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The hybrid cycle of facade in ec building UI to achieve building circularity

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ABSTRACT

The construction sector has the potential to improve its sustainability through the application of circular economy principles, which primarily emphasize two cycles: replacing conventional materials with biological alternatives and enhancing the recycling of technical materials. This study aims to analyze the current facade design of the Engineering Center (EC) Building at Universitas Indonesia (UI) as an initial study to explore Alternative Design (AD) with a hybrid approach of biological and technical cycles. This study's method mixes Building Circularity Calculation (BCC) and incorporates Material Passport (MP) and Material Flow Analysis (MFA). The study emphasized that utilizing mycelium brick (predominantly a biological material, comprising 63%) has outstanding potential to achieve building circularity implementation in the EC Building facade. The finding highlights a hybrid design strategy, incorporating a significant proportion of biological materials, could be a promising pathway for implementing building circularity in the EC Building. Biological materials are generally causing less environmental impact compared to technical materials, yet further mitigation strategies are required due to their shorter lifespan. To build based on these findings, exploring a wider range of building components and other possible variants of hybrid designs are recommended in future research.

Introduction

The economic system in the traditional model focuses on high consumption rates with the basic steps of raw materials-design-production-distribution-consumption-waste (Dongez, Manisa, and Basdogan 2021). A linear economy has major problems in the excessive use of resources resulting in high waste generation. The impact on the environment is not a priority to be considered in a linear economy (Dongez, Manisa, and Basdogan 2021). A linear economy has a system of take - make - dispose of caused by the supply of materials having a lower cost when compared to costs or wages for human labor, so that the use of materials is carried out extensively (Sariatli 2017). The building industry consumes a large amount of energy and resources and is responsible for over 40% of material use, 33% of greenhouse gas emissions, and 40% of all solid waste (Ness and Xing 2017). This is primarily due to the linear resource consumption paradigm, "take-make-consume-dispose," also known as the cradle to grave approach (Esa, Halog, and Rigamonti 2017). A step toward a more environmentally friendly approach may be taken through a Circular Economy (CE). In this regard, the concept of CE is primarily supported by the

EU and China, and it has gained more attention since the Ellen MacArthur Foundation (EMF) was founded in 2010. The Circular Economy theory is based on the principle of optimizing the use of resources, reducing waste, making goods and products last throughout their life cycles, and creating economic opportunities throughout the process of using them (Tirado et al. 2022). Geissdoerfer et al. (2017) define CE as "a regenerative system in which resource input and waste, emission, and energy leakage are minimized by slowing, narrowing, and closing material and energy loops," where slowing loops refers to extending the useful life of a product, narrowing loops refers to reducing resource use or achieving resource efficiency, and closing loops refers to recycling materials from the end-of-life back to production (Bocken et al. 2016). Consequently, a significant number of researchers are investigating the application of CE principles within various sectors of the building industry. By advocating building circularity, this approach promotes a sustainable, circular loop system that maximizes material value retention, significantly minimizing waste and controlling resource consumption.

As a result, there are abundant possibilities for designing circular components, yet often, both practice and policy tend to focus on one approach rather than exploring multiple options. For instance, a circular design team might create a biological design or a building component with a modular structure that can be upgraded and reused (a biological circular solution). One may consider both designs to be circular, one of which represents the biological flows and the other the technical flows. Circular performance will most consistently be produced when biological and technical components are used in a deliberate, reversible, hybrid application (Jansen et al. 2022).

Most previous studies regarding facade in tropical countries have limited on finding its thermal use (Majid and Ghazali 2021; Dewi et al. 2022). Facades is significant contributors to the embodied energy. Larasati et al. (2023) has explored the various types of facade materials in Indonesia, which found that precast concrete materials of 120mm and 150mm have EE gas emission twice of average. However, the study limited to the facade material variant. Further research regarding the biological and technical aspects has not been explored. This study aims to fill the gap by propose initial design exploration by applying a hybrid cycle of biological and technical components in Indonesia. To achieve this objective, this study will compare three different design alternatives. The alternative design facade will be integrated in a case study building in Indonesia. It is expected that the results of this study will be useful in recommending the circular building facade.

Methods

Location and climate conditions

Engineering Center (EC) building, an Universitas Indonesia's educational building located in Depok City, West Java, Indonesia (6° 21 '44.63 south and longitude of 106° 49' 30.51), is one of the buildings at the Faculty of Engineering used for studio classrooms, office, and cafe. EC is a suitable building to implement the hybrid system of facades. The building has been used for more than five years and is planned for a retrofit. The second skin facade of EC building currently uses 100% technical materials, which are aluminum as fin for sun shading and steel as the frame of the building's secondary skin. The facade system of the EC building can be seen in figure 1. The total ground floor area of the EC building is 2,424.46 m^2.

Figure 1. Engineering Center façade

Data collection

Data from literature is used to complete all the data needed for this research, the collection data are shown in table 1.

Table 1. Literature study of building materials

Author	Building materials	Material characterization	Findings
Passarini, et al. 2018	Metals	Technical	Circularity feature
Davis 1998	Metals	Technical	Density

Author	Building materials	Material characterization	Findings
Cooper, et al. 2014	Steel	Technical	Lifespan
González and Navarro 2006	Steel	Technical	Circularity feature
Kasparova 2021	Stainless steel	Technical	Circularity feature
Jindra, et al. 2022	Stainless steel	Technical	Lifespan
Cooper et al. 2013	Aluminium	Technical	Lifespan
Sung 2016	Thermo-bimetals	Technical	Lifespan
Kanthal 2008	Thermo-bimetals	Technical	Density
Ekolu 2020	Concrete	Technical	Lifespan
Jain and Bhadauria 2019	Concrete	Technical	Density
Marsh, et al. 2022	Concrete	Technical	Circularity feature
Hammond and Jones, 2008	Concrete	Technical	Circularity feature
Manandhar, et al. 2019	Bamboo	Biological	Lifespan
Rusch et al. 2019	Bamboo	Biological	Density
Stijn et al. 2022	Bamboo	Biological	Circularity feature
Girometta 2019	Mycelium brick	Biological	Circularity feature
Ross 2014	Mycelium brick	Biological	Lifespan
Xing et al. 2018	Mycelium brick	Biological	Density

Data analysis

Data analysis developed in this study consists of two parts: Material Volume Calculation and Building Circulation Calculation (BCC). The Material Volume Calculation is used to determine the dimensions, volume, and weight of the material based on the quantity of parts from the material data. The results of this calculation then utilized in the BCC. To calculate the volume of the material, all the dimensions of the parts are multiplied by the quantity of parts. Subsequently, the volume is multiplied by the material's density to obtain the weight of the material used.

Material volume calculation of existing and proposed facade designs in engineering center building

Material Volume is a calculation used to find the dimensions, volume, and weight of the material with the quantity of parts from material data. This calculation used to determine biological or technical materials by specifying their relative volume (V), weight (W), and relative mass (RM) within the variants (Jansen et al. 2022). The results of the material volume calculation will be used in the BC Calculation. The calculation of the volume of material is by multiplying all the dimensions of the parts by the quantity of parts. Then, the volume is multiplied by the density of the material to get the weight of the material used.

$$V = CS \times T \times L \times QOP \quad (1)$$
$$W = V \times D \quad (2)$$

CS represents the cross-sectional area of the material in meters, providing insight into its shape when viewed from one end. The variable T denotes the thickness of the material in meters, while L stands for its length. The term QOP refers to the quantity of parts, indicating how many individual sections or pieces are considered shown in Equation (1). For calculates the weight (W) of a material is calculated in Equation (2). The weight is measured in kilograms (kg). In this formula, V represents the volume of the material, which is measured in cubic meters (m^3). On the other hand, D denotes the density of the material, which shows how much mass exists in a specific volume. The density is expressed in kilograms per cubic meter (kg/m^3). The Relative Mass (RM) of a component is calculated in *equation* (3),

$$RM = W : TW \quad (3)$$

Where RM, expressed as a percentage, is Relative Mass, a component in relation to the entire system or object. The weight of the specific component is represented by W in kilograms, while TW indicates the total weight of the whole system or object, also measured in kilograms. By dividing the component's weight (W) by the system's total weight (TW), we can determine the component's significance or contribution to the overall mass of the system.

Building Circularity Calculation (BCC) of existing and Proposed facade designs in engineering center building

The Building Circularity Calculation (BCC) for the Engineering Center Building evaluates the sustainability and circularity of facade materials (Zhang, Han, and de Vries 2021). It gathers data on current and proposed designs by looking at material type, lifespan, recyclability, and energy consumption.

The Total Embodied Energy (TEEn) represents the sum of the energy consumed during the production and processing of each material used in a product or construction. In the formula $\sum$TEEn = EEn Mn1 + EEn Mn2 + EEn M3 + ..., each term like EEn Mn1 stands for the embodied energy of Material 1, EEn Mn2 represents the embodied energy of Material 2, and so on. These embodied energy values are measured in megajoules per kilogram (MJ/kg) and calculated in *equation* (4).

$$\sum \text{TEEn} = \text{EEn M (1)} + \text{EEn (2)} + \text{EEn M (3)} + \ldots \quad (4)$$

The Efficiency of Recycle Process (ERP) in kilograms is derived by multiplying the Circularity Feature Material (CFM), with the weight (W) of the material. In Equation (5) terms, it gives a quantitative measure of how efficiently a particular material can be recycled, considering the circularity features of the material. On the other hand, to understand this efficiency in relative terms or percentage, the Efficiency of Recycle Process is divided by the Total Weight (TW) of all the materials under consideration. This percentage value provides a comparative perspective, showing the proportion of the material's weight contributing to its recycling efficiency shown in Equation (6). The higher the percentage, the more efficiently that material can be recycled to its total weight.

$$\text{ERP (kg)} = \text{CFM X W} \quad (5)$$
$$\text{ERP (\%)} = \text{ERP (kg) : TW} \quad (6)$$

BCC is calculated using collated data, giving a quantifiable measure of the facade's circularity. Based on these findings, informed recommendations are made, suggesting design alterations or alternative materials for outstanding potential to achieve the concept of building circularity.

Results and discussion

In the quest to enhance the sustainability and efficiency of the Engineering Center, our study presents three innovative alternative designs (AD) for its second skin facade, each incorporating a unique blend of biological and technical materials aligned with the concept of building circularity.

Figure 2. AD 1 of Engineering Center (EC) Building

Figure 3. AD 2 of Engineering Center (EC) building

Figure 4. AD 3 of Engineering Center (EC) building

AD 1 (figure 2) utilizes biological materials, comprising 60%. The key component is a rotatable, vertically pressed bamboo panel that functions as an active shading system. Bamboo, known for its rapid growth and biodegradable properties, offers a renewable solution that seamlessly returns to nature as biological nutrients. This design emphasizes the use of natural materials to achieve energy efficiency, particularly in reducing the need for artificial cooling through its natural shading capabilities.

Conversely, AD 2 (figure 3) leans more towards technical materials, making up 78% of its structure. It features a sophisticated 'Breathable Architecture' system, utilizing thermo-bimetals materials combined with stainless steel frames. This intelligent system autonomously adjusts to environmental temperature variations, providing an energy-efficient method of controlling sunlight penetration. Additionally, it incorporates a rainwater collection system, enhancing the building's sustainability profile. This design stands out for its self-regulating capability, reducing reliance on external energy sources for building temperature control.

Lastly, AD 3 (figure 4) introduces a balance with 63.32% biological material, primarily using mycelium bricks. These bricks are not only biodegradable but also compostable after their lifespan, marking a significant stride towards the environment. The design is complemented with 36.68% technical materials, including steel frames and concrete, to ensure structural integrity. Unique to this design are manually rotatable steel panels that facilitate easy maintenance while also incorporating a rainwater harvesting system. Each of these designs demonstrates a distinct approach to integrating sustainability within architectural design. Material volume calculation from existing AD 1, 2 and 3 is calculated on table 2 to find the dimensions, volume, and weight of the material with the quantity of parts from material data. The results of the material volume calculation will be used in the building circularity calculation.

Table 2. Overview of the material volume of existing, AD 1, 2 and 3

Material	**Cross Ssection (CS) (m)**	**Thickness (T) (m)**	**Long (L) (m)**	**Quantity of parts (QOP)**	**Volume (V) (m^3)**	**Density (kg/ m^3)**	**Weight (W) (kg)**
a	**b**	**c**	**d**	**e**	**(b x c x d x e)**	**f**	**(b x c x d x e) x f**
Existing							
Aluminum	0.56	0.0016	95.2	18	1.5	2,710 (4)	4,160
Steel	028	0.0020	7.6	51	0.2	7,900 (4)	1,715
AD 1							
Pressed bamboo board	0.90	0.0200	3.8	136	9.3	800 (5)	7,442
Stainless steel	0.24	0.0012	62.4	34	0.6	8,010 (4)	4,902
AD 2							
Thermo-bimetals		0.0005		224	0.1	8,200 (2)	833
Stainless steel	0.24	0.0020	45.76	56	1.2	8,010 (4)	9,853
Mycelium brick	0.363	0.1700	0.38	234	5.5	552 (1)	3,029
AD 3							
Mycelium brick	0.10	0.0500	0.20	2,6928	26.9	552 (1)	14,864
Stainless steel	0.24	0.0016	15.42	102	0.6	8,010 (4)	4,841
Concrete	0.10	0.0100	0.05	5,3856	2.7	1,400 (3)	3,770

Source: (Xing et al. 2018) (1); (Kanthal 2008) (2); (Jain, Hindoriya, and Bhadauria 2019) (3); (Davis 1998) (4); (Rusch et al. 2019) (5)

After material volume, table 3 developed circularity of building component. This analysis will be used as the basis of building circularity calculation in this research. The data of seven materials used in the second skin design was collected. There are six points of the collected data; those are the characteristics of materials (biological/technical), renewability, strategy of circularity , environmental impact of embodied energy, and lifespan.

Table 3. Overview of the developed circular building components of existing and propose design

Material	Characterization	Renewability	Strategy of circularity	Circularity feature (%)	Embodied energy (EEn) (MJ/kg)	Lifespan (year)
Existing						
Aluminum	Technical	No (1)	Collected for recycling (1)	69 (1)	191 (6)	40 (9)
Propose						
Thermo-bimetals	Technical	No (10)	Collected for recycling (10)	75 (10)	109.1 (10)	35 (10)
Stainless steel	Technical	No (11)	High durability, energy-intensive to recycle (11)	85 (8)	56.7 (5)	50 (11)
Pressed bamboo board	Biological	Yes (2)	Fast growth, renewable, biodegradable (2)	100 (2)	59.9 (12)	3 (12)
Steel	Technical	No (13)	Collected for recycling (13)	75 (6)	32 (6)	35 (13)
Concrete	Technical	No (14)	Crushed for road base (3)	95 (5)	2 (5)	60 (14)
Mycelium brick	Biological	Yes (7)	Low energy, biodegradable (7)	100 (7)	29,3 (15)	20 (15)

Source: (Passarini et al. 2018) (1); (van Stijn et al. 2022) (2); (Marsh, Velenturf, and Bernal 2022) (3); (Girometta et al. 2019) (4); (Hammond and Jones 2008) (5); (González and García Navarro 2006) (6); (Girometta et al. 2019) (7); (Kasparova 2021) (8); (Cooper et al. 2014) (9); (Sung 2016) (10); (Jindra, Kala, and Kala 2022) (11); (Manandhar, Kim, and Kim 2019) (12); (Cooper et al. 2014) (13); (Ekolu 2020) (14); (Ross 2014) (15)

Building Circularity Calculation (BCC) of the existing and proposed material facade in Engineering Center Building will become the bridge between all the data collected in this research and the conclusion. The building circularity calculation will show the potential of existing and purpose material of the facade (table 4). Their potential is rated using a color-coded system: green indicates very high potential, orange signifies high potential, blue represents medium potential, and red denotes low potential.

Table 4. Building circularity calculation of existing, AD 1, 2 and 3

Material	Characterization	Lifespan	Weight (W)	Relative mass (RM)	Environmental impact	Efficiency of recycle process			
					Embodied energy (EEn)	Recycle material (ERP)		Discarded material	
		(year)	(kg)	(%)	(MJ)	(kg)	(%)	(kg)	(%)
Existing									
Aluminum	Technical	40	4,160.89	71	794,730.94	2,871.02	48.86	1,299.88	22
Steel	Technical	35	1,714.74	29	54,871.76	1,286.06	21.89	428.69	7.26
Total			**5,875.64**	**100**	**849,602.70**	**4.157.07**	**70.75**	**1,718.56**	**29.26**
AD 1									
Pressed bamboo board	Biological	30	7,442.92	60	445,771.01	7,441.92	60.29	-	-
Stainless steel	Technical	30	4,901.81	40	277,932.42	4,166.54	33.75	735.27	5.96

Material	Characterization	Lifespan (year)	Weight (W) (kg)	Relative mass (RM) (%)	Environmental impact: Embodied energy (EEn) (MJ)	Efficiency of recycle process: Recycle material (ERP) (kg)	Recycle material (ERP) (%)	Discarded material (kg)	Discarded material (%)
Total			**12,343.73**	**100**	**723,703.42**	**11,608.46**	**94.04**	**735.27**	**5.96**
AD 2									
Thermo-bimetals	Technical	35	833.01	6	90,881.48	624.76	4.6	208	1.52
Stainless steel	Technical	50	9,852.53	72	558,638.49	8,374.65	61.06	1,477	10.78
Mycelium brick	Biological	20	3,028.96	22	88,749.64	3.028.96	22.09	-	-
Total			**13,714.51**	**100**	**738,268.61**	**12,028.37**	**87.71**	**1,686.13**	**12.29**
AD 3									
Mycelium brick	Biological	20	14,864.26	63.32	435,522.70	14,864	63.32	-	-
Stainless steel	Technical	50	4,840.63	20.62	274,463.60	4,114	17.53	726.09	3.09
Concrete	Technical	60	3,769.92	16.05	7,539.84	3,581	15.26	188.50	0.80
Total			**8,610.55**	**100**	**717,526.14**	**22,560**	**96.10**	**914.59**	**3.90**

In the existing case, Aluminum and Steel are used, constituting the entire weight composition. Aluminum, with a higher relative mass, significantly influences the environmental impact. Both materials exhibit moderate recycling efficiency, but Aluminum boasts a longer lifespan of 40 years, compared to Steel's 35 years.

AD 1 introduces Pressed Bamboo Board and Stainless Steel, with bamboo accounting for 60% of the weight. This design shows a significant increase in the proportion of biological material, which may imply a lower environmental impact compared to the existing materials that only use technical material.

AD 2 combines Thermo-bimetals, Stainless Steel, and Mycelium Brick. Here, the emphasis shifts towards a higher proportion of technical materials (78%), with stainless steel dominating the composition. Mycelium Brick, a biological material, contributes to 22% of the weight.

Lastly, AD 3 employs Mycelium Brick, Stainless Steel, and Concrete. Mycelium Brick forms most of the weight, indicating a strong preference for biological materials and shows the lowest environmental impact in terms of embodied energy. This composition possibly offers an enhanced environmental profile. Lifespans vary widely, with Mycelium and Steel lasting 20 and 50 years, respectively, and Concrete extending up to 60 years.

Table 5. Resume of the developed circular building components of existing and propose design

Cases (RM bio/tech (%))	System implementation	TEEn (MJ/kg)	ERP (%)	Discarded materials (%)	Lifespan (year)
Existing (100 tech)	-	849,6K	70.74	29.26	35 - 40
AD 1 (60/40)	-	723,7K	94.04	5.96	30 – 50
AD 2 (22/78)	Rainwater Harvesting + Responsive Facade	738,2K	87.71	12.29	20 – 50
AD 3 (63.32/ 36.68)	Rainwater Harvesting	717,5K	96.10	3.90	20 - 60

The result based on table 5, reveals that AD 3, employing Mycelium Brick, demonstrates a high potential for recycling process efficiency and minimizing environmental impact, particularly in terms of embodied energy. This design suggests a balance between technical material which is used for long-lasting structure that combines a lean and durable design that used with biological components (Malabi Eberhardt et al. 2021). This design will expand the lifespans ranging from 20 to 60 years.

AD 1 has high potential focusing on Pressed Bamboo Board, shows significant promise in environment impact and recycling process efficiency. This studies in line with (Manandhar, Kim, and Kim 2019) that demonstrated using bamboo in construction, promotes sustainable building practices, as bamboo offers numerous environmental benefits that can encourage its adoption. AD 2 offers medium potential for extra features in terms of system implementation.

Comparatively, the existing facade design, which utilizes Aluminum and Steel, exhibits the lowest potential for circularity within the Engineering Center framework. These insights provide valuable guidance for architects and building engineers in integrating circularity principles into building designs, highlighting the importance of material selection and environmental considerations.

Conclusions

The building sectors are responsible for significant amount material usage globally. The study has developed hybrid design alternative to achieve circularity in building with a case study of EC Building, located in Universitas Indonesia. This study aims to fill the gap by proposing initial design exploration through a hybrid cycle of biological and technical components application. Three design alternatives are proposed with various proportions and materials in this research. Existing facade design and the proposed design alternatives are also calculated using building circularity calculation to identify which facade design will effectively implement the concept of building circularity. Three alternative designs have been compared to the existing regarding to its circularity aspects (TEEn, ERP, discard materials and lifespan). This study concludes that an AD 3 utilizing mycelium brick as the primary material emerges as the high potential hybrid design for the EC building's facade, displaying very high potential performance in building circularity calculation compared to the existing and other proposed designs. This result shows that biological material improves the circularity aspect of EC building's façade (Jansen et al. 2022; Manandhar, Kim, and Kim 2019). This study recommends that using approach to reduce environmental impacts immediately while avoiding significant lifespan reduction. This can be achieved by using biological materials wherever possible and technical materials when necessary, such as long-lasting structure (Malabi Eberhardt et al. 2021).

However, the research acknowledges its limitations due to the time and resource constraints and therefore suggests further investigation. To validate the findings and enhance applicability, actual experiments on the design alternative within the EC building are recommended to gather actual data on environmental impact, circularity features, and lifespan. Additionally, while this research mainly focused on facade materials within the EC building, further research could explore a wider range of building components and other possible variants of hybrid designs.

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Kwarista Dharma Smitha contributed to the research concepts preparation, methodologies, investigations, data analysis, visualization, articles drafting and revisions.

Ova Candra Dewi contributed to the research. concepts preparation and literature reviews, data analysis, of article drafts preparation and validation.

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