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Comparative Review of Assessment Methodologies of Building Embodied Energy

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Abstract

According to a report of UNEP, the building sector accounts for 40 percent of the total energy consumption in the world and is related with 33 percent of global greenhouse gas (GHG) emissions. During the whole life cycle of a building, the total energy consumption can be classified in two categories: embodied energy and operational energy. Operational energy means the energy consumed by a building to support its operation and maintenance； while the embodied energy is defined as the energy consumed in producing of a building, including the building material production, on-site delivery, and construction. Plenty of efforts have been devoted into the reduction of the energy consumption through the operational phase, however, there is a controversial about the evaluation methodology of embodied energy due to the lack of regulation or uniform standard. Currently, there are three prevailing methodologies to assess the building embodied energy: Process analysis, Output-Input analysis, and Hybrid analysis. The measurement procedure, requirement of database, system boundary, labour and time input as well as the evaluation result are all different. The evaluators need to select the suitable methodology to achieve their evaluation objectives. With the aim to give out a reference for the selection of methodology, a comparative review is conducted to compare the advantages, disadvantages, and feasibilities of the three methodologies; and the appropriate methods for different regions in the world are also pointed out.

Keywords: Embodied energy, LCA, Process analysis, Input-output analysis, Hybrid analysis

1. Introduction

According to a report of UNEP, the building sector accounts for 40 percent of the total energy consumption in the world and is related with 33 percent of global greenhouse gas (GHG) emissions [1]. To reduce the energy consumption of buildings has been a common task worldwide; therefore, governments, construction industries, as well as research institutions all have a strong aspiration to make out an accurate measurement of the energy consumption derived from the usage of a building. Normally, a building’s life period will last for 30 years or even longer, depending on the design criteria in different countries. During the whole life cycle of a building, the total energy consumption can be categorized in two kinds: operational energy and embodied energy. Operational energy means the energy consumed by a building in the usage phase to support its necessary service, including heating, cooling, air ventilation and provide power to building facilities, which is relevant with the adoption of energy efficient technologies, the energy saving electrical appliances, the envelope insulations, the occupant behaviours, etc. During the past years of effort, a lot of goals have been achieved in the reduction of building operational energy. Governments set up objectives to reduce the energy consumption of existing buildings and promote new green buildings. For example, Hong Kong government made Energy Saving Plan for built environment, which sets for targets of 40% reduction of energy intensity by year 2025, as the base year of 2005, and reduce the electricity consumption by 5% from year 2015 to 2020; UK and European Commission initiated The Energy Performance Building Directive (EPBD) to improve the energy performance of building during operation phase[1]; in Australia, the implementation and mandatory disclosure of NABERS(National Australian Built Environment Rating System), along with more strict building regulations imposed by government in 2006 and 2010, have facilitated the adoption of energy efficiency technologies in commercial buildings and residential households.

While so much effort has been devoted on reducing the operational energy, the relative proportion of embodied energy in the total building energy consumption in the life cycle becomes higher. Although a lot of research have been conducted to study the embodied energy, many issues are still indefinite. The first issue is the definition of embodied energy. Generally, embodied energy means that the energy consumed in life cycle stages of a building other than the operation (space conditioning, water heating, lighting, operating building appliances and other similar operational activities) [2], and the life cycle phased accounted to embodied energy include the production of building materials and components, the onsite construction, the post construction stages such as renovation and the final stages such as demolition and disposal [2, 3]. The whole life cycle of a building can be illustrated by Figure 1.

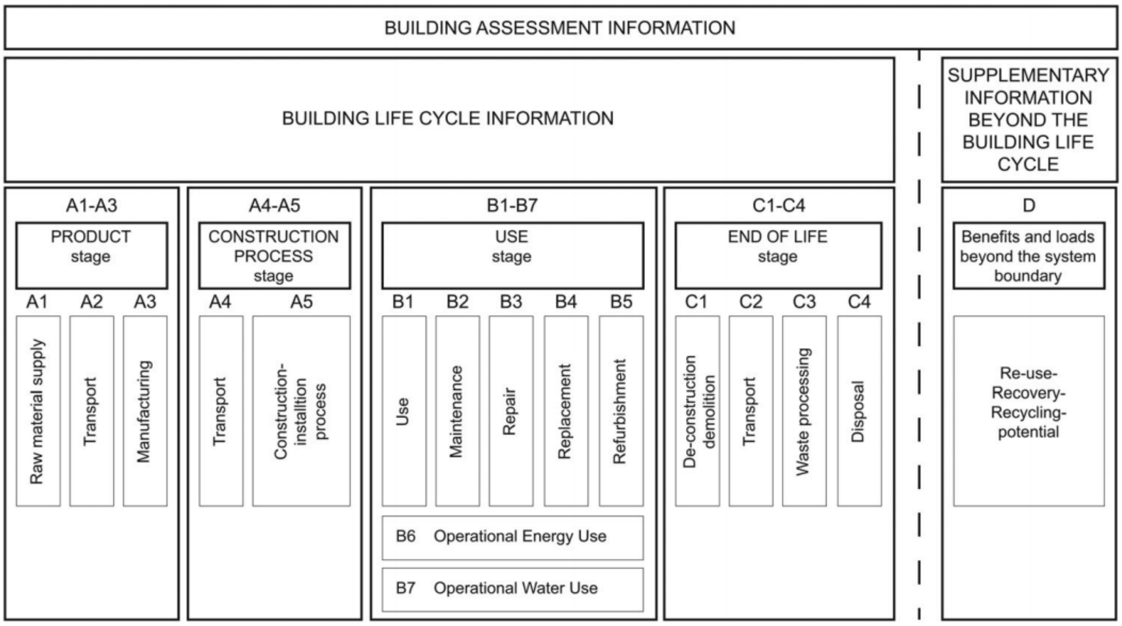

Figure 1 Life cycle stages from BS EN 15978:2011 Sustainability of construction works-assessment of environmental performance of buildings-calculation method [4]

The building lifecycle in Fig.1 can define five types of system boundary in embodied energy evaluation:

- System boundary type: Cradle to Gate:

This boundary includes only the production stage of the construction products integrated into the building. Processes taken into account are: the extraction of raw materials, transport of these materials to the manufacturing site and the manufacturing process of the construction products itself. Thus, in the case of a building the impacts of this stage are accounted for as the sum total of the "cradle to gate" impacts of its individual components.

- System boundary type: Cradle to Site:

Cradle to gate boundary plus delivery to the construction site.

- System boundary type: Cradle to Handover:

Cradle to site boundary plus the processes of construction and assembly on site.

- System boundary type: Cradle to End-of-Use:

Cradle to handover boundary plus the processes of maintenance, repair, replacement, and refurbishment, which constitute the recurrent energy and emissions. This boundary marks the end of first use of the building.

- System boundary type: Cradle to Grave:

The cradle to grave system boundary includes the "cradle to end of use" boundary plus the end of life stage with processes such as building deconstruction or demolition, waste treatment and disposal (grave).

Additionally, different scholars have different opinions and interpretations about the system boundary included into the embodied energy. Crowther and Upton both identify the embodied energy as the total energy required in the creation of a building, including the direct energy used in the construction and assembly process, and the indirect energy consumed to manufacture the materials and components of the buildings, which is in the respective of system boundary cradle to end of construction [5, 6]. In 2012, European Commission defined the embodied energy as the energy used in the production of materials and components, of which, the system boundary is in the respective of cradle to gate. In Knight and Addis's opinion, the embodied energy includes the energy consumed in the material production and transportation to site, of which, the system boundary is cradle to site [7]. Accounting of different system boundaries resulted to the various proportions of embodied energy in the total energy consumption, what is more, Nebel and Alcorn also pointed out the proportion of embodied energy in total life cycle depends highly on the geographic location and climate [8]. Because of so many uncertainties in the embodied energy assessment, the previous research came to various of conclusions about the range of embodied energy proportion. Sartori and Hestnes [9] took a literature survey on buildings' life cycle energy usage covering a total of 60 cases from nine countries and found out that the proportion of embodied energy is between 2-38% for a conventional building, and the minimum one is a university building in Michigan, USA [10]; the highest one is a Australian residential building[11]. For low energy buildings, this share could range from 9–46%, the minimum one is a residential building in Germany[12] while the maximum one is a residential apartment in Sweden[13]. Thormark also analysed the embodied energy of three Sweden low energy buildings and determined that the energy embodied in the building materials could be around 37–38% of the total life cycle energy [14].

The significant reason for the different proportions of embodied energy concluded by the previous studies is that up till now, there has not been a unanimous standard or protocol to measure the building embodied energy. The researchers choose different system boundaries and database in line accordance with their own objectives and perspectives. Life cycle assessment (LCA) is the core concept of embodied energy measurement, based on which, three methodologies are the most widely employed, including process based LCA, Input-output LCA, and hybrid LCA. A comparative review and discussion of the three methodologies are presented in this paper.

2. Life Cycle Assessment

Life cycle assessment (LCA) is the core thinking to measure the embodied energy of buildings. It is a systematic tool to evaluate the environmental aspects of a product, technology, or service by identifying and quantifying the energy and material uses and releases to the environment through all stages of its life cycle, which include extracting and processing materials; manufacturing, transportation, and distribution; usage, reuse, maintenance; recycling and final disposal. The International Organization for Standardization (ISO) has published LCA Standards ISO: 14040:2006 and ISO 14044:2006 to introduce the principles, methodological framework, requirements and guidelines of LCA[15, 16].

There are four main phases in a LCA study: Goal and scope definition, Inventory Analysis, Impact Assessment and Interpretation (see Fig. 2). The first phase (Goal and Scope) states the intention, objectives, functional unit, system boundaries, data requirements, assumption, and limitations, etc. The second phase (Inventory Analysis) involves data collection and calculation procedures to quantify relevant inputs and outputs of a product system. The data collection includes energy inputs, raw material inputs, other physical inputs, etc. as well as waste, emissions to air, discharges to water and soil, and other environmental aspects. The third phase (Impact Assessment) is aims at evaluating the significance of potential environmental impacts using the results of Inventory Analysis. The last phase (Interpretation) considers both findings from the inventory analysis and the impact assessment together to interpret the results and to recommend improvement measures.

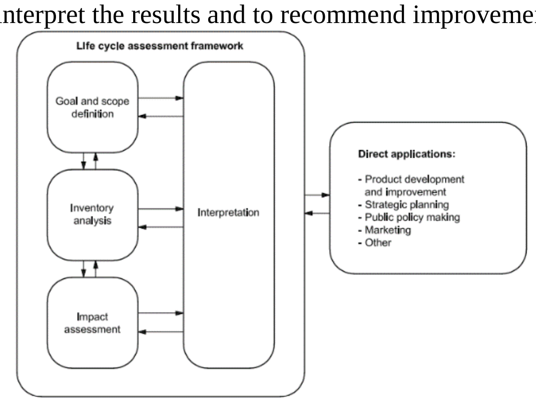

Figure 2 Stages of an LCA [16]

In the context of building embodied energy, LCA focuses only on the evaluation of energy inputs for different phases of the building life cycle only except the operational phase. Embodied energy of a building is the energy consumed by production of all the materials used in the building, including raw material extraction, material transportation, and manufacture; as well as the energy consumed during the period of erection/construction and demolition of the building. The embodied energy is made up by initial energy, recurring energy, and demolishing energy. Depending on the different system boundaries defined by evaluator, the detail components and resources of embodied energy is showed by Table1:

Table1: Components and system boundaries of embodied energy of building

			System boundary	Energy source
Building Embodied Energy	Initial energy	Material production	Cradle to gate	Extraction and processing of raw material; Assembly of products/components; Transportation between material factory.
		Construction	to site	Material Transportation to site; Construction activities on site; Disposal of construction waste.
	Recurring		to Renovation and maintenance	Replacement of material and component; Material Transportation to building; Maintenance activities; Transportation disposal material.
	Demolishing		End of life	Demolishing; Transportation.

The mathematical equation of initial and recurring embodied energy [17, 18]:

$$E_{initial} = E_{extraction} + E_{manufacture} + E_{construction} + E_{tranportation} \quad (1)$$

$$E_{material,i} = E_{extraction} + E_{manufacture} = \sum_1^i \alpha_i m_i \quad (2)$$

Where $E_{initial,}$ is the initial embodied energy of the whole building (in MJ); $E_{tranportation}$ is the embodied energy of the material or components transportation. $E_{material,i}$ is the embodied energy intensity factor for the i_{th} type of building material (in MJ/kg); and m_i is the mass of the i_{th} type of building material (in kg); and m_i should include not only the quantities of building material in-place but also the wastages incurred during construction; α_i is the embodied energy intensity factor for the i_{th} type of building material (in MJ/kg).

$$E_{tranportation} = \sum_1^i f_i m_i d_i \quad (3)$$

Where $E_{tranportation}$ is the embodied energy of the material or components transportation; f_i is the energy intensity of freight transportation in (MJ/ton km); m_i is the mass of the i_{th} type of building material in (ton); d_i is the transportation distance of the i_{th} material.

$$E_{construction} = \sum Q_j + \sum_1^r f_r w_r d_r \quad (4)$$

In the construction stage, the embodied energy mainly come from the usage of temporary of electrical power, the fuel for construction equipment, and the disposal of construction waste. Where Qj is the quantity of electrical or fuel energy consumption on the site, in MJ, f_r is the energy intensity of freight transportation in (MJ/ton km), w_r is the mass of the r_{th} type of construction waste in (ton), d_r is the transportation distance of the r_{th} waste.

$$E_{recurring,i} = [\frac{L_b}{L_i} - 1] \times \alpha_i m_i \quad (5)$$

$E_{recurring,i}$ is the recurring embodied energy of i_{th} material, L_b is the service life span of the building and L_i is the life span of the i_{th} building material.

3. Methodologies of LCA

The most frequently employed LCA methodologies are process based LCA, Input-output LCA and Hybrid LCA.

3.1 Introduction to Process based LCA, Input-output LCA and Hybrid LCA

Process based LCA

Process based LCA is a bottom-up technique. This method is based on data and information in the process of manufacture, from raw material extraction to production. When applying this method to measure the building embodied energy, the embodied energy databases for construction materials, material quantities as well as the specifications of building components are necessary.

This method is adopted by most of the regional or international LCA standards like ISO 14040, ISO 14044, EN 15804 (Sustainability of construction works, Environmental product declarations, Core rules for the product category of construction products); EN 15978 (Sustainability of construction works-assessment of environmental performance of buildings-calculation method), SETAC (Society of Environmental Toxicology and Chemistry), etc. And on the base of these international standards, like ISO, many LCA database and tools have been developed to provide user-friendly interface, which largely facilitate the evaluation process. However, one problem with process-based approach is the truncation error, for it is hardly to complete the whole production system of material, in the actual analysis, the information omission is unavoidable. Some previous studies pointed out that by process-based LCA, the incompleteness factor for building material is likely to be at least 10%, and there is also an opinion that nearly fifty percent of information will be lost in process analysis [3, 11, 19].

Input-output LCA

Input-output (IO) LCA is a top-down economic approach to estimate the life cycle environmental impacts of industry, because it uses sectoral monetary transactions data such as national input output table, the evaluation result of IO LCA is focusing on the industrial sector or even national economy. The rational of this methodology is input-output analysis, published by W. Leontief [20], and then his input-output analysis was updated and augmented by Hendrickson to develop Economic Input-Output Life Cycle Analysis (EIO-LCA). The EIO-LCA model uses economic input-output analysis matrices, and industry sector level environmental and non-renewable resource consumption data to assess to economy-wide environmental impacts of product and process [21, 22] . The input–output tables could determine the energy intensity of economic sectors and hence quantified the energy requirements of a product, based on its price [17]. Because the I-O-based intensities are obtained as the averages of relevant industrial sectors, this methodology suffers from a so-called ‘aggregation error’. It may incur large uncertainties in data as a result of its reliance on the assumption that all products within a sector share the same energy intensity per monetary unit [23]. This method is adopted by a standard developed by UNEP, Global Guidance Principles for Life Cycle Assessment Databases: A Basis for Greener Processes and Products.

Hybrid LCA

The hybrid LCA method combines the strengths of process based and Input-output. Treloar[24, 25] categorizes hybrid analysis into two types: Process based hybrid analysis, starting with process analysis of product production but compromise the total energy intensities derived from IO analysis, which can obviate the incomplete inherent with process analysis and Input-output based hybrid analysis, starting with the extraction of direct energy pathways from IO table and insert process analysis without unwanted data, which can improve the completeness and reliability of embodied energy analysis. The hybrid methods maintain the accuracy of process analysis within the complete system boundary identified by input-output data [19, 25]. It uses specific process data as many as possible and fill the system gaps with input–output data in order to assess the entirely of the supply chain of a product [17]. Treloar and Crawford developed hybrid energy coefficients to simplify the hybrid LCA of embodied energy by combining the available process data for individual materials with national average input–output data [26], therefore, the embodied energy is calculated by multiplying the quantity of each material in the building by this hybrid embodied energy coefficient.

However, the hybrid method also has the weaknesses of both the process based and I-O methods. As the hybrid method is aimed at achieving the most accuracy of estimation result, the cost of the hybrid method can be even higher than the process and the I-O methods, and the process is much more complicated than the other two. What is more, the quality of the hybrid method also depends on the availability and quality of data in both the process method and the I-O table[17].

3.2 Comparison of methodologies

The Process based LCA depends highly on the LCI database, and a perfect database should contain data of building materials, building services, energy supply, transport, and waste management service, etc. It is severely time consuming and labour intensive to construct a LCA database coving the complete system boundary. The Input-output LCA also faces the similar situation; the availability of region or national IO tables highly depends on the publications of government. Not all the country governments publish the IO table, and the comprehensive level of the IO table in each country is also different. For example, in the U.S. I-O table, the number of industrial sectors reaches nearly 700, thus suitable for a detailed analysis. [22], but the number of Japanese I-O table is approximately 400 [27, 28]. For other countries such as Thailand, the I-O table only has 100 sectors [29, 30]; and the number of Australia is around 200[11, 24]; although it is still effective in calculating intensities, but the assessment result will not be as accurate as that of America.

A comprehensive comparison of the three methodologies is shown as Table 2[15-17, 22, 31]:

Table 2: Comparison of the three LCA methodologies

Methodology	Process based LCA	I-O LCA	Hybrid LCA
Guideline/standard	ISO 14040/ISO 14044 UNEP EN 15978 SETAC	UNEP	N/A
Data source	Company/Manufacture data; Industrial data; Public institution data; Energy company data; Scientific publications	Government published IO table; National statistics about production, trade, investment, energy consumption;	Process LCA data; IO LCA data
Database-Country	ICE-Europe U.S. LCI Athena LCI-Canada Ecoinvent-Europe Gabi database-global CLCD-China ELCD-Europe	CMU EIO -US 3EID-Japan E3IOT-Europe	N/A
Tool/Software	Simapro Gabi eBalance BEES-construction industry, etc.	EIO-LCA	N/A
Advantage	Detailed analysis of specific processes; Product specific; Identify process improvements Tools and software available	Boundary is defined as the entire economy; Microscopic analysis; Data is free and open to public	Advantages of the two
Disadvantage	Subjective define of system boundary; Truncation error; Lack of comprehensive data; Time and cost intensive; Database is proprietary	Aggregation error; Difficult to identify improvements; Lack of comprehensive data; Time and cost intensive	Disadvantage of the two; more time and cost intensive.

Additionally, although many database and tools have been developed to support process based LCA, which highly make it more convenient to evaluators, one point must be noted that the lifecycle boundary of the database mentioned in Table 2 are all cradle to gate. This means when evaluating the embodied energy of building, the available tools could only facilitate evaluator to conduct the assessment within the material relevance, if the objective is to expand the lifecycle boundary, the evaluator need to find out the related data and information on his own effort.

3.3 Application of LCA in assessment of building embodied energy

Table3: Summary of reviewed papers in applying LCA

Year	Author	Location	Building type	Methodology
2005	Guggemos A[32]	USA	Commercial	Process analysis with Economic input-output data
2008	Aurora L [33]	USA	Residential	Input-output based hybrid
2010	Melissa M [34]	USA	Commercial	Process based hybrid
2006	Norman J [35]	Canada	Residential	Economic Input-output
2012	KV Ooteghem [36]	Canda	Commercial	Process analysis with published database
2011	J. Monahan [37]	UK	Residential	Process analysis with Simapro database
2008	JN Hacker [38]	UK	Residential	Process analysis with published data
2010	Gustavsson [39]	Sweden	Residential	Process analysis with published data
2007	S. Citherlet [40]	Switzerland	Residential	Process analysis with ESU database
2009	G.Verbeeck [41]	Belgium	Residential	Process analysis with Ecoinvent database
2000	Treloar [11]	Australia	Residential	Input-out based hybrid
2000	Roger Fay [42]	Australia	Residential	Process based hybrid
2002	Lenzen M. [43]	Australia	Residential	Input-out based hybrid
2006	Langston YL [44]	Australia	Residential	Input-output based hybrid
2015	EC Mpakati-Gama[45]	Malawi	Residential	Process analysis with published data
2002	B.V. Reddy[46]	India	Residential	Process analysis
2007	Oyeshola F.K[47]	Thailand	Commercial	Process based hybrid
2015	TJ Wen [48]	Malaysia	Residential	Process based hybrid with Gabi database
1995	Michiya Suzuki[27]	Japan	Residential	Economic Input-output analysis
1998	Michiya Suzuki[28]	Japan	Commercial	Economic Input-output analysis
2000	T.Y.Chen[49]	Hong Kong	Residential	Process analysis, available data from publications
2007	C.K.Chau[50]	Hong Kong	Commercial	Process analysis, global LCA database
2010	Hui Yan[51]	Hong Kong	Commercial	Process based hybrid, available data from publications

2013	XiaoLing Zhang[18]	Hong Kong	Commercial	Process based hybrid, available data from publications
2012	Yuan Chang [52]	China	Commercial	Process based hybrid, Input-output table and published data
2013	M.Y.Han[53]	China	Commercial	Process based hybrid, Input-output table and published data
2010	Yuan Chang[54]	China	Construction industry	Economic Input-output analysis, data from government publications

The sample of the literature reviewed tells that the most decisive factor in the selection of methodology to investigate the building embodied energy is the availability of life cycle inventory database and the national economic Input-output table. Input-output analysis is more likely to be adopted in the areas where the economic input-output table are available and comprehensive, such as USA, Japan, and Australia. The Green Design Institute of Carnegie Mellon University developed EIO-LCA model on the basic of the 519 sectors IO Table of the US economy; which facilitate the researchers to conduct input-out analysis, and one case in Canada also applied US EIO table to evaluate one Canadian residential building, by the assumption that the construction materials used in Canada is identical with that used in America. Australian researchers developed energy-based I-O model and I-O based hybrid model of the economy on the basis of national input-output table produced by Australian Bureau of Statistics (ABS).

For European researchers, process analysis LCA is more dominant than IO analysis that is because the lifecycle inventory database in Europe is localized and comprehensive such as ESU, Ecoinvent, etc. The participation of industry contributes a lot in developing the LCI database and LCA software like Simapro, Gabi to facilitate the evaluation process. And in Asian countries, the process-based hybrid LCA is welcomed in many studies. This methodology starts with the process analysis and employs some energy intensity data derived from I-O analysis to fill the data gap in LCI database, which help the study to make up the shortcoming of the local data and also be specific to building level.

Additionally, when C.K. Chau wanted to evaluate the environmental impacts of a building in Hong Kong, he pointed out that the European LCI database could not be used in Hong Kong directly, so he developed a method to adjust the European LCI data to meet the Hong Kong conditions, therefore the LCA results would reflect the local construction practice. According to C.K Chau, the localization of LCI data involves the following adjustment[50]:

1) Replacement of the fuel mix for electricity generation assumed in database by those whose countries in which the building materials are manufactured.
2) Inclusion of the impacts incurred by transportation of the materials or components from their originations to Hong Kong.
3) Inclusion of the impacts incurred by the local construction activities, such as the energy consumption in each construction processes.

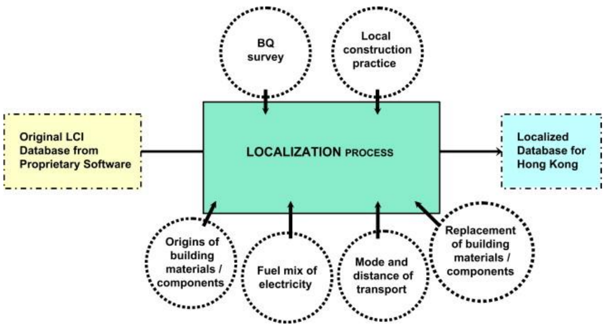

Fig.3 Illustration of information required for localization process [50]

4. Discussion

The comparison and past studies show that each of the three methodologies (Process, I-O, Hybrid) has the advantage, limitation and applicability of its own. If the purpose is to evaluate the embodied energy of one specific building, for example, when designing a green building, the designer need to know the embodied energy of the building materials and components and check out whether there is space to improve; or the building is participating a green building assessment system like LEED, HK-BEAM or BREEAM, etc., the process based LCA will be the choice. However, if the purpose is to get the average embodied energy consumption of industry, sector and national level, for example, to formulate industry energy saving policies, or to plan the energy consumption benchmark of industry level, Input-output based LCA could be the choice.

Additionally, when applying these methodologies in embodied energy evaluation, there are some considerations should be taken notice. The first consideration is all the three methodologies have geographical limitation. The material production technology, quality, manufacture process, usage of energy mix, economy development, transportation distance, etc., all these factors are different in different countries, and keep dynamically changing as the development of society, technology, and international situation. Therefore, even the localized lifecycle inventory database could not promise that the data reflect the current practice. As many previous studies mentioned above adopted the published material intensity data, the authors should know that the adoption of those published data is assumed that the materials to be evaluated is identical with the ones to be referred.

The second consideration is that the difference between primary energy and delivered energy in evaluation. Usually, the assessment of embodied energy is in terms of primary energy, which means the energy form from the renewable and non-renewable natural resources like coal, solar, natural gas, etc. In LCI database, the energy intensity of material is in the unit of primary energy. However, if the defined system boundary includes the construction process, in some cases, the electricity consumed for construction equipment, and temporary buildings on site are also calculated, however, electricity consumed onsite is classified by term "delivered energy", which is a misleading point.

For the last point, there have not been any regulations to demand the academy and industry to take which methodology for the quantification of embodied energy. No matter the methodology chosen, the system boundary defined, or the adoption of LCI database or open published data, all these issues depend on the evaluators' objectives, understandings, and preferences. The uncertainty and incompleteness almost exist in each step of the three methodology processes. As a result, it is hardly to compare the accuracy of evaluation results by the three methodologies.

5. Summary

In a summary, getting a clear evaluation of building embodied energy is significant in reducing building energy consumption through its whole lifecycle. The three dominant evaluation methodologies all have the advantages, disadvantages, and feasibilities of their own. Process based LCA is suitable for the assessment of component or building level and is supported by many LCI database and LCA software. Input-output LCA can be applied to evaluate the average embodied energy consumption of sectoral, reginal, or even national level. And the hybrid LCA shares the both merits and defects of the former two methods. The evaluator needs to choose the most appropriate method according to the evaluation objective (building level or industry, sector level), evaluation boundary (cradle to gate, site or end of life) and available resource (budget to purchase proprietary database, labour force in data collection, etc.) What is more, the localization of foreign database, the development of society, economy, manufacture technology, transportation mode, the dynamic changing international situations, and fluctuation of commodity prices, international trade tariff, etc. so many factors existing to cause uncertainty and inaccuracy, therefore, although it is hardly to judge the veracity of evaluation result, the evaluators need to pay attention and take some measures such as the adjustment factor, to achieve a more reasonable and acceptable result.

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