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Mitigating the Energy Consumption and the Carbon Emission in the Building Structures by Optimization of the Construction Processes

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Abstract: For decades, among other industries, the construction sector has accounted for high energy consumption and emissions. As the energy crisis and climate change have become a growing concern, mitigating energy usage is a significant issue. The operational and end of life phases are all included in the building life cycle stages. Although the operation stage accounts for more energy consumption with higher carbon emissions, the embodied stage occurs in a time-intensive manner. In this paper, an attempt has been made to review the existing methods, aiming to lower the consumption of energy and carbon emission in the construction buildings through optimizing the construction processes, especially with the lean construction approach. First, the energy consumption and emissions for primary construction materials and processes are introduced. It is followed by a review of the structural optimization and lean techniques that seek to improve the construction processes. Then, the influence of these methods on the reduction of energy consumption is discussed. Based on these methods, a general algorithm is proposed with the purpose of improving the construction processes' performance. It includes structural optimization and lean and life cycle assessments, which are expected to influence the possible reduction of energy consumption and carbon emissions during the execution of construction works.

Keywords: construction; processes; energy consumption; carbon emission; lean techniques; structural optimization; life cycle assessment

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1. Introduction

The energy crisis and climate change have become some of the biggest challenges facing humanity, and carbon emissions are the most important causes of global warming [1,2]. With the rapid growth of global Gross Domestic Product (GDP) and population, the energy demand has become a considerable concern for different industries. Additionally, the consequences of global warming have seriously threatened lives on earth; thus, the reduction of energy consumption and carbon emissions has received international attention [3–5].

While construction is considered the pillar industry for the global economy [6], it consumes about 40% of the world's energy, emitting about one-third of the total carbon globally and producing up to 25% solid waste each year [7–9] (see Figure 1).

The authors' main goals were to develop an algorithm that should help with mitigating energy consumption as well as carbon emissions in the construction industry. The research was made based on the publication available in scientific databases and scientific journals. The examples provided are based on observations by authors across the world. The authors are aware that local practices may influence the results of using the proposed approach, but at the general level, the algorithm should be useful and serve its purpose regarding local practices, which will be further researched and confirmed in the future. What is more, the LCA approach seems to influence the final results, especially at the stage of planning and decision making, as those have a major impact on the final result of actions taken during operation and influence regarding emissions, since proper planning is key in the construction industry.

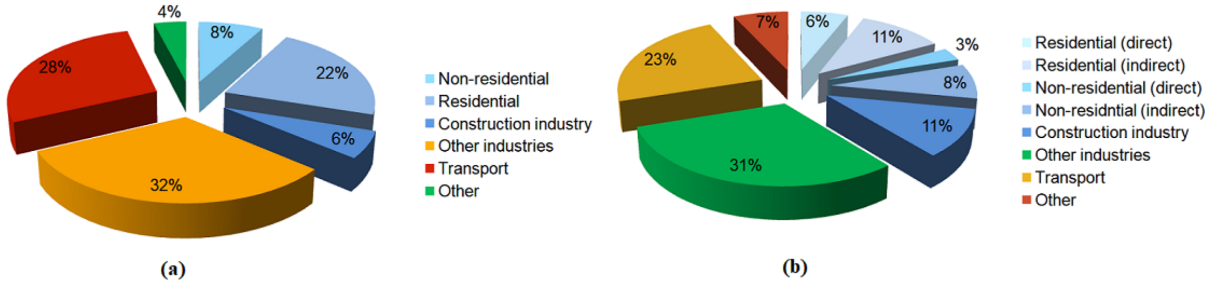

Figure 1. Global share of buildings and construction final energy and emissions, 2018 (**a**) energy consumption (**b**) emissions [10].

2. Background of the Study

The International Energy Agency (IEA) provided the information as illustrated in Figures 2 and 3, showing that, from 1971 to 2018, the world total energy consumption increased by about 250%. It can be observed that the total energy consumption in China has significantly grown compared to other regions. Other regions with the highest final energy consumptions are the United States, India, Federation of Russia and Japan. The total energy consumption can be divided into different consumer sectors: industry, transport, residential, other industries and non-energy consumption applications. Figure 3 demonstrates the final energy consumption of each sector in the high-consumer regions. Industrial final consumption in China is substantially higher compared to other regions. While the transportation sector in the United States has rather higher energy consumption. Moreover, during the same period, the World CO_2 emission from fuel combustion is almost doubled with notable growth in the region of China [11].

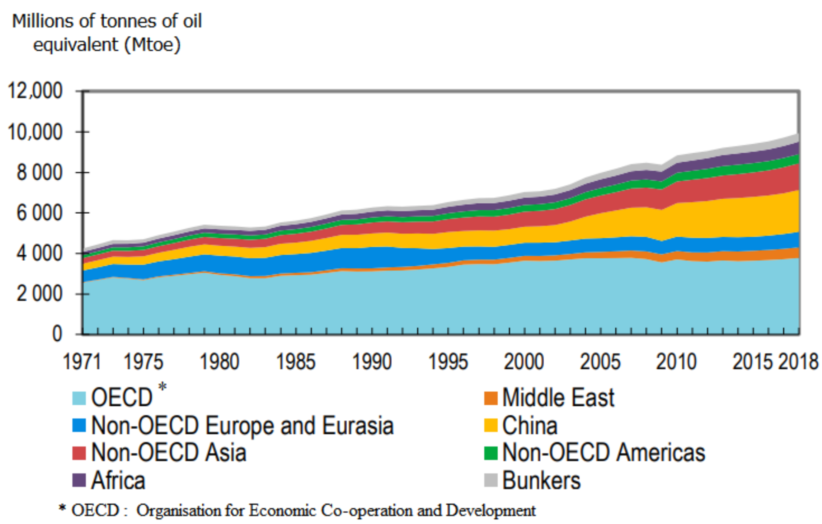

Figure 2. World total energy consumption from 1971 to 2018 by region [11].

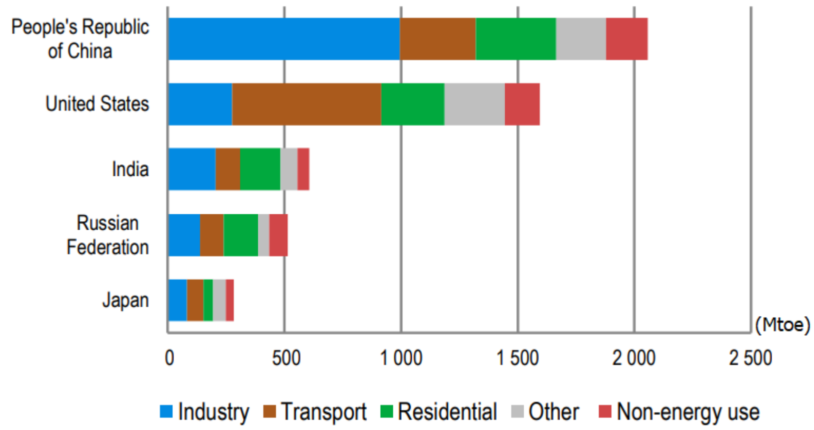

Figure 3. Top five countries by total final energy consumption [11].

Since the operation stage of buildings contributes the largest proportion of both energy consumption and emission of carbon, most researchers have extensively paid attention to improving the energy consumption in this stage of a building's life cycle [12–15]. Nonetheless, in the last years by improving the energy saving in buildings during their operation stage, the carbon emission ratio of the construction stage has been growing in proportion [16,17].The construction sector also has great potential in lowering energy consumption and carbon emissions [18]. Additionally, the operation stage lasts for decades while the construction stage is a shorter process in which carbon emission occurs in a short period of time [19]. The building sector is now considered one of the most significant energy consumption and waste generating sectors of the construction industry [20]. Therefore it is important and worthwhile to investigate the possibilities regarding reducing the emission of carbon during the construction stage.

The building Life Cycle (LC) consists of three stages: embodied, operation and end-of-life. At the embodied level, carbon emissions account for 14%–21% of net carbon dioxide emissions during the building life-cycle. However, the large scale construction of buildings causes significant embodied emissions in a time-intensive manner, which is another reason that demonstrates that urgent actions are required for emission reduction in the construction industry [21]. Furthermore, with the growing development of more energy efficient buildings, the relative proportion of embodied energy may increase [22–24].

Understanding the entire building phase is critical to lowering energy usage and carbon dioxide emissions. The construction process is divided into three stages: pre-construction, construction and service, which can also be divided into extraction, manufacturing, transportation, construction, maintenance and disposal. Numerous materials and equipment are used in buildings that consume energy and emit carbon dioxide throughout their LC. For the materials, these energies and emissions are regarded as embodied energy and embodied carbon. Performing the energy consumption reduction, the assessment of embodied energy and carbon emission for materials used in construction is one of the crucial steps that can enhance energy saving in the construction processes. Besides, with the purpose of reducing CO_2 emissions, some useful papers provide more details about sustainable building materials [25–28].

Therefore, for the sustainability assessment perspective of a construction building, it is important to determine the primary building materials, which directly and/or indirectly have an impact on the total embodied energy and carbon emissions. Based on a study [21], Table 1 shows an overview of CO_2 emissions and energy usage of building materials. The following formula was used to calculate carbon emissions during the manufacturing phase of primary building materials using the quota method:

$$QC_{Mg} = \sum_{i=1}^{n} CM_{ri} \times m_i, \quad (1)$$

where QC_{Mg} is the greenhouse gas emission equivalent generated during the processes of the production of construction material. CM_{ri} stands for the carbon emission factor in the production process of the i-th building material without taking into account recycling. m_i is the amount of i-th building material.

For energy consumption, the following formula was used:

$$QE_{Me} = \sum_{i=1}^{n} EM_{ri} \times m_i, \quad (2)$$

where $QE_{Me}$is the energy consumption for the i-th building material during the production process. EM_{ri} is the energy factor of the i-th building material in the production process without taking into account recycling.

Table 1. Embodied carbon emissions and the energy consumption of primary building materials (Reproduced from [21], the name of the publisher: Elsevier).

Materials	Carbon Emissions [a] (kg CO_2 e/m^2)	Energy Consumption (MJ/m^2)
Steel	142.33	1415.8
Commercial Concrete	123.94	209.37
Mortar	58.1	223.69
PVC Pipes	33.44	16.96
Doors and Windows	9.54	112.12
Wall Material [b]	68.19	260.29
Architectural ceramics	12.12	22.91
Water paints	5.03	19.82
Cooper core conductor cables	2.58	12.21
Wood	1.4	5.88
Waterproof Rolls	0.62	0.02
Stones	0.47	3.63
Polystyrene extrusion boards	21.25	15.81

[a] By using the carbon emission per square meter as an evaluation indicator, the effect of diffident building sizes can be efficiently eliminated so that the evaluation results remain consistent and comparable [29]. [b] Building blocks and bricks.

Transportation of materials is another main aspect of energy consumption. The transportation distance may vary depending upon the location of construction activity, which can be in an urban or rural area. Transporting materials to the building site consumes a lot of resources, according to the data provided by Reddy and Jagadish [30] as shown in Table 2. It presented the diesel energy consumption during transportation and the production of the building materials. It is noted that the transportation energy required for materials, such as steel and cement, is negligible compared to their production energy.

Table 2. Energy in the production and transportation of building materials (Reproduced from [30], the name of the publisher: Elsevier).

Material	Energy (MJ)		
	Production	Transportation	
		50 km	100 km
Sand (m^3)	0	87.5	175
Crushed aggregate (m^3)	20.5	87.5	175
Burnt clay bricks (m^3)	2250	100	200
Portland cement (tonnes)	5850	50	100
Steel (tonnes)	42,000	50	100

In another study by Kaewunruen et al. [31], they determined the transportation energy consumption and carbon emissions of a railway tunnel construction (see Table 3). It is reported that the rails and fastening systems, due to their weight, shape, distance and the method of transportation together, account for the majority of the total value of the energy consumption.

Table 3. Transportation characteristics and energy consumption for a railway tunnel construction [31].

Material	Transport Type, Distance and Fuel	Energy Consumption ($\times 10^6$ MJ)
Concrete	5 Trucks; 300 km; 0.08 L/km	0.0057
Accelerator	Truck; 400 km; 0.08 L/km	0.0015
Waterproof rubber belt	Truck; 300 km; 0.08 L/km	0.0011
Rebar	2 Trucks; 300 km; 0.08 L/km	0.0023
Ballast	Train; 50 km; 7.9 L/km	0.019
Sleepers	Train; 80 km; 7.9 L/km	0.03
Rails	Train; 400 km; 7.9 L/km	0.15
Fastening systems	Train; 400 km; 7.9 L/km	0.15

Another life-cycle stage with considerable energy consumption is the maintenance of the buildings and infrastructures. The maintenance process performs the production facilities of high productivity, includes predicted and unpredicted practices aiming to maintain a physical asset for the adequate operating conditions [32].

Kaewunruen et al. [33] studied the energy consumption and CO_2 emission of the Beijing-Shanghai high-speed railway and their results demonstrated that both emissions related to carbon and the consumption of energy during the operation and maintenance stage accounts for 31.60% and 35.32%, respectively, of the total values. In another study, Kaewunruen et al. [31] conducted the life cycle analysis of a railway tunnel construction. It is reported that around 55.2 per cent of the life-cycle energy is consumed by the maintenance process. Tunnel building consumes about 44.3 per cent of the total energy consumed (see Table 4). In the process of tunnel and rail, the energy consumption and emissions are based on the production and transportation of the materials. Their results show the importance of the maintenance stage in the consideration of the energy consumption of building structures.

Table 4. Life-cycle energy consumption and CO_2 emissions of a railway tunnel construction [31].

Stage		Energy Consumption ($\times 10^6$ MJ)	CO_2 Emissions (tonne)
Construction	Tunnel	859	48,038
	Rail	10	1472
Maintenance		1069	1472

By optimizing each of these stages in a construction process, energy consumption and emissions could decrease. One of the possible optimization methods is eliminating the wastes in a process. For example, by reducing the transportation distance, modifying the material production methods and avoiding unexpected events such as the repetition of a process, unpredicted destruction/rebuilt and over-generation of solid waste.

One of the waste elimination methods is the application of lean thinking in all activities between suppliers (construction executive) and customers (final users). The concept of lean in manufacturing refers to the efficient use of the available resources by terminating the Non-Value Added (NVA) activities or wastes [34]. Waste in lean manufacturing is represented as any processes that add cost to a product/service without adding value from a user's perspective. Lean manufacturing introduced a collection of tools that perform together synergistically to make a simplified and high-quality system that manufactures final products at the same pace of the customer's demand [35]. One of the wastes in a construction process could be the excessive energy consumption of a process, which can be eliminated through a lean management plan.

Conventional construction is a standard construction method, which usually involves using traditional materials and adhering to a specific set of parameters. In general, the conventional methods of production, transportation, operation and maintenance in the construction industry consume excessive energies, which is defined as a considerable amount of wasted energy. Due to the energy crisis and to obtain a more sustainable building structure, these over-consumed energies have to be eliminated. Numerous studies investigated the energy mitigation methods by different systems and manners.

The structure of a building or an infrastructure may be considered sustainable by proper response to the three main parameters of suitability: economic, social and environmental impacts [36]. In other words, it has to be resource-efficient without environmental impacts throughout its life cycle. Conventional design methods (for example masonry or wooden buildings) and materials, such as steel and concrete, have shown deficiencies after severe earthquakes. Bedsides the causalities and loss of economic value, in some cases, it can lead to consequential damages or collapsing of a building, which consequently arises the demand for repairing, replacement, additional transportation and waste disposal. Moreover, the energy consumption during the maintenance of buildings and infrastructures can be reduced by adopting the systems and methods that demand lower energies, particularly in the historical heritages, bridges and high-buildings that require ongoing monitoring and repairing.

That is why it is essential to enhance the structural performance of structures through an adaptive and flexible method and system. It could lead to more sustainable structures that can withstand hazardous events while minimizing the deflections, further repairs and causalities. Consequently, the energy consumption for repairing, monitoring and waste disposal could decrease.

Belleri and Marini [37] studied the significance of the seismic risk of the environmental impact of existing buildings, where the energy consumption is defined as a function of the building's life cycle. Since the seismic event is uncertain, the seismic effect is interpreted as an estimated loss, expressed as annual energy consumption and emissions.

In its first scenario, it was assumed that a building energy retrofit intervention aims to deliver an almost zero energy building performance without any impact on the seismic behaviour. As a result, if a seismic event occurs during the life cycle of a building, there is additional energy associated with post-earthquake reconstruction, which reflects the actualization of the predicted seismic loss.

It also demonstrates that, based on the relationship between the annual energy consumption and the seismic risk, the total zero energy performance is only a theoretical fact while practical consumption could be higher. In the second scenario, it was assumed that both building energy and seismic retrofit intervention occur. Since the anticipated seismic failure is significantly reduced after the seismic retrofit, if a seismic incident occurs after the structural retrofit intervention, the increased energy consumption due to building repair is significantly lower than in the first scenario.

Mergos [38] indicated that the optimization of the seismic architecture of Reinforced Concrete (RC) frames was investigated in order to reduce embodied CO_2 emissions. According to reports, the ductility ratio defined in earthquake-prone areas largely determined the minimum applicable CO_2 emission of RC frames. It can emit up to 60% of CO_2 as a seismic resistance structure with a moderate to high ductility ratio.

Moussavi and Akbarnezhad [39] investigated 15 different lateral force resisting mechanisms, including moment frames and shear walls, in moderate earthquake areas. The results demonstrated that the selection of the structural system has a significant impact on the LC environmental impacts (such as energy consumption and emissions). Yeo and Gabbai [40] investigated the optimum design of RC structures to minimize the embodied energy. The authors observed that minimum embodied energy design resulted in a reduction of about 10% in embodied energy while the relative cost of the minimum cost designs increased by 5%.

In this work, different studies that used lean techniques and seek to improve the construction process to reduce energy consumption are reviewed. There was also an attempt to investigate the feasibility of the application of structural optimization to integrate with lean techniques for maximizing the energy efficiency of the construction processes.

3. Materials and Methods

By introducing processes at the right time, with the right quantity, lean construction by waste reduction improves construction productivity by increasing resource utilization and reducing wasted process time [41]. Life Cycle Assessment (LCA) is a method of assessing the environmental impact of a building, including the extraction and processing of raw materials, manufacturing, transportation, construction, maintenance and disposal or recycling [42]. For reduction of energy consumption by the improvement of the construction-related processes, four lean techniques are reviewed.

Value Stream Mapping (VSM) is a technique that is related to lean manufacturing and was first adopted to create a map of production systems [43]. It is applied to analyze the current state, and to design a future state, of the series of processes that take a product or service from its beginning until it is delivered to the customer. Just In Time (JIT) is a methodology that mainly aims to reduce time taken in the production process as well as response times from suppliers to customers. Total Productive Maintenance (TPM) is another lean technique based on the improvement of the overall equipment effectiveness of plant equipment. TPM determines the causes for accelerated worsening and production losses while generating an adequate environment between operators and equipment to create ownership. Continuous flow is the effort of non-stop movement of a product through the production process from start to finish. In flawless continuous flow, the cycle time equals the lead time, as the product never waits to be processed.

The VSM was used by Rosenbaum et al. [44] during the phase of the production of a hospital in Chile to identify and quantify the source of waste with regard to the environment and proposed various methods to reduce waste and energy consumption. Heravi et al. [45] adopted four different lean production methods, using prefabricated steel frames to assess the environmental impact of an eight-storey residential building from the manufacturing, transportation and construction processes. Additionally, various studies proposed different methods and technologies that aim to decrease the environmental impacts of building structures (see Table 5).

Table 5. The methods presented in previous studies that aim to reduce the negative environmental impacts of construction processes.

Methods	Results	References
Use of low-energy materials.	Reduction of energy consumption by 4.2% by using the steel and concrete structure instead of the masonry and concrete structure.	[46]
Use of concrete constructions compared to steel constructions	Reduction of environmental impacts by 27% by using concrete construction in the construction stage compared to steel constructions	[47]
	The energy consumption and carbon emission of steel-based structures are 40% higher than the other type of buildings	[48]
Optimized design	Reduction of both direct and indirect energy use by 1.6% and 20%	[49]
	The carbon emission in lower ductile seismic design is 60% higher than ones with medium and high ductility	[38]
Modern technologies and methods	The use of tools, such as Building Information Model (BIM) and energy simulation software, create a balance between the embodied energy consumption and the operational energy used in the construction phase.	[42,50]

Table 5. *Cont.*

Methods	Results	References
Utilization of the recycled materials	Reduction of environmental impacts by 46% by utilizing recycled materials	[51]
	Using recycled steel and aluminium reduce the embodied energy about 50%	[52]
	The reduction of energy consumption of 80% for aluminium products and 7% for wood products.	[53]
The increasing use of local resources	Reduction of 10 to 34% of the environmental impacts and increase economic benefits	[54,55]
	A considerable reduction of 215% and 453% in the used energy in building and the impact of transportation	[56]
	Lowering the environmental and transport impacts leading to the reduction of emissions and energy consumption by vehicles and more suitable for the local climate conditions	[57]
More usage of pre-fabricated elements	More efficient construction processes method and a 3.2% decrease in emissions compared with conventional methods	[58]
	Higher energy efficiency in commercial buildings, as they typically have a lower amount of infill walls	[59]
	A reduction of 14.3% in CO_2 emission of in-situ pre-casted elements compared to the in-plant manufacturing	[60]
	A reduction in material embodied, assembly and operation emissions of 18%, 17.5% and 91.5%, respectively.	[61]
	A reduction of 35% in carbon emission by using pre-cast floor slabs compared to in-situ components	[62]
More usage of renewable energy	Self-supply-energy in order to reduce environmental impacts	[63]

3.1. Methodology

Lean methods that focus on waste disposal are suitable tools for reducing energy consumption and emissions in the construction process [64]. The focus of this research is to integrate manufacturing, transportation, execution and construction technologies through the use of VSM, JIT, continuous flow, TPM and structure optimization technologies. Using the life cycle assessment method, the environmental impact caused by the implementation of this general algorithm can be estimated.

The main goal is to create an accurate representation of the current state of the processes and to develop a diagnosis by evaluating the map and identifying the waste (NVA activities). Then, the environmental impact of production, transportation and construction processes are studied under the current and lean system. The current system includes conventional production, transportation and construction processes. Finally, a flawless future state of a construction process system is elaborated. Adopting a VSM map reduces or removes waste and maximizes value-added operations. Overproduction, inventories, mistakes and failures, waiting, motion and transportation, over-processing and underutilized people are all examples of waste that VSM can systematically eliminate [65]. Some of the VSM ideas that were used in the studies are represented in Table 6.

Table 6. VSM concepts [43].

Concept	Meaning
Push flow	A production mechanism in which each process strives to generate the greatest number of push flow units possible, moving its output downstream regardless of what its client process requires.
Pull flow	A production method in which each process only generates what the next requires. Units are being pulled from upstream processing by the processes.

Table 6. *Cont.*

Concept	Meaning
Inventory	The work in progress created by operation will be idle before downstream supply is in demand and ready.
FIFO lane	A processing lane in which the first device to join the process often exits first. The FIFO lane has a maximum capacity for processed units in order to solve variability problems. When this ability is reached, production must come to a halt. For goods with a lot of variations, the FIFO lane is recommended.
Kaizen event	A concentrated effort to solve manufacturing issues and improve the supply chain.
Kanban cards	The demand for supply or the withdrawal of units between operations is communicated by a symbol.
Supermarket (distributer unit)	Work-in-progress storage that is both managed and visible. It enables a pull flow between two activities without attempting to forecast output demand by connecting the activities with a Kanban cards scheme.
Takt time	The production rate that must be met in order to satisfy consumer demands.

3.1.1. First Case

The first case studied by Rosenbaum et al. [66] is a medical center with a total area of 35,000 m^2 located in Santiago, Chile. The current map analysis is conducted only for wall elements' production. The proposed VSM methodology in this study consists of seven steps:

1. Preliminary decisions
2. Data collection on-site
3. Data processing
4. Complexity of the current state map
5. Analysis and diagnosis of the current state
6. Elaboration of the future state maps
7. Recommendations for achieving the future state

They evaluate the concrete waste by the comparison of the volume of concrete contained in a mixer truck and the volume of the elements to be filled with concrete. For metallic and wooden waste, the evaluation was conducted by visual inspection. The estimated waste was then measured as the amount of all discarded materials and was applied to the total material demand. Figure 4 depicts the classification of 249 average waste materials by number.

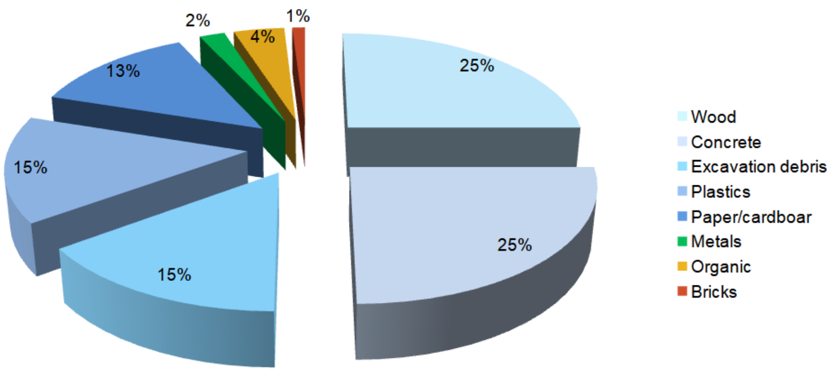

Figure 4. Waste classification in the project [66].

After collecting the data and indicating the invariants, the current state map was established, which is the base for further analysis and leads to the preparation of the future state map. The map's findings were then evaluated to determine the existing status of the valuable sources for various building components. The following are some of the issues that were found.

- Variability in the process: tasks that were performed in a random order took a significantly longer time and had a lower efficiency. For example, rebar construction took 19 min per square meter, but the findings revealed that only 62 per cent of that time was spent contributing to the project and the remaining time was idling.
- Human resource management difficulties: The use of human resources by subcontractors was superior to that of the general contractor. As an example, the contributory work index value of rebar installation performed by the subcontractor and the concrete pouring performed by the general contractor are 85% and 65%, respectively.
- Some activities resulted in significant inventory accumulation. For example, inventory for rebar spacers installation averaged 351 m^2. It could lead to spreading out the materials in the site area, exposing them to damage by machinery, equipment and environment.
- Value stream synchronization: A large tendency exists to accomplish activities later than scheduled. For example, the value of just in time percentage for concrete pouring shows that 94% of the process is completed later than scheduled.
- Low value-adding percentage: It demonstrated that only 33% of the cycle time is used to add value to the final product. This mainly occurred due to the great waiting time of units in inventory to be processed.
- Material resources supply: The unreliability of suppliers in meeting deadlines resulted in numerous delays and variability, leading to lower performance.
- Reception of supplies: The loss of pieces and parts were frequently reported, although they came systematically labelled in accordance with each specific element.
- Planning and control issues: Inadequate mid to long-term planning resulted in waste of materials and labour, as well as production delays.
- Waste management: There was no re-use or recycling of products, and the Landfill Diversion (LD) value indicates 0% diversion, whereas the waste metrics indicate significant inefficiency in resource and energy consumption.
- Site sustainability: High water usage and health issues due to inadequate piling up the excavation products.

Then the researchers established new indicators to achieve an adequate future state of the production system. For improving environmental impacts of the future implementations, they recommended some actions as follows:

- Merging activities: To optimize value-adding time and minimize inventory, the installation of rebars and spacers is carried out as a single operation.
- Work standardization: Work must be carried out in a continuous manner to ensure that all work obligations are met in full and that no projects are left unfinished.
- Total quality control: All contractors should be in charge of maintaining quality throughout their operations and making the required repairs in order to meet product quality requirements and deadlines. It should be possible to achieve a target of 100 per cent the first time around.
- FIFO lane: It is preferred for every activity since the construction method is on-site fabrication and supermarkets could not be implemented. when a product enters into a process, it must be the first one to leave it and when the FIFO lane is full, production of that product must stop and focus on other elements, which reduce the waiting time and inventories.
- Ordering and reception of supplies: The supply routes (here, concrete and rebars) ensure sufficient order anticipation and a well-established delivery schedule.
- VS synchronization: The future state value streams were tailored to relate to this rhythm with the capital and capacity available, and an appropriate Takt period for the output was calculated. It is done mainly by decreasing NVA times, which can help to tackle the schedule compliance problems of the current state.
- Subcontractor relationships that are long-term: To strengthen cooperation between the parties, it is critical to develop a strong team and create a level playing field. As a result, the subcontractors will be able to keep their job obligations.

- Waste management: A goal of 100% LD is defined for metals, organics, paper and cardboard waste because they can be easily recycled. For concrete residues, excavation rubble and bricks, a goal of 50% LD is established as they can be used in landscaping, refilling and drainage systems. A 100% LD goal is determined for wood waste as they can be easily recycled and also be used in other processes. Achieving these goals leads to an approximately diverted 70% of the total construction waste.
- Site sustainability: Establishing cleaning stations outfitted with water tanks and also prevent water contamination by adequate management.

3.1.2. Second Case

The second case studied by Heravi et al. [45] is an eight-storey residential building in Tehran, Iran, with a total construction area of 3720 square meters in which lean techniques were used to improve the processes of production, transportation and assembly of precasted steel frame (PSF) elements related to energy consumption and emissions.

The effects of processing, transportation and assembly processes on the environment were investigated in current and lean modes. The current mode includes conventional processes of production, transportation and erection of PSF elements. While the lean mode consists of the results of using the VSM technique to draw the current state map to define the capabilities for future improvement. In the initial phase, the JIT technique is adopted to amalgamate the production and assembly processes. As there is a need for a combined flow to coordinate the capabilities of the production stage and the requirement of the assembly stage, JIT is implemented as the earliest lean stage. In the second phase, TPM and continuous flow techniques are used to improve the current state map based on the integrated flow generated after the first phase.

The lean phases implemented in this study are related to adopting few steps. In the beginning, the VSM technique is used to identify wastes; then, in the next two stages, first JIT technique is adopted. Later, the TPM and continuous flow techniques are applied while decreasing the process wastes of the production, transportation and assembly phases of the PSFs are combined.

In order to assess the impact of the using lean techniques on the energy consumption and emissions during the mentioned processes of PSFs by the Life Cycle Assessment (LCA) framework are evaluated as follows:

- Life cycle inventory (LCI): In order to measure relevant inputs and outputs of a commodity system, inventory analysis necessitates collective and calculative behaviour [67].
- Life cycle impact assessment (LCIA): The results of the LCI are used in this process to assess the importance of possible environmental impacts [67]. LCIA is used to assess the importance of possible environmental impacts of a product system based on LCI data. Both current and lean modes are tested at this point to see how effective lean strategies are at reducing energy consumption and emissions.
- Interpretation: The aim of this phase is to review the inventory analysis and impact evaluation results together or just the inventory outcomes. The LCIA findings should be viewed in light of the study's objectives and scope.

One supermarket has been placed between the processing and assembly stages subsequent to using the VSM technique in the first process. The justification for this was to combine these two phases and lead development forward depending on the demands of the construction site by implementing an automated pull production mechanism. The continuous flow and TPM methods were then used in the second step to execute some of the construction processes concurrently. In addition, building machinery is classified according to its purposes, reducing the amount of time that the construction stage processes are idle. Furthermore, by categorizing the assembly machines, the TPM strategy is used to minimize idle periods and optimize resource usage. Finally, continuous flow helps to shorten the development stage's overall length.

TPM and continuous flow approaches have a major impact on construction methods. It uses the TPM technique to increase resource use and the continuous flow technique to enable certain building processes to be completed simultaneously. Table 7 displays the energy consumption of construction processes. It can be observed that adopting lean techniques considerably reduces the fuel consumption of the construction equipment. However, electricity consumption has been moderately increased.

Table 7. Consumption of the energy during the construction processes of PSFs [45].

Equipment	Time (h)		Consumption of Energy		Total Energy Consumption		
	Working	Idle	Working	Idle	Electricity (kWh)	Fuel (L)	Energy (GJ)
Current mode							
Crane	55	8	2042 (L)	297 (L)	-	2339	90.29
Elevator	15	1	41.46 (kWh)	1.84 (kWh)	43.3	-	0.468
Impact spanner	75	5	120.97 (kWh)	2.30 (kWh)	123.3	-	1.331
Overhead power	39	-	23.4 (kWh)	-	23.4	-	0.252
Total	184	14	-	-	189.98	2339	92.34
Lean mode							
Crane	44	6.4	1633 (L)	237 (L)	-	1870	72.19
Elevator	14.2	0.9	39.38 (kWh)	1.64 (kWh)	41	-	0.44
Impact spanner	48.7	3.2	157.26 (kWh)	2.99 (kWh)	160.3	-	1.73
Overhead power	34.4	-	20.62 (kWh)	-	20.6	-	0.22
Total	141.3	10.5	-	-	221.9	1870	74.58

The environmental effect is calculated by measuring the energy usage of different processes. Table 8 shows the impact of lean techniques on the PSF production, transportation and assembly processes that reduce energy consumption. It can be seen that, after applying the lean methods, the standby power consumption is greatly reduced.

Table 8. Total consumption of energy and emission of carbon dioxide [45].

Process	Electricity Consumption (kWh)			Fuel Consumption (L)			Total Energy (GJ)	Total CO_2-eq. GWP (kg)
	Working	Idle	Total	Working	Idle	Total		
Current mode								
Production	15,165	1848	17,013	-	-	-	183.73	11,845
Transportation	-	-	-	269.48	-	269.48	10.4	3.2
Erection	185.8	4.15	190	2042	297	2339	92.34	140
Total	15,326	1852	17,178	2311.48	297	2608.48	286.5	11,988.2
Lean mode								
Production	15,162	1054	16,215	-	-	-	175.12	11,289
Transportation	-	-	-	269.48	-	269.48	10.4	3.2
Erection	217.3	4.64	221.9	1613	237	1870	74.58	160.8
Total	15,379.3	1058.6	16436.9	1882.48	237	2139.48	260.1	11,453

The average annual area of steel structures in Tehran is 2,804,550 square meters. Energy consumption and annual emissions are shown in Figure 5. It demonstrates the impact of using lean techniques on Tehran's annual energy consumption and CO_2 emissions, reducing them by 45,988 GJ and 932 tons, respectively. Hence, It can be interpreted that applying lean techniques could efficiently reduce the environmental impacts of construction processes. The average annual number of constructed steel structure buildings.

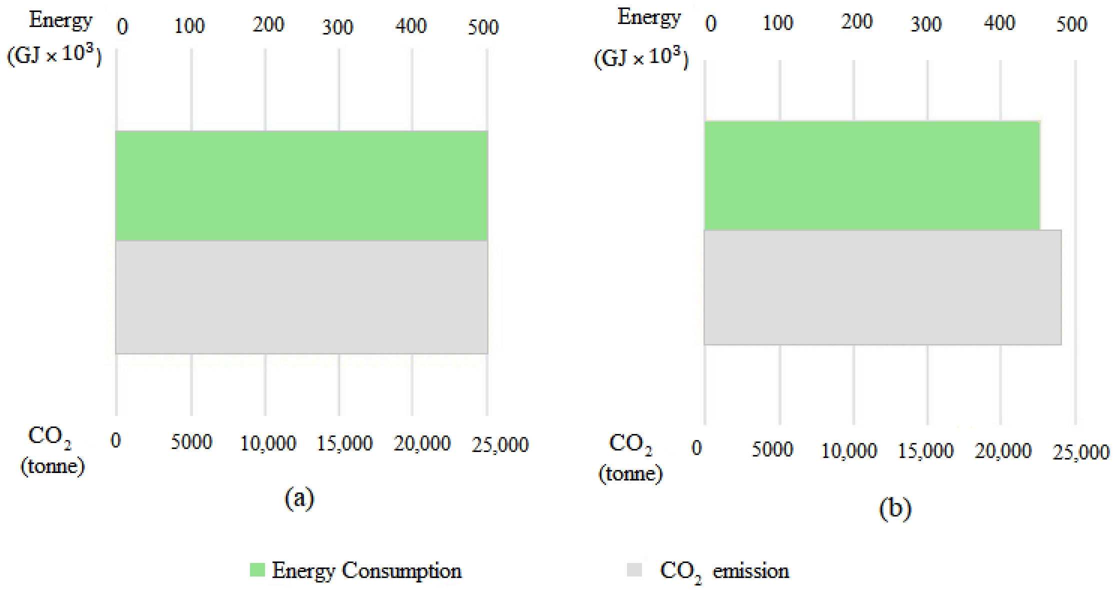

Figure 5. The annual consumption of energy and carbon dioxide emissions of current and lean modes related to erected steel frame buildings (**a**) under current mode (**b**) under lean mode [45].

3.2. Structural Optimization

3.2.1. Design Parameters

Yeo and Gabbai [40] investigated the potential benefit of structural optimization for embodied energy in RC structures. They proposed an objective function corresponding to the total embodied energy per unit length for an RC beam element as follows:

$$g(b, h, A_s, A_v) = \rho_s (A_s + \frac{A_v}{s}) E^s + L(bh - A_s - \frac{A_v}{s}) E^c, \quad (3)$$

where b and h are the width and height of the cross-section of the beam respectively. A_s and A_v also represent the area of longitudinal tension and area of shear reinforcement within distance s reinforcement respectively. s is the longitudinal spacing of shear reinforcement and ρ_s is the specific mass of steel. E_S is the embodied energy per kilogram of steel and E_C is the embodied energy per cubic meter of concrete.

The results for the values of the embodied energy and cost indicated that the optimization of structural member design for embodied energy results in reduction by 10% in embodied energy at the expense of an increase by 5% in cost relative to a cost-optimized member.

3.2.2. Structural System

Moussavi-Nadoushani and Akbarnezhad [39] determined the environmental impacts of a set of 15 different steel and concrete structural systems designed for 3, 10 and 15 storey buildings. The carbon footprint of each design is calculated using a statistical approach that considers emissions during the resource extraction, shipping, building, service and end-of-life processes.

The findings establish the significance of the relationship between the structural material form and the structure's carbon emissions at its end-of-life period. Concrete systems have approximately 50% higher end-of-life carbon emissions than steel structures, as seen in Table 9. It is mainly caused by considering lower daily outputs for the demolition of concrete buildings compared to steel buildings. In other words, it originated from the fact that the demolition of concrete buildings is more time consuming and energy-intensive than steel buildings.

Table 9. The cumulative life cycle CO_2 emissions correlated with various systemic structures per square meter (Reproduced from [39], the name of the publisher: Elsevier).

Stories	Structure Type [a]	Life Cycle Carbon Emission (kg CO_2-e/m^2)
3	S 3S MRF	1992.1
	S 3S BF	1965.5
	S 3S BF-MRF	1973.8
	C 3S MRF	1839.9
	C 3S SW	1624.3
10	S 10S MRF	1878.5
	S 10S BF	1863.4
	S 10S BF-MRF	1862.6
	C 10S MRF	1531.2
	C 10S SW	1379.1
15	S 15S MRF	2498.6
	S 15S BF	2463.4
	S 15S BF-MRF	2487.1
	C 15S MRF	2076.5
	C 15S SW	1962.7

[a] First letter indicates the material (C: Concrete and S: Steel); middle term indicates the number of stories (3S, 10S and 15S); third term indicates the lateral load resisting system (MRF: Moment Resisting Frame, BF: Braced Frame, and SW: Shear Wall).

3.2.3. Seismic Risk and Design

Belleri and Marini [37] studied the environmental impacts of the seismic risk analysis and proposed a framework to quantify the influence of seismic events on the environmental impact assessment of buildings. The framework, which is illustrated in Figure 6 consists of four steps:

1. Hazard analysis: A hazard curve is calculated based on the occurrence and form of faults, earthquake recurrence frequency, site distance, and soil conditions given a building and a site position
2. Structural analysis: It takes into account the construction of a finite element model that depicts the structural framework of the given structure.
3. Damage analysis: It enables the damage level of one or more damageable classes in relation to the systemic response to be established.
4. Loss analysis: It specifies the likelihood of exceeding the judgment element, such as the number of financial gains, downtime, or casualties.

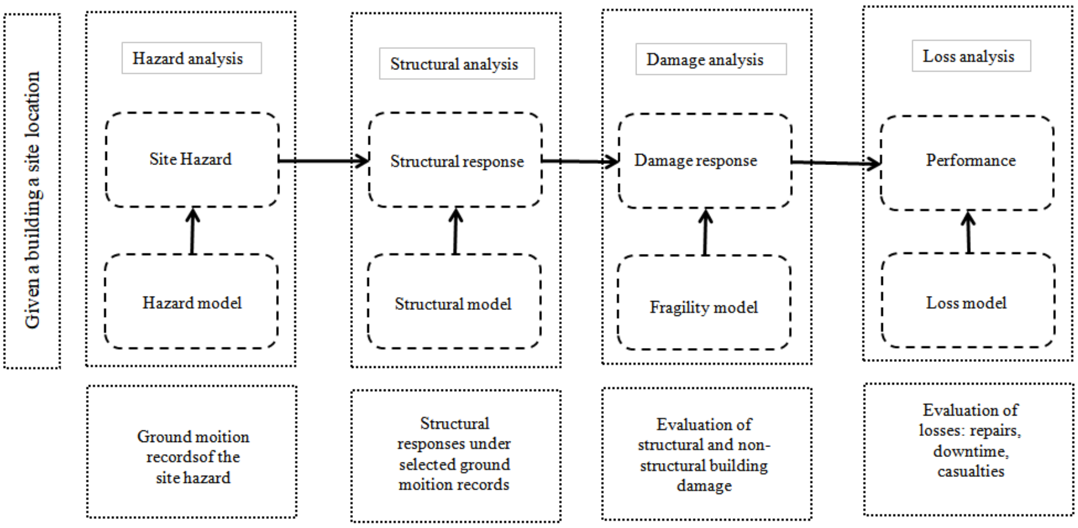

Figure 6. It specifies the likelihood of exceeding the judgment element, such as the amount of financial gains, downtime, or casualties (Reproduced from [37], the name of the publisher: Elsevier).

In another study by Mergos [38], there was an attempt to define sufficient design practices that decrease the environmental impact of earthquake-resistant RC frames. The study develops different optimum seismic designs of an RC frame to minimize the embodied carbon emissions. Therefore, a computational framework is proposed based on genetic algorithms to respond to complex problems with discrete design variables. The main goal was to examine and define the efficient design practices that reduce the embodied carbon emissions of seismically designed RC frames. The computational framework is proposed as the following equation:

$$F(x) = F_c(x) + F_s(x) + F_f(x) \rightarrow F(x) = V_c.F_{co} + m_s(x).F_{so} + A_f(x).F_{fo}, \quad (4)$$

where *F(x)* is the objective function and x is the design solution vector that includes n independent design variables x_i (i = 1 to n). Typically, $F(x)$ is defined to be the material cost $C(x)$ and the environmental impact $E(x)$ is determined in terms of embodied CO_2 emissions. The cost/environmental impact is calculated as the total of concrete $F_c(x)$, formwork $F_f(x)$ and steel $F_s(x)$. V_c (m^3) is the concrete volume, m_s (kg) the mass of steel reinforcement and A_f (m^2) the area of the formwork. F_{co}, F_{so} and F_{fo} are the unit prices of concrete, steel and formwork, respectively.

The process is related to the correct position of the reinforcement. When the appropriate reinforcement configuration is obtained, the design plan can be determined and the value of the objective function $F(x)$ is returned to the optimizer. The penalty value is added to the objective function value.

4. Results and Discussion: Integrated Method

By analyzing the methods and outcomes of the previously mentioned studies, a general algorithm is proposed that aims to optimize the environmental impacts by reducing the energy consumption and carbon emissions of the construction processes. This algorithm includes four primary stages illustrated in Figure 7.

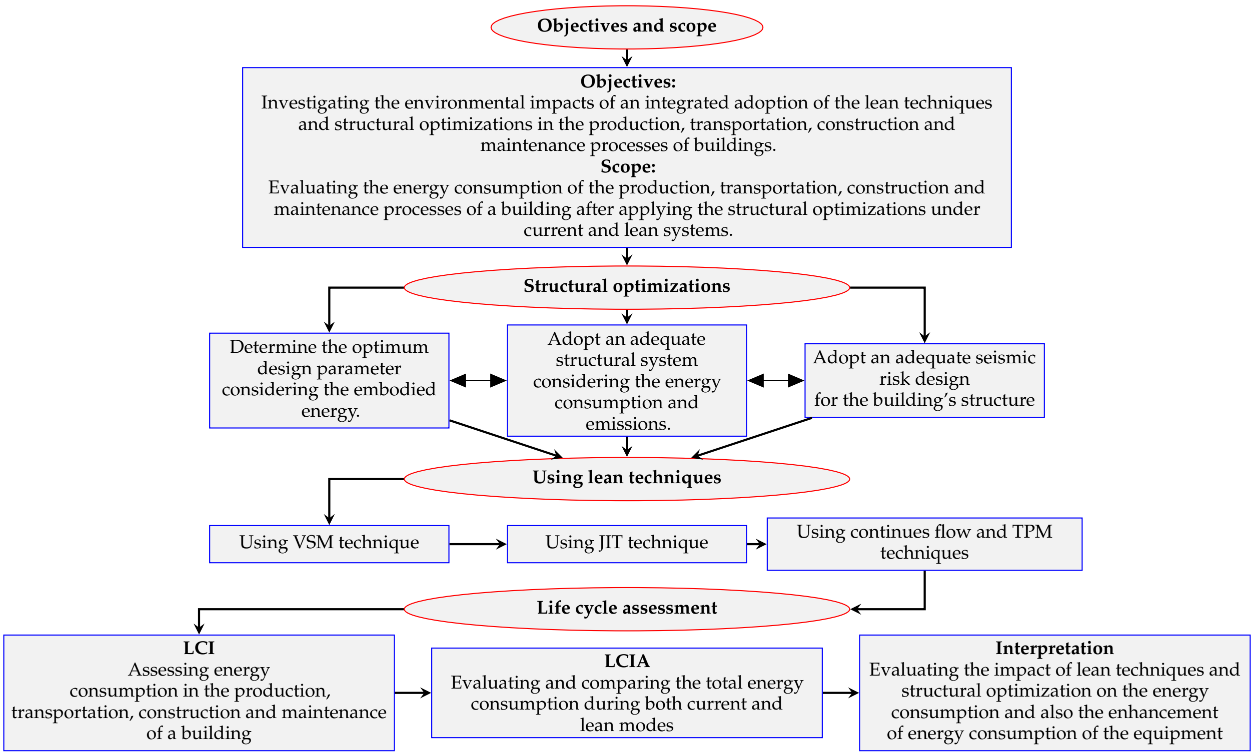

Figure 7. Proposed construction processes algorithm to obtain an optimum environmental impact.

In the first stage regarding the project goals, the objectives and the scope are defined considering the reduction of energy consumption in different processes. The objectives are proposed to integrate the lean techniques and structural optimizations with the purpose of evaluating the improvement of the energy consumption of the project by adopting the techniques and methods assigned in the scope of the project.

The second stage consists of three structural optimization practices that aim to reduce the environmental impacts of the structural design. These optimizations should correspond to the defined scope of the project. Since optimum designs with reduced environmental impacts increase the final cost [40]. These three components correspond to each other at the same time, as any changes in design parameters should be considered in seismic analysis and environmental impacts.

After adopting structural optimizations, lean techniques are applied in order to improve the production, transportation, construction and maintenance processes' performance. First, the VSM technique is applied in order to find the waste of each individual activities and assists to diagnose the issues and the drawbacks of the processes. The JIT technique is used to improve the production process as well as reducing waiting times and transport energy consumption and avoiding the over-production of components. In the last step of the lean phase, the continuous flow and TPM techniques are applied at the same time. This decreases the idle times and improves the efficiency of the resource and reduce the total duration of the construction stage.

Finally, the life cycle assessment phase is used to evaluate the efficiency of the previously applied methods on the environmental impacts of the processes. The energy consumption and CO_2 emissions of each individual process and during the total life cycle should be calculated. Furthermore, this would improve the sustainability of the construction life cycle considering the energy usage, emissions and general health of the involved human resources.

In each phase, there are some practices that have to be fulfilled to obtain the expected outcomes. These practices and results are demonstrated in Table 10.

Table 10. The procedure and the expected outcome of the proposed algorithm aiming to reduce the energy consumption and carbon emissions in the processes of the construction of a building.

Procedure	Practice	Outcomes	Reference
Structural optimizations			
Design parameter	Structural optimization by adjusting design parameters	10% reduction in the embodied energy	[40]
Structural systems	Adopting an adequate optimum structural system	Selection should be based on the impacts of the structural system on the total life cycle effects rather than individual life cycle phases	[39]
Seismic design	Applying the optimum seismic design approach	The ratio between the expected annual CO_2 emission related to seismic risk and the annual operational CO_2 after the thermal refurbishment is 10% and 87% for the building located in a high seismicity region, with and without structural retrofit, respectively	[37,38]
Lean techniques			
VSM	Drawing the current VSM of a construction process and then diagnose it in purpose to tackle the drawbacks	Improved current construction processes by identifying the wastes and idle activities leading to lower energy consumption and other environmental impacts	[44]
JIT	Materials are only ordered and received as they are needed in the next processes	Improvement of the production process as well as minimizing waiting times and transport fuel consumption and preventing over-production of components	[45]
Continuous flow and TPM	Evaluate the equipments working and energy consumption efficiency	Reduction of idle times and maximize resource efficiency and reduce the total duration of the construction stage	[45]
Life cycle assessment			
LCI	Assessing the energy consumption of the equipment used in different processes in idle and working modes of	Recognizing the high energy consumer types of equipment in different processes	[45]

Table 10. *Cont.*

Procedure	Practice	Outcomes	Reference
LCIA	Assessing the environmental impact regarding to the reduction of energy consumption	Finding the environmental impacts in the different process which assists to diminish the idle times which consequently reduces the energy consumption	[45]
Interpretation	Evaluate the influence of the applied techniques and methods on the energy consumption	Examining the impact of the applied techniques would help the construction processes to obtain the maximum energy efficiency in different processes	[45]

5. Conclusions

The authors in the study proposed an algorithm that helps to obtain an optimum environmental impact during the construction process. The algorithm is based on an in-depth literature review and will be further developed and investigated by the authors in different case studies particularly for optimization of the design parameters, which increases the project cost. In general, this algorithm could assist the construction engineers and managers to obtain a construction design and plan to decrease the energy consumption, which consequently might lead to sustainable construction with lower cost and emissions. Finally, this paper is related to an extensive research plan aiming to improve the structures' sustainability by reducing the energy consumption and CO_2 emissions by adopting different lean methods and structural improvements.

The authors in their research focused on the publications available in scientific databases and scientific journals. The examples provided are based on observations by researchers across the world. The authors are aware that local practices may influence the results of using the proposed approach, but at the general level, the algorithm should be useful and serve its purpose regarding local practices, which will be further researched and confirmed in the future.

Such a general approach, as a starting point, is needed, especially in the construction sector where huge potential is observed regarding the reduction of energy as well as a high influence on the global CO_2 level, which was presented in detail and further efforts should be made to improve the global situation regarding raised issues.

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