials and their corresponding transformities obtained from the library [41]. Incorporation of transformities as a library (or add-on) in BIM would facilitate the computation of emergy.

**Table 2.** Sample table of Material and their corresponding Transformities [41].

| Material | Transformity |
|---|---|
| Aluminum ingots (g) | $1.60 \times 10^{10}$ (sej/J) |
| Concrete (g) | $9.99 \times 10^{8}$ (sej/J) |
| Oil(J) | $5.30 \times 10^{4}$ (sej/J) |
| Machinery (g) | $6.70 \times 10^{9}$ (sej/J) |
| Wood (J) | $3.49 \times 10^{4}$ (sej/J) |
| Glass (g) | $8.40 \times 10^{8}$ (sej/J) |

To calculate emergy values, the data obtained from the BIM tool needs to correlate with the transformity values obtained from the transformity database. Therefore, to achieve interoperability between BIM tool and emergy analysis application, there is a need for a common data exchange platform for the emergy computation. This can be provided by using a data exchanger that facilitates the smooth flow of data between two systems as shown in Figure 3

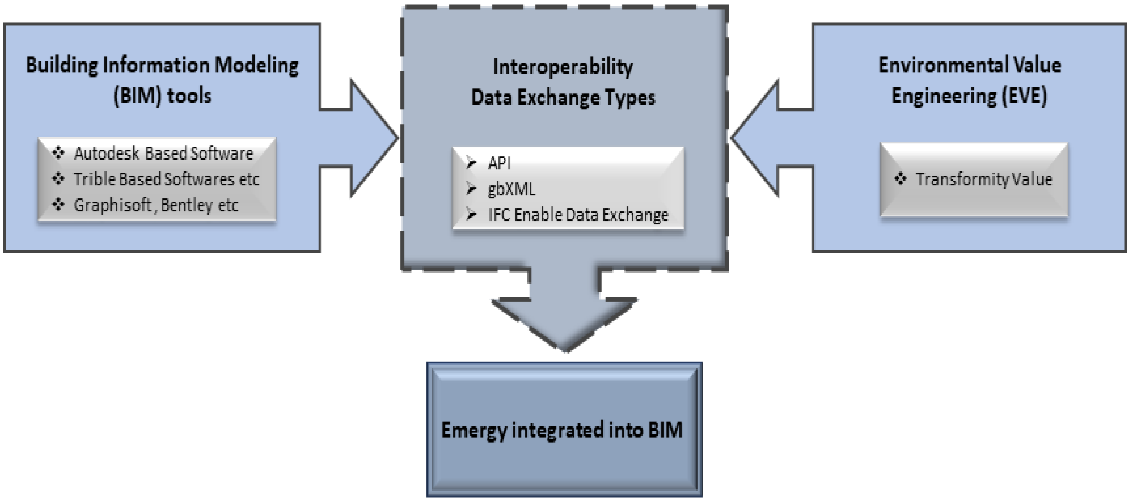



**Figure 3.** Interoperability between BIM and transformity value.

There are mainly three types of data exchange methods that are commonly used between BIM software and energy analysis tools as listed below [39]. One of these integration techniques can be utilized for the emergy analysis as well.

(a) *API-based data exchange*

Application Programming Interface (API) is a programming interface that help in communication between two applications. This can significantly reduce the loss of data during model translation. Kim et al. [32] developed a Modelic-BIM library to support BIM-based energy simulation that can semi-automatically convert BIM model information and perform building energy analysis. To integrate emergy with BIM, a similar API needs to be developed based on a specific BIM tool.

(b) *gbXML-enabled data exchange*

This approach uses the gbXML format to bridge the data transfer between BIM tools and energy simulation tools. Most of the BIM tools like Revit, Trimble, Grahisoft, etc support the gbXML format. Ham and Golparvard [44] developed a gbXML based BIM for reliable building energy performance modeling and mapping thermal properties of the building during an inspection. This was used to derive the actual thermal resistance of the building assemblies at the 3D vertexes.

(c) *IFC-enabled data exchange*

This format is developed by Building SMART [45] to facilitate and share information throughout the building lifecycle. Industry Foundation Class (IFC) is an internationally accepted schema supported by almost all BIM tools.

(iii) *Calculation of Emergy for different phases*

Emergy uses a systems approach to account for the environmental impact of the built environment in terms of the environment, fuel energy, goods, and services (labor) in all its 10 phases of the life cycle [13]. The ten phases of the built environment are:

A. natural resource formation
B. natural resource exploration and extraction
C. material production
D. design
E. component production
F. construction (assembly)
G. use
H. demolition
I. natural resource recycling
J. disposal

The total emergy value for each phase is the sum of emergies computed for the environment, fuel energy, goods, and services used in that phase. For example, concrete masonry is built from raw material such as aggregate, cement, sand, and additives. For the earth to generate these raw materials certain amount of energy is required. The required emergy is categorized as emergy for the environment. Likewise, with the help of labor and equipment, the materials are converted into concrete and these expenses are categorized as emergy required for the fuel, goods, and services. Total emergy value is calculated by adding environment, fuel, goods, and services as shown in Equation (2):

$$\text{Total Emergy Value (Em)} = \text{Environment} + \text{Fuel Energy} + \text{Goods} + \text{Services} \qquad (2)$$

The emergy value (subsequently the environmental impact) of the built environment in its current phase is obtained by adding the emergy value for that phase and the emergy values of all preceding phases. Figure 4 shows the emergy value of each phase of the concrete masonry wall system (wall section of one square meter in a surface area and eight inches in thickness) using Equation (1).

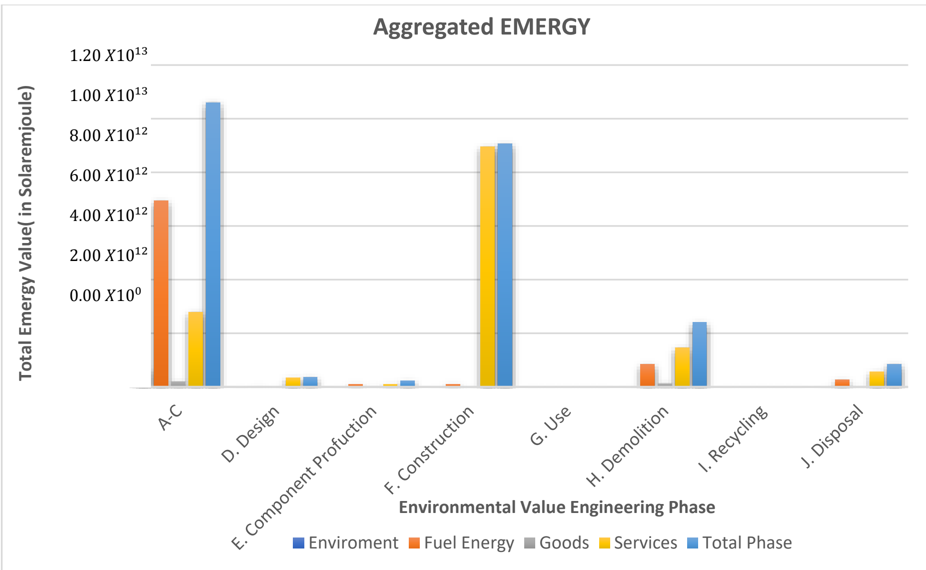



**Figure 4.** Aggregated EMERGY input source data for concrete masonry exterior wall system [13,15].

## 4. Case Study and Evaluation

The proposed framework for integration of emergy analysis with building information modeling is validated using a test case study. The emergy analysis integration is effective when the BIM components and parameters become interoperable with EVE attributes. The objective of this case study is to demonstrate the possible integration of EVE with Revit using a test wall section. Revit was selected because of its popularity in AEC industry. The following assumptions were made while evaluating the conceptual framework:

i. Building use was not considered
ii. The information presented in BIM software library (Revit® 2021 library) were used as standards for the materials used in this case study
iii. The case study used the transformity values from [15]

The section of the built environment selected for this case study was the composite wall comprising of a brick wall section, an air gap, OSB wall sheathing, 2 × 4 studs, insulation, vapor barrier, gypsum board, and paint as shown in Figure 5 below. The wall section is 8′ × 8′ and 8″ thick.

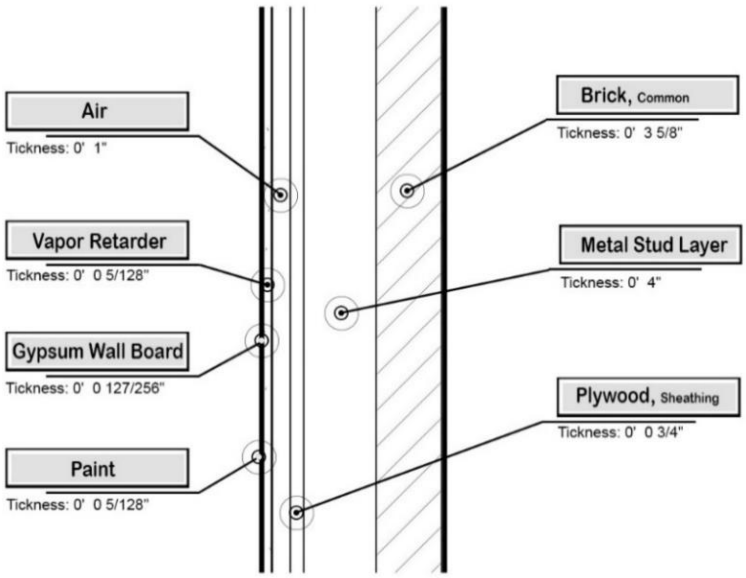



**Figure 5.** Detail of wall section used in the case study.

The composite wall information was modeled in Revit® 2021. The rendering showed detailed information related to a composite wall including the name of the material, the wall thickness, the use of material, and its function. The steps described in the framework developed in this study (Section 4) were followed in this demonstration and are detailed below.

### *4.1. Computation of the Material's Weight*

The weight of the material can be computed in Revit using the custom parameters. Stages involved in the calculation of weight are identification of (i) density and (ii) volume. The density of different materials used in the case study was obtained from the default material library in Revit® 2021. In addition to the physical properties, the material information in Revit® 2021 includes information such as identity information, graphics, appearance, and thermal properties of different materials. For example, the density of brick of our sample wall obtained from the default library was 121.73 lb/ft$^3$. Sometimes, the default material may not have all properties defined or the material may not be included in the Revit library. In those cases, users can manually add the material and/or its properties (such as density) to the library (Figures 6 and 7). For example, in this case, study, the density of paint was not found in the default Revit® database, so its properties (density = 37 lb/ft$^3$)

were added manually to the library. The thermal properties were also added to the library, which might be beneficial to calculate the emergy values during the use phase (*use phase is not considered within this case study*). After the addition of the material properties, the material is added to the database and it becomes part of the material library for future use.

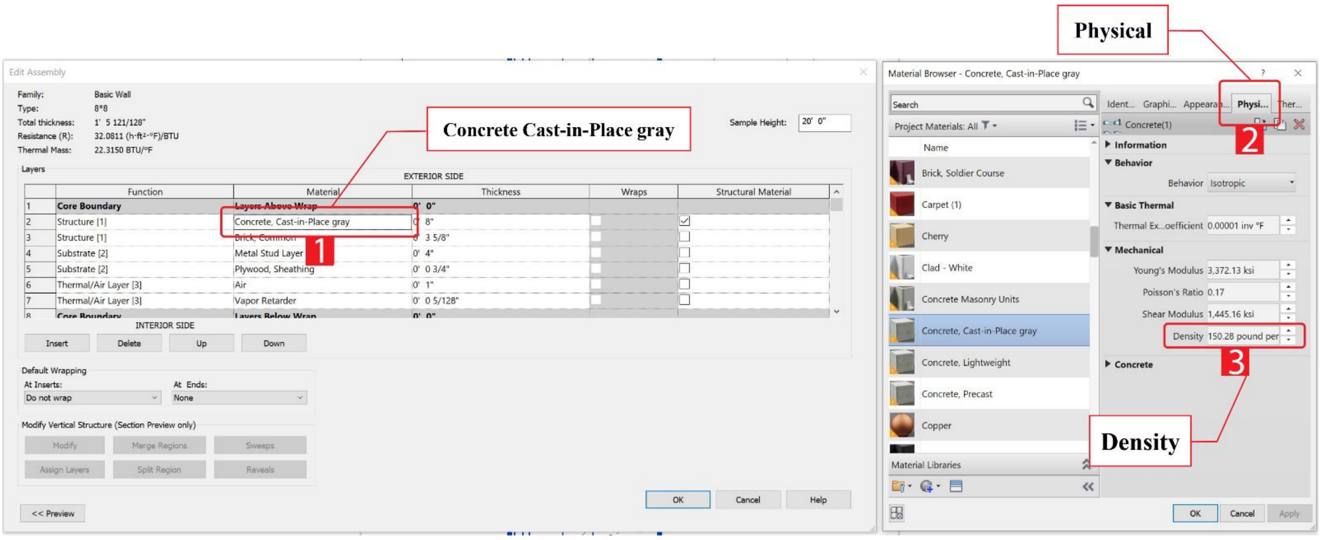



**Figure 6.** Addition of density for the new material.

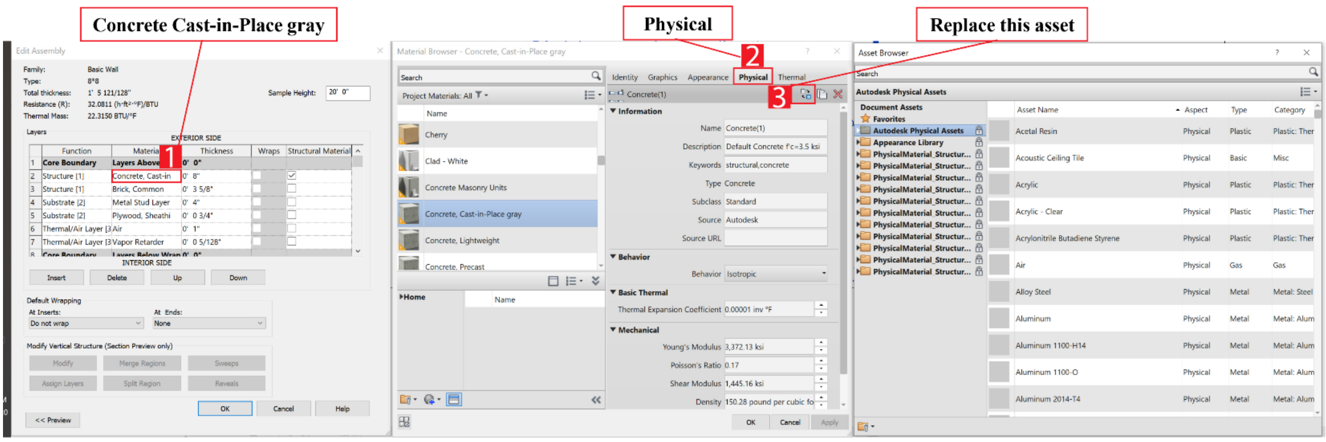
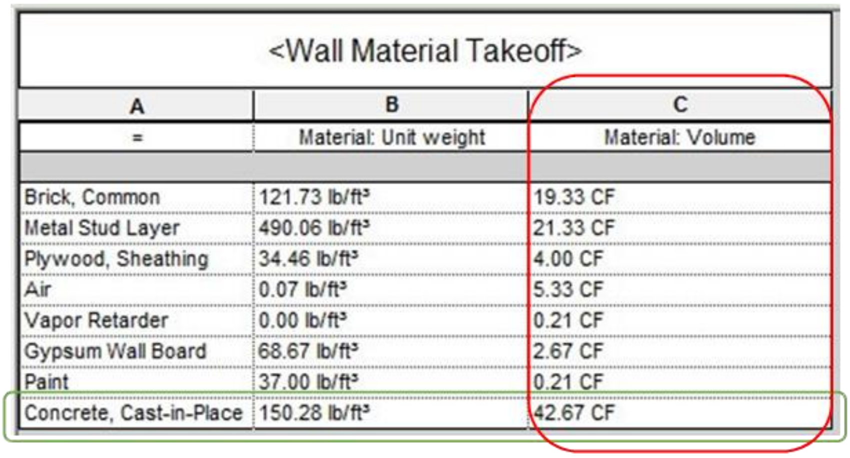



**Figure 7.** Physical assets library.

Figure 7 shows the process of adding the density of material. Revit®2021 has an inbuilt volume quantification system, which was used to compute the volume of different materials used in the test wall.

Figure 8 shows the material takeoff window from Revit where Column C shows the volume of the test wall material. While Revit® can calculate the volume of individual components of the composite structures, it does not account for the wastage during construction.



<Wall Material Takeoff>

| A | B | C |
|---|---|---|
| = | Material: Unit weight | Material: Volume |
| Brick, Common | 121.73 lb/ft³ | 19.33 CF |
| Metal Stud Layer | 490.06 lb/ft³ | 21.33 CF |
| Plywood, Sheathing | 34.46 lb/ft³ | 4.00 CF |
| Air | 0.07 lb/ft³ | 5.33 CF |
| Vapor Retarder | 0.00 lb/ft³ | 0.21 CF |
| Gypsum Wall Board | 68.67 lb/ft³ | 2.67 CF |
| Paint | 37.00 lb/ft³ | 0.21 CF |
| Concrete, Cast-in-Place | 150.28 lb/ft³ | 42.67 CF |

**Figure 8.** Wall takeoff.

Revit does not have weight/mass parameters; however, it allows the addition of custom parameters. Therefore, a custom parameter "weight" was added to 'Calculated Value' as shown in Figure 9. This custom parameter calculates the weight of different material from the densities and volume obtained in the above steps. Figure 9 shows the screenshots of the "weight computation step".

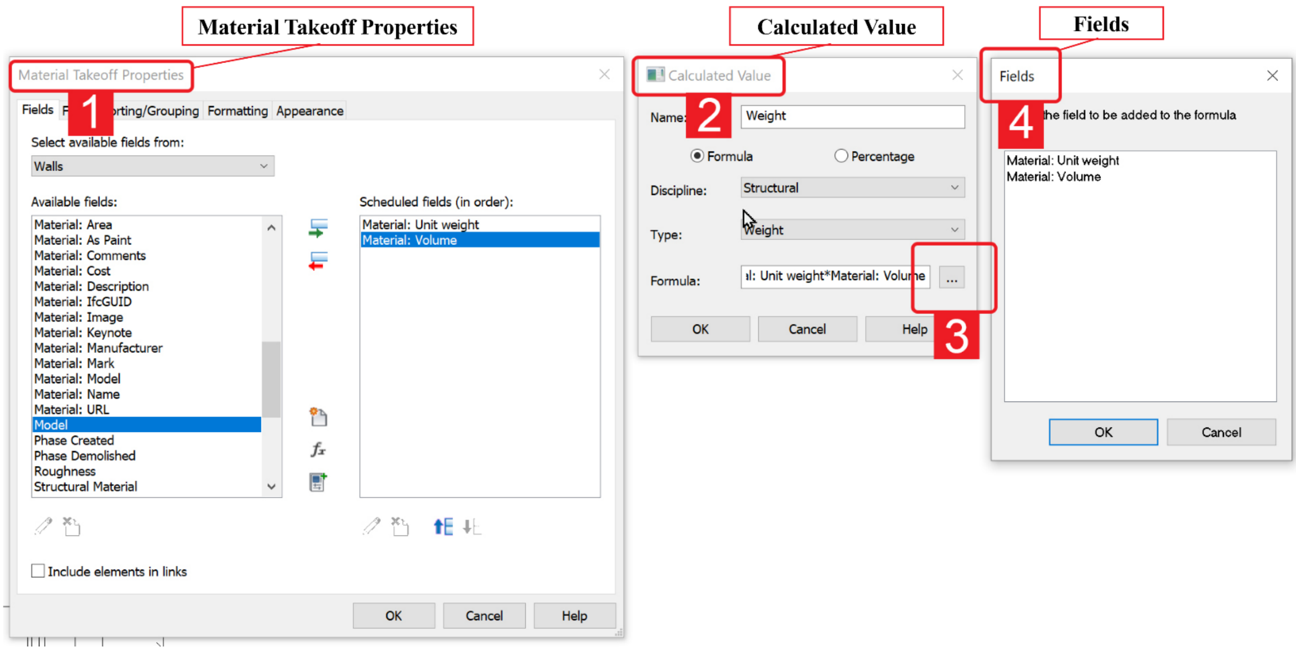
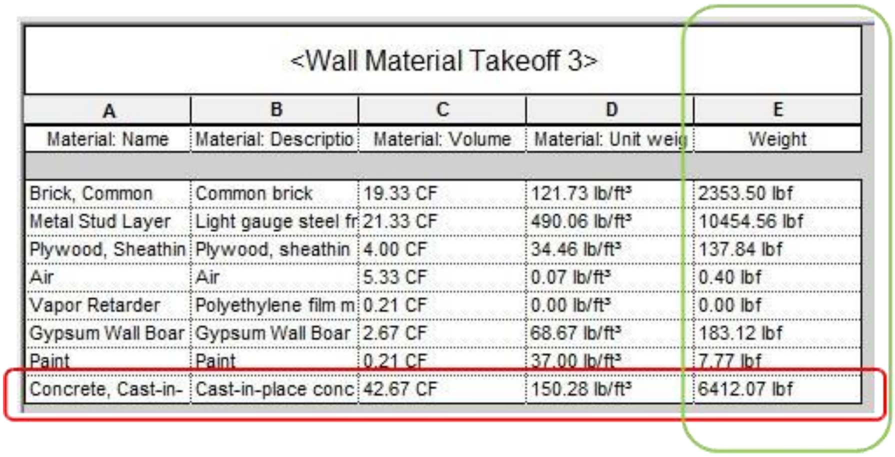



**Figure 9.** Adding a custom parameter "Weight".

After the definition of the 'weight" parameter was set, Revit® 2021 provided the weights of the materials used in the test wall as shown in Figure 10.



| <Wall Material Takeoff 3> | | | | |
|---|---|---|---|---|
| A | B | C | D | E |
| Material: Name | Material: Descriptio | Material: Volume | Material: Unit weig | Weight |
| Brick, Common | Common brick | 19.33 CF | 121.73 lb/ft³ | 2353.50 lbf |
| Metal Stud Layer | Light gauge steel fr | 21.33 CF | 490.06 lb/ft³ | 10454.56 lbf |
| Plywood, Sheathin | Plywood, sheathin | 4.00 CF | 34.46 lb/ft³ | 137.84 lbf |
| Air | Air | 5.33 CF | 0.07 lb/ft³ | 0.40 lbf |
| Vapor Retarder | Polyethylene film m | 0.21 CF | 0.00 lb/ft³ | 0.00 lbf |
| Gypsum Wall Boar | Gypsum Wall Boar | 2.67 CF | 68.67 lb/ft³ | 183.12 lbf |
| Paint | Paint | 0.21 CF | 37.00 lb/ft³ | 7.77 lbf |
| Concrete, Cast-in- | Cast-in-place conc | 42.67 CF | 150.28 lb/ft³ | 6412.07 lbf |

**Figure 10.** Obtained weight of the sample wall from Revit 2021.

### *4.2. Computing Transformity in Revit® 2021*

After computing the weights of materials in Revit® 2021, the emergy calculation required the addition of transformity values to Revit. However, Revit does not recognize transformity values due to unit inconsistency. Revit® assigns a default data type of string to the material property value. In addition, the weight of the material is also stored as a string datatype. Therefore, multiplication between weight and transformity requires the creation of a separate category of datasets where transformity and weights are converted to integer datatype. This data type inconsistency needs to be resolved for smooth integration. Revit has a functionality of unit conversion from SI (International Systems of Units) system to FPS (foot-pound-second). However, it cannot perform arithmetic operations between two different groups of data inputs. For example, Revit cannot multiply weight (lb) and transformity (solaremjoule/lb) to give emergy (solaremjoule) because of the value of weight and transformity within Revit are not stored as an integer but as a string. As a result, the unit consistency is not established between the weight of the material and the numerical transformity value (as transformity values are not recognized in the database).

Furthermore, Revit automatically assigns the transformity value of brick to metal stud, plywood, vapor retarder, gypsum, paint, etc. as well because these are all the components of the same composite brick wall. As a result, Revit® incorrectly computes the emergy values. To overcome this limitation, the information was exported as a text file to MS Excel for computation of emergy. The transformity values were added in Excel and emergy was calculated for each material using Equation (1). In future, an add-on can be programmed to convert string values to integers to facilitate the required numerical calculations. Table 3 below shows the emergy values for each material used in the test wall.

**Table 3.** Experimental validation of Emergy value.

| Material: Name | Unit | Weight | Transformity | Emergy (SEJ) |
|---|---|---|---|---|
| Brick, Common | lb | 2353.5 | $1.71 \times 10^{9}$ | $4.02 \times 10^{12}$ |
| Metal Stud Layer | lb | 10454.56 | $3.97 \times 10^{6}$ | $4.15 \times 101^{0}$ |
| Plywood, Sheathing | lb | 137.84 | $6.15 \times 10^{6}$ | $8.48 \times 10^{8}$ |
| Air | lb | 0.4 | $0.00 \times 10^{0}$ | $0.00 \times 10^{0}$ |
| Vapor Retarder | lb | 0 | $0.00 \times 10^{0}$ | $0.00 \times 10^{0}$ |
| Gypsum Wall Board | lb | 183.12 | $2.10 \times 10^{7}$ | $3.84 \times 10^{9}$ |
| Paint | J | 7.77 | $7.06 \times 10^{6}$ | $5.49 \times 10^{7}$ |
| Concrete, Cast-in-Place | lb | 6412.07 | $9.99 \times 10^{8}$ | $6.41 \times 10^{12}$ |

## 5. Discussion and Conclusions

The case study helped us demonstrate and test the framework for integrating emergy analysis with BIM. Specifically for Revit®2021, it has the in-built functionality to calculate volume, mass, and density of materials that can be leveraged to implement the current framework of emergy analysis. With a minimum level of intervention/improvement specifically, the transformity library will enhance the emergy calculation within the BIM and can automatically calculate an emergy value for the built environment. By including total life cycle energy from material formation to demolition, the proposed framework for incorporating BIM into the emergy analysis can help to improve the shortcomings of current energy analysis. In order to make an environmentally sound decision, current industry practices must consider the total emergy of materials or systems. Even though emergy analysis is primarily used to make decisions in ecological sciences, it is also relevant to the construction industry because all the materials used are sourced from the earth and take thousands of years to form.

The research's main contribution is to educate future researchers on a novel approach to analyze the impact of their design decision techniques; at the same time, incorporating into the latest BIM technology can optimize emergy computation. Some researchers hold the cynical belief that the overall emergy concept is highly hypothetical; however, even with its flaws, the concept can still be applied holistically. In addition, the integration will help AEC stakeholders to quantify emergy value efficiently during various phases of design, construction, and operation. In this study, a robust framework was developed to incorporate emergy analysis in the existing BIM tools. The proposed framework was validated using a case study involving a test building element of $8' \times 8'$ composite wall. The case study demonstrated the successful integration of emergy analysis within Revit®2021 using the inbuilt features of Revit and external tools such as MS Excel. This integration can help in determining the true environmental impact of various materials and alternatives in the built environment and help in improving the sustainability of the built environment by addressing the shortcomings of current energy assessment methodology.

## 6. Limitations and Future Work

While the study makes important contributions, it also identified some important limitations. As there are several BIM tools available in the market, the limitations might vary depending on what BIM tool is used. However, below are some major limitations:

(i) Interoperability: The information (such as weight of the material and transformity) flow between BIM tools and transformity library is a challenge in emergy computation as discussed on the case study. The degree of challenge varies depending on the type of BIM tools used. Currently, most of the BIM tools do not have a transformity library. Therefore, the addition of a transformity library to BIM tools will be useful for AEC stakeholders. With the addition of the transformity library, emergy analysis within BIM tools can become seamless.

(ii) Accuracy of transformity: The value of transformity is developed using the empirical method. It is difficult to account for all the energy requirement in the formation of natural resources. So, the accuracy of these empirically developed transformity value can sometimes be debated.

(iii) Availability of accurate density values: The density of material obtained from the BIM library may not always be of correct value. So, verifying the density value of the material used in the design and construction of building can be an esoteric process.

(iv) Too many materials to account: The construction of building involves a lot of materials. Accounting these material's corresponding weight and transformity value can sometimes be a challenge.

(v) lengthy process: Overall emergy calculation process is lengthy. It is required to check materials properties such as density, volume, and transformity. For the accurate emergy value, it is important to include all the material used in the building which makes this a very lengthy process.

For the future research consideration, it would be beneficial to develop a transformity library. Most of the BIM tools do not have a transformity library yet. So, addition of a transformity library onto BIM tools will enhance the emergy computation. With the addition of the transformity library, emergy analysis within BIM tools can become seamless.

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