TYPICAL LAYOUTS OF HIGH-RISE APARTMENTS AND EMBODIED ENERGY OF BUILDING MATERIALS IN DEVELOPING COUNTRIES - A CASE STUDY IN INDONESIA

MẶT BẰNG ĐIỂN HÌNH CỦA CÁC CĂN HỘ CHUNG CƯ CAO TẦNG VÀ NĂNG LƯỢNG TIÊU TỐN CỦA VẬT LIỆU XÂY DỰNG Ở CÁC QUỐC GIA ĐANG PHÁT TRIỂN - NGHIÊN CỨU ĐIỂN HÌNH Ở INDONESIA

Ho Anh Dung[1], Nguyen Xuan Long[2], Pham Van Hung[3], Vu Cao Anh[4]
[1,2,3,4] Vietnam Institute for Building Science and Technology
Email: [1] dungha.ibst@gmail.com
DOI: https://doi.org/10.59382/pro.intl.con-ibst.2023.ses2-18

ABSTRACTS: As a typical developing country, Indonesia is the only Southeast Asian country in the G20 nations. The country is undergoing rapid urbanization, and cities must be expanded vertically to accommodate this urbanization rate within constrained horizontal spaces. Although this helped address the housing shortage issue, it caused significant environmental impacts. Owing to structural requirements, high-rise buildings often need more building materials than low-rise and medium-rise buildings. In other words, tall apartment buildings consume more energy and emit more CO_2. This study applies the qualitative and quantitative methods to classify the standard design of high-rise apartments, then assessing environmental impacts of building materials in major cities in Indonesia. Findings of the study may be applied to develop low-carbon apartments and achieve sustainable development in developing countries, specially Vietnam.

KEYWORDS: Developing countries, high-rise apartments, standard design, building materials, embodied energy, CO_2 emissions, wooden building.

TÓM TẮT: Indonesia là một quốc gia đang phát triển tiêu biểu và là nước Đông Nam Á duy nhất được xếp hạng trong các quốc gia nhóm G20. Đất nước đang trong quá trình đô thị hóa nhanh chóng, và các thành phố phải được mở rộng theo chiều dọc để đáp ứng tốc độ đô thị hóa này trong các không gian chiều ngang hạn chế. Mặc dù điều này đã giúp giải quyết vấn đề thiếu nhà ở, nhưng nó lại gây ra những tác động đáng kể đến môi trường. Do yêu cầu về kết cấu, nhà cao tầng thường cần nhiều vật liệu xây dựng hơn so với nhà thấp tầng và trung bình. Nói cách khác, các tòa nhà chung cư cao tầng tiêu thụ nhiều năng lượng hơn và thải ra nhiều khí CO_2 hơn. Nghiên cứu này áp dụng các phương pháp định tính và định lượng để phân loại thiết kế tiêu chuẩn của các căn hộ chung cư cao tầng, sau đó đánh giá tác động môi trường của vật liệu xây dựng tại các thành phố lớn ở Indonesia. Kết quả của nghiên cứu có thể được áp dụng để phát triển các căn hộ carbon thấp và đạt được sự phát triển bền vững ở các nước đang phát triển, đặc biệt là Việt Nam.

TỪ KHÓA: Các nước đang phát triển, chung cư cao tầng, thiết kế tiêu chuẩn, vật liệu xây dựng, năng lượng tiêu tốn, khí thải CO_2, tòa nhà gỗ.

1. INTRODUCTION

As a typical developing country, Indonesia is the only Southeast Asian country ranked in G20 nations. The country is undergoing rapid urbanization, urban population is estimated to expand from 49.8% in 2010 to 66.6% in 2035, is about 305 million people by that time [1]. In an effort to accommodate this urbanization rate within constrained horizontal spaces, it is inevitable to expand the cities vertically [2]. In 2007, the government has released a project called Rusunami, which is known as a low-cost apartment development program, with the target of constructing 1000 low-cost high-rise apartment buildings for mid-to-low income people in major cities. Although this would help to address the housing shortage issue, it also bring about significant environmental impacts.

Due to structural requirements, high-rise buildings are often need much more building material quantity than low-rise and medium-rise buildings. This means that tall apartment buildings will consume more energy and emit more CO_2 emissions [3]. Utilizing building materials which can be manufactured with less energy and emissions, is one of the strategies to lower consumed energy and CO_2 emissions.

This study aims to analyze the standard designs of high-rise apartments and environmental impacts of building materials in major cities in Indonesia, then proposing proper solutions to develop low-carbon apartments and support for the sustainable development. The paper will serve as a reference for reseachers in other countries with similarities in climatic, geographical and socio-economic conditions such as Vietnam.

1.1. Standard designs of high-rise apartments

Standard designs show the typical layouts of buildings. They are normally developed by academic societies such as AIJ (Architectural Institute of Japan) in Japan, BRE (Building Research Establishment) in the UK, or CEER (Cost Effective Energy Retrofit) in the USA [4]. The standard design can be used as a base model for various kinds of building simulations, especially in comparative scenario analysis, for example, consultants can use standard designs to present several different solutions for simulated buildings similar to the building of their clients. In the near future, it should also be anticipated that the requirement for tools to analyze various scenarios for energy efficiency projects in the building sector would rise dramatically. Thus, it is necessary to investigate typologies of buildings and energy efficiency solutions, supporting authorities and stakeholders in the energy sector to determine proper upgrading strategies of the energy performance of buildings. It can be said that standard designs or typical layouts are very essential for any building standardizations such as low-carbon building standards.

Moreover, due to the increasingly unfavorable climate conditions, many existing buildings in developing nations have low thermal efficiency, either in the outer or inside environment. The need to improve the thermal climate indoors is growing as the social economy develops. As a result, these structures' energy-efficient and affordable rehabilitation have taken on greater importance in these nations. Due to the vast variety of building types, it is crucial to designate typical buildings for each type in order to provide direction for creating the appropriate retrofit plans in accordance [5].

Despite being a typical developing country with urbanization at a high rate, the construction of high-rise residences in Indonesia's major cities has not been as busy as it has been in other Asian metropolises until recently. Landed homes, such as detached and semi-detached homes, row homes, and townhouses, make up the majority of urban dwelling typologies in Indonesia [6]. In Indonesian cities, the cost of land has been steadily rising since the 1990s (Realestat Indonesia, 2017). This tendency made it more difficult to develop landed estates [7]. Furthermore, the terrible traffic jams ushered in the new idea of "Transit Oriented Development (TOD)". Since the TOD, high-rise apartment development has increased. Since 2004, the government has thought about providing homes to people of different income levels at the same time. The government mandated that every private apartment project must dedicate 20% of its building's floor area to creating “rusun” (vertically expanded dwellings) for the low-income population in order to prevent simply providing for the high-income community [8]. As a result, high-rise apartment buildings are now often seen in Indonesia's largest cities.

1.2. Embodied energy of building materials

Human activities such as services and productions have impacts to the environment at a certain level through stages during their life cycle. As people’s awareness about environmental protection has been increasing, the requirement of developing techniques to understand and solve environmental issues effectively has gained more attention. Life Cycle Assessment (LCA) was born and served as a powerful tool to assess environmental impacts of a product from raw material extraction through production, utilize, end-of-life, recycling and disposal. The building sector which globally accounts for more than 40% of natural resource use, 30% of energy use, and 30% of CO_2 emissions, is now at the center of a significant worldwide debate on how to protect the environment. Studies on the assessment of life cycle energy of buildings have been conducted in environmentally aware developed nations since the early 1990s [9].

The total life cycle energy of a building comprises operational energy (OE) and embodied energy (EE). While the former is defined as the energy used in the utilization phase of a building to maintain its indoor environment through activities such as lighting, cooling and heating, the latter is the amount of energy sequestered in building materials through production, construction, destruction and disposal. In order to achieve the sustainable development, the sector must limit both OE and EE consumption. Nevertheless, due to its greater proportion in the overall life cycle energy, operational energy was the only one taken into account until recently [10].

Buildings are made of several different materials, and each one requires energy and emits emissions during the stages of production, usage, and demolition [11]. Selecting construction materials that are energy-efficient can help promote environmental preservation. Thus, one of the first steps in protecting the environment is calculating the embodied energy of construction materials. The assessment of EE and CO_2 emissions of construction materials has previously been conducted in a number of studies, most of which are from industrialized nations. In constrast, there is still a significant gap in the evaluation of the EE and CO_2 emissions of building materials in case of emerging countries [12].

In Indonesia, the LCA as well as related EE and CO_2 emissions research of buildings are still in the infancy [13]. Therefore, it is rare to find studies on these fields in the country. For examples, Utama et al. (2008) conducted a life cycle energy (LCE) analysis for residential buildings with walls constructed from many different building materials in Semarang [14]. Surahman et al. (2015) used the input-output analysis method to examine LCE and CO_2 emissions of houses in Jarkata and Bandung [15]. However, these studies mainly concentrate on single landed houses and low-stories buildings, further studies should be conducted to investigate EE and CO_2 of construction materials in high-rise apartments in major cities in Indonesia.

1.3. High-rise wooden buildings

Reinforced concrete is well known as one of the most common building materials and has contributed an important role in the development of the construction sector. However, besides its advantages, reinforced concrete also brings about negative impacts on the surrounding environment during its whole life cycle. Thus, it is important to find more sustainable materials that could replace reinforced concrete to construct buildings. Among building materials, wood is increasingly recommended as the ideal alternative to protect the environment and foster sustainability. This is because of some reasons:

- It takes relatively little energy to produce wood products.
- It was found that 1 ton of CO_2 is absorbed and stored for each cubic meter of wood used in buildings.
- Compared to other building materials, wood releases fewer GHGs in the manufactured phase and does not emit CO_2 emissions throughout the whole building life cycle.
- Wood components are recyclable and renewable [16].
- Generally, wooden products using for construction may be divided into three major groups:
- Panel products which are frequently made by oriented strand board or plywood.
- Beam products which are created from laminated veneer lumber or glulam.
- Cross - laminated timber (CLT) or mass timber products.

Despite the wealth of studies on the environmental impact of wooden buildings, most of them concentrate on low-rise or medium-rise structures and in developed countries [17]. It is difficult to find such researchs in developing countries, especially in Indonesia. Therefore, to mitigate negative environmental impact as well as to support for the sustainable development, it is important to study the sustainable tall timber buildings in developing countries.

2. METHODOLOGY

2.1. Classification of typical layouts of high-rise apartments in major cities in Indonesia

Apartment buildings including Condominium (CD) and Rusunami (RM) in nine major cities in Indonesia: Bandung, Bekasi, Bogor, Depok, Jakarta, Makassar, Medan, Surabaya, Tangerang, were targeted in this study. According to the new Condominium Law in 2011 in Indonesia, CD is defined as a flat for the upper middle-class people while RM is a low-cost and owned apartment. The image and key plan of buildings, drawings of units and other information such as prices, construction years, and so on, were obtained from real estate agencies' websites (Figure 1).

Figure 1. Condominium (a) and Rusunami (b) apartment

Table. 1. Sample sizes of building and unit scale

Sample	Condominium	Rusunami	Total
Building	220	48	268
1BR units	382	88	470
2BR units	324	93	417

As shown in Table 1, a total of 268 buildings were investigated, comprising samples of one-bedroom units (1BR) of 470 and those of two-bedroom units (2BR) of 417. After collecting the drawings, we qualitatively classified them into similar types, coded as A or B, C, then defined them as dummy variables in the dataset. The samples in each type are further distinguished base on the arrangement of bedroom (BR) and living room (LR), and location of the toilet (WC) and balcony (BCN), coded as groups 1, 2, 3… and sub-groups a, b, c, etc.

Principle component analysis (PCA) was carried out to reduce the number of variables and define them as component factors. In order to determine the number of principal components, we chose factors with an eigenvalue > 1 and total variance cumulative > 50%. Kaiser-Meyer-Olkin (KMO) and Bartlett's Test of Sphericity were used to assess the availability of the dataset with the PCA method [18]. In the next steps, we conducted the hierarchical cluster analysis using the selected factors to quantitatively classify apartment units into similar types. All the continuous variables were standardized using Z-scores. The Ward linkage method and the Squared Euclidean distancing method were employed to obtain the dendrogram of the analysis. We checked all different clustering options to determine the most appropriate one, in which each cluster contains a single dominant unit type with maximum sample size.

2.2. Calculation of embodied energy and CO_2 emission of building materials

In order to calculate EE and CO_2 emission of building materials used for apartments, we applied material inventory analysis. First, we need to obtain the volume of materials (m^3) from design drawings or bill of quantity (BOQ) of buildings. However, due to the privacy policy and intellectual rights of property developers or construction contractors, we was unabled to obtain these data fully. Therefore, we just used drawings of some Rusunami apartments provided by Indonesian colleagues for the analysis. After that, we extracted information such as number of stories, ceiling height, foot print area, total floor area and materials used. We also used the input-output (I-O) analysis method to calculate EE and CO2 emissions of building materials. The I-O method is based on the I-O tables which show the economic transaction matrixes of products and services of several different sectors. The environmental impacts of a transaction in one sector can be evaluated across all the sectors of an economy by adding sectoral environmental burden values to the I-O tables, therefore, it is comparatively complete [19]. In Indonesia, there are three types of I-O tables which are local I-O table, inter-regional I-O table, and national I-O table [20]. Because this research analyzes high-rise apartments in several major cities in Indonesia and the national I-O table (2016) covers on most of sectors, therefore, it is recommended to use this I-O table for the analysis. The equations of calculating EE of building materials using I-O analysis are described as follows:

$$E = \sum_{k}^{n} (E_{dm} + E_{im}) \quad (1)$$

$$E_{dm} = \sum_{k}^{n} \left[\left(\frac{e_{dm}}{m} . (I - (I - M).A)^{-1} \right)_k . U_k \right] \quad (2)$$

$$E_{im} = \sum_{k}^{n} \left[\left(\frac{e_{im} . (I - A)^{-1}}{m} \right)_k . U_k \right] \quad (3)$$

Where:

E: EE of building material (GJ)

E_{dm}: Domestic EE of building material (GJ)

E_{im}: Imported EE of building material (GJ)

e_{dm}: Direct energy consumption of building material (GJ/ million IDR)

e_{im}: Direct energy consumption of building material (GJ/ million IDR)

I: Identity matrix

A: Input-coefficient matrix

M: Import matrix

$(I-(I-M).A)^{-1}$: Domestic Leontief inverse matrix of building material

$(I-A)^{-1}$: Imported Leontief inverse matrix of building material

U_k: Unit of building material k

m: Material intensity of building material (unit of material/million IDR)

On the other hand, the equations to estimate CO_2 emission of building materials using I-O analysis are described as follows:

$$ECO_2 = \sum_{k}^{n}(ECO_{2dm} + ECO_{2im}) \quad (4)$$

$$ECO_{2dm} = \sum_{k}^{n}\left[\left(\frac{e_{CO_2dm}.(I-(I-M).A)^{-1}}{m}\right)_k.U_k\right] \quad (5)$$

$$ECO_{2im} = \sum_{k}^{n}\left[\left(\frac{e_{CO_2im}.(I-A)^{-1}}{m}\right)_k.U_k\right] \quad (6)$$

Where:

E: Embodied CO_2 of building material (ton CO_2-eq)

ECO_{2dm}: Domestic embodied CO_2 of building material (ton CO_{2-eq})

ECO_{2im}: Imported embodied CO_2 of building material (ton CO_{2-eq})

e_{CO2dm}: Direct CO_2 emission of building material (ton CO_2-eq/million IDR)

e_{CO2im}: Direct CO_2 emission of building material (ton CO_2-eq/million IDR)

2.3. Scenario analysis

In this analysis, we proposed a standard building model and applied different materials for each scenarios to compare their EE and CO_2 emission. It was expected that sustainable materials such as wood would help to reduce EE and CO_2 emission of apartment buildings in comparision with non-renewable materials such as reinforcement concrete.

The base building model was proposed based on the prototype of a Rusunami apartment dedicated in the Regulation of the Minister of Public works No. 05/PRT/M/2007: Technical guidelines for construction of Rusunami apartment [21]. In Indonesia, the determination of the height classification is based on the number of floors buildings, which are determined by the local government district or city. A building has greater or equal to 8 floors is considered as a high-rise building [22]. Because there is no detail calculation in terms of building structure, we just propose the building with 8 stories. We also intergrated our classified standard 1BR and 2BR design into the building model. To simplify the calculation, we just concentrated on main building components and excluded foundation, roof and other auxiliary items.

In the first scenario, all structure components of the building use reinforcement concrete material.

The next scenario applied hybrid systems, which combine several materials and structural options. The concept of this scenario comes from the existing tall timber building using hybrid systems – Brock Commons Tallwood House in Vancouver, Canada [23]. The ground floor uses reinforced concrete structural components supporting mass-timber structural components from 2nd – 8th floor.

The last scenario is so-called panel systems. In panel systems, solid wall panels that are regularly spaced apart and are oriented in two directions in the design support both vertical and lateral loads. These panels, which are most frequently composed of CLT, should be arranged and spaced uniformly on each story of the building. Panel systems are typically better suited to residential buildings, where tenant needs are more fixed, as they tend to result in cellular plan configurations with limited flexibility for reconfiguration during the life of the building. The concept of this scenario comes from the existing tall timber building using panel systems – Woodcube in Hamburg, Germany [24]. The building uses reinforced concrete cores and stairs, meanwhile, walls, facades, and floor systems are composed from CLT panels.

3. RESULTS AND DISCUSSIONS

3.1. Typical layouts of high-rise apartments in major cities in Indonesia

3.1.1. At building scale

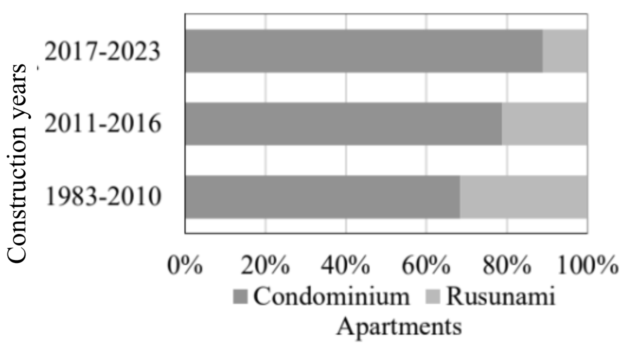

Figure 2. Construction periods of apartment buildings

Overall, the proportion of CD was greater than that of RM, with 82% and 18% respectively (n=268). Through the simple frequency analysis, we found that over the period of 40 years, from 1983 to 2023, the share of CD increased significantly from 68% to 89%, while the percentage of RM decreased sharply from 32% to 11% (Figure 2). This is understandable due to the increased incomes along with the economic growth, Indonesian people now prefer to live in more convenient apartments than in the past. The average price of CD was found to be 1412 USD/m^2, which was 473 USD higher than that of RM. The result also shows that most CD and RM buildings were tower buildings (vertical high-rise buildings) (76% for CDs and 52% for RMs) with single-core and double-loaded corridor (more than 90% for both). In general, CDs and RMs had 1 to 4 building blocks.

Although some CDs were higher than 40 floors, the height of CDs mainly ranged from 21 to 40 stories, and the percentage of such high buildings accounted for 63% in total. On the other hand, RM apartment buildings are lower than 40 stories. The proportion of 21-40 story buildings was 55% whereas that of lower than 21 floor buildings was 45%. Furthermore, we investigated 213 building plans to find the building orientation. It was found that there is no particular orientation tendency for buildings because the percentages of orientations were quite small and equal to each other.

3.1.2. At unit scale

a. 1BR unit

First of all, we qualitatively classified 1BR units into 3 main categories: A, B, and C. Type A is the so-called studio type, which is a single-room dwelling that combines the bedroom, kitchen, and living area into one large room. Types B and C have a bedroom separated from a living room, and the difference between these types is the arrangement of bedroom and living room. In Type B, the bedroom and living room are arranged along with the depth of the unit while these rooms of Type C are arranged along the width of the unit. Each category above was then classified further into groups and sub-groups. The units having similar toilet locations were allocated to the same groups. Also, units with similar balcony types and locations were classified into the same sub-groups. Figure 3 shows the dendrogram of cluster analysis. Because the two last clusters have the same dominant unit type, we determined to combine them as only one Type A1 to increase the homogeneity. Therefore, the final result comprises five Type A sub-groups (A1-A5) and one Type B sub-groups (B1) (Figure 4). Table 2 summarizes the standardized (averaged) dimensions of each type. As shown, Type A1 is found to be the largest cluster, accounting for 37% of the 1BR samples. This type is illustrated as a studio type with the average unit size of 24.1 m^2, with a toilet located at the corridor side, and a half balcony within the unit. There are slightly differences between Type A1 and Types A2, A4 about sizes and balcony type. In addition, the balcony was not included in Type A5 meanwhile the toillet was located at outside of Type A3. Type B1 was the larget unit type with 38.7 m^2 because it had a separated living room.

We conducted frequency analysis to observe the construction trend of the 1BR unit. Type A is the most common unit type for both CD and RM apartments, accounting for 76% and 88% of each share. Despite that there was 16% of 1BR unit Type C for CD apartments, it accounted for only 5% for RM apartments. The shares of CD and RM units type B were equal to each other, which are about 8%. It is witnessed that between 1983 and 2022, the popularity of CD 1BR units type A has dropped from 91% to 75%, and from 100% to 80% between 2005 and 2022 in the case of RM. This trend shows that now people in Indonesia want to own an apartment with a separate bedroom and living room such as Type B or C rather than a studio type apartment.

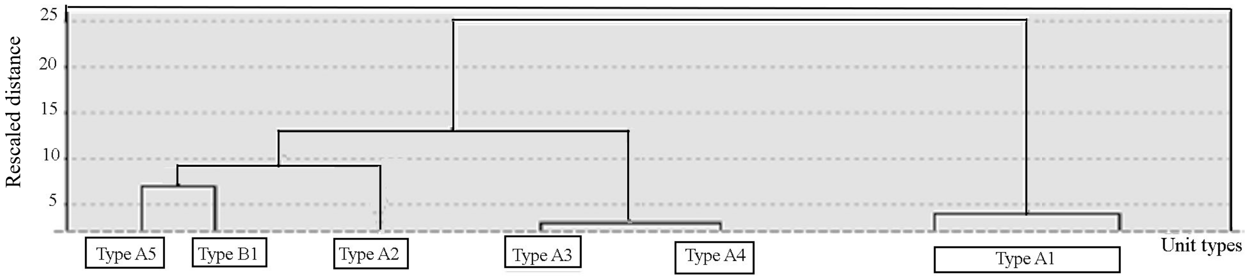

Figure 3. Dendrogram of cluster analysis for 1BR units

b. 2BR unit

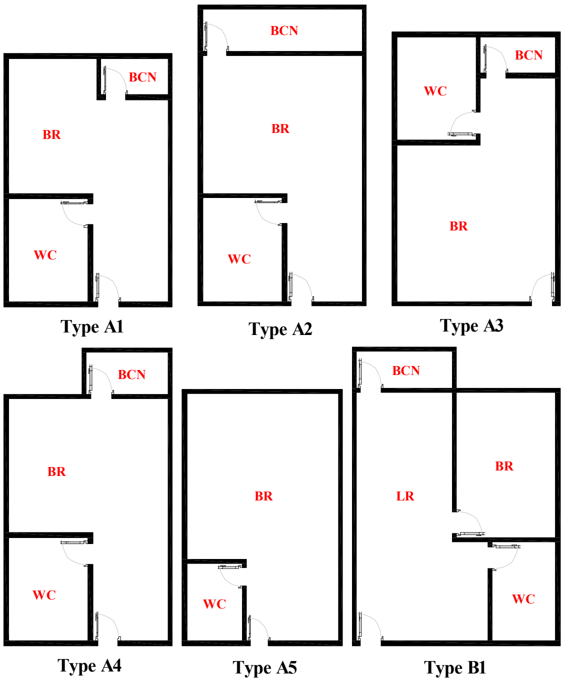

Figure 4. Typical drawings of 1BR unit types

Table 2. Characteristics of typical 1BR unit types

Type	A1	A2	A3	A4	A5	B1
%	37.02	17.66	16.17	10.21	9.15	9.79
Unit size	24.10	31.71	26.17	26.11	23.05	38.68
BR size	13.03	14.69	11.52	12.25	13.03	11.26
No. WC	1.00	1.00	1.00	1.00	1.00	1.00
WC size	2.91	3.99	3.23	2.75	3.10	3.44
No. balcony	1.00	1.00	1.00	1.00	0.49	1.00
Balcony size	1.72	3.22	2.01	1.5	0.91	2.37
No. door	3.01	3.22	3.29	3.40	2.00	3.89
No. window	1.10	0.99	1.12	1.42	1.19	1.20

Similar to the 1BR classification, drawings of 2BR units were visually divided into 2 main types: A and B. Type A is characterized by 2 bedrooms located side by side and along with the depth of the unit while 2 bedrooms of type B are arranged along the width of the flat. Both types then were classified into smaller groups and sub-groups based on criteria as explained before. In order to increase the homogeneity within clusters, we analyzed 2BR type A and type B separately. Fig. 5 illustrates the final clustering result for 2BR type A and B. As shown in Table 3, Type A1 was the largest group with 21 % of Type A share. This unit type has a toilet located next to bedrooms and corridor side, and a half balcony connected to a separated living room. Moreover, the proportions of Type A2 and A3 were 19% and 18% whereas the percentages of Type A4 and A5 were 13% and 12% respectively. Types A6 and A7 accounted for just 9% and 8% in total. On the other hand, Type B1 was the most typical type of 2BR Type B units, its cluster contributed to 40% of that. In this type, 2 bedrooms were constructed horizontally aiming to have more windows for lighting and ventilation. While the toilet is located at the corner between the master bedroom and corridor side, the half balcony is accessed from the living room and extended outside. It can be seen from Figure 5 and Table 3 that types B2 and B3 are slightly different from Type B1 in terms of bedroom arrangement, their percentages are 30% and 19% sequentially. Type B4 is less common than others, accounting for 12% in total. This unit type was displayed with 2 bedrooms opposite to each other, connecting by a small balcony in the middle.

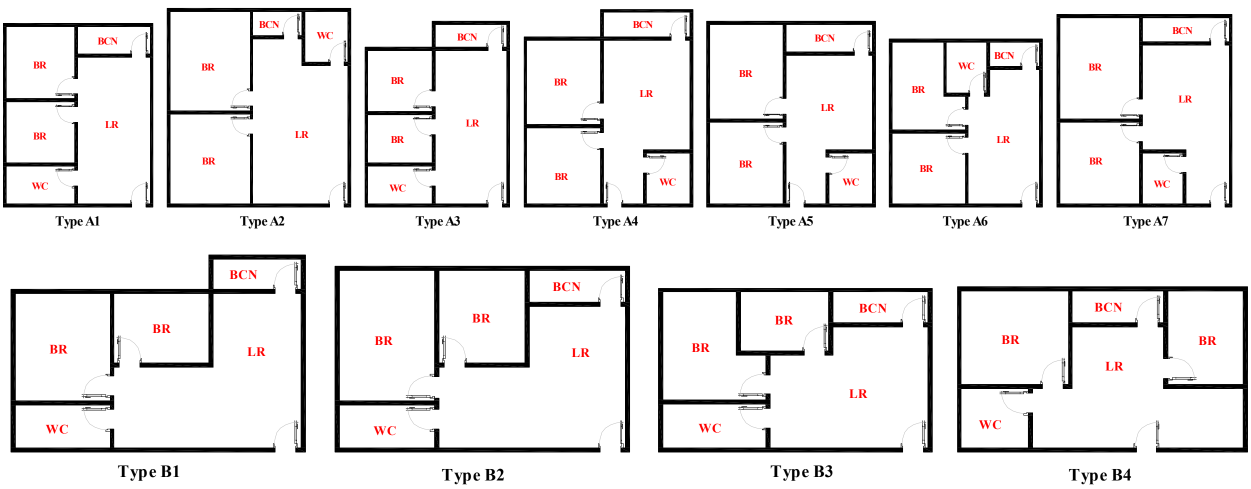

Figure 5. Typical drawings of 2BR unit types A and B

Table 3. Characteristics of typical 2BR unit types A and B

Type	A1	A2	A3	A4	A5	A6	A7	B1	B2	B3	B4
%	21.20	19.35	17.97	13.36	11.52	8.76	7.83	39.50	29.50	19.00	12.00
Unit size	41.68	55.04	41.51	47.66	47.64	38.40	50.10	60.97	64.42	44.75	54.45
BR1 size	8.20	9.92	8.25	8.18	8.95	8.58	9.10	9.32	8.84	7.76	8.56
BR2 size	11.09	12.66	10.94	11.53	10.96	11.45	12.85	13.35	13.50	12.26	11.27
No. WC	1.00	1.31	1.00	1.00	1.04	1.00	1.00	1.33	1.49	1.00	1.25
WC1 size	3.40	3.71	3.48	3.46	3.35	3.58	3.63	3.65	3.80	3.78	3.81
WC2 size	0.00	1.20	0.00	0.00	0.11	0.00	0.00	1.39	1.94	0.00	1.08
No. balcony	1.02	1.02	1.00	1.24	0.80	1.00	0.76	1.39	1.02	1.00	1.00
BCN1 szie	2.01	2.94	2.94	2.53	1.91	2.25	1.81	2.57	3.27	2.63	2.84
BCN2 size	0.19	0.07	0.00	0.60	0.00	0.00	0.00	1.26	0.12	0.00	0.00
No. doors	5.05	5.29	4.95	5.14	4.80	5.00	4.65	5.72	5.56	5.03	5.25
No. entrance door	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.01	1.02	1.00	1.00
No. LR window	0.68	0.31	0.49	0.17	0.48	0.21	0.65	0.23	0.49	0.29	0.54
No. BR1 window	0.39	0.48	0.74	0.24	0.40	0.47	0.65	0.72	0.86	0.58	0.71
No. BR2 window	0.97	1.10	1.03	1.03	1.04	1.00	1.12	1.28	1.03	1.11	1.08

* Size in m^2

Based on the result of frequency analysis, the construction tendency of 2BR units was also investigated. Among CD apartments, type B was the dominant type with 53% of the whole units compares to 47% for type A. Between 1988 and 2016, the percentage of CD 2BR unit type B rose rapidly from 39% to 63%, before going down to 38% in the next years. This means there was a reverse pattern for CD 2BR unit type A too. In contrast to CD apartments, type A unit was doubled than type B for RM apartments, with the rate being 70% and 30% correspondingly. From 2005 to 2022, the distribution of type A has grown gradually from 67% to 76% while that of type B declined remarkably from 33% to 24%.

3.1.3. Correlation between units and buildings

This section discusses the correlation between apartment buildings and typical units. As shown in Table 4, we categorized CDs and RMs based on heights and construction periods. Totally, there were nine CD types and six RM types used for the analysis. We made statistics to observe the relationship between buildings and units separately. Figure 6 and 7 indicate the percentages of six typical 1BR unit types in RM and CD buildings. In comparion with other types, type A1 was the most common 1BR unit type and it distributed more in buildings with the height ranged from 21 to 40 floors. Moreover, this unit type was trendy in RMs from 2011 to 2016 while after 2016 for CDs. Although type B1 has constructed in CDs after 2010, there were not any type B1 appeared in RMs.

Similarly, Figure 8 illustrates that types A1 and B1 were dominated the rest of 2BR unit types in CDs. They were also constructed mostly in 21-40 stories buildings from 2016 on. However, there was just a small proportion of type B1 in 21-40 floors RMs before 2011 (Figure 9).

3.2. Embodied energy and CO_2 emission of building materials in major cities in Indonesia

As explained before, due to difficulties in data collection, we have only one proper drawing record of a Rusunami apartment. Therefore, we calculated EE and CO_2 emissions of building materials of this representative building by using material inventory analysis, I-O analysis, and mentioned equotions. The results are shown in Tables 4 and 5.

Table 4. Building types based on heights and years

Building	Height	Year
CD	H1 (< 21 floors)	Y1 (Before 2011)
	H2 (21-40 floors)	Y2 (2011-2016)
	H3 (> 40 floors)	Y3 (After 2016)
RM	H1 (< 21 floors)	Y1 (Before 2011)
	H2 (21-40 floors)	Y2 (2011-2016)
		Y3 (After 2016)

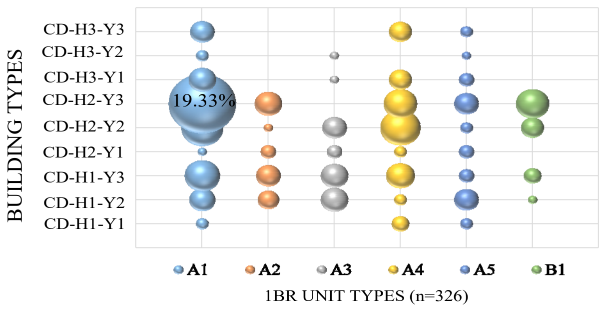

Figure 6. Distribution of typical 1BR unit types in CDs

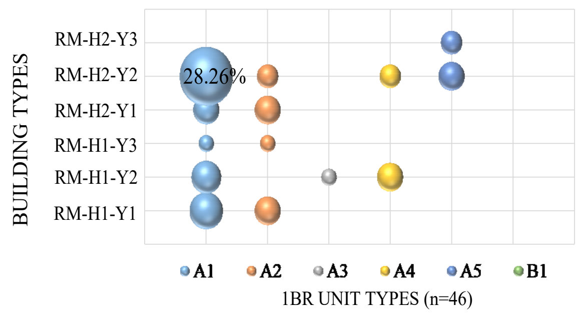

Figure 7. Distribution of typical 1BR unit types in RMs

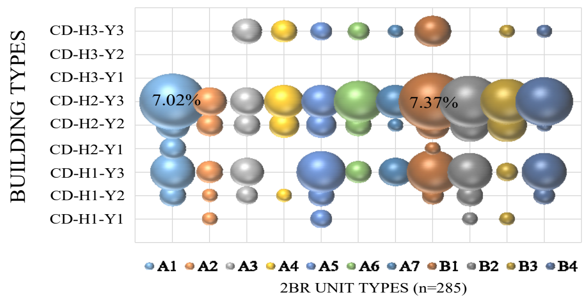

Figure 8. Distribution of typical 2BR unit types in CDs

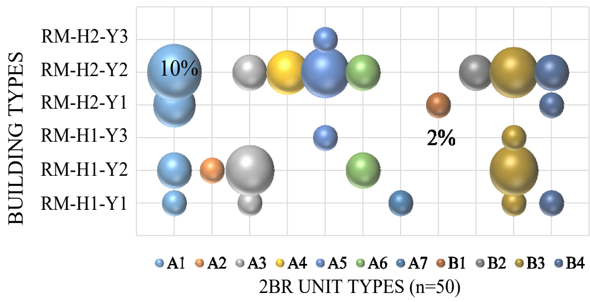

Figure 9. Distribution of typical 2BR unit types in RMs

Table 5. Embodied energy of building materials

Building materials	Quantity	Unit	Price/Unit	Million price/unit	Domestic EE intensity	Imported EE intensity	Total EE intensity	EE/ unit	EE
			(IDR/Unit)	(million IDR/unit)	GJ/million IDR	GJ/million IDR	GJ/million IDR	GJ/ unit	GJ
Cement	2611771	kg	1588	629.6	0.02	0.02	0.04	0.00	1589
Sand	117138	m^3	340600	2.9	0.02	0.02	0.04	0.01	1440
Gravel	36273	m^3	293400	3.4	0.02	0.02	0.04	0.01	384
Steel	6900691	kg	11720	85.3	0.03	0.10	0.13	0.00	10187
Ceramic	10739	m^2	31000	32.3	0.01	0.02	0.03	0.00	10
Gypsum	39088	sheet	74200	13.5	0.02	0.02	0.04	0.00	105
Paint	62098	kg	64806	15.4	0.01	0.01	0.03	0.00	107
Glass	8102	m^2	233300	4.3	0.04	0.05	0.08	0.02	154
Aluminum	612	m^2	30643	32.6	0.06	0.08	0.14	0.00	3
Wood	768	m^3	2437995	0.4	0.04	0.04	0.07	0.18	138
								Total	**14117**

Table 6. CO_2 emission of building materials

Building materials	Quantity	Unit	Price/Unit	Million price/unit	Domestic CO_2 intensity	Imported CO_2 intensity	Total CO_2 intensity	CO_2/ unit	CO_2
			(IDR/Unit)	(Million IDR/unit)	kg-CO_2/ million IDR	kg-CO_2/ million IDR	(kg-CO_2/ million IDR)	kg-CO_2/ unit	ton-CO_2
Cement	26117701	kg	1588	629.6	1.2	1.3	2.5	0.004	102.2
Sand	117138	m^3	340600	2.9	1.1	1.3	2.4	0.8	96.5
Gravel	36273	m^3	293400	3.4	1.1	1.3	2.4	0.7	25.7
Steel	6900691	kg	11720	85.3	2.2	7.1	9.4	0.1	756.2
Ceramic	10739	m^2	31000	32.3	0.9	1.1	2.0	0.1	0.7
Gypsum	39088	sheet	74200	13.5	1.1	1.3	2.4	0.2	7.0
Paint	62098	kg	64806	15.4	0.9	1.1	2.0	0.1	8.2
Glass	8102	m^2	233300	4.3	3.1	3.9	7.0	1.6	13.2
Aluminum	612	m^2	30643	32.6	4.2	6.5	10.7	0.3	0.2
Wood	768	m^3	2437995	0.4	2.2	2.5	4.7	11.5	8.8
								Total	**1019**

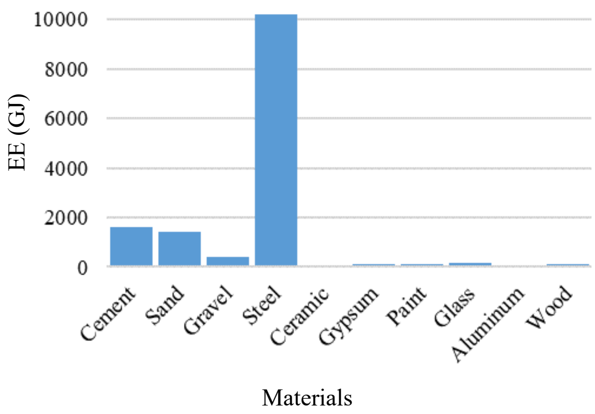

Figure 10. Embodied energy of building materials

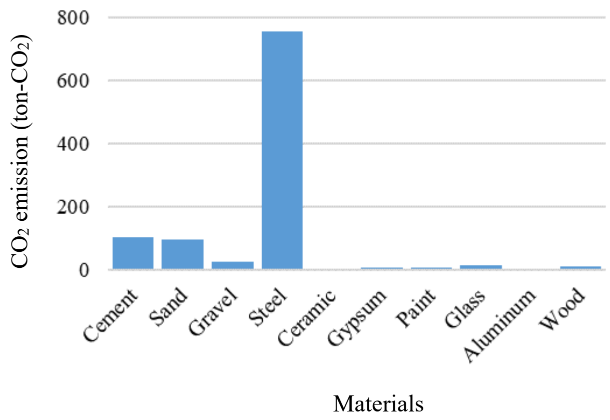

Figure 11. CO_2 emission of building materials

It can be seen from Table 5 that total EE of all building materials is 14117 GJ. Among that, steel has the highest embodied energy, with 10187 GJ. Cement and sand ranked second and third, with 1589 GJ and 1440 GJ respectively. In contrast, EE of aluminium and ceramic is lowest, with 3 GJ for the former and 10 GJ for the latter.

Moreover, Table 6 revealed that CO_2 emissions of building materials are various. On top of that, steel emitted CO_2 the most, with 756 ton-CO_2. Meanwhile, CO_2 emissions of cement and sand are lower, with 102 ton-CO_2 and 96 ton-CO_2 correspondingly. In comparison with these materials, CO_2 emissions of the rest of building materials are not significant. Totally, there is 1019 tons of CO_2 emitted from the materials of the building. Figure 10 and 11 visualized the results.

It is recommended that to achieve the most accuracy results of calculation, we need to collect bill of quantities of building materials. Due to lack of data, we just calculated the quantity of building materials based on a representative building provided by Indonesian colleagues. Therefore, the calculation might be overestimated or underestimated. In order to validate the result of the study, we can compare it to previous studies. However, not many studies of embodied energy and CO_2 emissions of building materials are found in Indonesia. For example, Surahman (2015) conducted a study to analyze embodied energy and CO_2 emissions of building materials in Jakarta and Bandung. There are some major differences between his study and our research. First, his study mainly focused on landed houses. Secondly, due to lack of data, the system boundary in our study was limited in only raw material extraction phase while his system boundary was more comprehensive. Third, due to the fluctuation of material prices in the market, the material intensities, and energy intensities and CO_2 intensities has been changed significantly, leading to the different results. Finally, our study applied the Indonesia I-O table 2016, which is updated in comparison with his table (2005). Further studies with more accurate material data would be supplementary for our study.

3.3. Scenarios of tall timber apartment

This section proposed three different scenarios of building, after that, we made a comparison of EE and CO_2 emission of scenarios to evaluate their environmental impacts.

In scenario 1, we proposed a building using reinforced concrete structural components. The procedures of calculation are the same as previous section, therefore, we just discussed the main results of the scenarios 2 and 3.

In scenario 2, we proposed a building with reinforced concrete podium supporting mass-timber upper floors. Totally, there is 4129 m^3 of wood used. Among that, 2365 m^3 of CLT panels used for walls and 1544 m^3 of CLT panels for floors. Moreover, the floor panels are also supported by 153 m^3 of glulam columns. Volume of concrete needed to construct the podium, core and stairs of the building, is 555 m^3. Volume of gypsum boards, which are used to encapsulate CLT components from fire, is 547 m^3. Upper floors, thus, EE of wood is the highest with 744 GJ. Steel and gypsum ranked second and third with 117 GJ and 59 GJ correspondingly. The EE of other materials is not significant compared to three building materials mentioned above. Totally, EE of building materials in scenario 2 is 142 GJ lower than that of scenario 1. Similarly, in this scenario, woodstructural components contributed to 47 tons-CO_2 to the environment. The emissions emitted from steel and gypsum are lower, with 9 tons-CO_2 and 4 tons-CO_2 respectively. Aluminum is the least polluted material, with only 0.01 tons-CO_2. Totally, CO_2 emissions of building materials is 63 tons-CO_2, which is 17 ton-CO_2 lower than that of scenario 1.

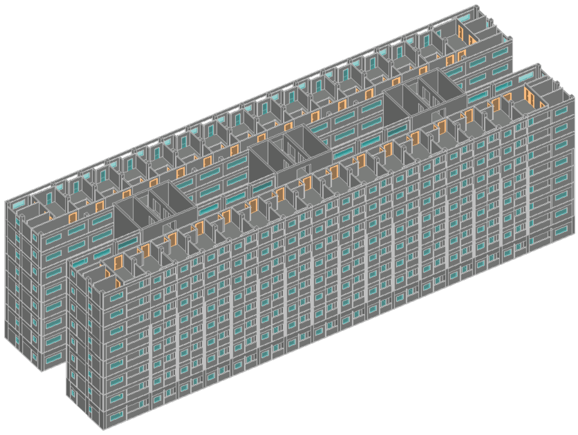

Figure 12. Building concept of scenario 1

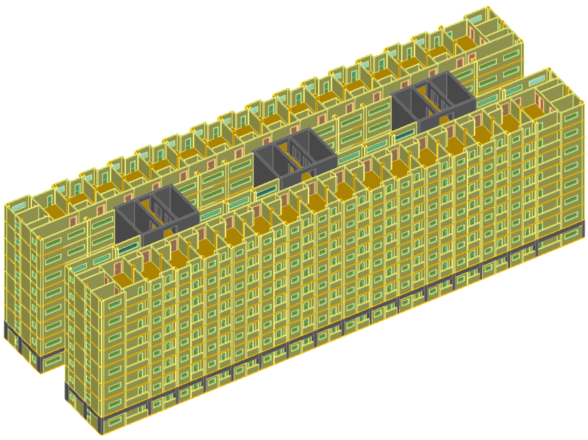

Figure 13. Building concept of scenario 2

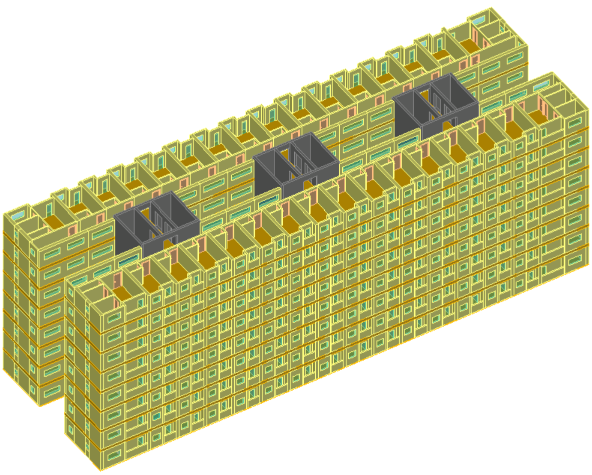

Figure 14. Building concept of scenario 3

Table 6. EE and CO_2 emissions of building materials in three scenarios

Scenario	1	2	3
Material	Reinforced concrete	Timber hybrid sytems	Timber panel systems
EE (GJ)	1110.46	968.26	904.77
CO_2 emissions (ton-CO_2)	80.73	63.38	58.35

In scenario 3, the building has reinforced concrete cores and stairs, while other components such as floors and walls use CLT panels without supporting columns. Totally, there is 4557 m^3 of wood used to construct the building, therein 2359 m^3 of CLT wall panels and 2132 m^3 of CLT floor panels. The total EE of building materials in scenario 3 is 905 GJ which is lowest among scenarios. Wood has the highest EE with 821 GJ, while that of steel is lower, with 50 GJ. Also, CO_2 emissions of wood are the highest with 52 tons-CO_2. It is followed by steel, with 4 tons-CO_2. The emissions from other building materials are not much, with less than 1 ton-CO_2 for each.

Table 7 indicates total EE and CO_2 emissions of building materials in three scenarios.

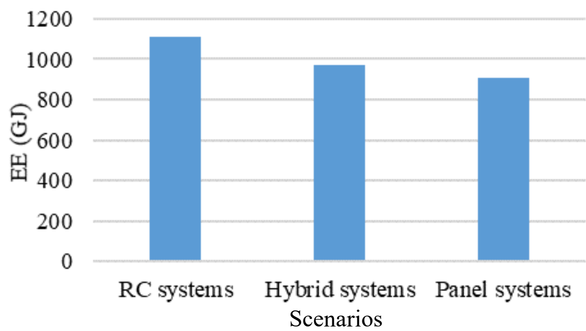

Figure 15. EE of three scenarios

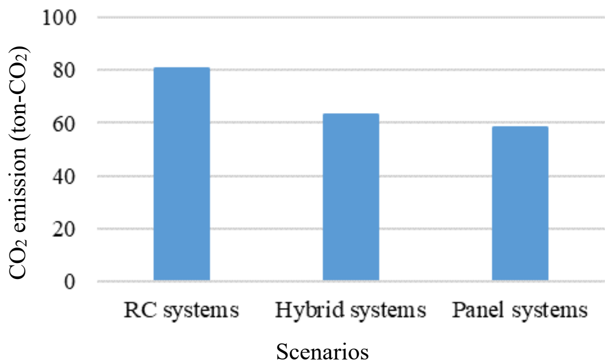

Figure 16. CO_2 emission of three scenarios

Because using building materials such as steel and concrete which intensively consume energy to produce, the building in scenario 1 has the highest

EE with 1110 GJ. It is followed by scenario 2 which uses timber hybrid systems with 968 GJ. In contrast, most structural components in the building in scenario 3 are composed of timber, therefore it has the least EE with 904 GJ. Also, the building in scenario 1 contributes CO_2 emissions to the atmosphere the most with 81 tons-CO_2. Scenario 2 ranks second with 18 tons-CO_2 lower than that of scenario 1, meanwhile, scenario 3 seems to be the most friendly environmentally with only 58 tons- CO_2 emitted. Figure 15 and 16 visually compare EE and CO_2 emisisons of the buidling in three scenarios respectively.

The results of scenario analysis show that by replacing wooden products in place of other energy-intensive materials, the total EE and CO2 emissions of building materials would reduce significantly. This substitution may provide a potential strategy to limit climate change caused by the construction industry. Nevertheless, it is argued that wood substitution also increases wood harvesting, and reduces the amount of carbon emissions absorbed and saved in trees, leading to a trade-off between carbon absorption and replacement [25]. In other words, this substitution would affect "carbon neutrality", which is the balance between the amount of sequestered carbon in carbon sinks and that of released carbon in the atmosphere [26]. Zero carbonization of construction materials is a promising technique to reach carbon neutrality targets in the building sector. Therefore, in order to clarify the benefits of wood substitution towards the environment, it is also important to study how to accurately estimate the carbon emissions in consideration of the carbon neutrality.

4. CONCLUSIONS

Standard designs represent the typical layouts of a building. They are normally developed by academic societies and can be used as a base model for various kinds of building simulations, especially in comparative scenario analysis, and therefore essential for any building standardizations such as low-carbon building standards. Most developed countries have their own standard designs, but there are few in developing countries. This research proposed a classification methodology which integrated qualitative and quantitative methods to analyze typical layouts of high-rise apartments in several major cities in Indonesia.

On the other hand, buildings are made of several different materials, and each one requires energy and emits emissions during the stages of production, usage, and demolition. Selecting construction materials that are energy-efficient can help promote environmental preservation. Thus, one of the first steps in protecting the environment is calculating the EE and emissions of construction materials. The assessment of EE and CO_2 emissions of construction materials has previously been conducted in a number of studies, most of which are from industrialized nations. In constrast, there is still a significant gap in the evaluation of the EE and CO_2 emissions of building materials in case of developing countries such as Indonesia. This study estimated EE and CO_2 emissions of building materials in Indonesia by using material inventory analysis and the I-O analysis method.

In this study, we also proposed a standard building model and applied different materials for each scenarios to compare their EE and CO2 emission. The results show that by replacing wooden products in place of other energy-intensive materials, the total EE and CO2 emissions of building materials would reduce significantly. This substitution may provide a potential strategy to limit climate change caused by the construction industry.

Due to lacking data, there are still limitations in our study. However, it is expected that this study would serve as a reference for reseachers in other countries with similarities in climatic, geographical and socio-economic conditions such as Vietnam.

REFERENCES

[1] F.I. Nugrahanti, T. Kubota, D. Larasati, A.R. Trihamdani, K. Morita, H. Inoue, *Low Carbon Affordable Apartments in Hot-Humid Climate of Indonesia: Design Concept of the Full-Scale Experimental House*, 192 (2020) 90–96.

[2] S. Bardhan, *Embodied energy analysis of multi storied residential buildings in urban India,* WIT Trans. Ecol. Environ. 143 (2011) 411-421.

[3] R. Azari, N. Abbasabadi, *Embodied energy of buildings: A review of data, methods, challenges, and research trends,* Energy Build. 168 (2018) 225–235.

[4] S. Kim, T. Mrozowski, N. Ehrlich, L. Hembroff, B. Lieburn, M. Mazor, A. Mcintyre, C. Mutton, G. Parsons, M.G. Syal, R. Wilkinson, *Housing Archetype Analysis for Home Energy-Efficient Retrofit in the Great Lakes Region*, (2014).

[5] X. chen Gui, Y. teng Ma, S. qin Chen, J. Ge, *The methodology of standard building*

selection for residential buildings in hot summer and cold winter zone of China based on architectural typology, J. Build. Eng. 18 (2018) 352–359.

[6] L. Industri, *Properti Komersial,* (2016).

[7] Y. Budisusanto, T. Aditya, R. Muryamto, LADM Implementation Prototype for 3D *Cadastre Information System of Multi-Level Apartment in Indonesia,* Proc. 5th L. Adm. Domain Model Work. (2013) 456–475.

[8] O. Kharchenko, No Title p, *Phys. Rev. E.* (2011).

[9] S. Tae, S. Shin, J. Woo, S. Roh, *The development of apartment house life cycle CO2 simple assessment system using standard apartment houses of South Korea,* Renew. Sustain. Energy Rev. 15 (2011) 1454–1467.

[10] L.F. Cabeza, C. Barreneche, L. Miró, M. Martínez, A.I. Fernández, D. Urge-Vorsatz, *Affordable construction towards sustainable buildings: Review on embodied energy in building materials,* Curr. Opin. Environ. Sustain. 5 (2013) 229–236.

[11] H. Wallbaum, Y. Ostermeyer, C. Salzer, E. Zea Escamilla, *Indicator based sustainability assessment tool for affordable housing construction technologies,* Ecol. Indic. 18 (2012) 353–364.

[12] W.Z. Taffese, K.A. Abegaz, *Embodied energy and CO2 emissions of widely used building materials: The Ethiopian context*, Buildings. 9 (2019) 1–15.

[13] E.I. Wiloso, N. Nazir, J. Hanafi, K. Siregar, S.S. Harsono, A.A.R. Setiawan, Muryanto, M. Romli, N.A. Utama, B. Shantiko, J. Jupesta, T.H.A. Utomo, A.A. Sari, S.Y. Saputra, K. Fang, Life cycle assessment research and application in Indonesia, *Int. J. Life Cycle Assess.* 24 (2019) 386–396.

[14] A. Utama, S.H. Gheewala, *Life cycle energy of single landed houses in Indonesia*, Energy Build. 40 (2008) 1911–1916.

[15] U. Surahman, T. Kubota, O. Higashi, *Life cycle assessment of energy and CO2 emissions for residential buildings in Jakarta and Bandung,* Indonesia, Buildings. 5 (2015) 1131–1155.

[16] L. Tupenaite, V. Zilenaite, L. Kanapeckiene, T. Gecys, I. Geipele, *Sustainability assessment of modern high-rise timber buildings,* Sustain. 13 (2021) 1–22.

[17] J. Li, B. Rismanchi, T. Ngo, *Feasibility study to estimate the environmental benefits of utilising timber to construct high-rise buildings in Australia,* Build. Environ. 147 (2019) 108–120.

[18] D.J. Bartholomew, Principal components analysis, *Int. Encycl. Educ.* (2010) 374–377.

[19] A. Säynäjoki, J. Heinonen, J.M. Junnonen, S. Junnila*, Input–output and process LCAs in the building sector: are the results compatible with each other,* Carbon Manag. 8 (2017) 155–166.

[20] Y. Budisusanto, T. Aditya, R. Muryamto, LADM Implementation Prototype for 3D *Cadastre Information System of Multi-Level Apartment in Indonesia,* Proc. 5th L. Adm. Domain Model Work. (2013) 456–475.

[21] U.U.N. 24, No Title, *Rev. Bras. Ergon*. 9 (2007) 10.

[22] R. Indonesia, *Peraturan Pemerintah Republik Indonesia Nomor 36 Tahun 2005 Tentang Pelaksanaan Undang-Undang No.28 Tahun 2002 Tentang Bangunan Gedung.,* (2005).

[23] Forestry Innovation Investment, Brock Commons Tallwood House, Nat. Wood. (2017).

[24] IBA Hamburg GmbH, *Smart Material House WOODCUBE,* (2014) 26.

[25] T. Helin, L. Sokka, S. Soimakallio, K. Pingoud, T. Pajula, *Approaches for inclusion of forest carbon cycle in life cycle assessment - A review, GCB Bioenergy*. 5 (2013) 475–486.

[26] X. Wu, Z. Tian, J. Guo, *A review of the theoretical research and practical progress of carbon neutrality,* Sustain. Oper. Comput. 3 (2022) 54–66.