A Lean & Green approach for the ecoefficiency assessment on construction sites: description and case study

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Research Article

Keywords: Lean & Green, Sustainable construction, Life cycle management, Value Stream Mapping, Eco-efficiency

Posted Date: April 15th, 2021

DOI: https://doi.org/10.21203/rs.3.rs-274743/v1

Abstract

Lean and Green seeks to increase added value and reduce waste generation, while also improving environmental sustainability performance in production activities. However, no studies were found exploring the potential results by combining Lean and Green with eco-efficiency assessments in the construction sector. Therefore, this paper aimed at proposing and testing a Lean and Green approach in three steps. Step 1 was based on the Value Stream Mapping application to calculate the Value Added of construction activities; step 2 focused on the Life Cycle Assessment of evaluated construction activities, and step 3 performed an eco-efficiency assessment of construction sites to guide decision-makers on selecting more lean and sustainable construction materials and strategies. A case study was developed for a 300m²-house construction considering two build options (reinforced concrete frame vs. light steel frame). The results affirm that light steel framing showed a Value Added 43% higher than the reinforced concrete in step 1, whilst having 8% less Global Warming Potential impacts in step 2. Step 3 concluded that light steel framing was 1.38 times more eco-efficient than the concrete structure. The proposed approach can be suitable for any building system evaluation in terms of construction technologies, materials, and/or production strategies and investigations towards more sustainable production.

1. Introduction

The concept of sustainable production has become significantly important in Architecture, Engineering and Construction. It stimulates better results in terms of quality, productivity, profitability and efficiency, reduced carbon emissions and energy demand (Evangelista et al., 2018), waste materials (Banawi and Bilec, 2014) and water consumption (Abd El-Hameed et al., 2017). This change characterizes a new production mindset, that puts together pressures and forces to rethink the construction processes (Saieg et al., 2018) from early design stages to a building's end of life. Indeed, considering the environmental impacts of a building's entire life cycle has come to the forefront of sustainability in the construction sector (Rezaei et al., 2019) and a holistic vision seems to be more appropriate given such a paradigm change.

Lean thinking contributes significantly in terms of "doing more with less", with basic assumptions towards higher productivity and efficiency to add more value for the final customer (Womack and Jones, 1996). Dües et al. (2013) and Vinodh, Arvind and Somanaathan (2011) affirm that lean practices are synergistic for green processes. Green thinking brings a new consciousness about environmental wastes and consequences to the production site (Deif, 2011).

Environmental experts and researchers have investigated the relationship between Lean and Green practices (Dües et al., 2013; Kurdve et al., 2014; Garza-Reyes, 2015). Until the 1990's, companies have typically investigated end-of-pipe treatment and control technologies to reduce toxic materials and emissions. The association of lean manufacturing with sustainability emerged at the end of the 1990's. Florida (1996) introduced the Lean & Green concept to improve manufacturing processes and increase productivity to give better opportunities for environmental improvements. This was followed by ideas like “lean is green” to associate quality to environmental management (King and Lenox, 2001), and to waste and cost reductions (Bergmiller and Mccright, 2009). Babalola et al. (2019) identified an association between waste reduction and sustainable construction to lean principles, as a methodology to minimize waste, maximize value and reduce costs thereby providing high performance buildings, optimizing environmental, social, and economic benefits (Horman et al., 2006).

All these contributions have confirmed the synergy of Lean and Green. However, their applications are mainly on the shop-floor areas of manufacturing companies (Vinodh et al., 2015; Garza-Reyes et al., 2018) and studies available for the construction sector are scarce.

Riley et al. (2005) explained that this synergy is indeed efficient when applied to the design-build stage, contributing up to 20% initial costs savings because of energy efficiency and reduced waste. Besides energy efficiency, improved indoor environment quality, increased health and occupant productivity and minimization of resource usage are other typical benefits of Lean and Green (Lapinski et al., 2006).

Similarly, eco-efficiency can be used to better integrate Lean and Green approaches towards environmentally sustainable manufacturing (Garza-Reyes, 2015; Alves et al., 2016; Abreu et al., 2017; Carvalho et al., 2017; Leme et al., 2018). The eco-efficiency concept supports analysis to deliver competitive products looking also at the environmental performance of products and processes. Again, no studies on the construction sector were found, which reveals a research and practice gap to be explored as to potential results of jointly applying Lean-Green and eco-efficiency assessments to the construction sector.

On one hand, Value Stream Mapping (VSM) is a lean tool that can use metrics to detect opportunities for simultaneously improving value aggregation in the production stream and assessing production waste over the construction phase (Rosenbaun et al., 2013). On the other hand, Life Cycle Assessment (LCA) methodology can provide in-depth data on environmental life cycle impacts (Haes, 1993). Combining VSM and LCA facilitates material, energy and information flow analysis within a company, as well as the development of new strategies towards sustainable production (Pampanelli et al., 2014; Vinodh et al., 2015).

Therefore, this paper aims to propose and test an integrated Lean and Green approach for eco-efficiency assessment of construction works using VSM and LCA tools. Section 2 describes the proposed approach and the tests made for a selected case study (reinforced concrete frame vs. light steel frame). In Section 3 we discuss the results and display our conclusions and remarks in Section 4.

2. Material And Methods

The proposed Lean and Green approach works as follows: VSM was considered as the lean tool able to identify the main material, energy and information flows (Rother and Shook, 2000) in the construction process. LCA was then used to quantifying the potential environmental impacts associated with the cradle-to-handover system under evaluation (ISO, 2006a, 2006b). The results were obtained by jointly analyzing VSM and LCA outcomes as eco-efficiency indicators, which combined economic and environmental performance information for case study interpretation.

2.1 Step 1: Lean construction analysis

All the actions required for the production flow from raw material until delivery to customer are together called the “value stream”. The VSM tool helps to map the entire stream in diagrams, to analyze results based on a set of metrics, and to design a future-state vision to be implemented on the shop-floor (Rother and Shook, 2000).

The processes analysis consists of collecting data in a production flow (in this case, at a construction site) by using metrics and packing gathered data into indicators (Rother and Shook, 2000). VSM diagrams allow the identification of real consumption and waste throughout the value stream, and the identification of opportunities for improvements in terms of time, quality and/or economic issues. Table 1 represents metrics used for data collection. Table 2 shows the indicators that can be calculated, which help to uncover the economic performance of processes by converting added value into currency metrics.

Table 1: Metrics used to calculate VSM indicators

Metric	Unit	Description
Start date	Day, month, year	Service start date.
Conclusion date	Day, month, year	End of service.
Office hours	Hours	Working hours in a week.
Working days	Unit	Total number of working days.
Non-working days	Unit	Total number of days in e.g. weekends and holidays.
Suspended working days	Unit	Total number of days where services were suspended due to unexpected events on the construction site (e.g. security problems, late delivery of materials).
Number of employees	Unit	Total number of employees.
Distance Traveled	Kilometers	Total distance traveled - between the departure and return by the trucks for material delivery.
Material purchased (M_{pur})	Kilograms	Amount of material delivered to construction site.
Material in project (M_{proj})	Kilograms	Amount of material requested in project.
Materials or services cost	Currency (Brazilian Real)	Total costs of materials or services requested in project.
Labor costs (C_lab)	Currency (Brazilian Real)	Total operational costs such as direct and indirect labor used in the site management (workers, managers).

Table 2: VSM indicators chosen for economic analysis.

Reference	Indicator		Unit
ECONOMIC	Lead time	L/T	Hours (H)
	Cycle time	C/T	Hours (H)
	Value added time	VAT	Hours (H)
	Wasted material	M_{was}	Kilogram (kg)
	Embedded material	M_{emb}	Kilogram (kg)
	Value added	VAP	Currency (Brazilian Real - R$)
	Non-value added	NVAP	Currency (Brazilian Real - R$)

The metrics in Table 1 were used to calculate, for example, the total value added to the production stream (VAP) as indicated in Table 2. The VAP indicator is the sum of the total costs with embedded materials (C_M_{emb}) and labor (C_lab).

$$VAP = C\_Memb + C\_lab \quad (1)$$

Where, the M_{emb} is the net balance between total materials purchased (M_{pur}) and total wasted materials (M_{was}). M_{was} was defined as the difference between M_{pur} - M_{proj}. Thus, VAP is calculated in monetary terms – in this case, expressed in Brazilian currency (R$).

The total production waste in the flow (NVAP) can be calculated as a fraction of the wasted time plus materials and other resources (people, transport, stocks) not incorporated in the construction and that should be minimized to increase profitability.

The time associated with the VAP is defined as VAT, i.e., the total value-added time in the stream. VAT represents the sum of the cycle time (C/T) of each process under investigation (process 1 to process n), as shown in Equation 2 (Rosenbaum et al., 2008).

$$VAT = \sum_{1}^{n}(Cycle\ time) \quad (2)$$

VAT represents a part of the lead time (L/T) necessary to finish the construction activities under investigation. As such, a high VAT lowers L/T and increases VAP. Therefore, to aggregate more value it is necessary to increase VAT and VAP. In general, the lead time (L/T) in construction is high because of the high amounts and variability of the required materials and services. For example, structural elements are not identical to each other as in a mass manufacturing system (Rosenbaum et al., 2013), but if VAT is higher, L/T tends to be lower as NVAT activities can be minimized.

2.2 Step 2: Green construction analysis

ISO 14040 and 14044 (2006a, 2006b) standards orient the use of life cycle assessment (LCA) to the identification of life cycle environmental hotspots in processes, services, and products. The general methodology can be organized into four steps: (i) goal and scope definition, (ii) life cycle inventory analysis, (iii) life cycle impact assessment and (iv) LCA interpretation. The proposed Lean and Green approach follows the same structure of an LCA, since it uses the information extracted from the VSM application in Step 1, as foreground input flows. However, data is converted to quantify environmental impacts and to estimate the environmental performance of construction processes.

LCA for construction works should follow the criteria established by BS EN 15978: 2011 (BSI, 2011). This standard breaks a construction life cycle into product stages (modules A1 to A3), construction stage (modules A4 to A5), use stage (modules B1 to B7) and end of life stage (modules C1 to C4) and selects seven impact categories: Global warming potential (GWP – kg $CO_{2\ equiv.}$), stratospheric ozone layer depletion potential (ODP – kg $CFC_{11\ equiv}$.), acidification potential of land and water (AP – kg $SO_{2\ equiv.}$), eutrophication potential (EP – kg $PO_{4\ equiv.}$), formation of photochemical oxidants potential (POCP – kg Ethene $_{equiv.}$), abiotic resources depletion potential for elements (ADP_el – kg Sb $_{equiv.}$) and for fossil fuels (ADP_ff – MJ $_{equiv.}$).

For the application of the Lean and Green approach, only GWP impacts were calculated for the eco-efficiency assessment. However, the remaining categories described here could be used for an extended eco-efficiency investigation.

The VSM data was used to consolidate the foreground data for the life cycle inventory step, from a cradle-to-handover perspective. Previous studies have stated that the “cradle to handover” (similar to “cradle to gate”, but more appropriate for construction services), can provide significant information to define the environmental consequences of the construction itself (Gámez-García et al., 2019).

Thus, the LCA of the case study described in section 2.3 followed BS EN 15978:2011 (BSI, 2011). Given the focus on the construction works, a cradle-to-handover perspective (stages A1 to A5) was adopted for two structural variants: reinforced concrete frame and light steel frame. The function unit used was the performance (in terms of GWP) of the whole structural frame produced by each construction technique.

The openLCA software tool v.1.7 and the ecoinvent database version 3.6 were used to supply background data for completing the product systems of concrete structure and light steel framing during the LCA modelling process. Information on the datasets and background LCI flows used for LCA modeling was provided as supplementary material. The environmental hotspots analysis was used to understand GWP impacts of each material and construction activity in both structural variations considered for a high-end house design in Brazil.

2.3 Step 3: Eco-efficiency construction analysis

Environmental management can be performed by including an eco-efficiency assessment of product systems (ISO, 2012). Within the eco-efficiency assessment framework, the environmental impact can be evaluated by using LCA results, and the added value of the system can reflect the production in monetary terms. Therefore, the ratio between product value and environmental impacts was used to calculate eco-efficiency indicators for the construction process. For the case studied, we used the ratio between VAP and environmental impacts (Equation 3) to express results in terms of Brazilian currency per unit of global warming impact (R$/kg CO2 equiv). We also used a factor (Equation 4) that expresses the relative level of improvement in eco-efficiency in simple numerical terms (the ratio of the Ecoef indicator to the current situation versus the future alternative).

$$\mathrm{Ecoef} = \frac{\mathrm{VAP}}{\mathrm{GWP}} \tag{3}$$

$$\mathrm{Improv\_Factor} = \frac{\mathrm{Ecoef}_{(\mathrm{future\ state})}}{\mathrm{Ecoef}_{(\mathrm{current\ state})}} \tag{4}$$

According ISO 14045:2012 (2012), eco-efficiency indicators should be analyzed by comparison, to highlight the most eco-efficient system relative to others. In this case, eco-efficiency analyses should be performed for at least two scenarios: the current scenario (baseline) and an alternative scenario that pursues a more sustainable production. In our study, the current scenario is a reinforced concrete frame, whilst the alternative (future) scenario is a light steel frame structure. Depending on the VAP and GWP results for the current and future scenarios, four hypothetical situations may occur (Table 3) to provide recommendations to best guide decision-making in construction.

Table 3: General recommendations framework based on the proposed Lean & Green approach

Hypothetical situation	**Result**	**Recommendation**
H1	Future VAP and GWP are lower than the current state	Review hypothetical scenarios to find other practices that can increase VAP in the future state, otherwise, maintain the current state
H2	Future VAP and GWP are higher than the current state	Review hypothetical scenarios to find other practices that can reduce GWP in the future state, otherwise, maintain the current state
H3	Future VAP is lower than the current state; Future GWP is higher than the current state	Review hypothetical scenarios to find other practices that can increase VAP and reduce GWP in the future state, otherwise, maintain the current state
H4	Future VAP is equal or higher than the current state; Future GWP is lower than the current state	Change to the future state. Where applicable, find additional practices to increase VAP in the future state

By definition, eco-efficiency is achieved only by reducing ecological impacts whilst delivering products with a competitive price for stakeholders (WBCSD, 2000a). As such, only H4 leads to real eco-efficiency results because the VAP is increased and the GWP is reduced at the same time in a future state (WBCSD, 2000b). In H1, despite the GWP reduction in the future state, the design change does not increase the VAP. H2 and H3 do not lead to sustainable production either, because the measures taken for the future state do not decrease the GWP.

2.3 Case study description

The case study considered two scenarios for the construction of a 300m²-house in Brazil. The current state considered a reinforced concrete structure and the future state a light steel frame scenario. Both structures were divided into six subprocesses (Figure 2): (1) deep foundation, (2) shallow foundation, (3) ground floor, (4) first slab, (5) first floor and (6) second slab. The research included primary data gathered through site observations, incoming invoice query, interpretation of structural projects and previous know-how of construction processes and logistics. The datasets generated during and/or analyzed during the current study are available from the author by reasonable request.

Additionally, the proposed Lean and Green methodological framework is summarized in Figure 3. The scheme in Figure 3 means that, for a synergistic relationship, not only must lean principles positively influence the implementation of green strategies, but also the other way around. Together, Lean and Green can guide decision-makers towards the best eco-efficiency results and production practices.

3. Results And Discussion

3.1 Reinforced concrete frame

The service costs such as labor for excavation, cutting and bending steel rebar, wood formwork manufacturing and concrete pouring services were included into the system boundaries. Indirect costs were accounted as services performed in parallel with the construction services, such as electricity and water supply. This data was processed to build a VSM diagram (Figure 4) with lean indicators such as C/T, L/T, and VAT.

Only 26.2% of the time consisted of activities that added value to the end customer. The other mapped activities only generated costs and the materials were not incorporated into the concrete structure. From the client's point of view, these activities can be assumed as non-added value to the stream (LEI, 2011).

The processes with the highest L/T were (2) shallow foundation, (6) second slab, and (4) first slab. Process (2) was slower than the others, as it required a lot of manual activities for the excavation of foundation blocks and strip footing. This service also had an additional vulnerability to weather conditions that could require more effort for mud removal and re-excavation of the trenches. The rework activity does not add any value to the final product and can be considered as waste that takes time, human and financial resources (PICCHI, 2000), therefore increasing L/T and decreasing VAT. Processes (6) and (4) were similar to each other and required the making and fixing of the plywood formwork and concrete pouring activities.

The manufacturing of wood shapes did not add any value to the final product most of the time. In terms of productivity, the need to cut the plates and the use of the fixing elements took several hours of work, as the activity required the development of non-standard parts because it depended directly on the dimensions of the structural part and the movement on site to look for tools (handsaw, hammer) or auxiliary materials. In addition, the plates and fixing elements were cut a significant distance from where they were needed, and only after they were cut to size were they transported to the structure site. All these facts led to the waste of transportation and movement (PICCHI, 2003). They also contributed to the waste in terms of waiting time, since the assembly and fixing of the shuttering did not always occur in a continuous flow.

In terms of material waste, the wood forms and the fixing elements (boards, and battens) received several different cuts, both in the first use (ground floor) and in their reuse (upper floor). This led to significant waste generation because, if there was a plan to cut and keep the parts, the materials could be recovered many times. Finally, at the end of construction, these materials were discarded as solid waste for landfill, generating environmental and financial waste.

It is necessary to identify first which kind of waste could be eliminated or mitigated by employing other construction methods depending on the context of the construction site in question, such as the use of metal forms pre-sized specifically for structural parts and for the loads that must be withstood during concreting. This would avoid hours of work on cuts, fixing, waste generation and the disposal of slabs and wood, increasing VAP in construction.

The VSM (Figure 4) shows the total amount of materials used for the execution of the processes and the VAP calculation. The total amount of materials considers the sum between the costs of materials purchased, labor costs and indirect construction costs (Mattos, 2006). The results found for the VAP and other parameters are summarized in Table 4.

Table 4: VAP and NVAP indicators for the construction - concrete structure

Processes	**Initial investment (R$)**	**NVAP (R$)**	**VAP (R$)**	**Utilization rate (%)**
(1) Deep foundation	19,113.07	6,952.31	12,160.77	63.6%
(2) Shallow foundation	45,143.45	16,295.61	28,847.84	63.9%
(3) Ground floor	18,245.47	6,894.04	11,351.42	62.2%
(4) First slab	53,639.46	13,396.98	40,242.48	75.0%
(5) First floor	14,109.17	5,099.28	9,009.89	63.9%
(6) Second slab	40,812.02	16,062.16	24,749.86	60.6%

The average utilization rate of the processes was 64.9%. In other words, one third can be classified as waste costs originating on the construction site, as also discussed by Grohmann (1998). The highest values of NVAP were found for processes (2), (4) and (6). Despite the process (4) having the third largest NVAP, it was also the one that has the highest utilization rate = 75.0%. This shows that large volume activities like process (4) can hide waste costs.

In terms of green indicators, the LCA study was performed based on the product system and the life cycle inventory of a concrete structure, shown in Figure 5 and Table 5, respectively, resulting in the GWP impacts in Table 6.

Table 5: Life cycle inventory for the concrete structure scenario

	(1) Deep foundation	(2) Shallow foundation	(3) Ground floor	(4) First slab	(5) First floor	(6) Second slab
INPUT						
MATERIAL CONSUMPTION						
Concrete 25 MPa (m^3)	8.00	31.00	4.50	29.50	4.50	20.50
Steel rebar (kg)	1,158.66	2,243.68	823.20	2,909.55	357.00	1,424.85
Plywood for outdoor use (m^3)	-	-	1.15	2.24	0.64	2.00
Wood (m^3)	-	-	0.83	1.94	-	-
Concrete transportation (t.km)	706.56	10,951.68	397.44	10,421.76	397.44	5,431.68
Steel transportation (t.km)	42.64	330.27	30.29	428.29	13.14	157.30
Plywood/wood transportation (t.km)	-	-	10.79	21.00	5.97	18.75
OUTPUT						
Deep foundation structure (kg)	19,069.47	-	-	-	-	-
Shallow foundation structure (kg)	-	65,844.96	-	-	-	-
Ground floor structure (kg)	-	-	11,230.24	-	-	-
First slab structure (kg)	-	-	-	68,967.79	-	-
First floor structure (kg)	-	-	-	-	10,897.00	
Second slab structure (kg)	-	-	-	-	-	48,339.67
WASTES						
Concrete waste (m^3)	0.51	4.45	0.15	2.41	0.10	0.92

Steel rebar waste (kg)	55.17	106.84	39.20	138.55	17.00	67.85

Table 6: GWP results for the concrete structure scenario

	Processes	GWP (kg CO_2 equiv./structure)
(1)	Deep foundation	4,263.09
(2)	Shallow foundation	13,202.61
(3)	Ground floor	3,560.19
(4)	First slab	15,810.37
(5)	First floor	2,162.34
(6)	Second slab	9,486.53
Total amount of impacts		**48,485.13**

Process (4) was the biggest contributor to the whole product system's GWP, representing 33% of the total structure's impact. Figure 6 shows a mass-based contribution analysis of all the materials required in the concrete structure. Concrete represents approximately 40% of all mass consumed in the cradle-to-handover life cycle. The cement considered in the concrete production represents up to 40% for each cubic meter of concrete produced. The steel used in the concrete parts has 38% mass relevance and due to its production chain, it represents a relevant contribution in the product system, as also pointed out by Bento (2016).

After VSM and LCA, its was observed that ready-mixed concrete and steel rebar, fundamental materials for making reinforced concrete structures, were responsible for significant waste and life cycle environmental impacts during construction. From the results, the need to eliminate or reduce the waste of resources is clear (time, material and money), along with a need to replace the use of reinforced concrete (concrete and steel bars). According to Almeida and Picchi (2018), the light steel frame method can rationalize processes and mitigate waste generation by reducing execution time and material losses when compared to traditional construction methods. Cabeza et al. (2014) also mentioned that light steel framing can represent up to a 44% reduction in net CO_2 emissions in relation to a reinforced concrete structure, for example.

3.2 Light Steel Framing

To elaborate a new future state, the VSM diagram (Figure 7) was applied to the same house and scope definitions previously discussed.

Light steel framing reduces L/T by up to 60%. The reduction in L/T means the reduction of the period between the beginning and the end of the construction services, which in turn will primarily lead to the reduction of indirect costs and, secondly, to the reduction of the NVAP. This happens because the materials can be delivered in dimensions that will be used at the construction site eliminating the need for cutting and bending, increasing the material utilization rates as well (see Table 4). For the same reason, subprocess (4) presented the best value for VAP again, showing materials use could reach a level of approximately 92%, which for the construction site scenario is an excellent target for reducing waste.

Considering that these parts form a specific project that guide the correct assembly of the steel profiles, the prefabricated parts can also reduce waiting and movement times within the construction site. As a result, waste can be significantly reduced, thereby reducing indirect costs, waste costs and increasing VAP, as detailed in Table 7.

Table 7: VAP and NVAP for the light steel framing scenario

Processes	**Investment (R$)**	**VNAP (R$)**	**VAP (R$)**	**Utilization rate (%)**
(1) Deep foundation	14,466.42	5,713.72	8,752.70	60.5%
(2) Shallow foundation	29,923.01	8,732.10	21,190.91	70.8%
(3) Ground floor	25,070.70	3,291.84	21,778.86	86.9%
(4) First slab	96,161.70	7,743.26	88,418.45	91.9%
(5) First floor	19,048.02	1,799.03	17,248.99	90.6%
(6) Second slab	29,442.10	6,022.50	23,419.60	79.5%

The LCA was also performed for the future state scenario and Figure 8 shows the product system for light steel framing. The life cycle inventory for light steel framing is detailed in Table 8.

Table 8: Life cycle inventory for the light steel frame scenario

	(1) Deep foundation	(2) Shallow foundation	(3) Ground floor	(4) First slab	(5) First floor	(6) Second Slab
INPUT						
MATERIAL CONSUMPTION						
Concrete 25 MPa (m^3)	5.60	21.70	-	-	-	-
Steel rebar (kg)	811.06	1,570.58	-	-	-	-
Steel rolled (kg)	-	-	2,561.89	8,760.69	698.70	566.60
Cold-formed steel (kg)	-	-	23.58	629.51	1,036.42	978.46
Galvanization (m^3)	-	-	1.51	40.29	66.33	62.62
Oriented Strand Board (m^3)	-	-	-	5.08	-	4.00
Concrete transportation (t.km)	494.59	40.55	-	-	-	-
Steel rebar transportation (t.km)	15.73	7,666.18	-	-	-	-
Steel rolled transportation (t.km)	-	-	641.20	156.12	430.31	242.66
Cold-formed steel transportation (t.km)	-	-	-	126.15	-	8.16
OSB transportation (t.km)	-	-	-	62.54	-	62.54
OUTPUT						
Deep foundation structure (kg)	13,538.51	-	-	-	-	-
Shallow foundation structure (kg)	-	50,968.05	-	-	-	-
Ground floor structure (kg)	-	-	2,326.93	-	-	-
First slab structure (kg)	-	-	-	11,504.46	-	-
First floor structure (kg)	-	-	-	-	1,561.61	-
Second slab	-	-	-	-	-	3.752,64

structure (kg)						
WASTE						
Concrete waste (m³)	0.28	1.09	-	-	-	-
Steel rebar waste (kg)	40.55	78.53	-	-	-	-
Steel rolled waste (kg)	-	-	256.19	876.07	69.87	56,66
Cold-formed steel waste (kg)	-	-	2.36	62.95	103.64	97,85
OSB waste (kg)	-	-	-	197.92	-	197,92

The GWP results for the light steel framing system are shown in Table 9.

Table 9: GWP impacts for the light steel frame

	Processes	GWP (kg CO_2 equiv./structure)
(1)	Deep foundation	2,981.15
(2)	Shallow foundation	9,586.01
(3)	Ground floor	5,152.92
(4)	First slab	18,757.16
(5)	First floor	4,174.34
(6)	Second slab	3,811.93
Total impacts		**44,463.52**

Similarly to the concrete structure, process (4) was the main hotspot. It represents 42% of the structure's total GWP. The greater impact potential can be explained by looking at the contribution analysis (Figure 9), in which a high mass flow can be seen for the construction activities, representing approximately 11.000 kg per functional unit. The hot rolled steel production was responsible for up to 90% of consumption and cold-formed steel contributed up to 10%. As for GWP, Figure 10 shows that the concrete structure process generated 48.485,13 kg CO_2 equiv., while the light steel framing generated 44.463,51 kg CO_2 equiv., with a net difference equal to 4.021,61 kg CO_2 equiv. per functional unit. Light steel framing proved to be more advantageous than the concrete structure with an 8.2% reduction in life cycle greenhouse gas emissions.

3.3 Eco-efficiency assessment: concrete vs. steel structure

The results obtained for VAP and GWP in both the construction methodologies were used to generate eco-efficiency indicators.

In this case study, the eco-efficiency factor calculated by Equation 4 showed that light steel framing was 1.38 times more eco-efficient than concrete structures as a whole (Figure 11).

Figure 11: Comparison between eco-efficiency indicators per process for both the construction processes.

The eco-efficiency calculated by Equation 3 showed that the results were higher for the light steel framing in the six construction processes under investigation. The biggest eco-efficiency gap was found for process (6) with a relative difference of 57.5% between the two systems.

However, an in-depth analysis of the results was required to really interpret the eco-efficiency results with the support of the four reference-cases from Table 3. By doing this, it was concluded that only if processes (3), (4) and (5) are rethought to reduce GWP impacts, the change for the future state would really lead to more sustainable production.

In order words, an in-depth investigation is required for each of the six processes in terms of individual VAP and GWP results before taking a decision. The suggested hypothetical situations in Table 3 proved to be an important input to help decision makers find more sustainable strategies to be used in construction business activities.

From Figure 11, it was observed that the total number of environmental impacts (GWP) was higher for the concrete structure than for the light steel frame. On the other hand, the total amount of VAP was higher for the concrete scenario than for the light steel frame. Therefore, there was a trade-off between the two comparative construction scenarios.

For process (1), VAP and GWP have decreased from R$ 12,160.77 (concrete structure, Table 4) to R$ 8,752.70 (steel structure, Table 7) and from 4,263.09 kg CO_2 equiv. (Table 6) to 2,981.15 kg CO_2 equiv. (Table 9), respectively, when moving from the current (concrete structure) to the future state (steel structure). The process (2), however, showed VAP results from R$ 28,847.84 (Table 4) to R$ 21,190.91 (Table 7) and GWP changes from 13,202.61 kg CO2 equiv. (Table 6) to 9,586.01 kg CO_2 equiv. (Table 9), moving from the current to the future state scenario. For processes (1) and (2), light steel framing enables a reduction in the structural load because of the lightness of pillars, beams, slabs and walls, decreasing the structural sections and the amounts of materials consumed. Therefore, reducing the weight of the structure is a valid alternative for reducing the GWP impacts. Based on Table 3, both of these two processes are classified into H1, with the recommendation of adopting the future state to be decided case-by-case. In this case, we opted for a neutral position in the decision, as Figure 11 shows a balance between the comparative eco-efficiency results for these processes.

As shown in Tables 6 and 9, processes (3), (4) and (5) have lower result values for GWP impacts on the current state than for the future state. For process (3), for example, the VAP increased from R$ 11,351.42

to R$ 21,778.56 and GWP increased from 3,560.19 kg CO_2 equiv. to 5,152.92 kg CO_2 equiv. when both moved from the current to the future state. According to Table 3, these processes are classified as H2, where the recommendation is to keep the current state and review the scenarios for the future state to support other practices to reduce GWP. In the processes (3), (4) and (5), the fact that light steel framing uses prefabricated materials and has a shorter C/T generates a reduction of indirect costs, the number of materials required (in kilograms) and, consequently, on waste generation. All of these contribute to changing the current state scenario to the future state option. However, there was an increase in the amount of GWP because the future state has higher impacts when compared to the concrete structure. Therefore, this fact does not lead to more sustainable production.

For the current and future states, process (6) has virtually the same result for VAP. Regarding the GWP, there was a substantial reduction of 59.81% moving from a concrete structure to light steel framing. According to Table 3, it would fall into the H4 situation, where the recommendation of the proposed Lean and Green approach is to make the changes from the current state to the future state. Therefore, this change would contribute to better eco-efficiency.

The final decision for this case study was to build the house by combining the use of mixed structures (reinforced concrete with light steel frame). This situation would lead to a really sustainable environmental construction, where processes (3), (4) and (5) would give focus on the concrete structure, while process (6) would be performed with steel frame. Processes (1) and (2) could be based on concrete or steel frame because the eco-efficiency results were the same.

Comparing with other integrated Lean and Green approaches (Abduh et al., 2014; Pampanelli et al., 2014; Hallam and Contreras, 2016), this paper proposes eco-efficiency assessments as a differential that bring the analytical process closer to the reality of businesses. In business, decisions tend to be made prioritizing increased profits and not necessarily reducing negative environmental impacts (Rezende et al., 2019). On the other hand, the Lean and Green approach developed proposed a simple manner for dealing with lean and green principles by calculating eco-efficiency indicators based on VSM and LCA tools and by using the reference-cases H1 to H4 to classify construction improvement recommendations.

4. Conclusion

This article has proposed a way to achieve sustainable production on construction sites by proposing a Lean and Green approach based on an eco-efficiency assessment. We selected a case study and compared the same house built with two different construction systems: concrete structure and light steel framing. The Lean and Green approach uses VSM as a lean tool, and LCA as a green tool. In the end, the decision-making process for construction workers and managers was based on an eco-efficiency assessment of the construction, which is a relatively new way to evaluate construction activities, since there is still a lack of papers in this area.

The Lean and Green approach developed is composed of three phases (see Figure 1), the VSM tool enabling a deep understanding of material and information flows in the construction stream. It was possible to see the sources of waste generation and to suggest improvement opportunities related to the minimization of lead times, cycle times, value added time and value added to the product. The environmental impacts were quantified through an attributional LCA based on BS EN 15978:2011 (BSI, 2011) and ISO 14040 (2006a) and 14044 standards (2006b). Lastly, the data was analyzed through eco-efficiency indicators.

The Lean and Green approach developed also proposed a separate analysis of the results, (i) considering only VSM results; and (ii) based on the LCA process results. In this way, it was possible to find other hotspots beyond the eco-efficiency assessment itself.

The application of the Lean and Green approach showed that light steel framing was more eco-efficient than the concrete structure, making it possible to affirm that, for this case study, the change would achieve a more sustainable production in terms of economic and environmental aspects. However, the analysis based on six construction processes revealed that not all of the individual processes resulted in a better ecoefficiency when comparing the future state with the current state scenario, and for these cases the recommendation would be to keep the current state scenario. Therefore, it was suggested to follow the guidelines proposed in Table 3, which provided recommendations according to eco-efficiency results. The final decision was to adopt a mixed structure.

The hypothetical situation H1 should be used case-by-case by decision-makers because the eco-efficiency trade-offs are not clear. H2 to H3, mean that environmental impacts do not decrease in a possible future state, and the recommendation would be to rethink the construction methods, because sustainable production cannot be achieved as a whole. In H4, the recommendation was to adopt the future state, because it reduces environmental impacts and, at the same time, increases the value added to the construction. Only H4 will enable the achievement of a more sustainable production according to the definition of eco-efficiency: “delivery of products with competitive prices and reduction of ecological impacts for the customer”.

It is important to emphasize that these conclusions are dependent on the location of the construction site (e.g. country, city, neighborhood), providers, constructors and their teams, because eco-efficiency results are closely linked to local prices, service execution procedures (that could result in lower or higher waste), and the selected environmental impact categories.

Declarations

Acknowledgments

This work was supported by the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) under grants 302722/2019–0 and 406017/2018-2.

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Figures

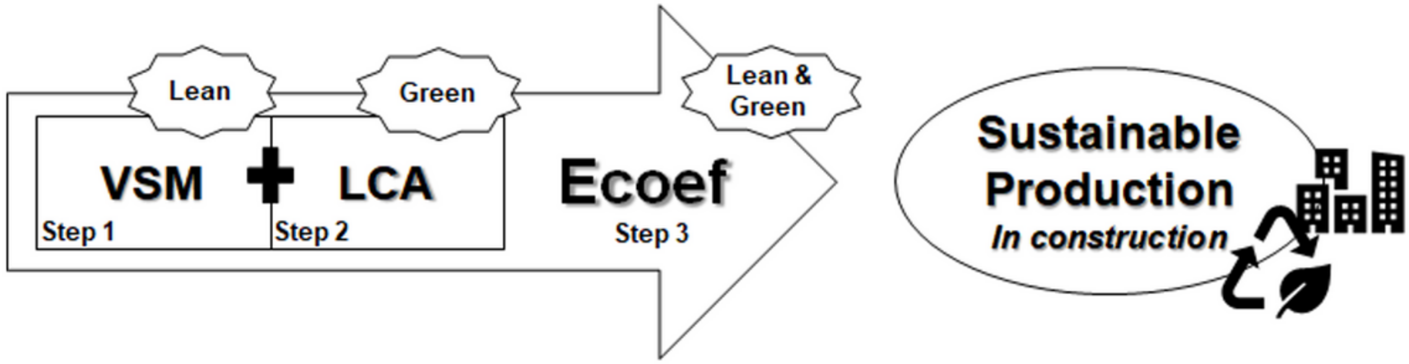

Figure 1

The proposed Lean & Green approach in three steps

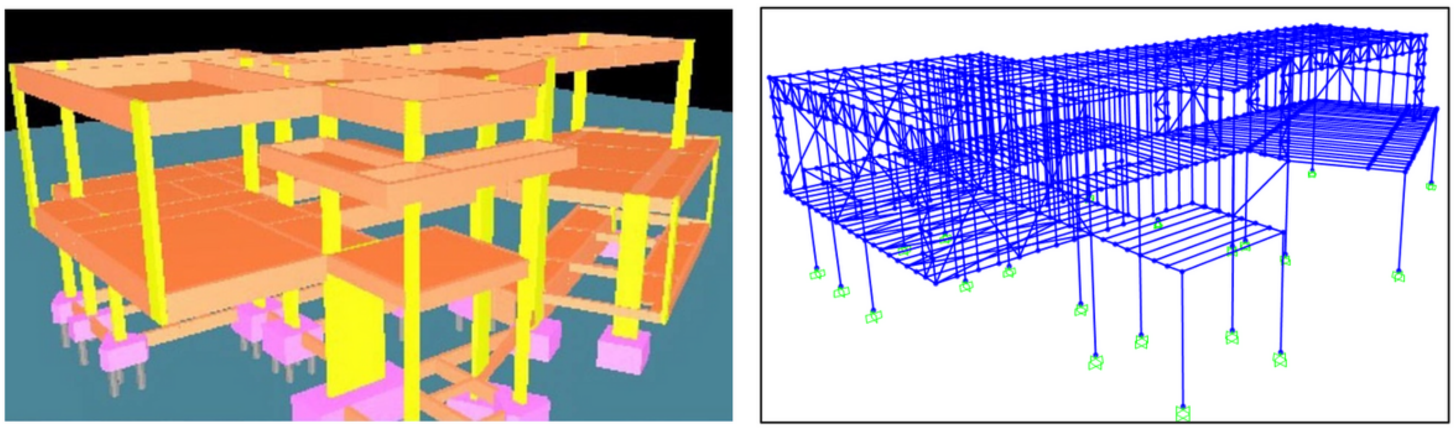

Figure 2

Structural conception variations: (left) reinforced concrete structure; (right) light steel frame

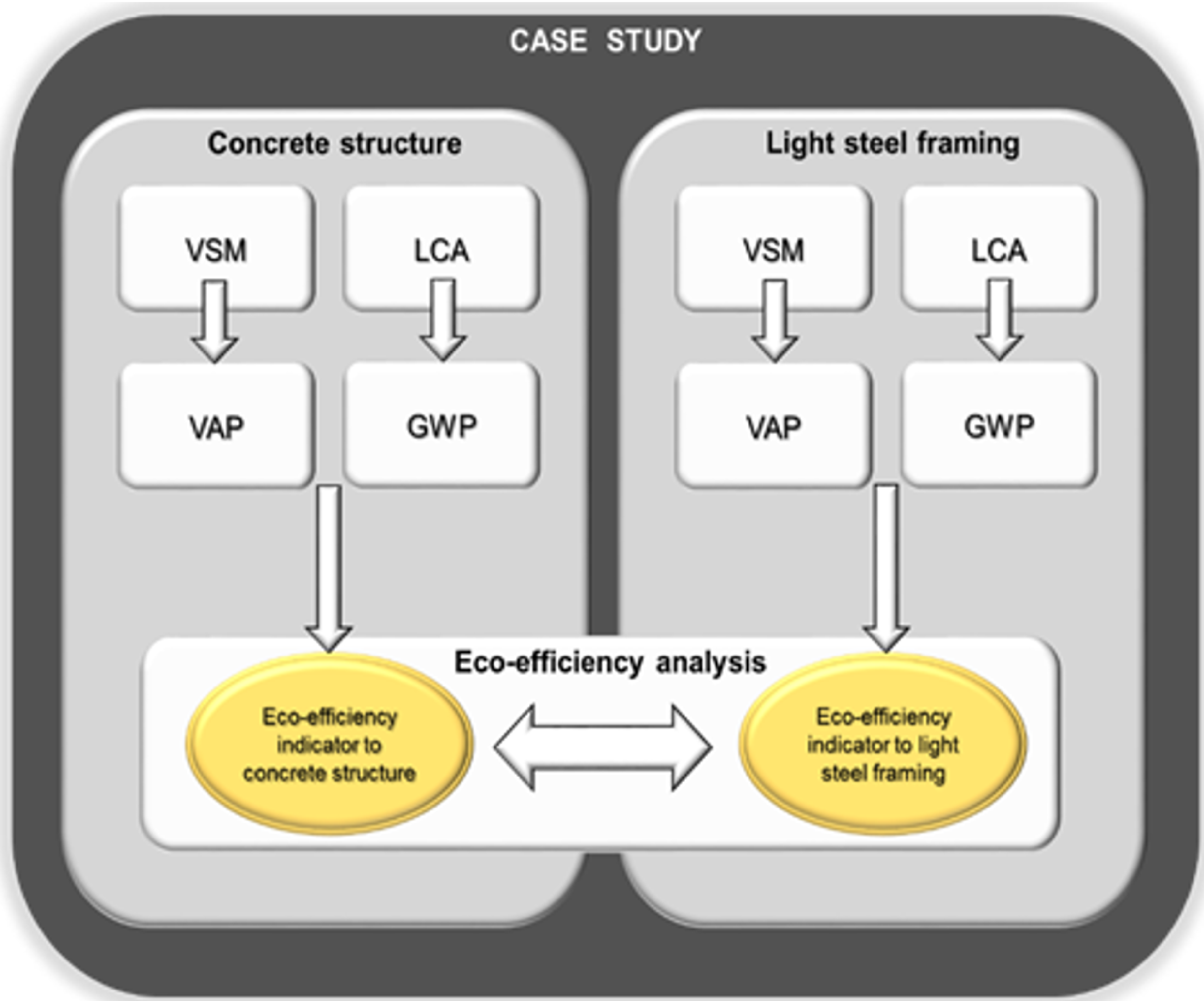

Figure 3

The proposed Lean & Green analysis for the reinforced concrete structure vs. light steel frame

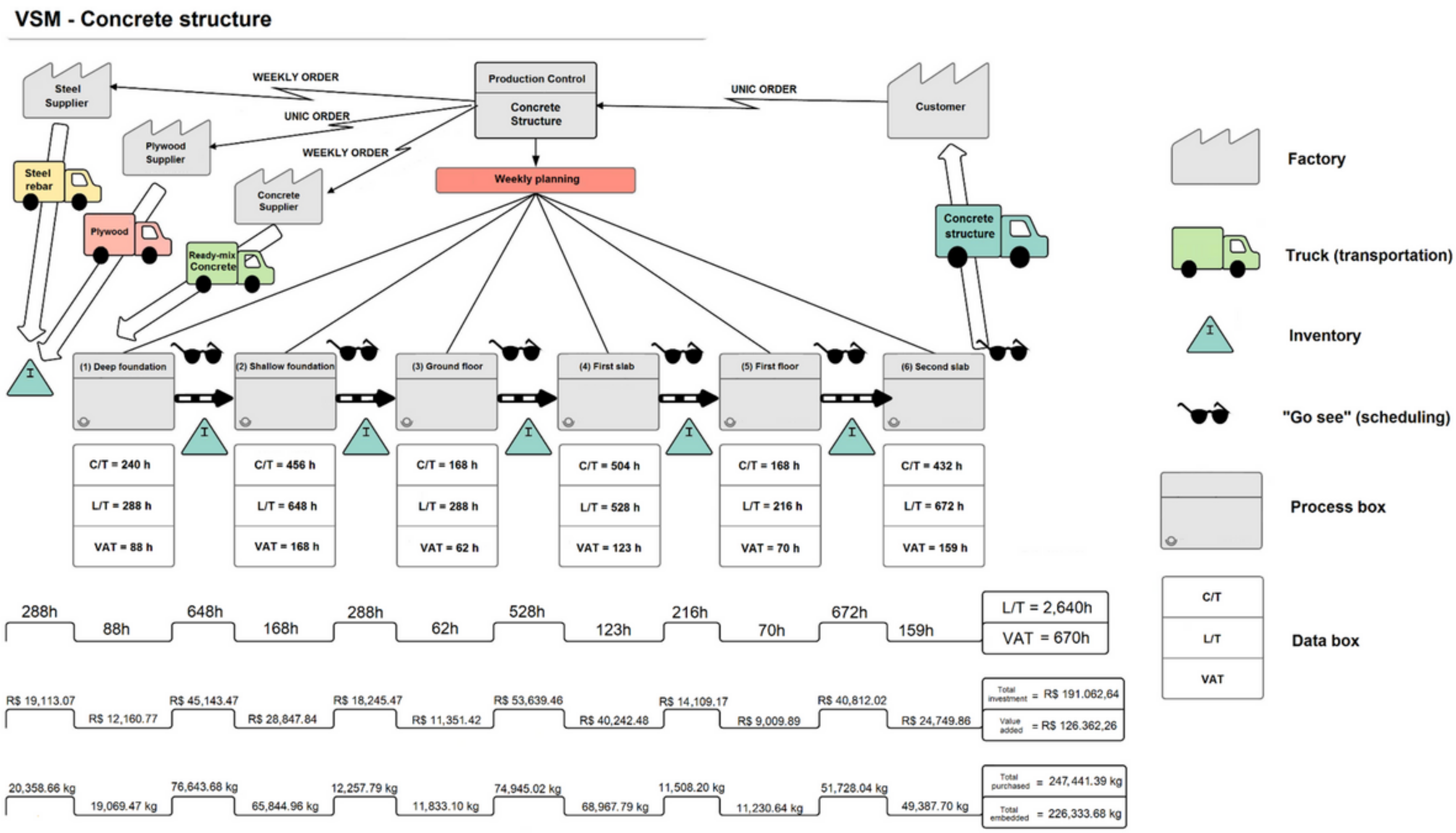

Figure 4

Current state VSM (reinforced concrete frame)

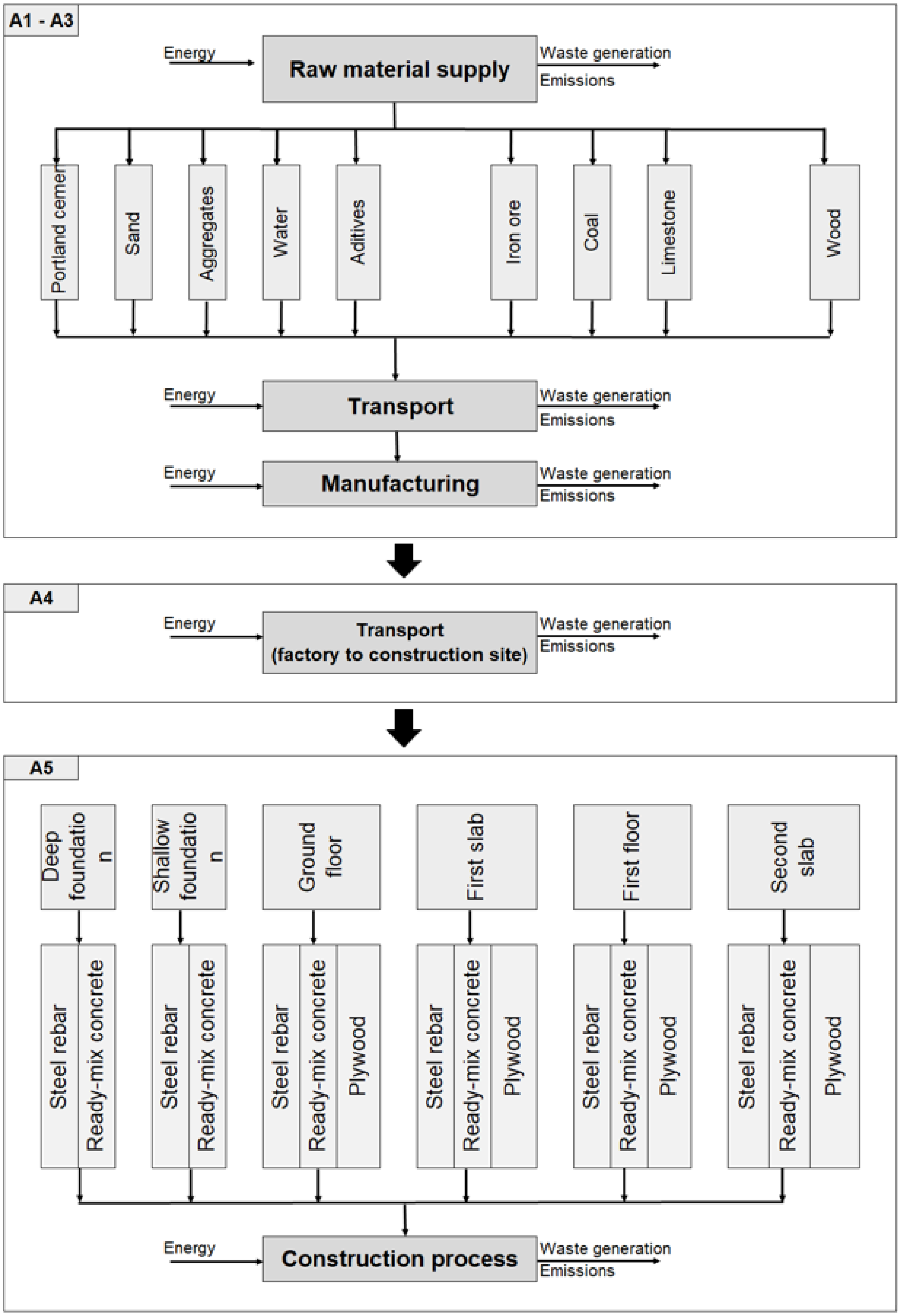

Figure 5

Product system of the concrete structure

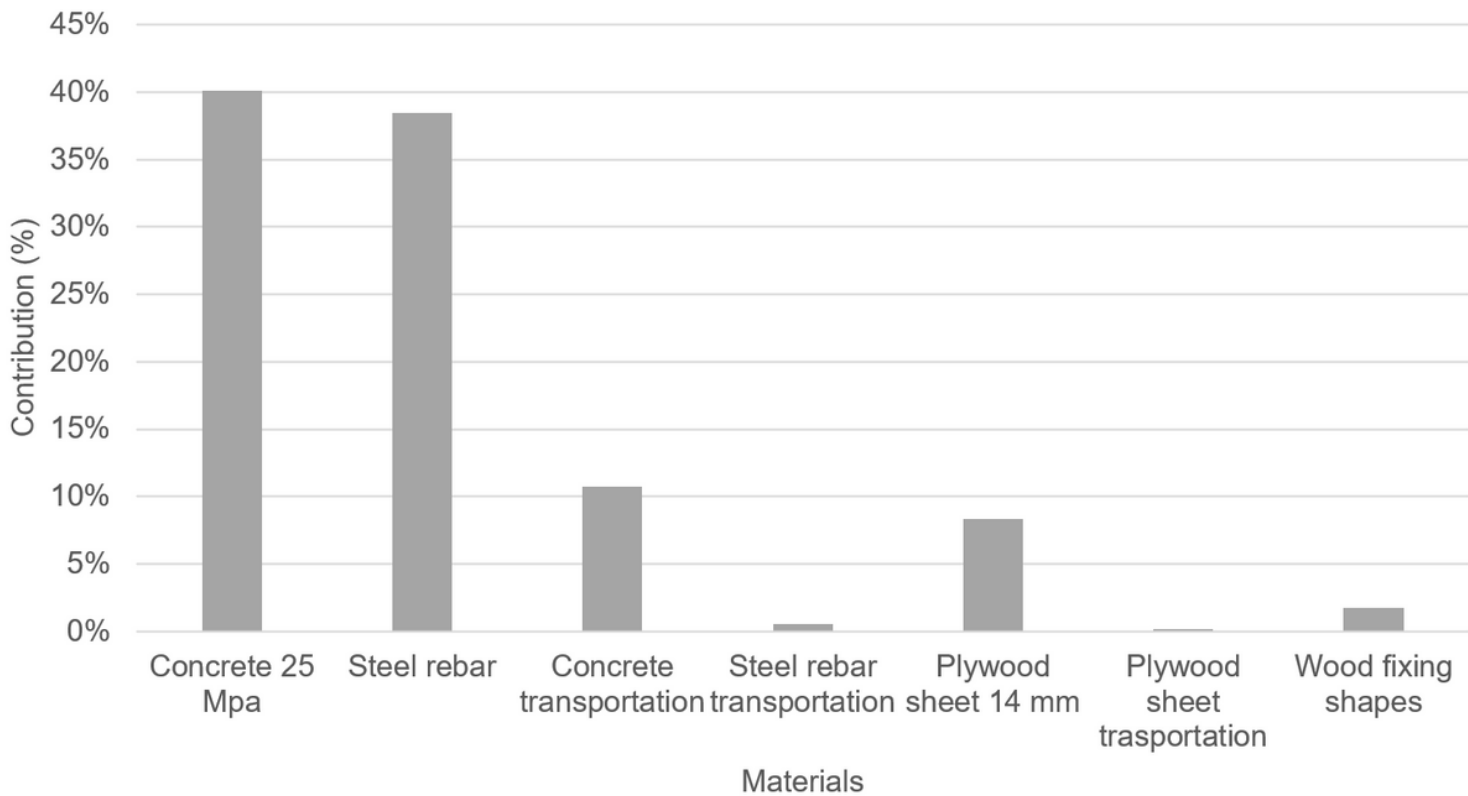

Figure 6

Process (4) - contribution analysis per type of material in the concrete structure scenario

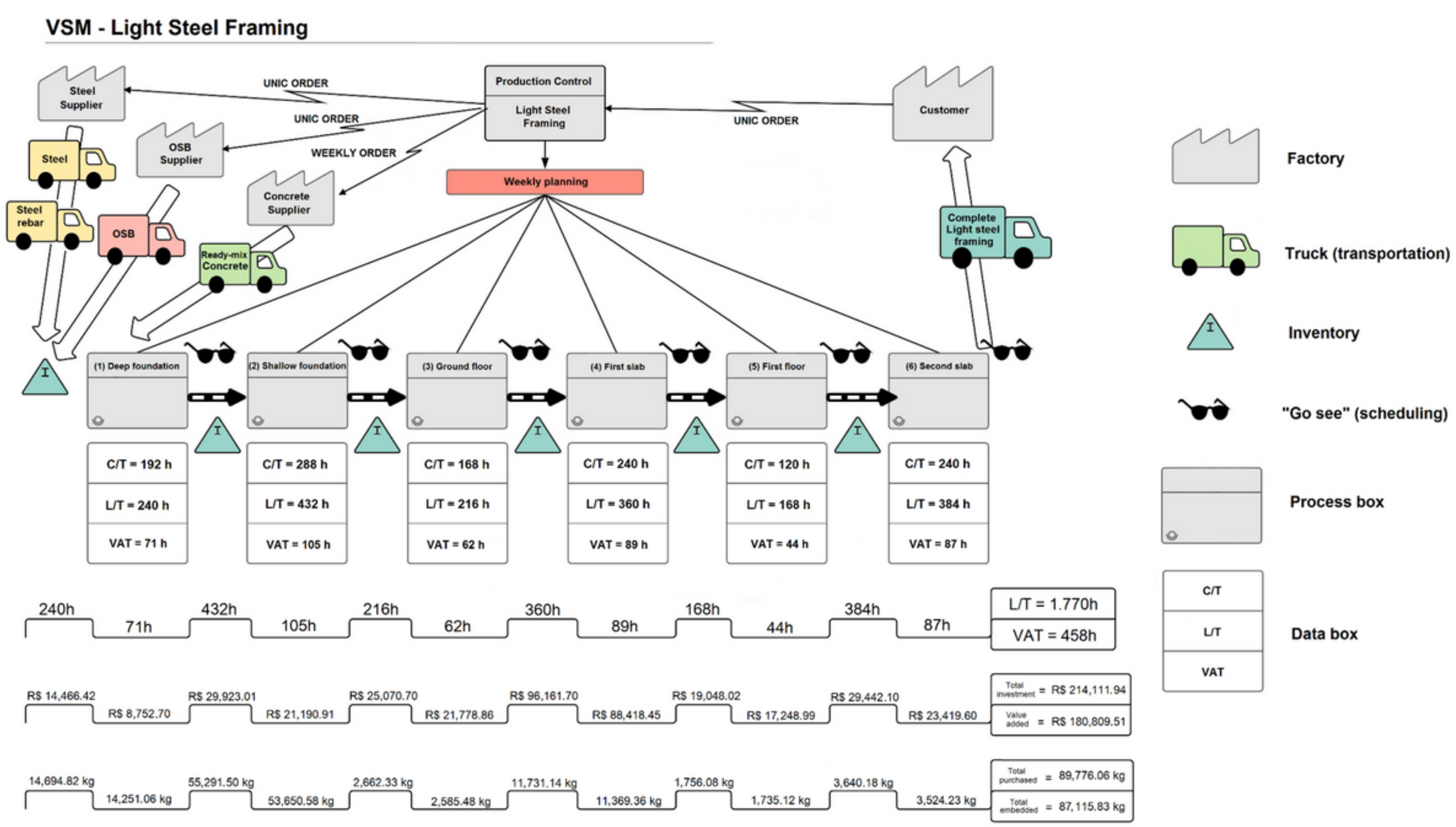

Figure 7

Future state VSM for the light steel framing scenario

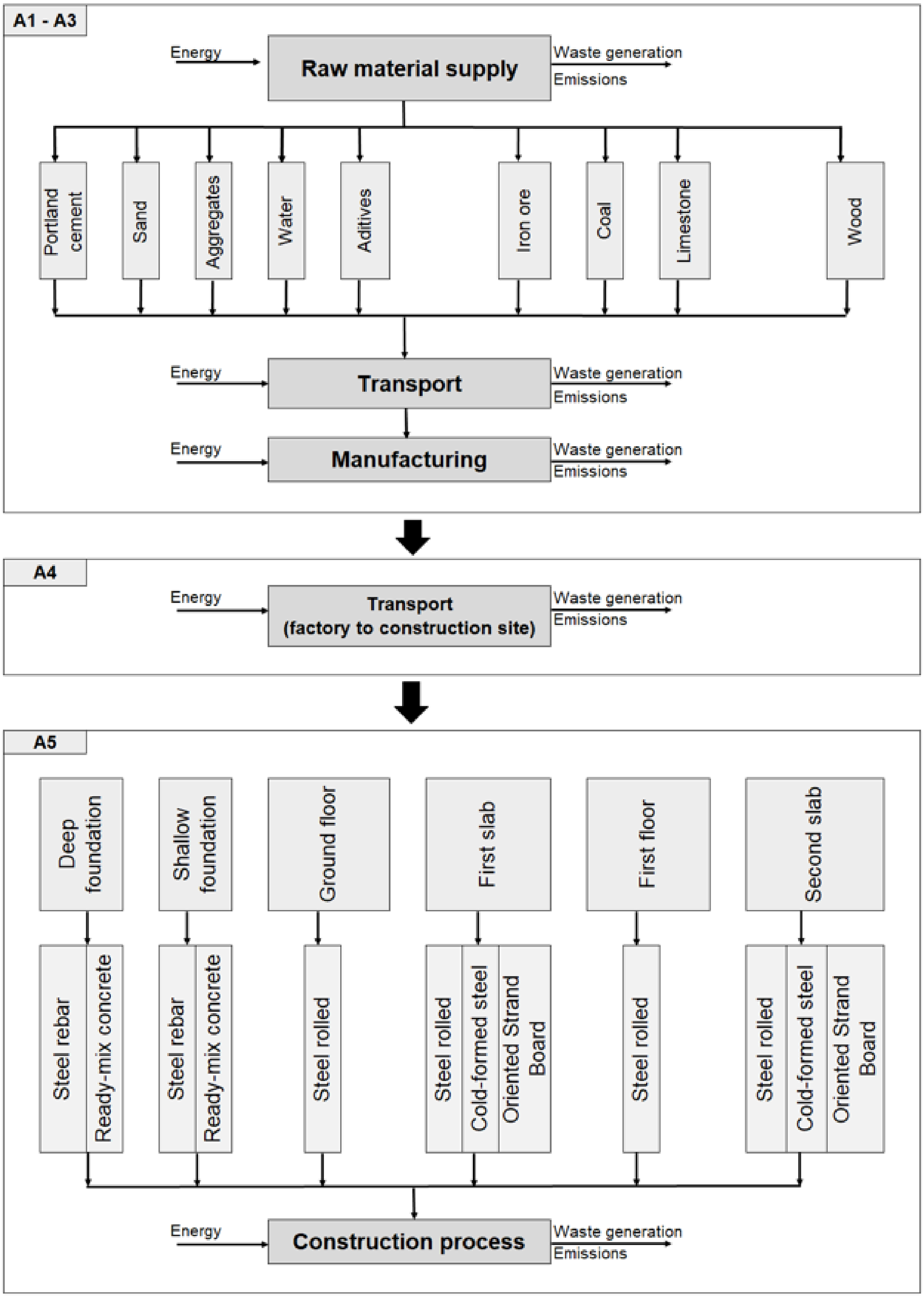

Figure 8

Product system for the light steel framing scenario

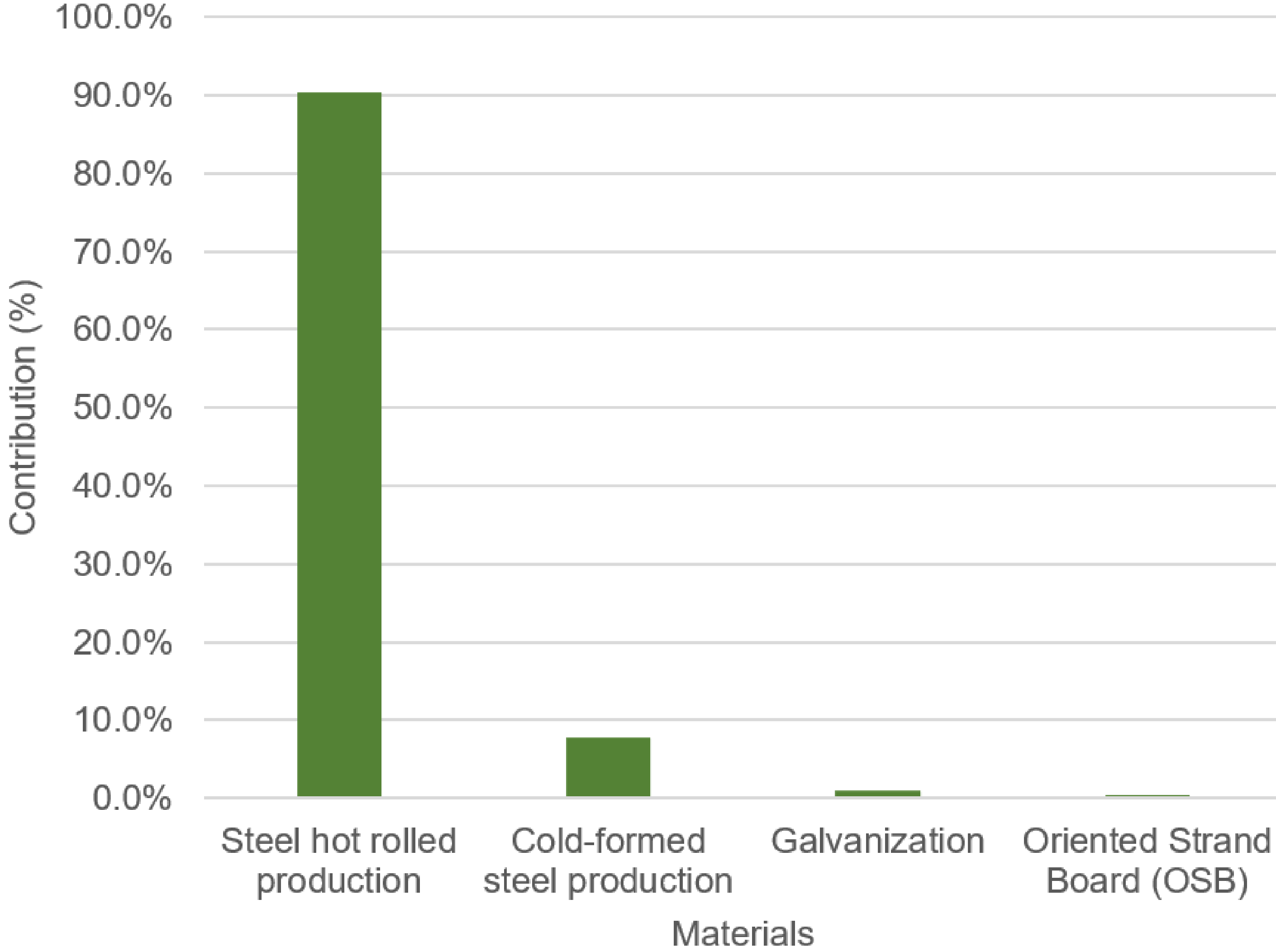

Figure 9

Process (4) - contribution analysis per type of material in the light steel framing scenario

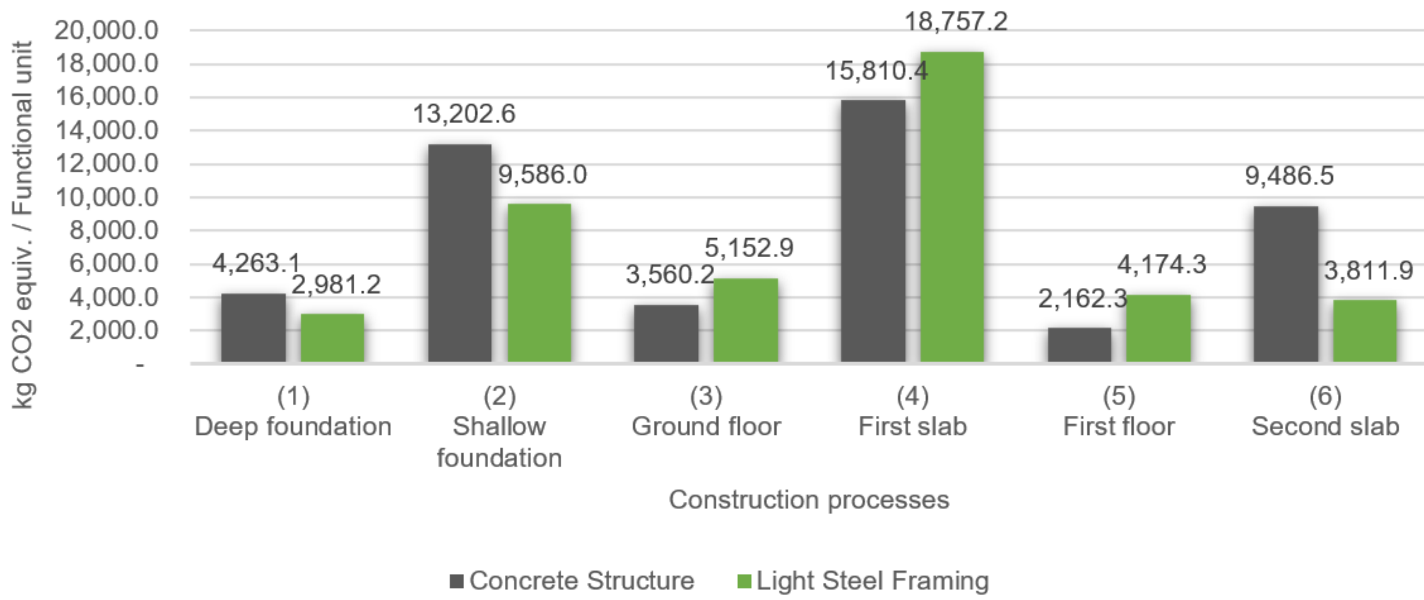

Figure 10

Comparison of GWP impacts per process and for both scenarios – concrete vs. steel structure

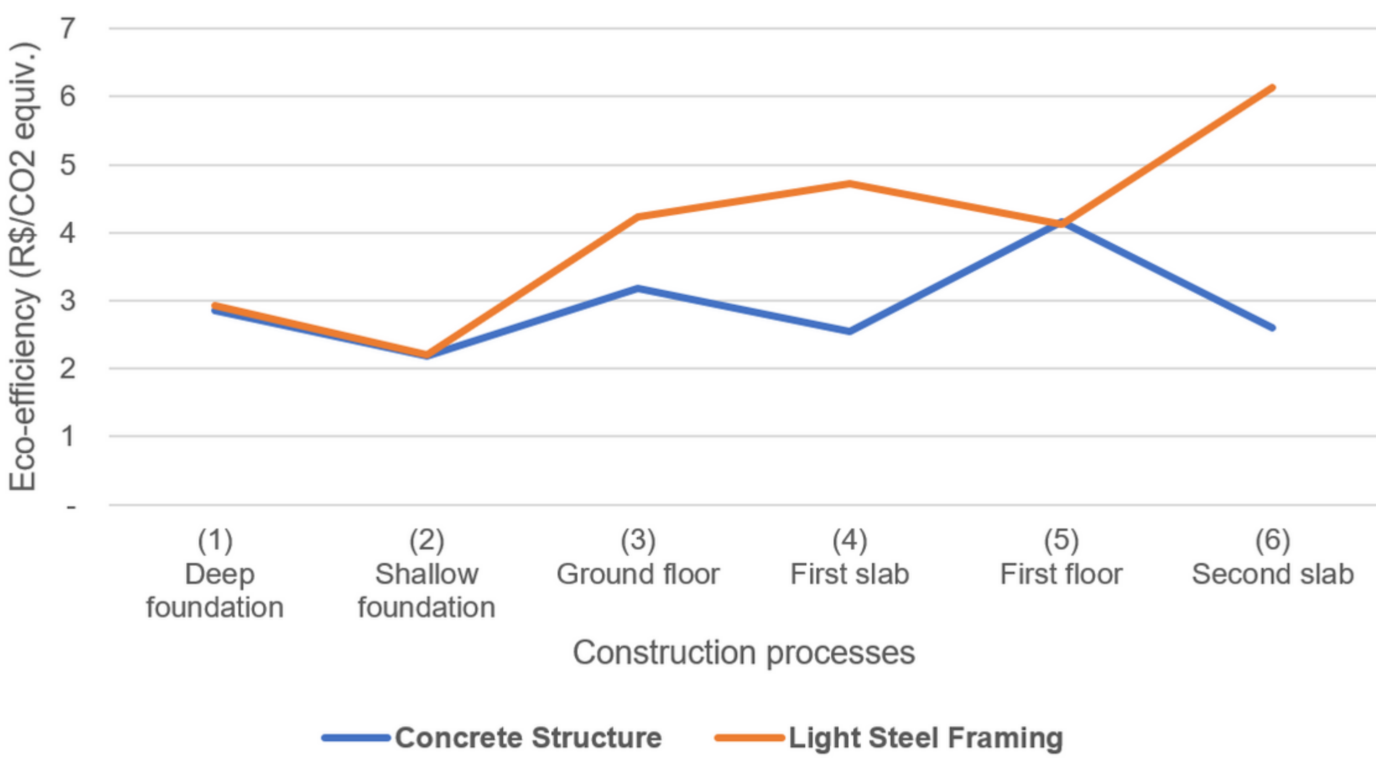

Figure 11

Comparison between eco-efficiency indicators per process for both the construction processes.

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