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# Material circularity indicator for accelerating low-carbon circular economy in Thailand's building and construction sector

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## Abstract

Thailand's steady growth of urban areas and industrial estates, the construction sector needs to adopt a low-carbon circular economy (CE) model that emphasizes material circularity and resource efficiency. This research aims to measure the low-carbon CE of the construction industry through significant representative products, life cycle assessment and material circularity indicator (MCI) were measured on significant representative products materials were evaluated. In the results of the study, it was found that the MCI and GHGs revealed the following results: 1 ton of construction steel products = 0.73 and 2.32 $kgCO_2$/ton, 1 bag (50 kg) of mortar and cement products = 0.17 and 16.92 $kgCO_2$/bag, 1 $m^3$ of ready-mixed concrete at compressive strength 240 kilograms per square centimeter = 0.11 and 253.63 $kgCO_2/m^3$, 1 $m^3$ of wood and composite wood products = 0.17 and 745.84 $kgCO_2$/bag, also 1 $m^2K/W$ (meters squared Kelvin per Watt) of glass wool insulation = 0.50 and 1.63 $kgCO_2/m^2K/W$, respectively. These values are indicated as national baselines for monitoring CE performance that contribute to the industry's long-term viability and turn to sustainability in Thailand through the key strategic issues in Thailand's CE and low-carbon society. The GHGs reduction of 11 million tons is expected, which can also increase the 10% of material circularity, also the estimation of the economic value, by considering the value added from material reduction and the price of carbon credit from construction and demolition waste reduction affect the Thai construction industry by approximately 67 million dollars.

KEYWORDS

circular economy (CE), construction, GHG emissions, material circularity, MCI

## 1 | INTRODUCTION

Construction is one of the businesses that consume huge quantities of natural resources. According to the Global Material Resources of OECD, the usage of construction materials such as sand, gravel, limestone, and crushed stone is expected to quadruple to roughly 69 gigatons in 2060. Furthermore, metal consumption is expected to rise from 8 gigatons in 2017 to 19 gigatons in 2060.[1] From the projections, the industry segment will double in size in the future. In comparison to 2017, urbanization is a major contributor. As reported by UN World Urbanization forecasts, the share of worldwide urbanization in 2016 was 54.38 percent, compared with rural areas, because of the exponential increase in urban people since 1950. During 2009–2019, the total investment in construction accounted for an average of 8.1% of the Gross Domestic Product (GDP). In Thailand, most of the domestic construction, namely public and private construction with the proportion of investment value at 56:44 in 2019. It was found that the total investment in construction in 2019–2021 will grow by 3.5% - 5.0%, 5.0–7.0%, and 7.5–9.5%, with public construction projects tending to expand at an accelerated rate in 2020 and 2021.[2] The aforementioned factors are the reasons why the construction industry in Thailand is needed to transition to a circular economy (CE) model. There are still problems with garbage and waste.

The CE, guided by the Ellen MacArthur Foundation, is an economic and industrial model that considers the use of natural resources in the most efficient system. To achieve a balance between humans and nature and solve the problem of waste management. The CE differs from the linear economy, which is the straight-line economy that does not consider reuse. Production using new materials derived from nature, consumption, and disposal causing a large amount of waste creates interdependence during economic development with the use of limited natural resources. A linear economy cannot work in the long run and pointing out that resource use is reaching its limit.[3] A comprehensive consideration of the CE in the construction industry requires consideration throughout the construction lifecycle, from design, production of raw materials used, construction, and use, to end-of-use and scrap disposal. Every step mentioned it is important to understand which stakeholders are involved in each step. To drive the CE, the construction industry must be supported in the transition to circularity. A CE is a systematic approach to improving a product's overall sustainability. To achieve maximal circularity, methods to improve product life and material turnover are included. To support Thailand's construction industry's transition to a CE through the construction life cycle aspect, assessments, and indicators, it is critical to investigate the ability to measure and monitor that Thailand's construction industry has accelerated the transition to a CE. The indicators suitable for the construction industry use the concept of selecting various indicators that are currently available.[4] From the selection of indicators, the researchers selected existing indicators to be studied as follows: Reuse Potential Indicator,[5] Material Circularity Indicator (MCI),[6] Longevity Indicator (resource duration) ([7,8]), and Material Reutilization Score (C2C certification framework).[9]

This research aims to evaluate the efficiency of the CE is measured through a circularity indicator. To be able to continuously monitor and improve the national CE baseline in building materials to present the potential of CE transformation in Thailand's construction for a real transition to a CE society. The article is structured as follows. In Section 2 Thailand's action plan for CE transition in the construction sector and the challenges that have been implemented are introduced. Section 3 presents the methodologies for measuring the low-carbon CE and Section 4 covers the research results and discussion along with the CE scenarios of representative materials, material circularity, and GHGs are presented. Section 5 concludes the article and summarizes the research results.

## 2 | CIRCULAR ECONOMY TRANSITION IN THE CONSTRUCTION SECTOR

Construction material is one of the industries consuming resources extensively and causes harmful environmental impacts. Although the value creation and employment related to this industry are high, the environmental impact must be minimized by applying the CE model at all stages from design and planning until construction to ensure better construction practices, which cause fewer pollution problems. The construction material industry can potentially be an eco-friendly industry in Thailand.

### 2.1 | Thailand's action plan for circular economy transition

*A CE can be integrated into the construction material industry through a main driving force of innovation and technology to create tangible success cases or champions, which can be used as a role model for multiplication toward sustainable development*. Figure 1 shows the results of an action plan for the construction material industry to develop innovation and technology to support eco-friendly construction practices, which was one of the outputs of the Bio-Circular-Green Economy in action.

Driving CE in the construction material industry. The goal of the driven mechanism is divided into three phases as follows:

- **Short-term** (1–2 years) Develop data/digital infrastructure for construction material, proven circularity scenario viability, develop networks to engage stakeholders, support the development of eco-friendly innovation and technology for construction materials and practices, proven circularity scenario viability.
- **Medium-term** (3–5 years) Support modular construction for Governmental Projects to reduce waste and pollution problems. Set up the Sandbox to support modular construction for Governmental Projects on the budgeting, tax benefits, and building permits.
- **Long-term** (beyond 5 years) Support the sustainable urbanization structure and the CE lifestyle and built environment or sharing economy.

The expected outputs of circular construction development consist of the innovation and technology for eco-friendly construction that will be developed. Resource consumption efficiency will be increased. Then, the GHG emission and climate change problem will be mitigated.

### 2.2 | Challenges in transformation to a sustainable circular economy

The construction industry is a ‘resource-intensive’ one that also generates construction and demolition waste (CDW), accounting for

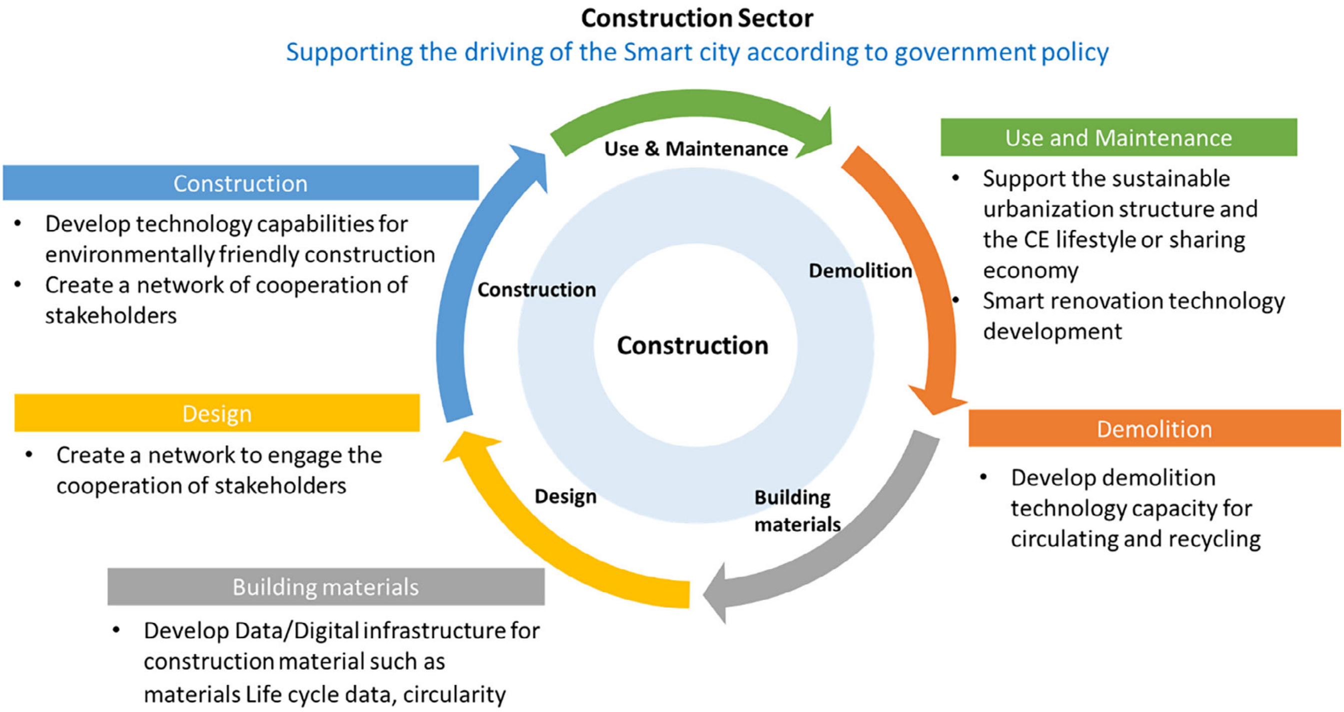



**FIGURE 1** Action plan for circular economy in the construction materials industry.

30%–40% of the waste in landfill systems worldwide. Challenges in the construction industry are associated with growth in the gross domestic product, meanwhile, the massive expansion of natural resource consumption and waste that occurs in this industry through the supply chain and building and construction sector is responsible for 38% of global $CO_2$ emission.[10] A study on the Resolved Multi-regional input–output (R-MRIO) database,[11] in 2015 found that the construction sector is one of the key sectors of the economy that consumes the most materials around 36%, and the second major contribution to GHG accounting for 16% of national emissions. As results shown that Figure 2, Thailand's consumption-based GHG emission footprint in 2015 is shown where those embodied in domestic products and imported goods are separated. From the chart, the largest share of more than 50 million tons $CO_2$eq. Other prominent sectors were the construction sector, the electrical and machinery sector, and the education, health, and other services sector; each had created around 30–40 million tons of $CO_2$eq in 2015.

In Figure 3, a Sankey diagram is plotted to trace the material footprint embodied in imports. The result shows that around one-third of the footprint in 2015 originated in China. Most of it was caused by acquiring electricity and various raw material, especially metal to manufacture electrical appliances, machinery, and construction products, then exported to Thailand.

The challenges of creating sustainability in the construction industry are related to the growth of the country's gross domestic product, the management of the resource, and the management of waste that occurred in the construction industry throughout the supply chain starting from the acquisition of raw materials used in construction, design and planning, construction process, waste management, and the reuse of the remaining materials with the highest efficiency. Accordingly, the management of this waste in Thailand is inefficient while construction waste continues to increase because of the growth in infrastructure construction. In this regard, the development of a CE will help improve resource decoupling of the construction, as well as increase recycling, both in quantity and quality, in the future.

Apart from high resource utilization, CDW accounts for 30%–40% of waste in landfills systems worldwide.[4] This group of waste usually consists of large or heavy materials, such as concrete and wood from buildings, asphalt from roads and roof components, gypsum (main drywall component), metal, bricks, glass, plastic, demolition building materials (doors, windows, internal connection equipment), as well as stumps, trees, and stones that caused by site preparation for Thailand's construction. Furthermore, CDW is also classified as municipal solid waste (MSW).[12] It was found that 70% of waste generated from construction and demolition was concrete, followed by brick, steel, ceramic, and tile.

According to the mentioned problems, both the overuse of resources and the CDW for the development of a sustainable construction industry in Thailand should adopt the efficient “close-the-loop” guideline starting from the production of building materials, construction, and demolition, as well as increased management for the companies by designing, buying, and producing materials and energy for the construction. The application of CE, therefore, is used to design and create a building construction or refurbishment is required to take into account of environment and utilization of resources.

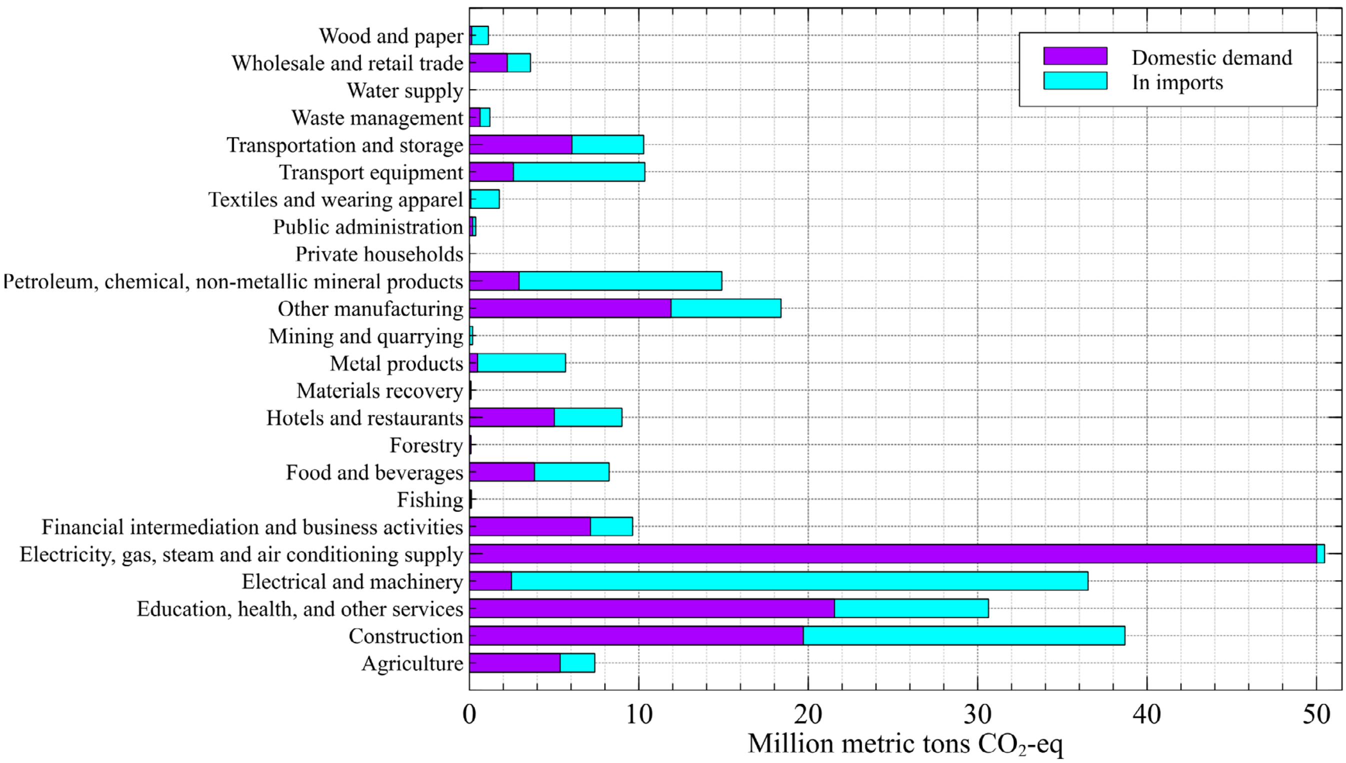



**FIGURE 2** Thailand's consumption-based GHG emission footprint in 2015.

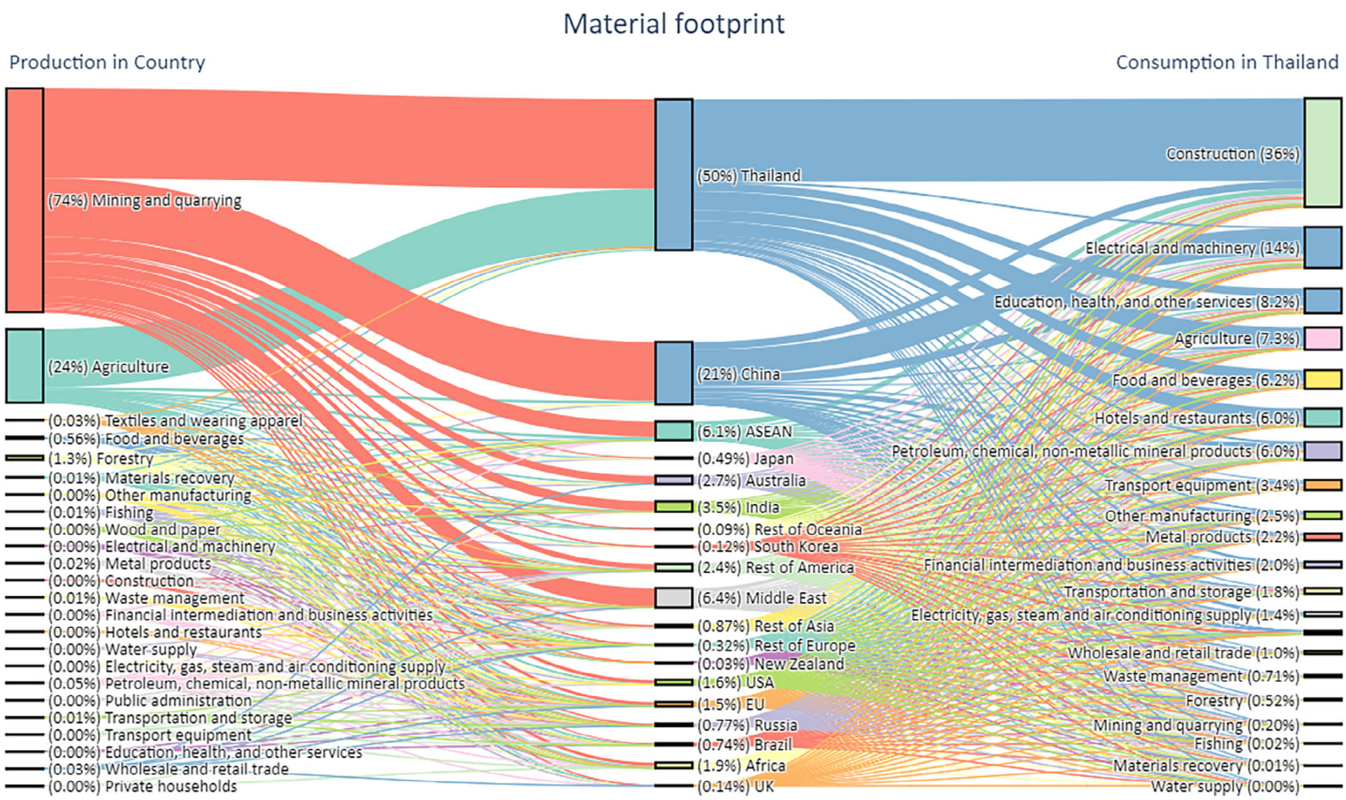



**FIGURE 3** The consumption-based material footprint of Thailand.

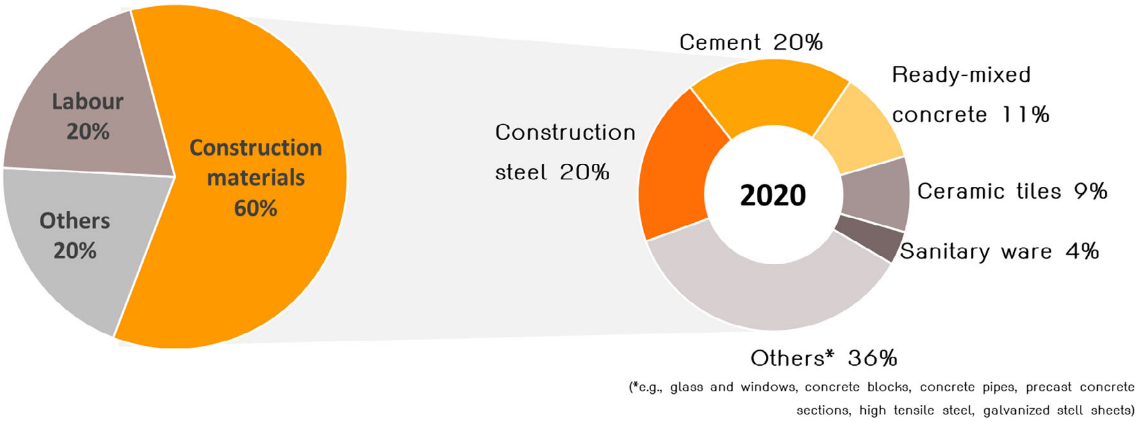
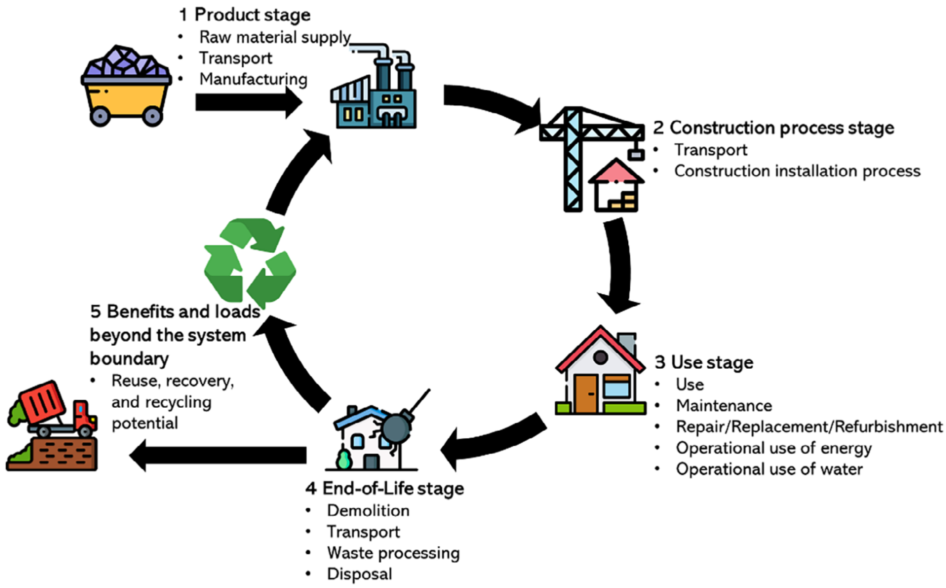



**FIGURE 4** Market share of building materials in Thailand.[2]

**FIGURE 5** The life cycle of building construction (adapted from Reference 3).




## 3 | MEASURING THE LOW-CARBON CIRCULAR ECONOMY

EU policy suggests a monitoring framework focusing on waste (e.g., waste generation and food waste) and recycling [e.g., recycling rates (RRs), the contribution of recycled materials to raw materials demand], complemented with more economic and socially oriented indicators.[13] The list of indicators for measuring progress toward SDG 12, which the CE policy aims to support, includes material footprints and domestic material consumption, both per capita and per GDP (SDG 12.2), as well as national RRs and tons of materials recycled (SDG 12.5).

A CE is a systematic approach to improving a product's overall sustainability. To achieve maximal circularity, methods to improve product life and material turnover are included. To support Thailand's construction industry's transition to a CE through the construction life cycle aspect (Figure 5), assessments, and MCIs, it is critical to investigate the ability to measure and monitor that Thailand's construction industry has accelerated the transition to a CE.

### 3.1 | Representation of building material products

Construction material is a crucially important upstream component of the construction and real estate sectors. From the statistical data, it is found that the market share of building materials in Thailand is shown in Figure 4.

Therefore, the first consideration of studying materials that are important to Thailand's construction industry to determine the appropriate circularity value to drive the country's CE consists of five material groups. As shown in Table 1, this is the main building material group. After that, consider expanding the material group to cover all other material groups. In summary, the guidelines for considering the materials that represent the building materials of the country are considered:

1. The proportion of production of construction materials in the country
2. Availability of data to be used in determining circularity efficiency indicators
3. Cooperation from companies or related agencies in the country

There will also be a meeting of operators involved in the construction value chain to seek approval on the representative materials used to track and transition to a sustainable construction industry.

## 3.2 | Life cycle assessment

Life cycle assessment (LCA) is one of the powerful quantitative tools to assess environmental information of the products, the system boundary considering the use of resources and the emissions from a product's life cycle, that is, from the stages of raw material provision, production, and use, to disposal and recycling as shown in Figure 5.

**TABLE 1** The representative building materials for Thailand construction for measuring the low-carbon circular economy.

| Materials group | Building material |
|---|---|
| Construction steel | Rebar |
| | Structural steel |
| | Wire rod |
| Mortar and cement | Finishing mortar |
| | Bricklaying mortar |
| | Pouring mortar |
| | Portland cement |
| Concrete | Ready-mixed concrete (RMC) |
| Wood and composite wood | Wood fiberboard |
| | Cement board |
| Insulation | Glass wool insulation |

The methodology of LCA has been explained in detail[14] to evaluate the emissions from products or processes that will affect the number of environmental impacts. LCA is increasingly being used to support decisions related to construction materials.[15–21] The unit of function (FU) is a quantitative description of a product's functional basis as a reference for calculating the GHG emissions of that product whilst the FU definition is typical in LCA. FU may depend on the properties or functional characteristics of the product being studied. For example, a unit of duty is defined as 1 ton of rebar, therefore the carbon footprint represents rebar is 100 $CO_2$eq/1 ton of rebar (emissions indicated in kg of $CO_2$eq/FU).

In this study, LCA is used for assessing the GHGs of the representative building materials, so the functional unit was defined as 1 ton of construction steel products, 1 bag (50 kg) of mortar and cement products, 1 $m^3$ of ready-mixed concrete (RMC) at compressive strength 240 kilograms per square centimeter (KSC), 1 $m^3$ of wood and composite wood products, and 1 $m^2$K/W (meters squared Kelvin per Watt) of glass wool insulation. According to the aim of this article, we would like to focus on the production stage, and then this study covers cradle to gate (use and end-of-life phase have not been considered). However, the data source of GHGs for studied products is verified according to carbon footprint of product (CFP) standards for products established by Thailand Greenhouse Gas Management Organization (Public Organization) or TGO[22] as shown in Table 2.

## 3.3 | Circular economy Indicators

The indicators suitable for the construction industry use the concept of selecting various indicators that are currently available.[4] The turnover efficiency of the construction industry can be measured from the following options: (1) reduce the use of resources; (2) increase the use of resources from renewable or recyclable sources; (3) reduce pollution; (4) reduce the value of material wastage; and (5) increase the value of product durability. However, this study quantifies the low-

**TABLE 2** Data for GHGs of the representative building materials.

| | | GHG ($kgCO_2eq$/FU) | | |
|---|---|---|---|---|
| **Building material** | **Functional unit (FU)** | **Raw material extraction** | **Production (incl. distribution)** | **End of life** |
| Rebar | 1 ton | 1.76 | 0.39 | 1.79E-03 |
| Structural steel | 1 ton | 2.40 | 0.10 | 1.14E-03 |
| Wire rod | 1 ton | 2.09 | 0.21 | 0.01 |
| Finishing mortar | 1 bag (50 kg) | 6.22 | 1.21 | 0.15 |
| Bricklaying mortar | 1 bag (50 kg) | 5.52 | 1.24 | 0.14 |
| Pouring mortar | 1 bag (50 kg) | 6.30 | 1.23 | 0.15 |
| Portland cement | 1 bag (50 kg) | 44.02 | 1.51 | – |
| Ready-mix concrete | 1 $m^3$ | 232.65 | 2.35 | 18.57 |
| Wood fiberboard | 1 $m^3$ | 0.70 | 0.70 | 0.01 |
| Cement board | 1 $m^3$ | 0.16 | 910.00 | 910.00 |
| Glass wool insulation | 1 $m^2$K/W | 0.51 | 0.89 | 0.23 |

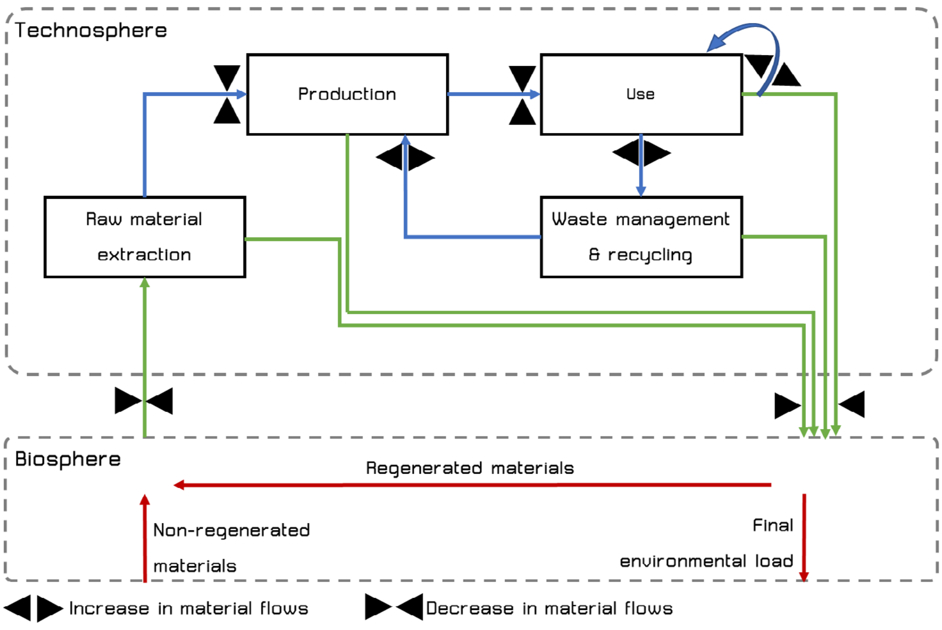



**FIGURE 6** The dependence model of the environment flows (adapted from Reference 23).

carbon CE products through the construction life cycle on representative building materials. Both technical and biological aspects are required for investigation. So, the dependence model of the environment flows[23] shown in Figure 6 illustrates that the input flow represents the extraction of resources, and the output flow represents waste and emissions going back into the ecosphere, these blue and green flows as the key material and environmental flows. Red flows represent biotic resource outputs to the ecosphere that can be decomposed, and a portion of the resulting nutrients may be taken up by living organisms on land and in water, while other portions (e.g., mineral waste) remain in the environment. Portions of $CO_2$ emissions may be regenerated into biomass via plant photosynthesis, which can be harvested in agriculture and forestry, while the rest may remain in the ecosphere. Resources that become input flows to the anthroposphere are either mineral (including fossils) or biomass, which consists of regenerated and non-regenerated components (with larger regenerated portions coming from agriculture, forestry, aquaculture, and minor portions from wild catch and logging of wilderness).

Since we have studied the appropriateness of the indicators. The MCI was found to be consistent with the context of measuring a low-carbon CE for the Thai construction industry. Because the MCI computational framework corresponds to the life cycle from resource consumption (from technical and natural materials) production processes, use, disposal, and recycling which can use the same conceptual framework as the LCA therefore, it is a suitable indicator in the context of this study. MCI can be used to monitor the performance of circularity simultaneously addressing the key environmental flows, and the utility of the resource measures material flows across several life cycle phases. MCI is defined through a function of virgin feedstock, waste generation, and product utility and it can be a comparative indicator where the utility factor is defined with an average product. It assumes that recovered material can be processed into a similar quality as the original virgin material.

## 3.4 | Material circularity indicator

Product-level MCI measures how restorative and regenerative the material flows associated with the product are. It is suggested that the circularity of a product should be inferred from both how linear the material flows are and how intensive the product could be used. To quantify these, linear flow index (LFI) is developed to indicate the linearity of a product in the economy, while Utility ($X$) is introduced to measure the length and the intensity of use. First, LFI is computed, in an equivalent unit, as

$$\mathrm{LFI} = \frac{\sum_{\gamma} V_{\gamma} + W_{0,\gamma} + \frac{W_{F,\gamma} + W_{C,\gamma}}{2}}{\sum_{\gamma} 2M_{\gamma} + \frac{W_{F,\gamma} - W_{C,\gamma}}{2}}, \tag{1}$$

where $V$ is the mass of virgin feedstock, $M$ is the total mass of the product, $W_0$ is unrecoverable waste directly to landfill after the use phase, $W_F$ is unrecoverable waste generated by recycling any recovered materials to become recycled feedstocks of the product, and $W_c$ is unrecoverable waste generated by recycling parts of the product to become any recycled feedstocks. The subscript $\gamma$ refers to the subassembly, part, or material of the product. The precise definitions and how these quantities should be estimated are provided in Ellen MacArthur Foundation and Granta Design.[6]

Next, Utility ($X$) is given by

$$X = \left(\frac{L}{L_{\mathrm{AVG}}}\right)\left(\frac{U}{U_{\mathrm{AVG}}}\right), \tag{2}$$

where $L$ is lifetime, $U$ is called functional unit, and the subscript AVG indicates the mean of all the similar products in the market. The functional unit of cement, for instance, could be the area of plastering.

Finally, MCI is

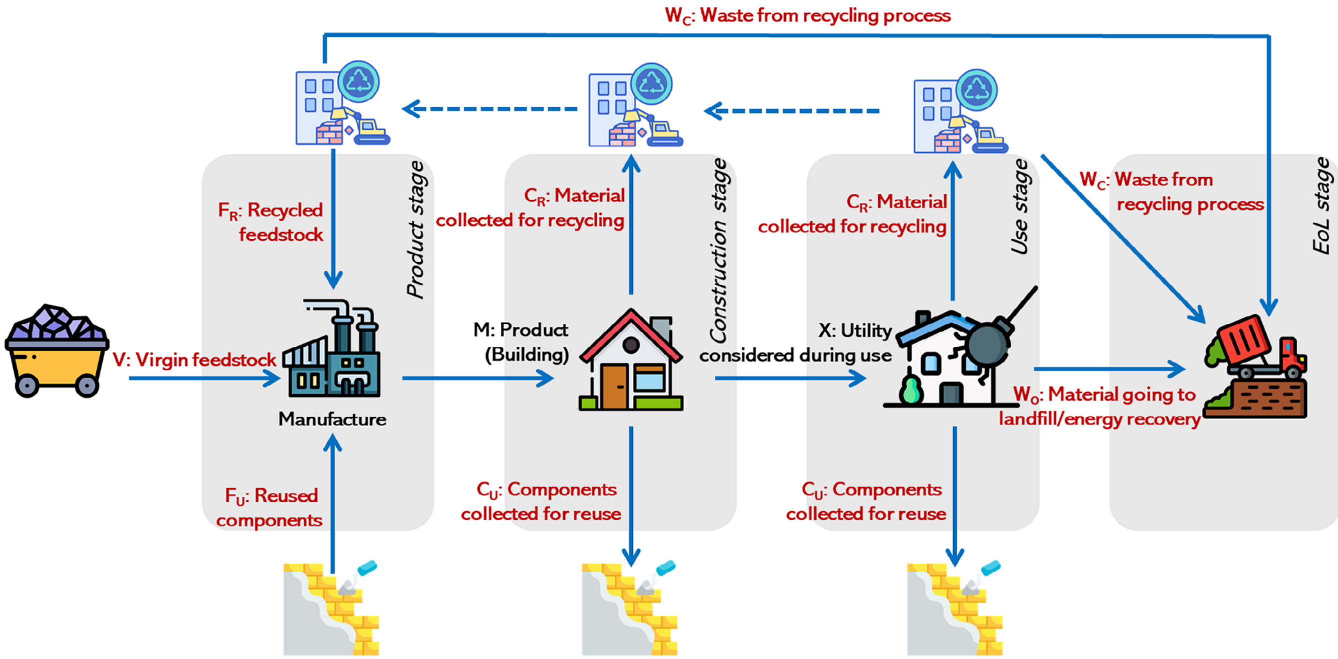



**FIGURE 7** Material circularity framework of building material (adapted from Reference 6).

$$\mathrm{MCI} = \max\left(0, 1 - \mathrm{LFI} \times \frac{0.9}{X}\right). \tag{3}$$

It takes a value between 0 (fully linear) and 1 (fully restorative).

The diagram of the product's life cycle in the CE framework is shown in Figure 6, one of the key results is the MCI,[6] which can be used as a decision-making tool, as shown in Figure 7, for the product designer and buyer for choosing materials conforming to the CE concept with the effective utilization of resources. According to the figure, it can be seen that the MCI = 1 means that all materials used must come from reused or recycled materials (100% recycling efficiency), as well as no waste, is generated during production and when the product expires, it must be able to be reused without a loss (Zero waste to landfill). When the MCI = 0.1 means that the product has a completely linear flow and all materials used come from virgin materials with no reused or recycled waste. However, when MCI < 0.1 means that the product has inferior quality and properties to the average product in the industry, for example, a shorter lifespan or inferior quality or usability. On the contrary, if the MCI > 0.1 means that the product has high quality and properties compared with an average product in the industry.

However, the primary data is collected specifically for this study from manufacturers of construction material production, national statistics, and relevant from significant stakeholders which are set practical baselines to measure the progress toward them as presented in Table 3.

## 4 | RESULTS AND DISCUSSION

According to the representative products shown in Table 1, the MCI has been applied to calculate the potential of circularity in Thailand's construction. In addition, GHG emissions assessments for building material products are verified according to CFP standards for products established by TGO. The results show in Table 4, the MCI value and GHG of the baseline scenario of each product and then also demonstrate the CE scenario for improving the efficiency of CE for each product based on Thailand's industry context. The baseline determines the production process or practice in the context of the country at present (for the year 2022). Data on construction industry production and consumption through the study of these significant representative materials are investigated as the baseline values of Thailand's construction industry. Therefore, these baseline values are important to provide you with valuable information to assess performance levels at a nation in monitoring and comparing the efficiency of improving material circularity and the environmental impact of the Thai construction industry's production and consumption.

Thus, the CE scenario that set to find the target for national policy, the first scenario to move toward a more CE by increasingly using recycled and renewable feedstocks. Second, product lifetime extension or keeping products in use longer (e.g., by reuse/redistribution) is a major component of the transition toward a more CE, it reduces waste and saves resources while preserving the economic value embedded in products. Third, shaping new material cycles by designing long-lasting materials with a high material value for end-of-life management, to develop additives and adhesives which improve or enable the mechanical recycling of end products from the collected recyclables. Next, making more intensive use of products such as the product as a service business model or performance models. Then, sourcing biological materials from sustained sources will be used in the product. Finally, ensuring biological materials remain uncontaminated and biologically accessible. The result of the study presents the appropriate CE solution for improving the efficiency in the CE based

**TABLE 3** Data and parameters for calculating the MCI of the representative building materials.

| Parameters | Rebar | Structural steel | Wire rod | Finishing mortar | Bricklaying mortar | Pouring mortar | Portland cement | Ready-mix concrete | Wood fiberboard | Cement board | Glass wool insulation |
|---|---|---|---|---|---|---|---|---|---|---|---|
| *M*: Mass of a product | 1000.00 | 1000.00 | 1000.00 | 50.00 | 50.00 | 50.00 | 50.00 | 1000.00 | 1000.00 | 1000.00 | 1000.00 |
| *V*: Mass of virgin material | 319.59 | 110.91 | 271.10 | 50.00 | 50.00 | 50.00 | 49.26 | 984.38 | 549.55 | 876.35 | 90.29 |
| $F_R$: Fraction of feedstock derived from recycled sources | 0.68 | 0.89 | 0.73 | – | – | – | – | – | 0.45 | 0.10 | 0.80 |
| $F_U$: Fraction from reused sources | – | – | – | – | – | – | – | 0.02 | – | – | 0.11 |
| $F_S$: Fraction of a product's biological feedstock from sustained production | – | – | – | – | – | – | – | – | – | 0.02 | – |
| $W_O$: Mass of unrecoverable waste through a product's material going into landfill or energy recovery | 199.78 | 126.88 | 751.33 | – | – | – | – | 1000.00 | 800.00 | 997.01 | 1000.00 |
| $C_R$: Fraction of mass of a product being collected to go into a recycling process | 0.80 | 0.63 | 0.12 | – | – | – | – | 0.00 | – | 0.00 | – |
| $C_U$: Fraction of mass of a product going into component reuse | 0.00 | 0.25 | 0.12 | – | – | – | – | 0.00 | – | – | – |
| $C_E$: Fraction of mass of a product being collected for energy recovery | – | – | – | – | – | – | – | – | 0.20 | | – |
| $B_C$: Carbon content of the biological material (Default value = 45%) | – | – | – | – | – | – | – | – | 0.45 | 0.45 | – |
| $W_C$: Mass of unrecoverable waste generated in the process of recycling parts of a product | 2.73 | 0.30 | 0.62 | – | – | – | – | – | – | 2.99 | – |
| $E_C$: Efficiency of the recycling process used for the portion of a product collected for recycling | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | – | – | – | – |
| $W_F$: Mass of unrecoverable waste generated when producing recycled feedstock for a product | 2.33 | 0.43 | 3.64 | – | – | – | – | 0.00 | 50.05 | 7.65 | – |
| $E_F$: Efficiency of the recycling process used to produce recycled feedstock for a product | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 0.97 | 0.90 | 0.90 | 1.00 |
| *W*: Overall amount of unrecoverable waste | | | | 50.00 | 50.00 | 50.00 | 50.00 | 1000.00 | 825.02 | 1002.33 | – |
| *X*: Utility of a product | 1.00 | 1.00 | 1.00 | 1.04 | 1.17 | 0.81 | 0.90 | 1.00 | 0.76 | 1.00 | 1.00 |
| *L*: Actual average lifetime of a product | – | – | – | – | – | – | 50.00 | 50.00 | 3.13 | 37.54 | 17.50 |

(Continues)

**TABLE 3** (Continued)

| Parameters | Rebar | Structural steel | Wire rod | Finishing mortar | Bricklaying mortar | Pouring mortar | Portland cement | Ready-mix concrete | Wood fiberboard | Cement board | Glass wool insulation |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $L_{av}$: Average lifetime of an industry-average product of the same type | - | - | - | - | - | - | 50.00 | 50.00 | 4.10 | 37.54 | 17.50 |
| $U$: Actual average number of functional units achieved during the use phase of a product | - | - | - | 2.75 | 2.43 | 0.77 | - | - | 1.00 | 1.00 | - |
| $U_{av}$: Average number of functional units achieved during the use phase of an industry-average product of the same type | - | - | - | 2.65 | 2.07 | 0.68 | - | - | 1.00 | 1.00 | - |

on the characteristics of products and possible solutions in Thailand's context. Table 4 addresses the CE scenarios that have been used for measuring the MCIs and GHGs. The CE scenarios are consisting of:

- $S_V$ refers to the reduction of virgin feedstock used in the product
- $S_{W0}$ refers to the reduction of unrecoverable waste in landfill
- $S_{F(X)}$ refers to product lifetime extension or increase in the utility of the product
- $S_{CE}$ refers to increasing the mass of a product being collected for energy recovery
- $S_{FS}$ refers to increase biological feedstock from sustained production

However, the CE scenarios presented in this study can be modified for different contexts because, in this study, we investigated our industry's potential. For instance, when $S_V$ is applied to the CE scenario of the studied product, GHGs of raw materials (Table 2) can be reduced because substituting virgin materials for recycled materials. In addition, MCI could be increased because the fraction of feedstock derived from recycled sources is higher (Table 3).

## 4.1 | Steel product

The results show that construction steel has a good circularity because it is almost 100% recyclable. From the calculation of the MCI at the national baseline level, rebar has an MCI of 0.77, structural steel has an MCI of 0.89, and wire rod has an MCI of 0.54, and a benchmark of construction steel in Thailand has an MCI of approximately 0.73. Structural steel reveals the best MCI value but also the highest environmental impact. As for wire rods, it shows to have the lowest MCI value, but their GHGs were still higher than that of rebar which has a higher MCI. As for the improved scenario assuming that more steel can be reused after demolition, it was found that although the MCI value is higher, the greenhouse gas emissions are still high. This is because more greenhouse gas emissions are generated in the process of acquiring raw materials rather than disposing of end-of-life products. However, the recovery of steel scrap for reuse is crucial for adding scrap into the steelmaking process. This must be done concurrently to achieve the best circulation and the least environmental impact.

## 4.2 | Mortar and cement

The MCI of cement is approximately 0.2 on the baseline, indicating that its circulation is mostly linear because the material cannot be recycled or reused again.[24] Consequently, when materials are at end of life, these materials are disposed to landfills. Moreover, new virgin material from natural resources is used in cement production. When MCI is improved by adding a substitute raw material of 30% for mortar or adding a substitute raw material of 10% for portland cement, MCI of finishing mortar, bricklaying mortar, pouring mortar, and

**TABLE 4** MCI and GHG values according to the baseline and CE scenarios of building materials.

| Building material | Functional unit (FU) | Baseline MCI | Baseline GHG[a] ($kgCO_2eq/FU$) | CE scenario | MCI Value | MCI %Δ[b] | GHG ($kgCO_2eq/FU$) Value | GHG %Δ[b] |
|---|---|---|---|---|---|---|---|---|
| Rebar | 1 ton | 0.77 | 2.14 | $S_V$ | 0.81 | +6% | 2.00 | −6.78% |
| Structural steel | 1 ton | 0.89 | 2.50 | $S_{WO}$ | 0.95 | +6% | 2.50 | −0.05% |
| Wire rod | 1 ton | 0.54 | 2.31 | $S_V$ | 0.58 | +7% | 2.18 | −5.34% |
| Finishing mortar | 1 bag (50 kg) | 0.14 | 7.59 | $S_V$ | 0.26 | +94% | 5.63 | −24.60% |
| Bricklaying mortar | 1 bag (50 kg) | 0.22 | 6.90 | $S_V$; $S_{F(X)}$ | 0.35 | +56% | 5.16 | −24.00% |
| Pouring mortar | 1 bag (50 kg) | 0.19 | 7.68 | $S_V$ | 0.32 | +69% | 5.70 | −24.60% |
| Portland cement | 1 bag (50 kg) | 0.11 | 45.50 | $S_V$ | 0.13 | +18% | 43.55 | −4.48% |
| Ready-mix concrete | 1 $m^3$ | 0.11 | 253.63 | $S_V$; $S_{WO}$ | 0.13 | +17% | 246.52 | −3.00% |
| Wood fiberboard | 1 $m^3$ | 0.18 | 581.68 | $S_{FS}$ | 0.19 | +11% | 580.01 | −0.29% |
| Cement board | 1 $m^3$ | 0.16 | 910.00 | $S_V$; $S_{WO}$ | 0.19 | +21% | 909.00 | −0.11% |
| Glass wool insulation | 1 $m^2K/W$ | 0.50 | 1.63 | $S_V$; $S_{WO}$ | 0.69 | +36% | 1.51 | −7.45% |

*Note*: $m^2K/W$, the thermal resistance of the unit area of a material has the unit in meters squared Kelvin per Watt.
[a]Certified carbon footprint of product (CFP) label of TGO.[22]
[b]The percentage of the change between the base case and CE scenario case.

hydraulic cement can increase more to around 94%, 56%, 69%, and 18%, respectively. In addition, GHG emissions of finishing mortar, bricklaying mortar, pouring mortar, and hydraulic cement can decrease by around 25%, 24%, 25%, and 4%. Cement industries can promote a CE in several ways. Recovery of materials through the use of alternative raw materials is a way to support the CE.[25]

However, this study proposes solutions for circularity efficiency improvement of MCI of cement products. The proposed solution is mixing fly ash by 30% in a mortar.[18] Moreover, this study assesses the circularity efficiency of hydraulic cement compared with portland cement. As a result, the MCI values of mortar and hydraulic cement are higher. Besides, the amount of GHG emissions is lower as well. Moreover, this way supports the CE and sustainable development. In addition, market share increases.

## 4.3 | Ready-mixed concrete

Open loop recycling: One of the most widespread applications for reusing recycled concrete aggregate (RCA) from demolition is to become a road aggregate or a pavement subbase material.[26] Since the 1970s, RCA has been used in the construction of hundreds of highway projects in the US and around the world. Most of RCA was used as aggregate (base) 65.5%, followed by asphalt concrete 9.7%, as fill 7.6%, as high-value riprap 7.6%, as a component in new concrete mixtures (closed loop recycling) 6.5%, and as others 3.2%.

This study focuses on two RMC products, that is, 240 KSC strength at 1 $m^3$. The baseline MCI is equal to 0.11, while the GHGs of 240 KSC is 253.63 $kgCO_2eq/m^3$. Recommendations for increasing the MCI and reducing greenhouse gas emissions for the 240 KSC are using the RCA as a substitute for the natural coarse aggregate would result in a 17% increase in the MCI and a 3% decrease in GHGs −0.13 and 246.52 $kgCO_2eq/m^3$.

## 4.4 | Wood and composite wood

To improve and develop the production process to minimize virgin materials (such as products mixed with adhesive binder), wood manufacturing suggested in the research of Vitor Uemura Siliva, 2021,[27] should be applied. Moreover, an application of the European Forest-Based Sector in the United Kingdom which aims to increase the fraction of mass of a product collected of wood products to 90% and the RR of wood products to 70% can improve the MCI of wood products by up to 0.72–0.82. At the product level, the MCI is related to physical characteristics, the technology of production, and usage; therefore, the parameter that should be focused on is the proportion of materials recycled ($F_R$) and material from sustained production ($F_S$) materials and the solution management after end-of-life phrase, which directly affects the MCI value. According to research, lifespan has a higher impact than the postlife management method, as well as the material proportion.

However, it is also necessary to develop a waste collection system and production technology to increase the proportion of materials derived from end-of-life materials. This can improve MCI values by reducing waste in landfills and minimizing the amount of material circulating in the system. Waste management has a slight impact on GHG reduction when compared with raw material acquisition and energy consumption. Moreover, the volume and price of the product directly affect the average MCI value and the average MCI value is close to the MCI that has high-volume and high-priced products.

## 4.5 | Glass wool insulation

The results show that the MCI value of fiberglass insulators in Thailand is 0.50 using an average lifetime of the product is 18 years, whereas the MCI value obtained from the material flow of destruction

**TABLE 5** The estimation of total economic value from increasing the 10% of MCI.

| Materials group | CDW composition (%) | CDW (ton) | Material price (Baht/kg) | Economics loss of CDW (Million baht) |
|---|---|---|---|---|
| Construction steel | 1 | 11,000 | 26.61 | 292.74 |
| Mortar and cement | 6 | 66,000 | 7.73 | 510.16 |
| Concrete | 46 | 506,000 | 0.81 | 411.13 |
| Wood and composite wood | 14 | 154,000 | 266.00 | 40,964.00 |
| Insulation | 2 | 22,000 | 120.37 | 2648.15 |
| Total Economic loss of material reduction (Million baht) | | | | 44,826.17 |
| Value added from material reduction (Million baht) | | | | 1945.46 |
| Total value GHGs of CDW reduction (Million tons) | | | | 11.89 |
| Price of carbon credit from CDW reduction (Million baht) | | | | 403.11[a] |
| Total economic value from circularity increases by 10% (Million baht) | | | | 2348.56 |

[a]The average price of carbon credit in 2020 is 33.9 baht/ton GHG (URL: http://carbonmarket.tgo.or.th/).

residential buildings in Switzerland in 2015 was 0.61 using an average lifetime of product at 40 years.[28] Thailand's MCI was found to be 0.5 less because insulation waste always goes to landfills. By contrast, Switzerland manages 22% of insulation waste by recycling feedstock in the production process. Furthermore, the lifetime of the product in Switzerland is 2.22 times longer, which has a direct effect on The Utility factor *F*(*x*)—directly related to the MCI value. Therefore, the industrial sector should be encouraged to circulate the material as in the scenario mentioned above. The MCI value will be nearly equal to that of Switzerland because the product will be recalled as recycling feedstock to replace cuttle bottles or will be refurbished and then installed at the new facility, which is another approach that should be promoted in the future.

From the assessment of the MCI, it is found that recalling the product as recycled feedstock to replace cuttle bottles or refurbishing the products to install at the new facility can increase the MCI value by 36% from the typical production. It not only promotes the positive aspects of material recycling but also results in a 7% reduction in greenhouse gas emissions. However, in formulating a realistic plan to motivate the tangible circulation of materials, one should consider the cost of transporting the insulation waste from the site to produce new products or refurbishment, such as transporting insulation waste from landfills to be a reinforcing material in the production of composite wood.

## 5 | CONCLUSIONS

The effective implementation of the CE not only increases recycling (SDG.12.5), prevents and reduces the generation of various types of waste (SDG 12.3 and SDG 12.4), but also toward reducing the use of domestic resources (SDG 12.2) and when promoting sustainable production and consumption through the promotion of procurement of recycled raw materials (SDG 12.7) shows the relationship which is the concept of creating and maintaining the value of materials and products. The MCI, referring to the key environmental flows, and the utility of the resources measures material flows across several life cycle phases. It is also restored and restored by design and aims to provide the most useful and valuable products, components, and materials, distinguishing between the technical and biological cycles. Various fractions of the product are collected for recycling at the end of the life cycle as well as changing the efficiency of the recycling process and product utilization. The results of the analysis highlight the key variables for obtaining the best circularity and environmental performance of a product. In addition, the circularity value can be used as a tool for many policy-driven approaches to the CE. In Thailand, it is included in one of the indicators of a CE and low-carbon under the 13th National Economic and Social Development Plan (2022–2026).

According to the results of the CE solution for improvement scenarios, it found that Thailand has the potential to increase the efficiency of the circularity of construction materials. Considering that almost circularity value is increased above 10% compared with the MCI baseline values of representative building materials. While considering the way to improve the circularity value, it also affects the GHG emission value. Thus, it is obviously emphasized that this approach to improving circulation has a positive effect on leading to a low-carbon society. In addition to CDW, the estimation of construction waste generation in Thailand was 1.1 million tons of CDW.[29,30] The GHG emission reduction of 11 million tons is expected, which can also increase the 10% of material circularity, also the total economic value, by considering the increase in resource and material consumption and the decrease in the GHG emissions affect the Thai construction industry by approximately 67 million dollars (2348.56 million baht) as shown in Table 5.

Therefore, if the CE is driven or implemented seriously, it will greatly affect the country. It may start from the five target materials presented, which are already the main building material groups. Through the benefits of this research, we know the environmental impact values and material circularity figures for building materials based on the CE concept. In addition, MCI can be a tool for monitoring the national baseline for CE transition and recommendations for building materials that lead to efficient use of resources and reduce environmental impacts. In addition, seven material groups are being studied, comprising bricks, roofing materials, door and window (glass) materials, ceilings, flooring materials, pipe materials, and sanitary ware to represent the industry and cover further studies on the building circularity indicator to move toward a circular city and built environment.

## AUTHOR CONTRIBUTIONS

**Nongnuch Poolsawad:** Conceptualization; formal analysis; investigation; methodology; resources; validation; writing – original draft; writing – review and editing. **Tassaneewan Chom-in:** Data curation; investigation; resources; validation. **Jantima Samneangngam:** Data curation; investigation; resources; validation. **Prakaytham Suksatit:** Data curation; investigation; resources; validation. **Khaowpradabdin Songma:** Data curation; investigation; resources; validation. **Saowalak Thamnawat:** Data curation; investigation; resources; validation. **Somrath Kanoksirirath:** Data curation; investigation; methodology. **Thumrongrut Mungcharoen:** Funding acquisition.

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## DATA AVAILABILITY STATEMENT

Data available on request from the authors.

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