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LCA of Mortar with Calcined Clay and Limestone Filler in RC Column Retrofit

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Abstract: Cement manufacture contributes about 5–7% of the global carbon dioxide emission. The fastest short-term remedy is to replace parts of ordinary Portland cement (OPC) in concrete with supplementary cementitious materials (SCMs) to reduce CO_2 emissions. Calcined clay and limestone filler have proven to be potential substitutes to good quality SCMs such as fly ash and slag because of their abundance, low cost, and potential reactivity to calcium hydroxide to form calcium silicate hydrates (C-S-H) which are responsible for the strength and other mechanical properties of concrete. A life cycle assessment (LCA) to evaluate the environmental impact of mortar with calcined clay and limestone filler in reinforced concrete (RC) column retrofitting is carried out using data from a multi-purpose complex project in Rizal province in the Philippines. A total of four retrofitting methods are evaluated based on two retrofitting techniques (RC column jacketing and steel jacketing) with two material alternatives (pure OPC-based mortar and mortar with partial replacements). Results show that RC column jacketing using patched mortar with partial replacement of calcined clay and limestone fillers is the least environmentally damaging retrofit option. The use of these SCMs resulted in a 4–7% decrease in global warming potential and a 2–4% decrease in fine particulate matter formation. Meanwhile, RC column jacketing decreased the effect on human carcinogenic toxicity by 75% compared to steel jacketing.

Keywords: life cycle assessment; calcined clay; limestone filler; supplementary cementitious material; retrofit; RC column jacketing; steel jacketing

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1. Introduction

Over the years, there has been a widespread drive in the building industry to adopt more sustainable techniques [1]. This widespread adoption of sustainable practices is a result of climate change and the environmental implications of development [2]. While the UN's sustainable development goals (SDGs) continue to emphasize the growth element in its interpretation of sustainable development, achieving such goals in the construction industry remains difficult [3]. One possible reason is the huge volume of materials used in the construction of the built environment especially on a global scale. It is estimated that about 40% of the global materials are accounted for by the construction industry [4]. In the manufacture of Portland cement alone, it is projected that the yearly global production is 4.1 billion tons which accounts for about 5–7% of the global carbon dioxide emission [5]. Despite numerous alternatives and technologies, the carbon footprint of manufacturing and using construction materials, such as ordinary Portland cement (OPC), continues to grow [6].

One way to reduce the amount of CO_2 embodied in cement is to change its processing or composition [7]. The cement proportion can be reduced in concrete through the use of supplementary cementitious materials (SCMs) [8]. Replacing parts of cement in concrete with SCMs is the faster short-term remedy to reduce CO_2 emissions [9]. The common SCMs such as limestone, granulated blast furnace slag (GBFS), and fly ash (FA) currently represent the overwhelming majority of mineral additions [10]. However, clinker substitution using these common SCMs is leveling off, which translates to a low estimate of clinker substitutes' contribution to additional CO_2 reduction [10]. There is a need for new sources of good quality SCMs to modify this trend [11]. Calcined clay and limestone filler are abundant in adequate quantities to meet Portland cement demand but are generally unexploited.

Clay is an abundant material in the world that is relatively inexpensive and easily accessible [12]. It is also a material with a wide range of mineralogical compositions, which has resulted in a large body of research devoted to the investigation of the feasibility of employing clays from specific deposits to produce SCM in the calcination process [13]. Clays, especially those with kaolinite, generate reactive materials when calcined to around 700–850 °C which boosts their potential as a supplementary material to cement [14]. Kaolinitic clay is one of the most important clay minerals due to its reactivity potential [15]. The product of the calcination of Kaolinitic clay is called metakaolin which is considered the most active mineral among the pozzolanic clay group [15].

The silica and alumina compounds found on clays chemically react with calcium hydroxide to form calcium silicate hydrates (C-S-H) which are responsible for the strength and other mechanical properties of concrete. There are numerous studies concerning the potential utilization of calcined clay as SCMs in concrete. The compressive strength of the resulting concrete composite is the most crucial aspect needed to ensure equivalence of functional unit as employed in this life cycle assessment (LCA) study. In a study by Pierkes et al. [16], for example, the effect of 20% to 40% partial replacement of calcined clay with 2–4% addition of anhydrite to the compressive strength of concrete is investigated. The results suggest that by selecting the suitable chemical and mineralogical composition of the raw materials and adjusting the amount of sulfates, the strength of calcined clay may be improved [16]. Another study by Brooks and Johari [17] suggests that the compressive strength of calcined clay concrete increases with partial replacements of up to 15%. The highest compressive strength obtained is 103.5 MPa for the concrete with 15% metakaolin replacement [17]. In another study by Khan et al. [18], the compressive strength of concrete reached a maximum of 36 MPa with 30% calcined clay with limestone filler and gypsum replacement. Another study by Bishnoi et al. [19] found that ternary blend cement made of 50% clinker, 30% calcined clay, 15% limestone filler, and 5% gypsum was of adequate quality to warrant manufacture. Calcined clay has also been used in engineered cementitious composite (ECC). ECC is a special type of concrete with strain hardening behavior which potentially solves the brittle nature of OPC concrete. Zhang et al. [20] found that incorporating 2% PVA fiber content to OPC concrete with 30% replacement of metakaolin and 15% limestone filler decreases the compressive strength of the ECC control sample by about 42%. However, the resulting 28th-day strength still reached as high as 32 MPa. For mortars, Argin and Uzal [21] showed that 20% replacement of calcined clay with limestone powder with varying water requirements obtained a maximum compressive strength of 51 MPa. For comparison purposes, a purely OPC-based mortar with a water to cement ratio of 0.65 can attain a strength of up to 35 MPa [22].

This LCA study investigates the usage of calcined clay with limestone filler as SCMs to cement in structural retrofitting applications in a multi-purpose complex project situated in Rizal province, Philippines. There are several reasons to retrofit existing structures. Sustainable and resilient urban communities must protect existing assets against aging, environmental deterioration, and damage caused by extreme events such as earthquakes, typhoons, and floods that might compromise the structural performance and consequently, the safety level of the assets during their life cycle [23]. Additionally, several existing reinforced concrete (RC) structures do not comply with modern seismic codes, making them more vulnerable to damage and collapse during earthquakes [24]. Reliable seismic retrofit interventions on existing RC structures should be able to raise the structure's safety level and prevent damage during moderate to strong earthquakes [25]. Steel jacketing and RC jacketing are commonly employed in RC column strengthening [26]. As such, these two common retrofitting techniques are considered in this study. RC column jacketing is a popular retrofit approach that attempts to increase a column's strength and deformation capacity to avoid shear, axial, or flexural failure [27]. It has been the most often used strengthening solution throughout the last century because of the availability of materials and technology [28]. Reinforced concrete column jacketing is classified as an 'add element' approach since it involves adding concrete and steel reinforcement to the exterior of an existing column's cross-section [29]. This retrofitting technique can be used to force a weak beam-strong column strength hierarchy while avoiding the usage of a soft story mechanism [28]. The increased rigidity of the structure is uniformly distributed, therefore new foundations are not required in this case [30]. Meanwhile, steel jacketing is the process of externally attaching steel plates or profiles to the perimeter of a reinforced concrete component. The primary goal of seismic retrofitting is to increase ductility or shear strength to compensate for the lack of transverse reinforcement [28]. The steel-jacketing retrofitting technique offers reinforced concrete members with increased deformation and strength capacity [31]. However, because of their weight, they may be difficult to apply [28]. The RC section is extended by welding or attaching it to a steel section, with the space between the concrete and steel filled with grout [32]. Attaching a steel plate to the flexure faces of the reinforced concrete column significantly delayed concrete crushing in the plastic hinge zone [33]. In both retrofitting methods considered, mortar is used as a patched or infill material.

One of the important uses of LCA is to assess alternative solutions in order to give environmental parameters to improve decision-making [34]. LCA results can be used to determine whether the proposed alternative is significantly better than the reference technology [35]. The LCA studies about concrete started in 2012 when Habert et al. [36] determined the reduction in environmental impact by concrete strength improvements in concrete bridges. In the same year, Van Den Heede et al. [37] investigated the environmental impact of fly ash and blast-furnace slag as incorporated in a submerged marine environment. Since then, there has been a rapid increase of published LCA studies about concrete which validates the acceptance of this approach not only in assessing the environmental impact but also in the continuous search for sustainable building materials. The LCA study as applied to building retrofit is also important since the results will demonstrate the environmental differences between retrofit techniques, material type, and quantities, allowing for better engineering judgment for practical applications in the built environment.

This paper primarily investigates the environmental impact of mortar with calcined clay and limestone filler as supplementary cementitious materials (SCMs) and compares it with OPC-based mortar as applied in reinforced concrete (RC) column retrofit. The study analyzes the environmental impact of the steel jacketing retrofitting technique as compared to the RC column jacketing technique. A total of four retrofitting methodologies are considered: (1) Method 1A—RC column jacketing with OPC mortar, (2) Method 1B—RC column jacketing with calcined clay and limestone filler as SCM to OPC mortar, (3) Method 2A—steel jacketing with OPC mortar as "infill" material, and (4) Method 2B—steel jacketing with "infill" material of OPC mortar with partial replacement of calcined clay and limestone filler. The significance of this paper lies in the provision of objective and detailed data that will allow researchers and industry stakeholders to better understand calcined clay and limestone fillers as SCMs and support environmentally responsible measures. According to the best of the authors' knowledge, this is the first LCA on calcined clay with limestone filler as applied to the common retrofitting techniques such as RC column jacketing and steel jacketing. This research also provides a direct comparison of environmental effects, with the purpose of determining the environmental factor with the greatest impact and consequently identifying targeted and efficient solutions.

2. Materials and Methods

2.1. Use of Mortar with Calcined Clay and Limestone Filler for Retrofitting Works

The retrofitting technique and the design mix of the materials considered in the LCA study are discussed in this section. The structure considered in this study is a multi-purpose complex to be constructed in the municipality of Jala-Jala, Rizal, in the Philippines. The Jala-Jala multi-purpose complex has a floor area of around 1600 m^2 (44.38 m $\times$ 36.12 m). The roof apex is +8.20 m above natural ground elevation. The structural framing of the multi-purpose complex is made of reinforced concrete. The design compressive strength of concrete is 4000 psi. The yield strength of the main reinforcements is 60 ksi while the yield strength of secondary reinforcements is 40 ksi. The reinforced concrete frame is supporting a roof rafter system utilizing W18 $\times$ 175 main sections with W10 $\times$ 45 lateral supports. The structure was modeled for analysis using the aid of the structural software, Staad Pro. The model of the concrete frame is shown in Figure 1 while the model of the roof rafter system is shown in Figure 2. The structure was designed based on the requirements outlined in the National Structural Code of the Philippines 2015 [38].

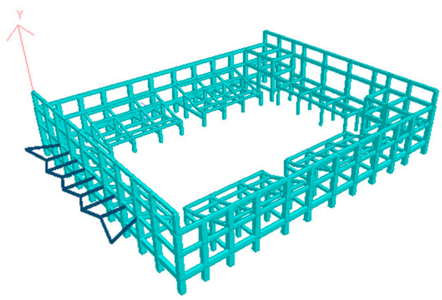

Figure 1. A 3D Staad model of Jala-Jala multi-purpose complex.

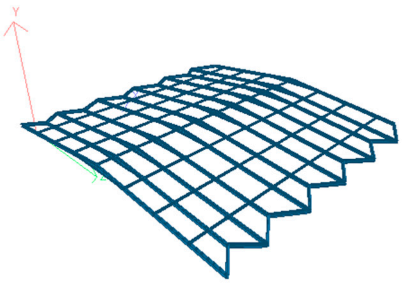

Figure 2. A 3D Staad model of the roof rafter system of Jala-Jala multi-purpose complex.

In Methods 1A and 1B, new longitudinal and lateral reinforcements are added to the retrofitted column after chipping the spalled concrete as shown in Figure 3. There is an expected increase in terms of the final column dimension (L1 $\times$ W1) with concrete cover equal to C1. After the placement of the steel reinforcements, the mortar is patched on the entirety of the column's length. In Methods 2A and 2B, there is no need to place new reinforcements. Instead, the mortar will be patched directly on the column after chipping the spalled concrete as shown in Figure 4. Hence, the final column dimension (L2 $\times$ W2) is the same as the original column dimension. The concrete cover is equal to C2. Grade 36 steel plates of 4–6 mm thickness are "jacketed" on the perimeter of the affected column. The corners of the plates are fully welded to ensure continuity. The performance characteristics should be consistent with each product system considered. It is imperative to consider the equivalent compressive strength for the mortar to be patched in both retrofitting techniques to ensure direct comparison. The secondary sources of data are utilized as shown in Table 1. Definite sources are determined for all the raw materials with corresponding transportation distances as summarized in Table 2.

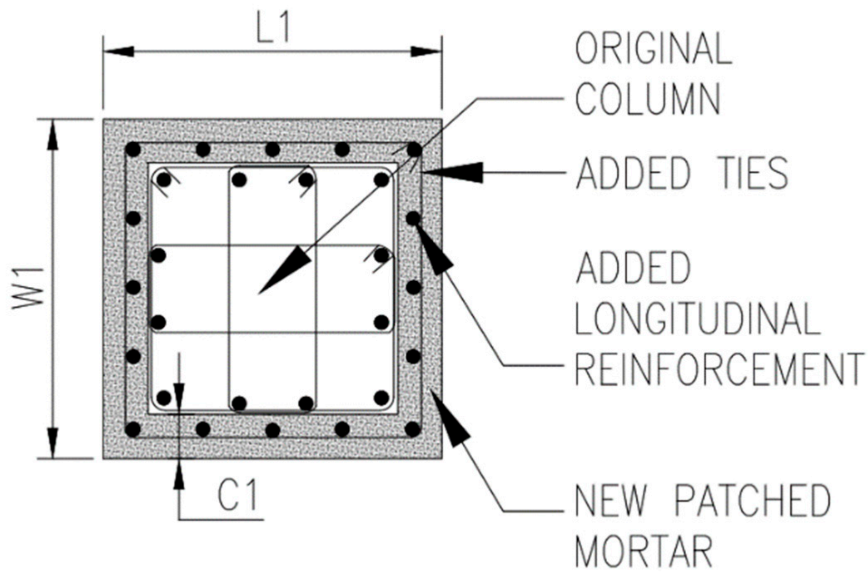

Figure 3. Method 1A/1B: RC column jacketing method.

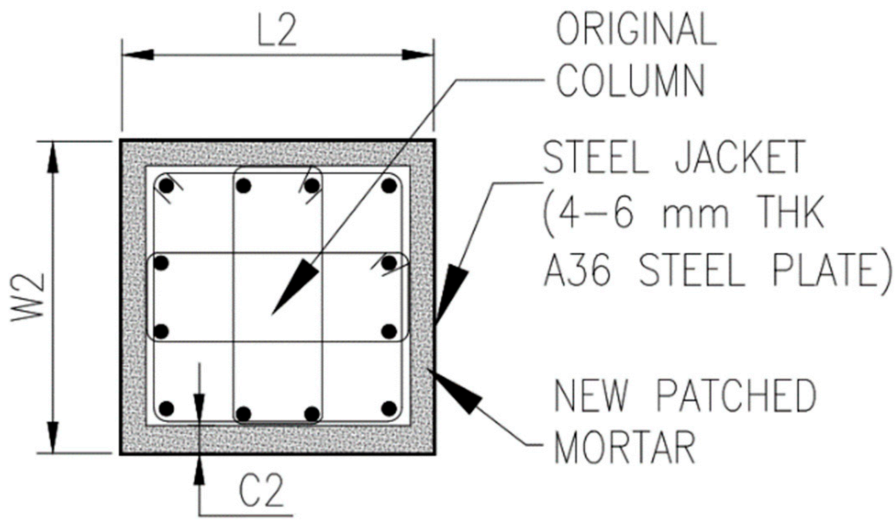

Figure 4. Method 2A/2B: Steel jacketing method.

Table 1. Compressive strength of mortar to be patched in the RC column based on secondary sources.

Mortar Used	Retrofitting Method	Compressive Strength (28 Days)	Composition	Design Mix (kg per m^3)	Reference
OPC with Partial Replacement of Calcined Clay and Limestone Filler	Method 1B and Method 2B	35.5 MPa	Cement Fine Aggregates Calcined Clay Limestone Filler Water (w/c = 0.53)	400 1375 80 20 265	[21]
Pure OPC Based	Method 1A and Method 2A	35 MPa	Portland Cement Sand Water (w/c = 0.65)	544 1342 354	[22]

Table 2. Transportation distances from raw material sources to the site.

Material	Route		Transport Distance (Raw Material to Plant)	Transport Distance (Plant to Site)	Transport Type
	From	To			
Natural Aggregate	Quarrying Site in Rizal	Concrete Batching Plant in Rizal	15 km	45 km	Truck (16–32 t)
Cement	Cement Factory in Rizal		15 km	45 km	
Calcined Clay	Source in Batangas		105 km	45 km	
Steel	Raw Material Source in Bulacan	Steel Mill in Rizal	75 km	70 km	

All raw materials are available locally.

2.2. *Life Cycle Assessment*

Life Cycle Assessment (LCA) considers environmental aspects and potential environmental impacts (for example, resource consumption and the environmental implications of releases) across a product's life cycle, from raw material acquisition to use, end-of-life treatment, recycling, and final disposal (i.e., cradle-to-grave) [39]. The LCA method was used to quantify the environmental impacts of the processes and products of the two retrofit options with different material alternatives using the cradle-to-gate approach. The method is based on ISO 14040 [39] and ISO 14044 principles and consists of four phases: (1) the goal and scope definition, (2) the life cycle inventory (LCI) analysis phase, (3) the life cycle impact assessment (LCIA) phase, and (4) the life cycle interpretation phase.

2.2.1. Goal and Scope Definition

The objectives of the study are to (1) conduct a comparative LCA study on the environmental impacts of two different retrofit alternatives for reinforced concrete columns with two different material alternatives: (a) OPC-based mortar (Methods 1A and 2A) and (b) mortar with calcined clay and limestone fillers (Methods 1B and 2B); (2) draw conclusions and recommendations to aid the decision-making process for each retrofit alternative studied; and (3) provide and draw recommendations on the possible application of concrete with calcined clay and limestone filler.

2.2.2. Functional Unit

The functional unit considered is a single structure retrofitted to design specifications (i.e., the dimensions and materials necessary for all RC column retrofitting methods) to satisfy the ultimate and serviceability limit states of collapse prevention.

2.2.3. System Boundary

The LCA system boundary approach considered is the cradle-to-gate model which is from raw material extraction until installation. The end-of-use disposal costs are expected to be identical regardless of the retrofitting method and material selection. In the pre-installation phase, raw material extraction and the manufacture of the required products are considered while the preparation and installation processes are considered in the retrofitting stage or installation phase. The transportation of the products from the raw material extraction to the project site is also considered. All these processes are evaluated in terms of their environmental impact. Figure 5 shows the system boundary of the LCA study. The main difference of both retrofitting techniques is in the raw material extraction as both techniques utilized different sets of materials. The installation process is also dependent on the material used.

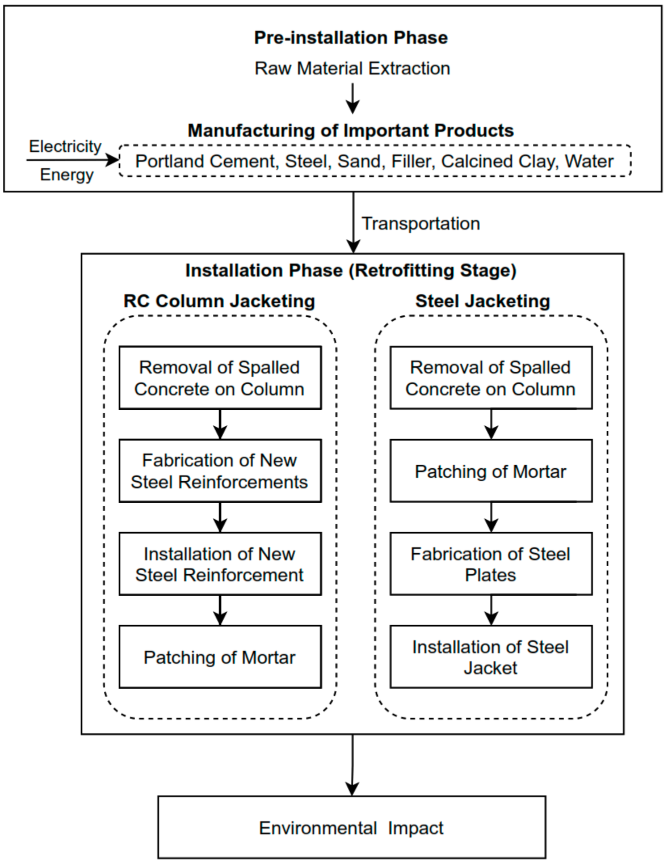

Figure 5. System boundary used in the study.

2.2.4. Data Collection for LCI, Analysis, and Interpretation

Once the LCI has been created, quantities can be based on the results of the design and analysis of the structure used in the case study. A bill of materials is created and converted to the functional unit defined in this paper, as well. To maintain data consistency, the library Ecoinvent 3 and the endpoint method of ReCiPe 2016 Endpoint H/World 2010 H/A were utilized. Each methodology with varying material requirements is run in SimaPro version 9.2.0.1 for evaluation and interpretation. Characterization results for each midpoint category are analyzed as the obligatory level of impact assessment. Normalized values for the impact categories are also determined in order to produce a consistent unit for all impact categories and to demonstrate the relative contribution of each impact category to global environmental concerns. Normalized values are calculated by dividing the characterization results by a reference value for each impact category depending on the impact assessment method used. Weighting factors based on ReCiPe 2016 Endpoint H/World 2010 H/A are employed for each normalized impact category indicator to form the single score result as not all impact categories are equally important [40]. The hierarchic perspective is used since it is based on the most prevalent policy principles in terms of time-frame and other environmental issues as opposed to the individualist and egalitarian perspectives, which are more short-term and precautionary, respectively [41].

3. Results and Discussion

3.1. Life Cycle Inventory (LCI) Analysis Phase

3.1.1. Column Design and Bill of Materials

A retrofitting requirement is idealized to determine which columns are most likely to fail first in the case of extreme column deterioration over time. A reduction in the cross-section of steel reinforcement with a corresponding decrease in the effective concrete area is assumed. New design forces are analyzed, and the ineffective columns are identified. New column specifications are determined for each retrofitting method as shown in Figure 6. The required volume of mortar to be patched on the affected columns for each retrofitting method is computed. Table 3 summarizes the material quantities required for each of the methods based on the design mix considered. These material quantities are used as an input to SimaPro.

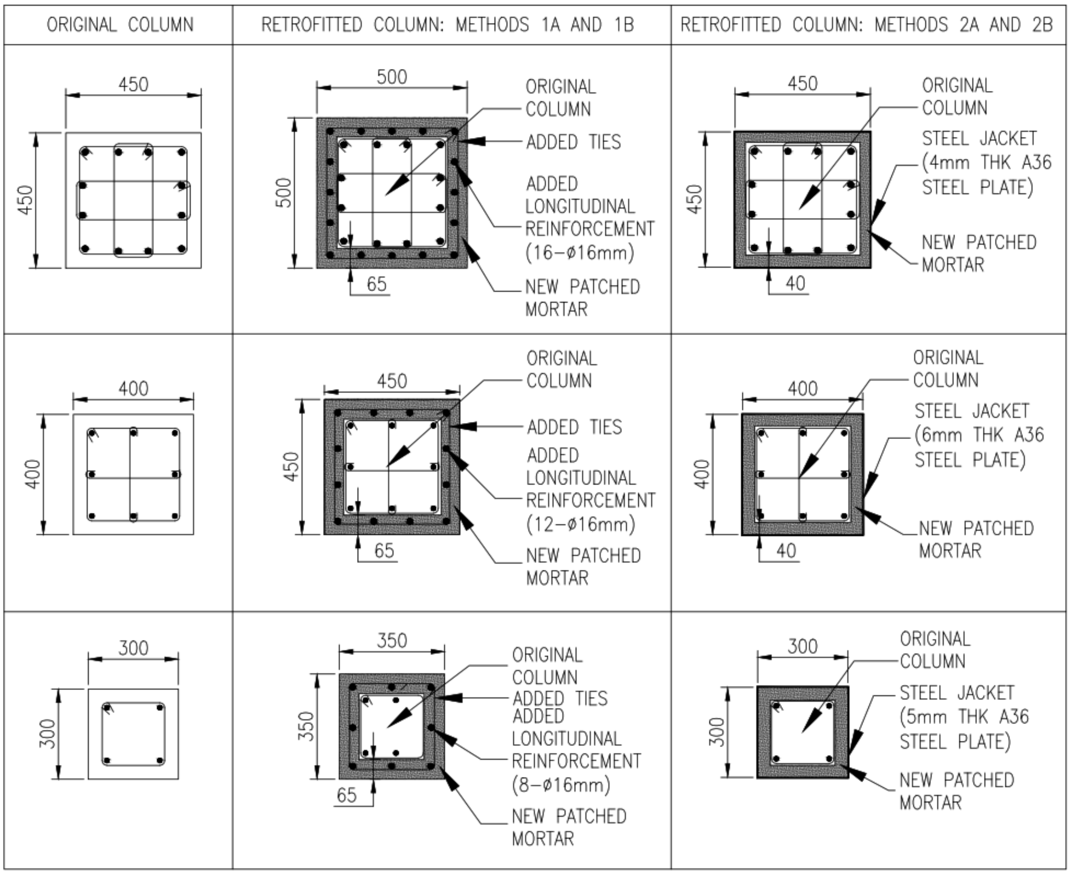

Figure 6. Retrofitted RC column specifications.

Table 3. Summary of the bill of materials for each retrofitting method.

Retrofit Method	Cement	Calcined Clay	Limestone Filler	Fine Aggregates	Reinforcement Bars	Steel Plate	Water
Method 1A	7880			22,928	4716		5380
Method 1B	6200	1217	306	20,907	4716		4033
Method 2A	4840			11,726		8944	3095
Method 2B	3600	701	177	12,024		8944	2321

All quantities are expressed in kilograms. The background color denotes non-existent values.

3.1.2. Life Cycle Inventory

A sample life cycle inventory for Method 1B is presented in this section as shown in Table 4. The required materials and processes for each method and the corresponding SimaPro inputs are likewise shown in the table. Since the structure is located in the Philippines, the input data required for the materials and processes selected from the Ecoinvent 3 library are based on Rest-of-the-world (RoW) or global (GLO) geographical locations. This type of geographical selection is conducted to provide a more realistic representation of the activities associated with the inventory inputs especially when the desired location is not available in the Ecoinvent database. The GLO dataset corresponds to cover the average global production, whereas the RoW dataset represents the world minus all local geographies for which a process is listed in the database [42]. However, it should be emphasized that not all activities have a RoW dataset. The RoW dataset is not created if the production of the reference product is less than 0.5% of the production output of the global dataset [42]. For such cases, the GLO dataset was selected. Tap water, diesel, and electricity are the typical GLO dataset selections. The RoW dataset was selected for Portland cement, sand, reinforcing steel, calcined clay, limestone filler, and transportation. The output data in the form of environmental impacts are also shown in the table. It must be highlighted that only the midpoint categories with the most impacts are shown as output in the inventory. The categories with the most impact are: (1) Human carcinogenic toxicity in terms of kg 1.4 DCB emitted eq, (2) Particulate matter formation in terms of kg PM2.5 eq, and (3) Global warming potential in terms of kg CO_2 eq. The midpoint to endpoint conversion factors based on Huijbregts et al. were used to calculate the specified units [40].

Table 4. Inventory data and major environmental impacts associated with Method 1B.

Category		SimaPro Input	Input Values	Units	Human Carcinogenic Toxicity	Particulate Matter Formation	Global Warming Potential
					kg 1.4-DCB Emitted eq	**kg PM2.5 eq**	**kg CO_2 eq**
Materials	Portland Cement	Cement, Portland {RoW} | production | APOS, U	6200	kg	89.08	3.37	5279.89
	Sand	Sand {RoW} | gravel and quarry operation | APOS, U	20,907	kg	19.09	0.20	85.91
	Reinforcing Steel	Reinforcing steel {RoW} | production | APOS, U	4716	kg	15,041.03	15.13	9364.68
	Tap Water	Tap water {GLO} | market group for | APOS, U	4033	kg	1.73	0.01	3.20
	Calcined Clay	Calcined clay {RoW} | market for calcined clay | APOS, U	1217	kg	14.92	0.16	311.82
	Limestone Filler	Limestone, crushed, washed {RoW} | market for limestone, crushed, washed | APOS, U	306	kg	0.16	0.01	1.50
Processes	Concrete Production	Diesel, burned in building machine {GLO} | processing | APOS, U	237.8	MJ	1.54	0.06	21.59
		Heat, district or industrial, natural gas {RoW} | market for heat, district or industrial, natural gas | APOS, U	161.6	MJ	0.08	0.00	6.24
		Electricity, medium voltage {GLO} | market group for | APOS, U	62.4	kWh	2.10	0.10	44.76
	Transportation	Transport, freight, lorry 16–32 metric ton, EURO6 {RoW} | transport, freight, lorry 16–32 metric ton, EURO6 | APOS, U	550.0	tkm	5.46	0.09	93.30

3.2. Life Cycle Impact Assessment and Interpretation

3.2.1. Impact Assessment Method

The impact assessment methodology selected is ReCipe 2016 Endpoint with the hierarchism (H) perspective. This method is selected since the characterization factors are representative of the global scale, unlike the other assessment methods which are regional in scale (i.e., European scale, North American scale, etc.) [43]. Two sets of impact categories and accompanying sets of characterization criteria are used in this strategy as shown in Figure 7. The midpoint level consisting of 18 impact categories classifies the associated categories as "problem-oriented". These midpoint level impact categories will then be sorted into damage pathways to ultimately define the endpoint categories or "damage-oriented" categories. This is done by multiplying damage factors and categories grouped into a common endpoint that is aggregated.

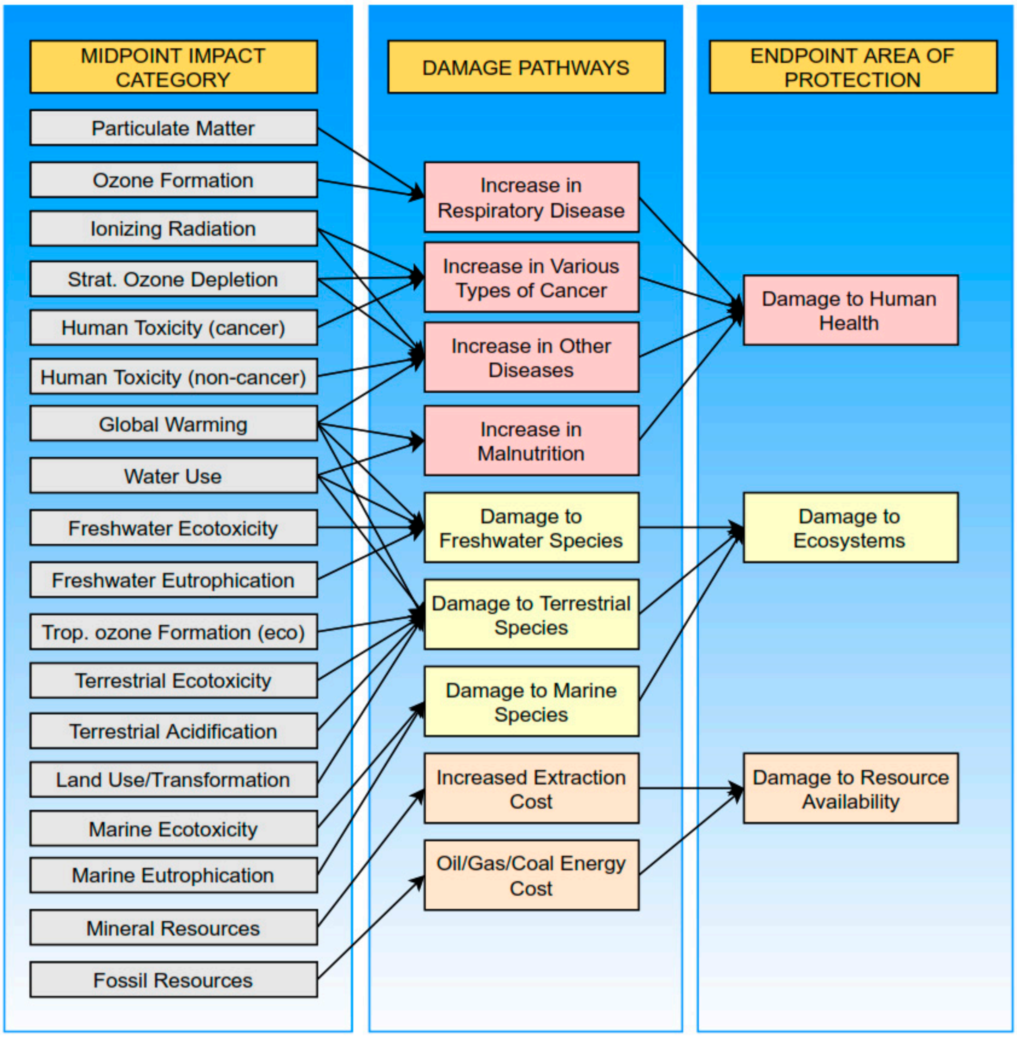

Figure 7. Relations between the midpoint impact categories and the endpoint damage categories.

3.2.2. Process Network

It must be noted that the process network shows the materials used in the assemblies or the flow of any process. The arrows between the processes show the direction of the flows. The line thickness of the arrows represents the environmental load expressed as a percentage due to that process flow. The thicker the line, the higher the environmental load. As shown in Figures 8 and 9, using SimaPro to analyze the process network in Methods 1A and 1B, the reinforcing steel contributes the highest impact with about 87–89%. The next contributor is cement production with about 10–13%. The lower impact of Method 1B compared to Method 1A regarding the cement production is expected since partial replacement is made using calcined clay and limestone filler. The impacts of the other materials such as calcined clay, limestone filler, and aggregates including the transportation process are negligible compared to the major environmental contributors.

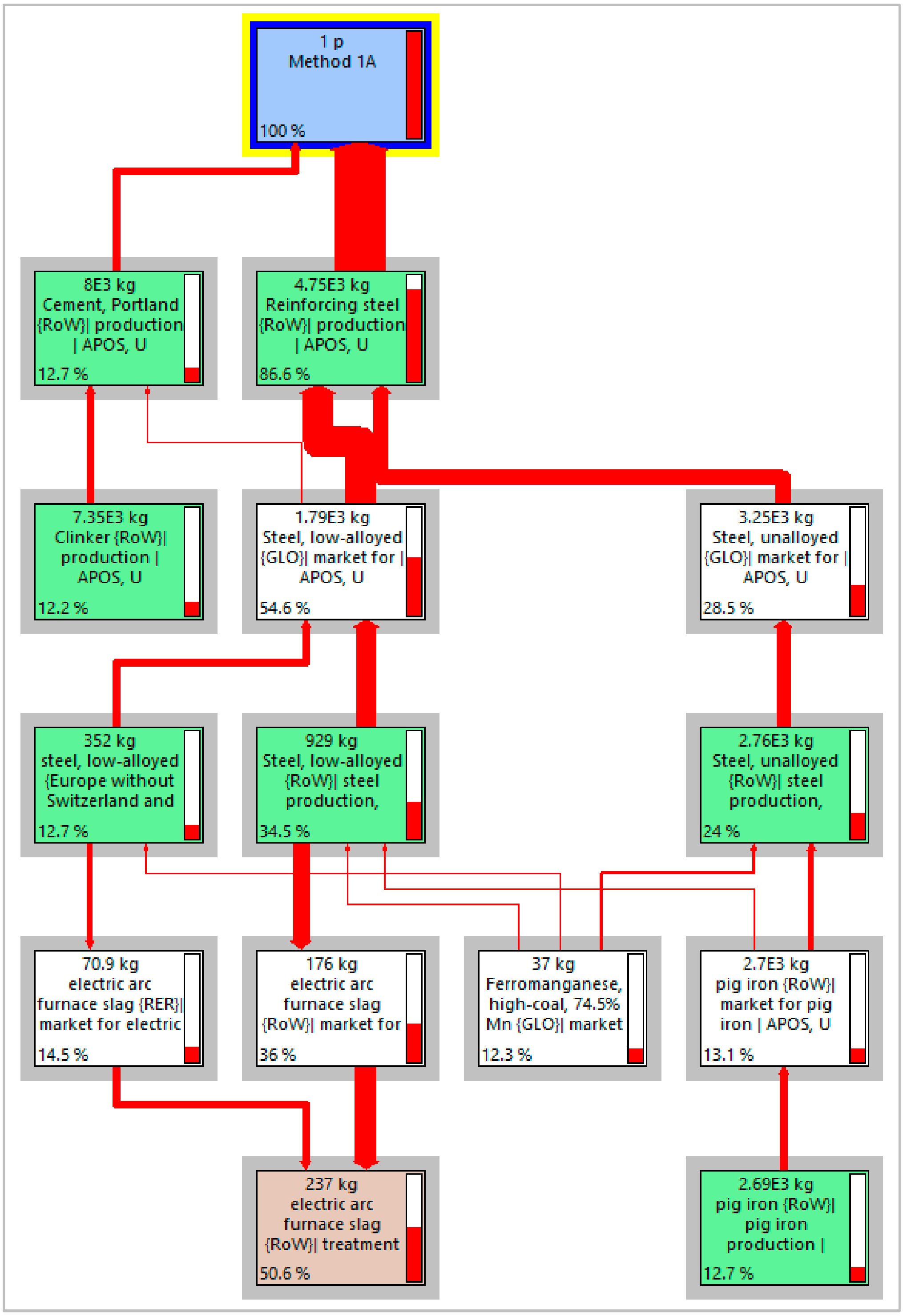

Figure 8. Process network results for Method 1A showing ~12% node cut-off. Process network results indicate that the reinforcing steel has the highest environmental impact with 87% followed by the Portland cement production with 13% impact.

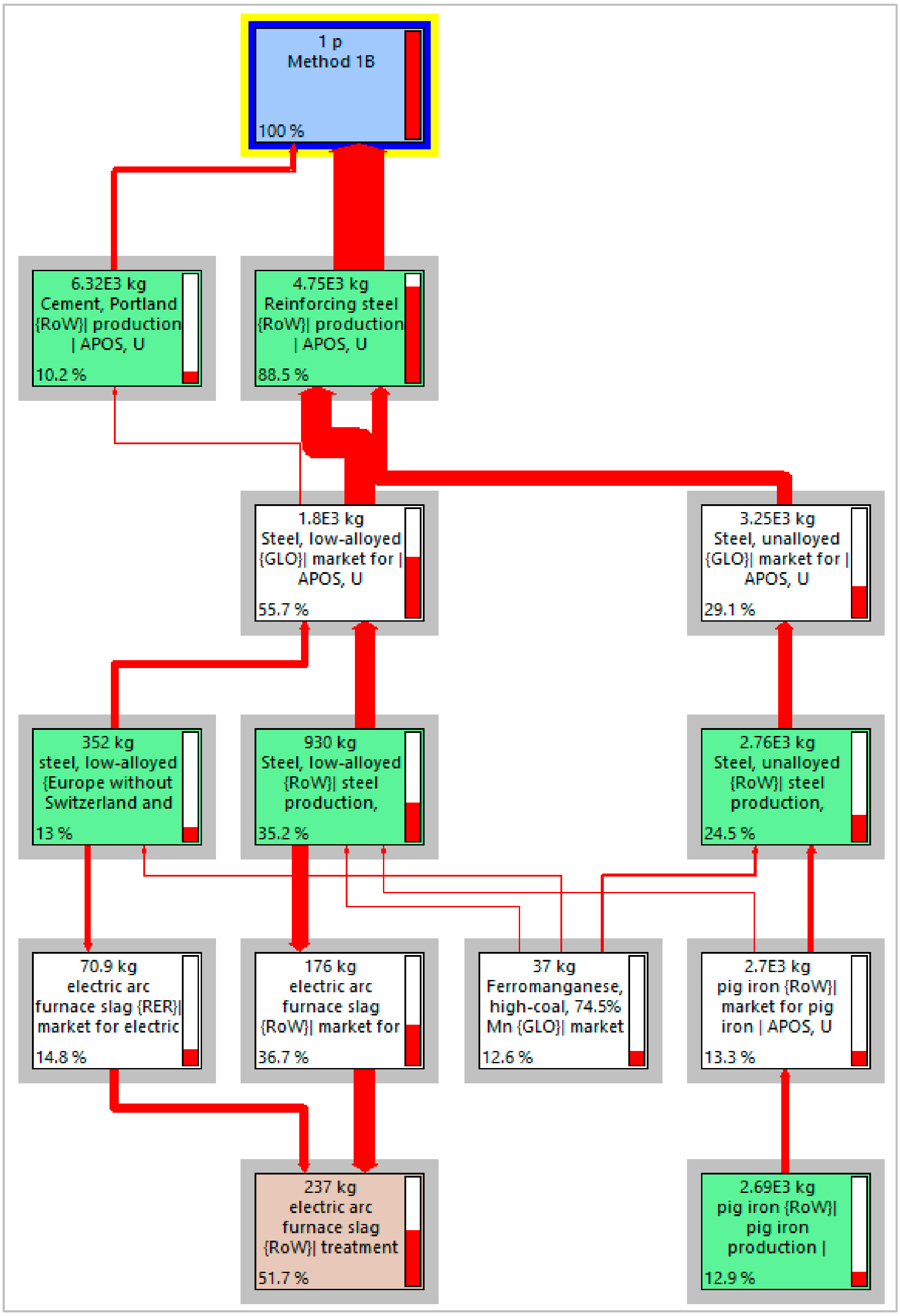

Figure 9. Process network results from for Method 1B showing ~10% node cut-off. Process network results indicate that the reinforcing steel has the highest environmental impact with 89% followed by the Portland cement production with 10% impact. Based on Figures 8 and 9, there is an indicated reduction in the environmental impact of Portland cement production with the incorporation of calcined clay with limestone filler in the mortar mixture (i.e., from Method 1A to Method 1B).

As shown in Figures 10 and 11, using SimaPro to analyze the process network in Methods 2A and 2B, the low-alloyed hot-rolled steel contributes the highest impact with about 97–98%. The next contributor is cement production at about 2–3%. The reduced impact of cement production is also expected since the volume of the mortar patching is quite low for the steel jacketing method. As the volume of mortar patching also lowered, the difference between Methods 2A and 2B due to the change in the type of mortar used is also less with a difference in the impact of only about 0.65%. The same observation about environmental impact is made in terms of other materials and the transportation processes as in Methods 1A and 1B.

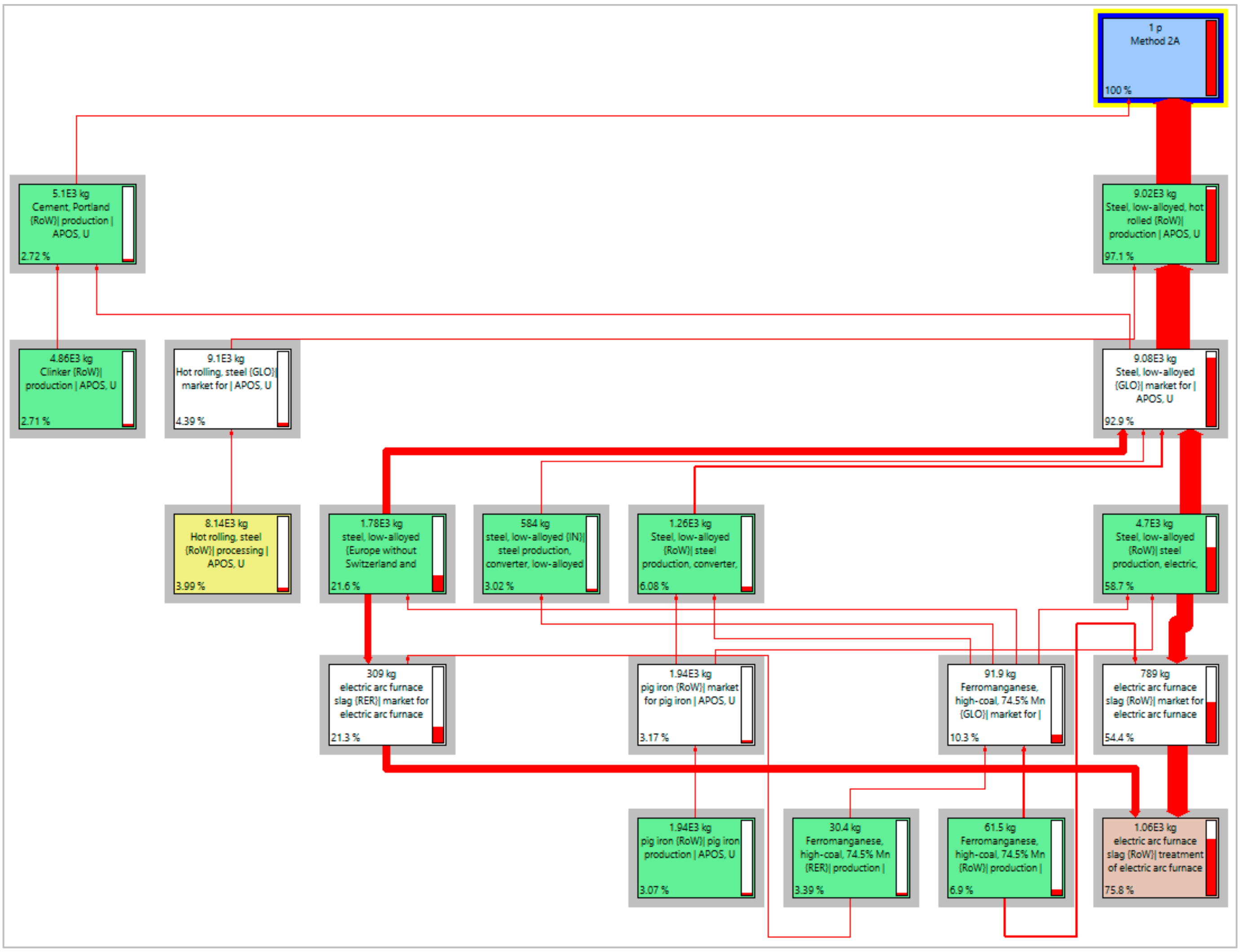

Figure 10. Process network result for Method 2A showing ~2.7% node cut-off. Process network results indicate that the reinforcing steel has the highest environmental impact with 97% followed by the Portland cement production with 2.72% impact. The significant reduction in the impact of Portland cement production is due to the decreased mortar volume in the steel jacketing method as compared to RC column jacketing.

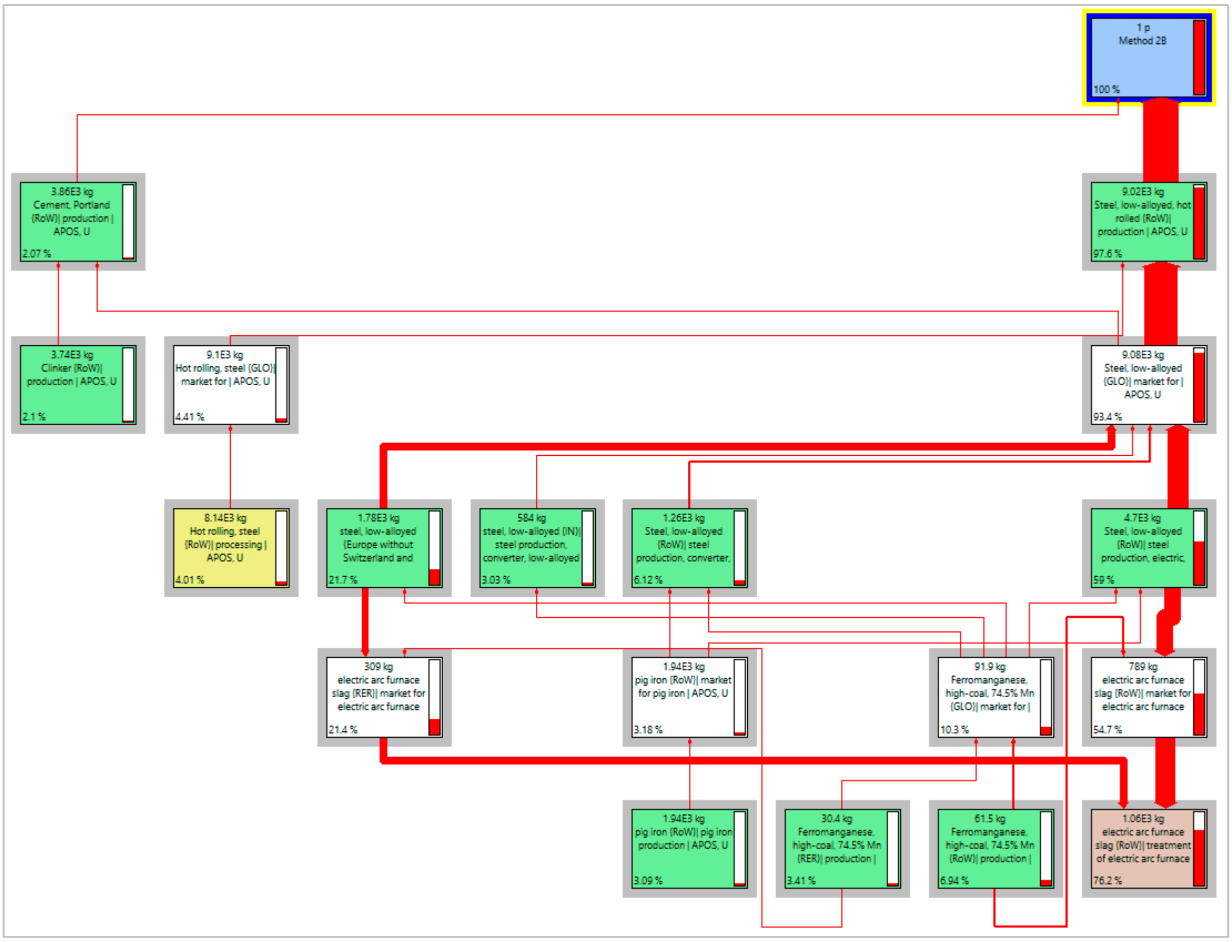

Figure 11. Process network result for Method 2B showing ~2% node cut-off. Process network results indicate that the reinforcing steel has the highest environmental impact with 98% followed by the Portland cement production with 2% impact. The significant reduction in the impact of Portland cement production is due to the decreased mortar volume in the steel jacketing method as compared to RC column jacketing. There is also a reduction in the environmental impact of Portland cement production with the incorporation of calcined clay with limestone filler in the mortar mixture (i.e., from Method 2A to Method 2B).

The impact on the aspects of the natural environment, human health, or resources further substantiates the effect of steel in comparison to other materials and methods. Consider for example the impact assessment characterization for Methods 1A and 1B as shown in Figures 12 and 13, respectively. It can be inferred that the reinforcing steel contributes the most in all aspects. Additionally, the same material has the most impact on human carcinogenic toxicity which is consistent with the study by Tokar et al. [44] suggesting that metal ions act as human metallic carcinogens that cause lung cancer due to frequent inhalation. It is also observed that global warming potential is reduced from about 41% to 35% when Method 1B is preferred over Method 1A. This reduction is primarily due to the partial replacement of the Portland cement with calcined clay and limestone filler which resulted in less CO_2 emission during manufacture. Other parameters such as human toxicology, ozone depletion, and terrestrial acidification have also been reduced. This means that there is less pollution by utilizing the calcined clay with limestone filler as a partial replacement to OPC. It is also evident that calcined clay has low impact contributions relative to the other materials considered as shown in Figure 13. It must be emphasized that the impact assessment characterization for the steel jacketing method also depicted the same observations as above.

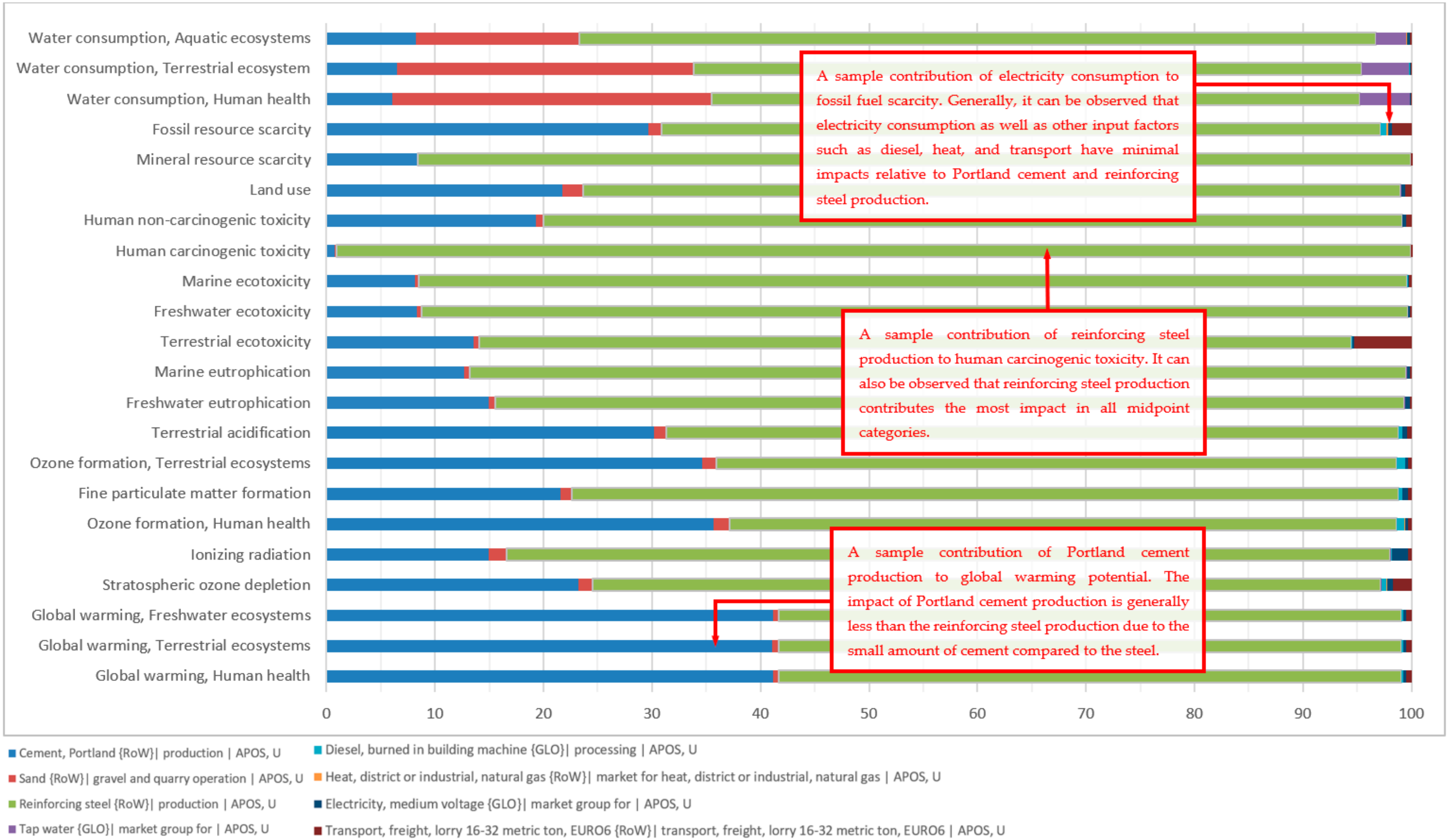

Figure 12. Impact assessment characterization analyzing 1 p 'Method 1A'.

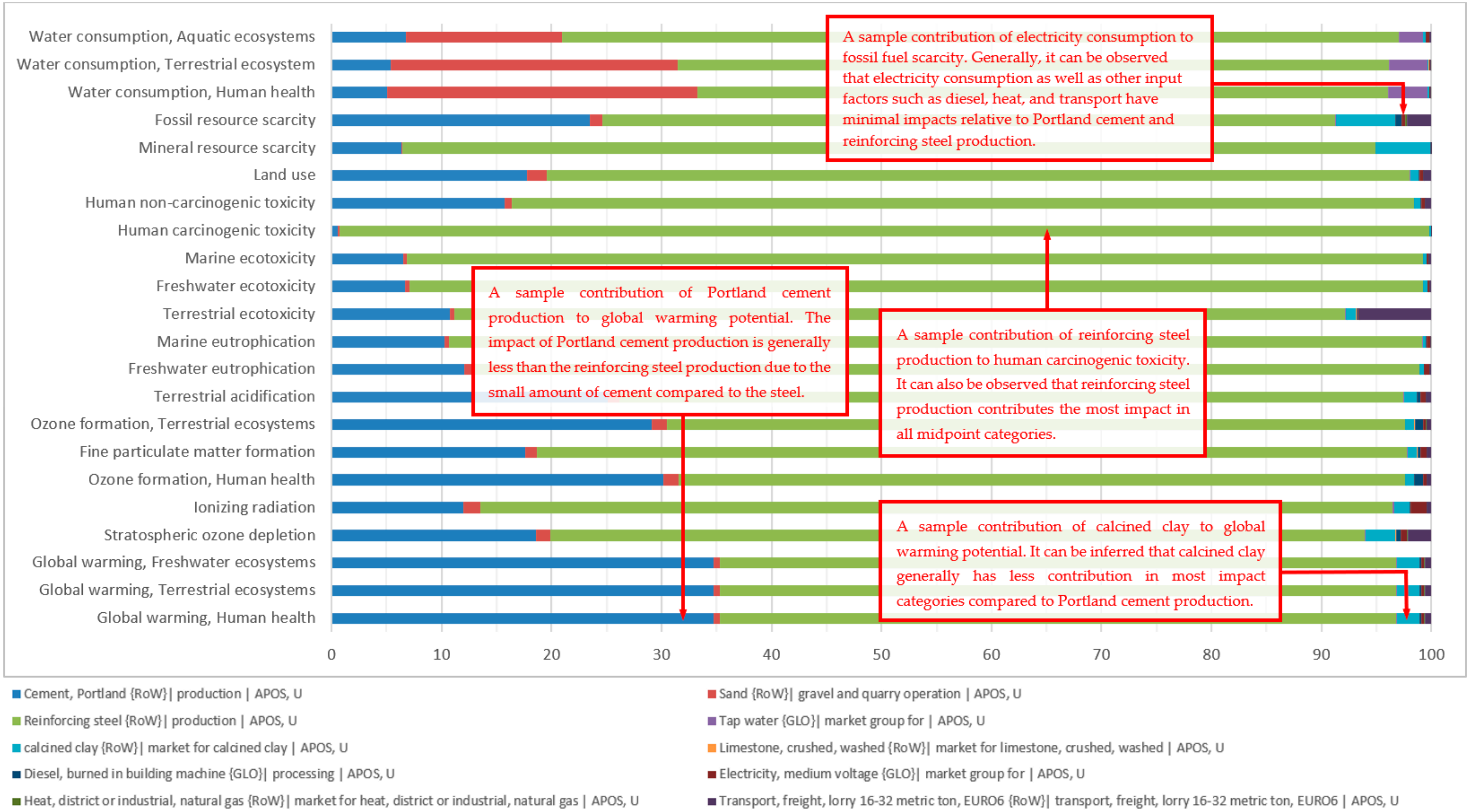

Figure 13. Impact assessment characterization analyzing 1 p 'Method 1B'.

3.2.3. LCA Comparison

A comparative impact assessment is also done considering all the methods using SimaPro as shown in Figures 14–16. The midpoint categories are first evaluated as to which are considered as problem-oriented categories, as shown in Figure 14. It can be observed from this figure that Method 1B has the least impact in almost all the midpoint categories while Method 2A has the most impact in almost all the midpoint categories. The only midpoint category wherein Methods 1B and 2B have more impact versus their counterparts is the mineral resource scarcity. This is primarily due to the extraction of more minerals with the addition of calcined clay and limestone filler. Meanwhile, the midpoint category which obtained the most variation from Methods 2A and 2B vs. Methods 1A and 1B is the human carcinogenic toxicity. After the midpoint categories, the endpoint categories or damage-oriented parameters are evaluated by investigating the impacts on human health, ecosystem, and resources as shown in Figure 15 with tabular results in Table 5. The method with the least impact on the endpoint categories is Method 1B. This is followed by Method 1A and 2B while the method with the most impact is Method 2A. It can also be inferred from this figure that there is a huge disparity in terms of impact when comparisons are made between Methods 1A and 1B vs. Methods 2A and 2B. This means that the steel jacketing technique yields a higher impact compared to the RC column jacketing technique. This result is expected due to the amount of low-alloyed hot-rolled steel utilized in Methods 2A and 2B compared to the reinforcing steel requirement for Methods 1A and 1B. As discussed, the steel material is the greatest contributor among all the materials considered. It can also be inferred from the figure that the decrease in impact from Method 2A to Method 2B and from Method 1A to Method 1B becomes higher when the ecosystem category is considered as opposed to human health and resources. The overall comparison in terms of environmental impact can be obtained from SimaPro's single score. This is a useful metric for assessing environmental impact since it considers the overall environmental load for each impact category considered, which includes categorization, damage assessment, normalization, and weighting results. The ReCiPe single score is also considered contemporary, frequently used, and well recognized, which merits its use [45]. Furthermore, the utilized hierarchic version of the ReCiPe method in determining the single score is considered politically and scientifically accepted [43]. The resulting single score for each method is shown in Figure 16. It can be noted from this figure that Methods 2A and 2B are on the 4000–4250 Pt range while Methods 1A and 1B are on the 1350–1400 Pt range which indicates that the steel jacketing method has greater environmental impact compared to the RC column jacketing.

Table 5. Tabular impact assessment comparison of endpoint categories for all methods.

Damage Category	Units	Method 1A	Method 1B	Method 2A	Method 2B
Human Health	DALY	0.081	0.079	0.242	0.241
Ecosystems	species. yr	6.91×10^{-5}	6.49×10^{-5}	9.13×10^{-5}	8.81×10^{-5}
Resources	USD2013	672	671	1003	998

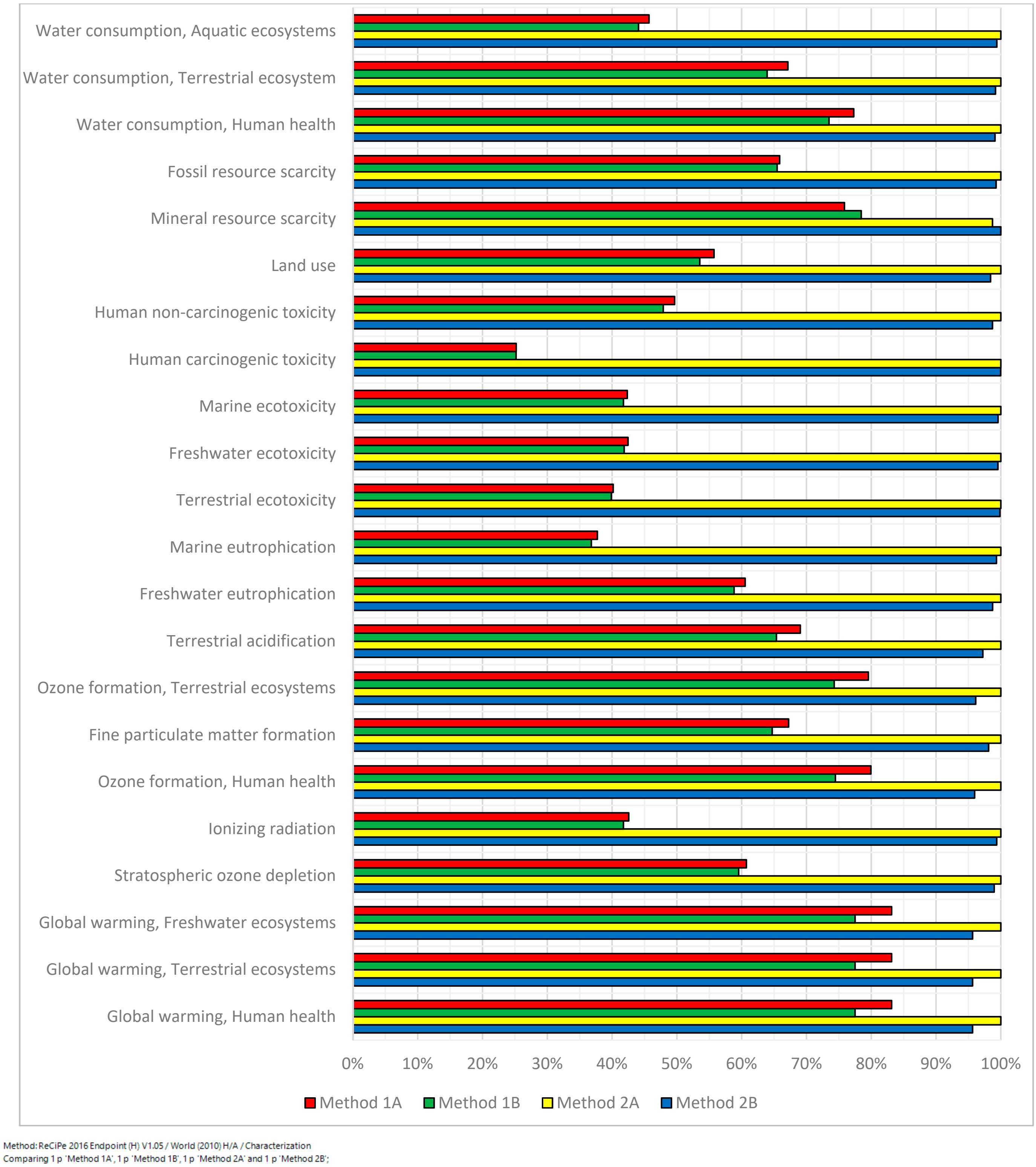

Figure 14. Comparison of impact assessment characterization for all methods. Method 2A has the highest impact in most categories followed by Method 2B, Method 1A, and Method 1B.

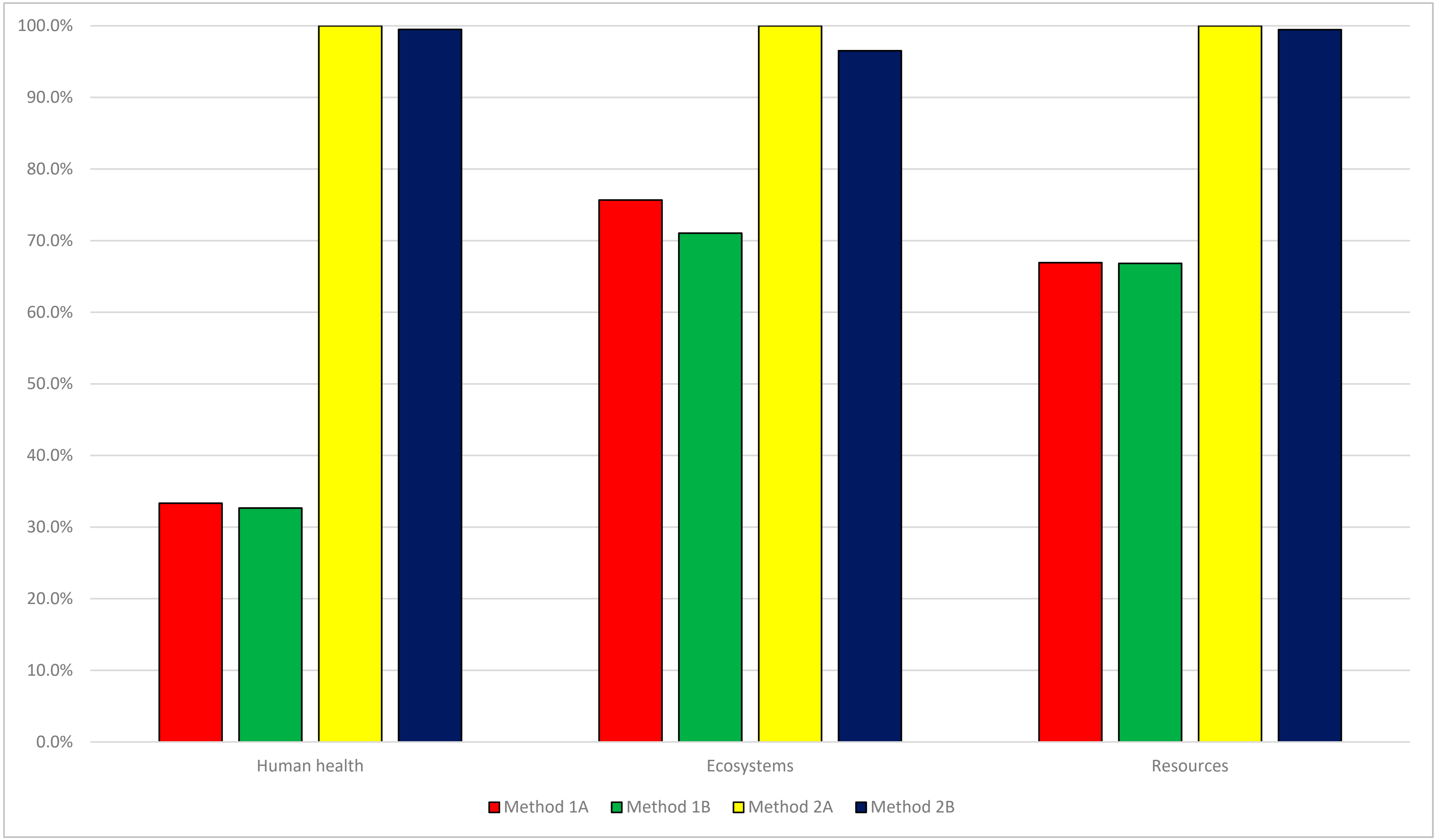

Figure 15. Impact assessment comparison based on end-point categories for all methods (Method: ReCiPe 2016 Endpoint (H) V1.05/World (2010) H/A/Damage Assessment—Comparing 1p 'Method 1A', 1p 'Method 1B', 1p 'Method 2A', and 1p 'Method 2B').

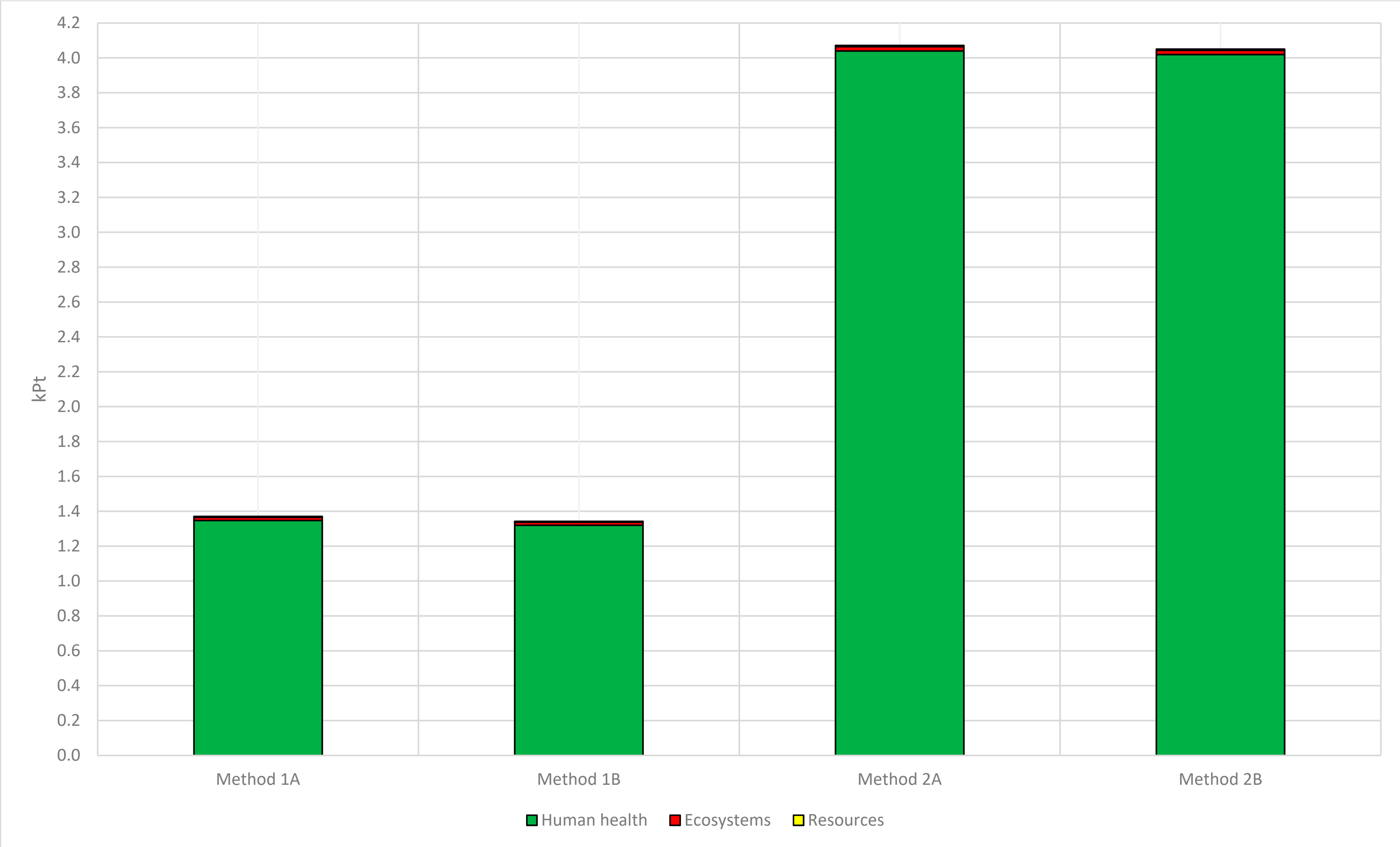

Figure 16. Impact assessment comparison based on single score results for all methods (Method: ReCiPe 2016 Endpoint (H) V1.05/World (2010) H/A/Single Score—Comparing 1p 'Method 1A', 1p 'Method 1B', 1p 'Method 2A', and 1p 'Method 2B').

It is very important to determine the greatest contributor to the end-point categories or damage-oriented factors. This is necessary since researchers or engineers can pinpoint which impact category to work on for potential improvement. This can be done by verifying the actual characterization values for each mid-point impact category as shown in Figure 17. It can be observed from this figure that human carcinogenic toxicity, fine particulate matter formation, and the global warming associated with human health are the mid-point categories with the most impact. All other midpoint categories have a negligible impact or with <50 Pt. The results of SimaPro are consistent with the existing literature since it is well known that cement production is a major CO_2 emitter while metallic ions derived from iron-ore (raw steel material) are natural human carcinogens because of fine particulate matter inhalation. The midpoint categories are centered on only three major impacts. From this observation, it can be inferred that environmental categories are very broad and there could only be specific categories that contribute the most impact, which necessitates prioritization.

Since the midpoint categories which contribute the most impacts are already determined, it is still crucial to relate these categories to quantifiable units. Midpoint to endpoint conversion factors utilizing a hierarchic approach in the ReCipe2016 Endpoint assessment method was utilized [40]. It can be inferred that the top midpoint categories all have DALY (disability-adjusted life years) units. The DALY units are converted to kg CO_2 eq for global warming, kg PM2.5 eq for the particulate matter formation, and kg 1.4-DCB emitted to urban air eq. for the human carcinogenic toxicity. It can be observed that the global warming potential is decreased by 857–1109 kg CO_2 eq or about 4–7% when partial replacements of calcined clay with limestone filler are utilized as shown in Figure 18. Meanwhile, the global warming potential is decreased by 3560 kg CO_2 eq or about 19% when the RC column jacketing technique is utilized over the steel jacketing technique. For the fine particulate matter formation, a decrease of 0.56–0.75 kg PM 2.5 eq or about 2–4% is observed when partial replacements of calcined clay with limestone filler are utilized as shown in Figure 19. However, this is magnified to a decrease of 9.86 kg PM 2.5 eq or about 34% when the RC column jacketing technique is employed over the steel jacketing technique. The kg PM 2.5 eq is a measure of fine particulate matter emission [46]. For the human carcinogenic toxicity, it can be observed that the emissions are almost equal for Methods 1A vs. 1B and Methods 2A vs. 2B with a decrease of not more than 11 kg 1.4-DCB emission or <1.0% as shown in Figure 20. This is somewhat expected since the main contributor for this category is steel production, and the steel amounts are equal for Methods 1A vs. 1B and Methods 2A vs. 2B.

Upon analyzing both the midpoint and endpoint categories of the life cycle impact assessment phase, Method 1B is considered as the method with the least environmental impact followed by Method 1A, Method 2B, and Method 2A.

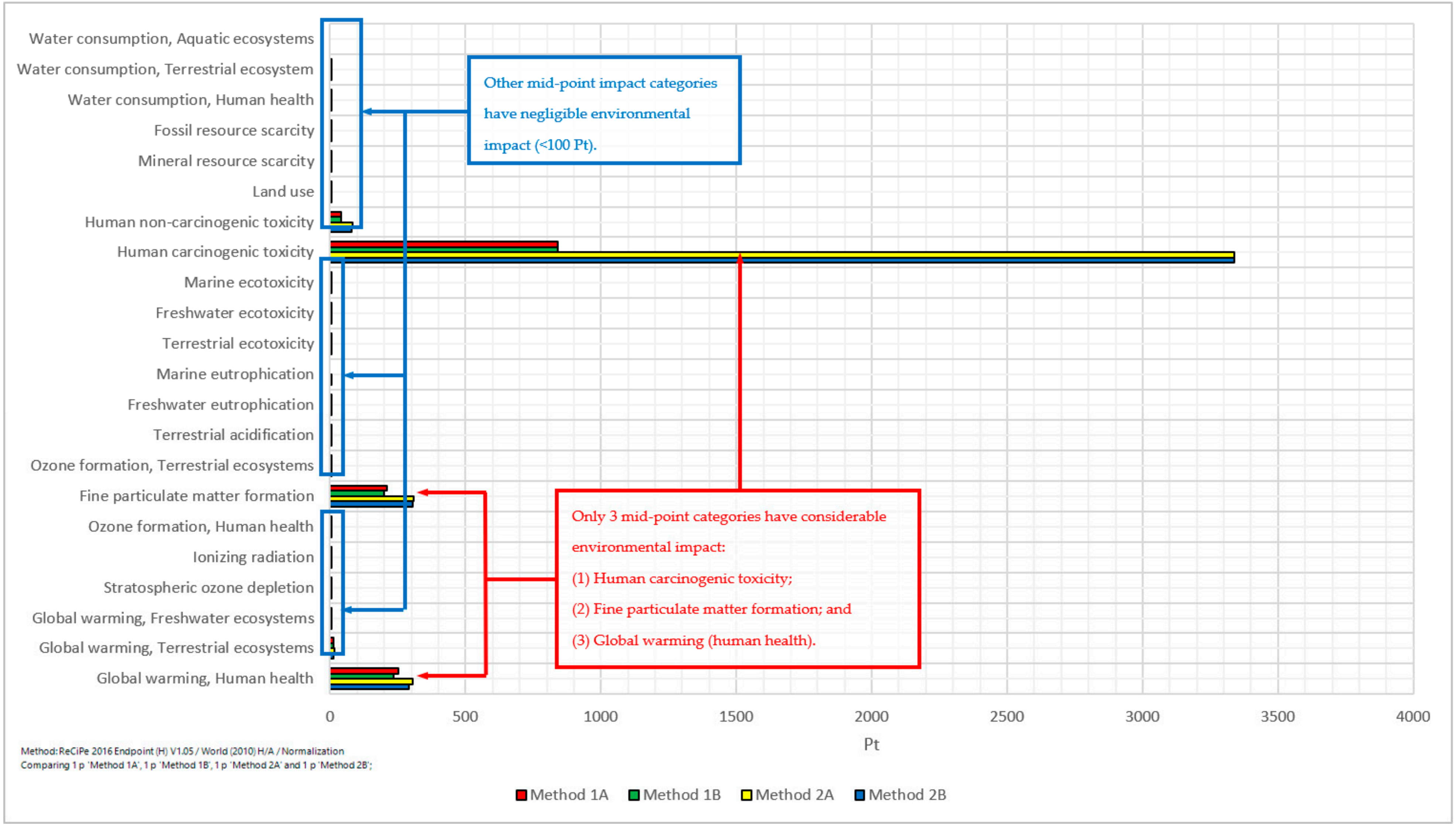

Figure 17. Comparison of actual characterization values for each mid-point category for all methods.

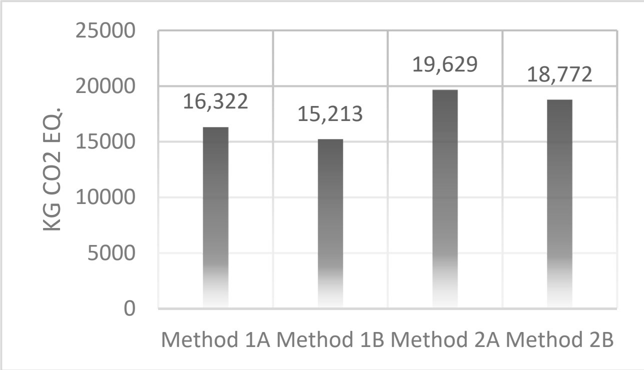

Figure 18. Comparison of global warming (human health) impact.

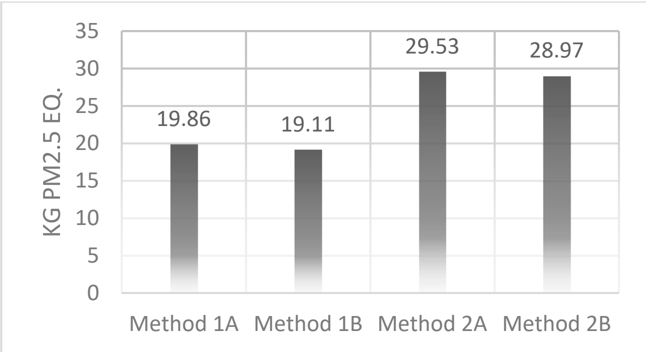

Figure 19. Comparison of particulate matter formation impact.

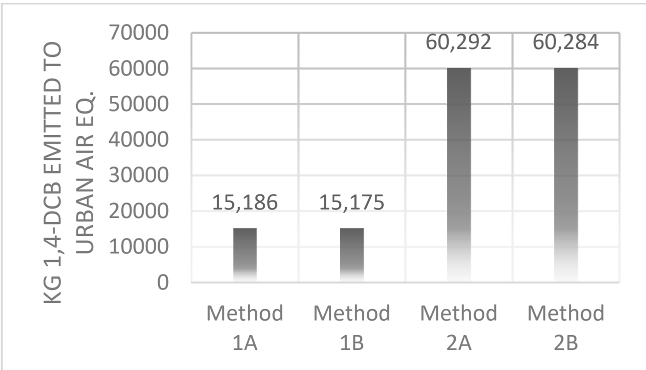

Figure 20. Comparison of human carcinogenic toxicity impact.

3.2.4. Limitations of the Life Cycle Impact Assessment and Interpretation

It should be emphasized that the environmental impacts of the four retrofitting approaches are primarily based on the quantities of materials used for each method and material alternative. Recently published secondary sources from Argin and Uzal [21] and Claisse [22] depicting actual design mixes that are comparable for both material alternatives were used to estimate the environmental effects of utilizing OPC-based and calcined clay-modified mortars. The comparability lies in the uniform compressive strength for both material alternatives. Since both materials have the same compressive strength, this assures that the comparison is made between two equivalent material alternatives. The validity of the results of this study is bounded by the mortar design mixtures and their corresponding compressive strengths as employed in the analyses.

4. Conclusions and Recommendations

Sustainable approaches in construction are needed amidst the diminishing global resources. The use of calcined clay and limestone filler as supplementary cementitious material (SCM) to concrete is a viable way to decrease the CO_2 emission due to cement production. A case study about retrofitting alternatives is presented using an actual multi-purpose complex situated in Jala-Jala, Rizal. Four retrofitting alternatives are considered: Method 1A—RC column jacketing with the use of mortar with ordinary Portland cement (OPC), Method 1B—RC column jacketing utilizing mortar with partial replacement of calcined clay and limestone filler, Method 2A—Steel jacketing with the use of OPC-based mortar, and Method 2B—Steel jacketing utilizing mortar with partial replacement of calcined clay and limestone filler. Secondary data sources are used to represent equivalent strength for OPC-based mortar and its counterpart with calcined clay and limestone filler.

Results of the LCA process network indicate that steel production constitutes the greatest environmental impact compared to Portland cement production, calcined clay, limestone filler, fine aggregates, and other energy resources such as electricity and diesel. It was also observed that freight transportation has a negligible impact compared to the production of steel and Portland cement. Based on LCA comparison, the method with the least environmental impact is Method 1B followed by Method 1A, Method 2B, and Method 2A. The midpoint categories which were determined to have the most impact are global warming, fine particulate matter formation, and human carcinogenic toxicity.

The use of calcined clay with limestone filler as the patched material in the retrofitting works resulted in a 4–7% decrease in kg CO_2 eq and a 2–4% decrease in kg PM 2.5 eq. Meanwhile, the employment of RC column jacketing over steel jacketing lessened the effect on human carcinogenic toxicity with an estimated decrease of 75% in kg 1.4-DCB emitted to urban air eq. These results solidify the justification for Method 1B as the method with the least environmental impact.

The results presented show that there is a great potential in the use of calcined clay with limestone filler as SCMs in concrete production because of its lower environmental impact than OPC-based concrete. Furthermore, since clay and limestone minerals are abundant, the reduction in CO_2 emission can be amplified if this concrete mixture is utilized not only in retrofitting but also in new building construction. The use of calcined clay with limestone filler as SCMs can potentially address the volume gap between the Portland cement production and good quality SCMs, hence driving CO_2 reduction through clinker substitution even further. The results also demonstrate that the RC column jacketing yielded a lower environmental impact than the full RC column steel jacketing. The study also confirms that CO_2 emission, fine particulate matter formation, and human carcinogenic toxicity are the environmental impact categories with the highest impact in concrete and steel production.

As part of the future work, cost and schedule analyses are being conducted to supplement the findings of this LCA study. The social aspect can also be investigated as part of a much broader work to complete the triple bottom line (TBL) approach comprising of People, Profit, and the Planet consistent with Sustainable Development Goals set by the United Nations [3]. Another important recommendation is to conduct actual design mixes and mechanical tests to establish the optimal mixes for both material alternatives in order to improve the LCA inputs. The durability of the mortar alternatives can also be considered in future work. This research could also be extended by exploring other retrofitting options such as the use of carbon fiber, reduced steel jacket lengths, etc. Another extension of the study is to investigate process or material production improvements other than material alternatives as they can be another source of environmental impact mitigation. Other recyclable materials in material development can also be explored.

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