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Environmental Cost of Locally Manufactured Hollow Concrete Block in Jordan Using the Life Cycle Assessment Approach

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Abstract Purpose - The purpose of this paper is to investigate the embodied environmental loads of locally manufactured hollow concrete brick supply chain, as the most common building material in the Jordanian architecture context, where sustainability has gained mainstream attention in the recent decade as a response to the global quest for an environmentally responsible building sector. Design/methodology/approach - The quantitative framework of a streamlined, process-based LCA based on ISO 14040 series protocols was followed to evaluate, analyze, and interpret the energy consumption, water demand, and greenhouse gas emissions, of the detailed cradle-to-site production cycle of locally manufactured HCB, using two different production methods as real-life case studies. Findings - Formulating a generalized approach to calculate embodied energy in transportation via an obtained mathematical equation with distances and several desired produced brick units as the main variables, as well as estimating the consumed electrical energy values by brick plant machinery for any HCB unit count including their associated GHG emissions footprint. Practical implications - Reducing building's embedded impacts in the same way operational energy has already been reduced, fulfilling the concept of sustainability. Originality - Findings serve as a notable potential to aid Jordanians in establishing a reliable, transparent reference database, and ranking guidelines regarding national construction materials, assisting architects in materials selection decisions at early design stages, and possibly improving the environmental performance of materials supply procedures.

Keywords Life Cycle Assessment, Bricks, Supply Chain, Emissions, Building Materials

1. Introduction

In recent times, many industrial sectors throughout the world economy have raised concerns regarding the adverse impacts on the environment because of their human-related activities, yet our finite planet cannot endure the high rates of resource depletion, energy consumption, and waste generation associated with the escalating demand for new buildings by the world's growing population. More attention is paid to the sustainability movement in present-day architecture since the building and construction sector illustrates a prime candidate for the concept of sustainable development and a superior opportunity to manage the environmental effects of human activities. Thus, the environmental burdens of the building's operational phase have been reduced, whereas efforts to decrease embodied loads in the construction supply chain of building materials appear to be overlooked and less advanced.

Jordan, as a developing country enduring unstable energy supply, and natural resource shortages among its most pressing problems; has adopted several green building regulations concerning its regional perspective lacking the explicit consideration for quantitative life-cycle analysis methodologies. Environmental impacts of local materials supply chains prevent a comprehensive evaluation when determining the sustainability of the selected materials.

Concrete brick is a principal building material used in Jordan, especially for skeleton structures, internal and external partitions. The most common form of manufacturing bricks in Jordan is the traditional and manual method, in which most of the labor depends mainly upon human power with the aid of some simple compression machines used to press concrete to create concrete bricks.

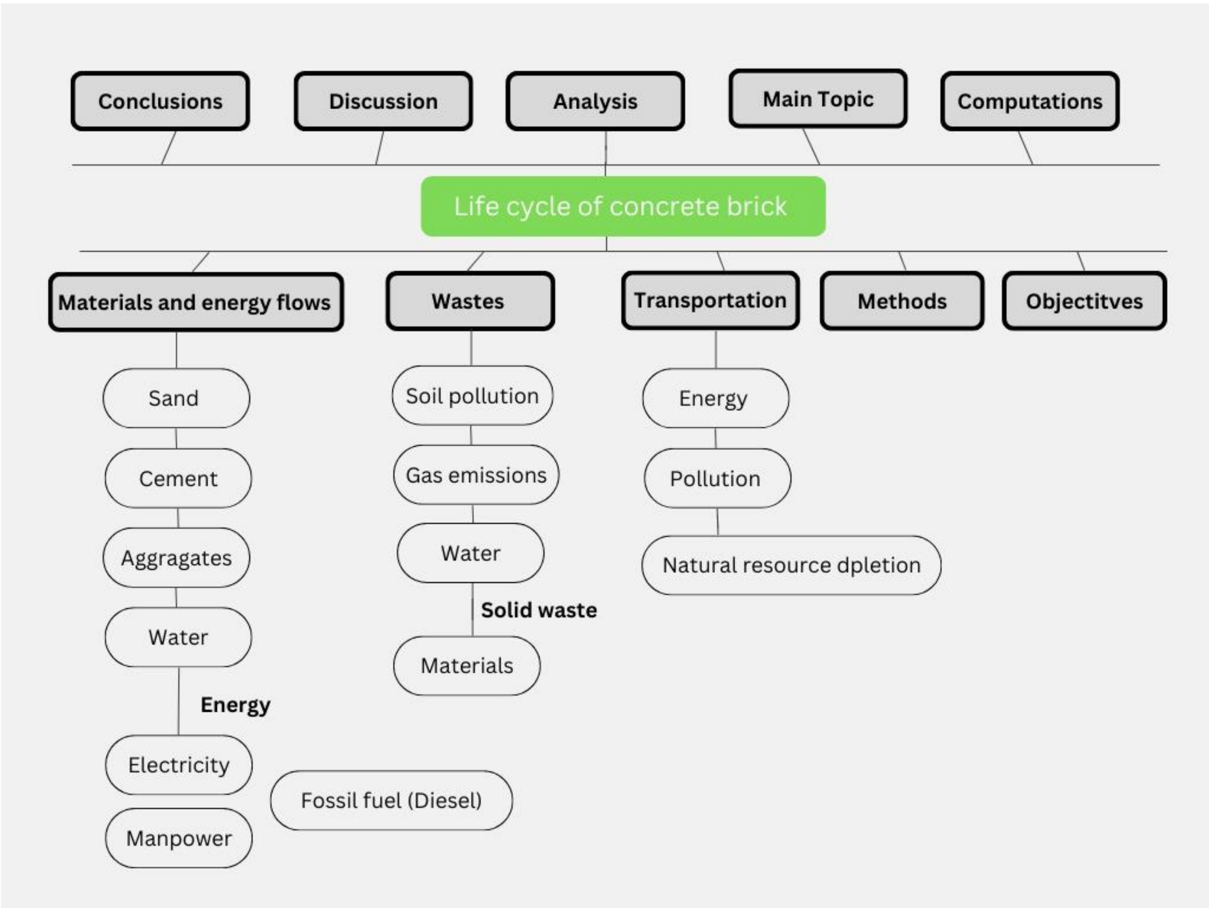
The procedure is summarized by supplying aggregates, sand, cement, and water to be mixed in certain ratios and then feeded to a compression machine to manufacture concrete bricks. Until now no innovations have been made to develop new materials to replace bricks components as an introduction to produce sustainable brick units. But a more developed machinery has been used to accelerate brick production that exists in the Jordan construction industry by now.

The main objective of this article is to analyze and understand the energy and material flows from the very beginning to the end of the process; and to understand the accompanying solid and liquid waste produced as a result; as well as resulting air pollution.

The main procedure adopted mainly the detailed analysis of brick manufacturing process, and quantifying each element involved in the production. Where two procedures are analyzed: the manually and automated processes.

The procedure developed a set of equations that enables to compute quantities of energy types involved in the production of concrete bricks; some of them are a function of distance where energy is the main consumed source in such operation.

As well, this article focused upon the environmental impacts of the whole procedure, and this will help in setting improved policies toward brick manufacturing in Jordan. The general research framework is depicted in figure 1 below.



Source: authors, 2023

Figure 1. The flow chart shows the main method of life cycle analysis adopted in this study

2. Materials and Methods

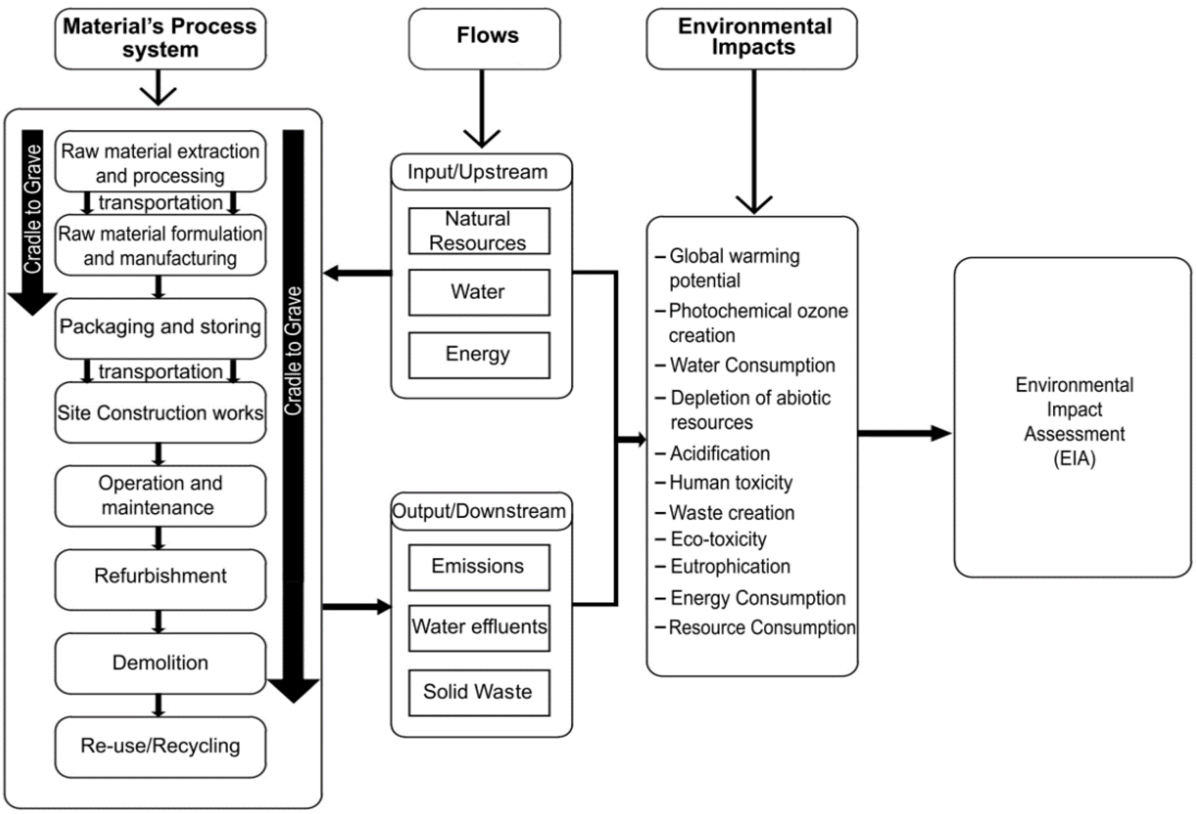
2.1. Life Cycle Assessment (LCA) of Building Materials

Concerns have been raised about human activities and the environment. More attention is paid to the construction industry and its effects on the environment in modern days [1]. Thus many validation processes have been issued based on LEED standards for energy saving in buildings and construction processes [2]. The life cycle assessment approach is widely used to compare many building materials and their effects on the environment, like the comparison between steel and concrete, for example [3], [4].

ISO 14040 portrayed the definition of LCA as follows: "LCA is a technique for assessing the potential environmental aspects associated with a product, by compiling an inventory of relevant inputs and outputs, evaluating the potential environmental impacts associated with these inputs and outputs, and interpreting the results of the inventory and impact phases about the objectives of the study, throughout its life cycle right from raw materials extracting and processing, through manufacturing, transporting, distributing, using, reusing, maintaining, to final disposal or recycling"; As shown in figure 2 [5], [6].

According to Hanandeh [7], the cradle-to-grave life cycle technique has been used to assess the six most prevalent single-family dwelling building layouts in Jordan. Options included single hollow concrete block (HCB) (economic), double-layer HCB (improved economic), double-layer HCB with an insulation layer (insulated economic), limestone cladding, insulated limestone wall, and insulated limestone-clad with a multi-layer block (luxury). Open LCA v1.4 software was used to simulate the environmental impacts, which were then, evaluated using the ReCiPe Midpoint (H) LCA technique based on a typical Jordanian family's thermal comfort level and HVAC demands; Focusing on climate change, acidification, and particulate.

The findings also showed the effects of the building's energy usage and water resources being utilized as proxies for its overall performance. However, even if more sophisticated wall construction with insulation saves energy usage during the operation phase, it has larger environmental implications during the life span of the structures when the material manufacturing and the construction, demolition, and disposal phases are taken into account.



Source: adapted from [10]

Figure 2. A flow diagram mapping LCA system boundary including process phases of producing materials along with inputs/outputs flows

About regional researches, Egyptian straw/raw, sand, clay, and cement bricks evaluated in a comparative manner by Mohammed and Negm [8] for their environmental effects using SimaPro software under the IMAPCT 2002+ of mid-point and end-point techniques, focusing on the residential sector. The functional unit for each brick type is one Kilogram. The authors concluded that straw/raw brick scores the most environmentally friendly material grades, contrasting clay brick and cement brick. From an international point of view, Bribián et al [9] have conducted a comparative analysis of the most commonly used building materials in Spain, including brick sand tiles, insulation materials, cement and concrete, wood products, steel, aluminum, copper, and glass, as well as some eco-materials, using three distinct impact categories. Primary energy demand (in MJ-Eq) was calculated according to the CED method, GWP (in kg CO_2-Eq) according to the IPPC 2007 methodology, and water demand (in liters). The SimaPro v7.1.8 software utilized in conducting this research, along with the Eco invent 2.0 data base.

Many scholars showed interest in past research work done regarding the life cycle assessment of concrete hollow blocks intended for sustainability in its widest meaning, Saravan J. and Venkateswara Rao [11] where investigated research works related to sustainable bricks with almost 23 different materials including concrete bricks mixture in different countries such as sewage sludge, paper mill sludge, glass waste sludge, and granite sludge just to mention. In Brazil, Condeixa, Haddad, and Boer [12] evaluated the impact of brick inner walls of a traditional house, were the impacts were carried out using the CML2001 method for a life span of the building of 50 years; they were able to identify the most impactful material component and solid waste behavior and generation and distance traveled in the transportation of materials and waste. Similar work was done by Korentz and Nowogonska in Poland [13], Colangelo F, Forcina A, Farina I., and Petrillo A. [14], studied the environmental impacts of construction and demolition waste of incinerator ashes and marble sludge with concrete in this case using SimaPro software, Hajek P., Fiala C., and Kynclovs M. [15], Zimele Z., Sinka M., Bajare D., and Jakovics A. [16], where they assessed which of the traditionally used building materials are more sustainable aiming at a nearly zero energy buildings were they concluded that a best alternatives among many, was the aerated concrete brick wall and expanded polystyrene insulation. Okka Adiyanto, Effendi Mohamad, Rosidah Jaafar, and Muhammad Faishal [17], investigated the LCA of eco-brick production using PET particle-reinforced epoxy resin composites, they found that such a proposed scenario makes no further eco-print pressures upon the environment. Many other related studies can be found in [18], [19], [20], [21], [22]. The following table lists further literature on LCA for brick manufacturing in different countries with different methodologies investigating different environmental issues, a short review summary is shown in Table 1.

Table 1. Review of selected scientific literature related to brick life cycle and related environmental issues.

Authors	Country	Problem	Methodology	Results
Luby S.P., Biswas D., Gurley E.S., Hossain I. [23]	Bangladesh	Brick Manufacturing in Bangladesh uses inefficient coal-burning technology that generates air pollution	Interviews, field surveys.	Low-cost changes and modifications will improve the manufacturing process resulting in less air pollution.
Brooks N., Biswas D., Hossin R., Yu A., Saha S., Saha S., Saha S., Luby S. P. [24].	Bangladesh	Measuring fine particulate matter PM2.5, and their association with child asthma symptoms, chronic obstructive pulmonary disease (COPD), and general respiratory symptoms.	Field study, interviews.	Existing regulations are inadequate to protect nearby communities from the substantial health burden brick manufacturing imposes.
Skouteris G., Ouki S., Foo D., Saroj D., Altini M., Melidis P., Cowley B., Ells G., Palmer S., O'Dell S. [25]		Brick manufacturing processes rely on less manageable water resources which results in excessive water consumption.	Mathematical modeling techniques are utilized for the targeting of water regeneration, with an interception unit used to partially purify the water resources for further re-use/recycle.	The water consumption footprint of a brick is improved when the brick manufacturing industry operates sustainable water management strategies.
Levi K., Raut A. [26]	India	How to use the concept of embodied energy analysis as a construction design assessment tool. A process-based analysis is used.	Using a case study method to evaluate the energy consumption of the brick industry in the west Godavari region in India.	The obtained values for three types of brick manufacturing, the authors found that fly ash brick is the most sustainable alternative.

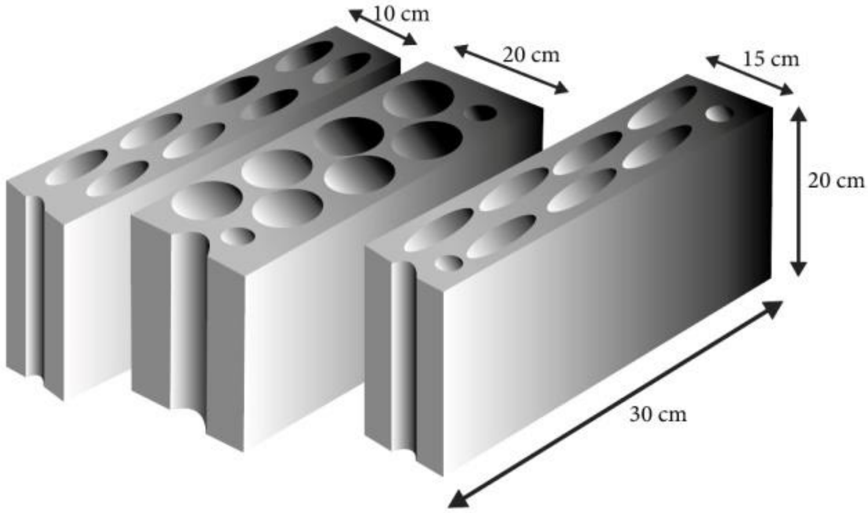
Studies about the adoption of cleaner technologies in brick manufacturing are found in literature [27, 28]. About hemp Crete utilization in brick production in Europe [29], a whole lifecycle analysis and environmental issues in Mexico [30].

2.2. Concrete Bricks in Jordan

HCBs belong to a vast range of locally manufactured building materials in Jordan. They are pre-formed concrete products that are mostly molded and hardened before they are transported to the construction site and utilized in big rectangular blocks that typically weigh between 11 and 19.5 kg. The brick manufacturing industry demands extensive resource inputs, mainly made from a mixture of powdered Portland cement, water, sand, and aggregate. This formula yields a light gray block with a smooth-surfaced texture and a high compressive strength. When compared to other general-purpose concrete mixes, this one results in a highly dry, stiff material that maintains its form even after being taken from the block mold. To guarantee a consistent module in building construction, the shapes and sizes of the majority of cement blocks have been standardized at (20, 15, or 10 X 20 X 40 cm), taking into account the space for a bead of mortar in this measurement as shown in table 2 and figure 3 below. Continuousattentionisrequiredthroughouttheblockmanufac turingprocesstoensure that the finished product has the necessary characteristics [31]. Manufacturing process flow varies depending upon the applied system method, whether it is manual, semi-automatic, or fully automatic. As in the case of Jordan, semi-automatic and fully automatic are the typical common methods; thus, both techniques have been studied and analyzed systematically in the subsequent sub-sections. To put it briefly, through the semi-automatic production process, input materials are weighed while being added to the mixer machine manually by a factory worker. The admixture is then moved with a manual wheelbarrow to the molder/vibrate or machine that requires one human worker to operate it to form the brick's shape. Next, bricks are loaded into a lorry truck after curing/watering manually. On the contrary, during the full-automatic production mechanism, raw ingredients are electronically weighed in the batching system with a weighing accuracy of ≤ ± 2% before being poured into the mixer. Trapped moisture is then detected using ultrasonic sensors, and the quantity of water to be supplied is automatically adjusted. In cases where there is a severe environment, the water may first go through a chiller or warmer before being utilized. The mix is fed into a mold and vibrated, producing an average of 100 pallets per hour. As soon as the blocks leave the machine, laser beam sensors measure the height of the blocks to ensure they are of the correct size. Afterward, the newly wet bricks enter a drying chamber where the curing process takes place, while the stack-tying process is done manually. Produced bricks from both methods are transported to the construction site, where on-site workers use fresh mortar to bond HCB into a single unit as they build walls to the appropriate height and width [32].

Table 2. Brick specifications in Jordan. Source: Adapted from [33]

Code	Brick type (cm)	dimension (mm)	Weight /Kg	Density(kg/m ³)	Compressive Strength	Void %(max)	Fire Rating	Truck 12 m^3 load	Truck 24 m^3 load	Unit/Bundle
A	Hollow Block 10	40 × 20×10	11	≥2000	≥4	37	1	800	1320	165
B	Hollow Block 15	40×20×15	16	≥2000	≥4	42	1.6	600	960	120
C	Hollow Block 20	40×20×20	18	≥2000	≥4	52	2	500	720	90



Source: Authors, 2023

Figure 3. Dimensions of different HCBs in Jordan

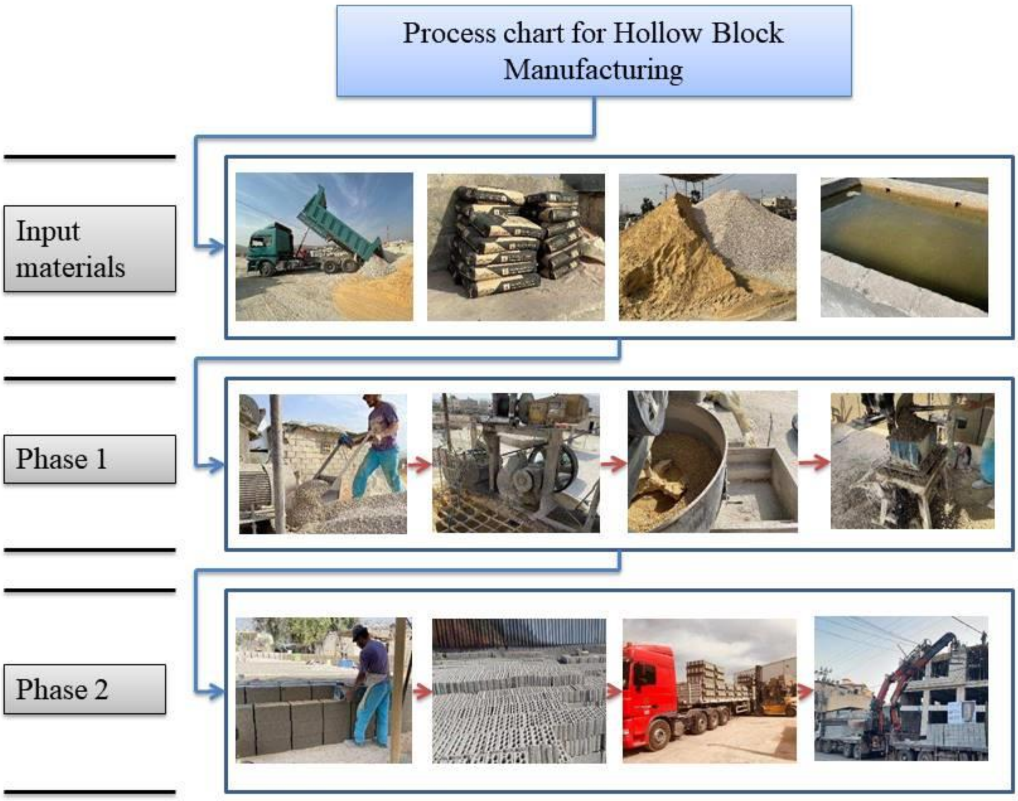
2.3. LCA Framework Implementation

To execute an LCA process for BMCC, it is essential to pass through four analytical, interdependent steps: Goal and Scope Definition, Life Cycle Inventory Analysis (LCI), Life Cycle Impact Assessment (LCIA), and Interpretation as follows:

a. System boundary definition- Phases and Flows

Using a streamlined LCA study has restricted the concrete brick's life stages to be assessed from cradle to site, i.e., from quarrying raw materials, through the manufacturing factory, all the way to fixing the product in the final position in the building fabric. Use and demolition phases were excluded, hence, only input material quantities and embodied energy values were analyzed. Through site visits and systematic field observation, process flowcharts of the two manufacturing methods; semi-automatic and full-automatic HCB's production provided in Figures 5 and 7 linked with picture arrays shown in Figures 4 and 6, and Figure 7 respectively. For the sake of this study, production operations have been broken down into three key components: pre-factory phase, factory phase, and on-site phase.

1. The Pre-Factory Phase quantifies raw material inputs (cement, water, aggregates, and sand) in specific amounts that are needed to produce an identified number of HCB units of each aforementioned size, coupled with reviewing data on the required transportation to deliver each input material to the factory location using a lorry truck with a precise carrying volume.
2. The Factory Phase, describing each manufacturing procedure that the above-mentioned materials go through, resulting in the final form of HCB, also states the input energy types and quantities consumed while completing each process, in addition to the generated output emissions amounts.
3. In the On-Site Phase, which comprises transportation to the construction site and unloading operations, in addition to laying and bonding bricks into single-unit walls, necessary energy types and values were shown as well.



Source: Authors, 2023

Figure 4. Process of semi-automatic HCB production, starting from raw materials supply, and ending with the construction site

Pre- Factory Phase

Process	Bill of Raw Materials Input
In (1-3)	
a) Portland Cement	50 kg
b) Sand	250 kg
c) Aggregates	700 kg
d) Water	70 kg

Process	Transport to brick factory by lorry truck with 12 m³ carrying volume	
B1		
E	Energy Input	Quantity
	Diesel	24 L/hr

Factory Phase

Process	Loading raw Materials into the mixer machine	
B2		
E	Energy Input	Quantity
	Manpower	4.7 METs

Process	Mixing raw materials in a 1.5 diameter pan	
B3		
E	Energy Input	Quantity
	Electricity	5.6 kWh

Process	Moving admixture to molder by manual wheelbarrow	
B4		
E	Energy Input	Quantity
	Manpower	4.5 METs

Process	Molding + Vibrating bricks	
B5		
E	Energy Input	Quantity
a)	Electricity	1.92 kWh
b)	Manpower	3.1 METs

Process	Drying + Curing by Watering twice a day for 5 days	
B6		
E	Energy Input	Quantity
	Manpower	1.6 METs

Process	Output Quantities
Out(1)	
20 cm HCB	50 Unit – 900 kg
15 cm HCB	60 Unit – 960 kg
10 cm HCB	80 Unit – 880 kg

On- Site Phase

Process	Transport to construction site by lorry truck of 12 m³ carrying volume	
B7		
E	Energy Input	Quantity
	Diesel	24 L/hr

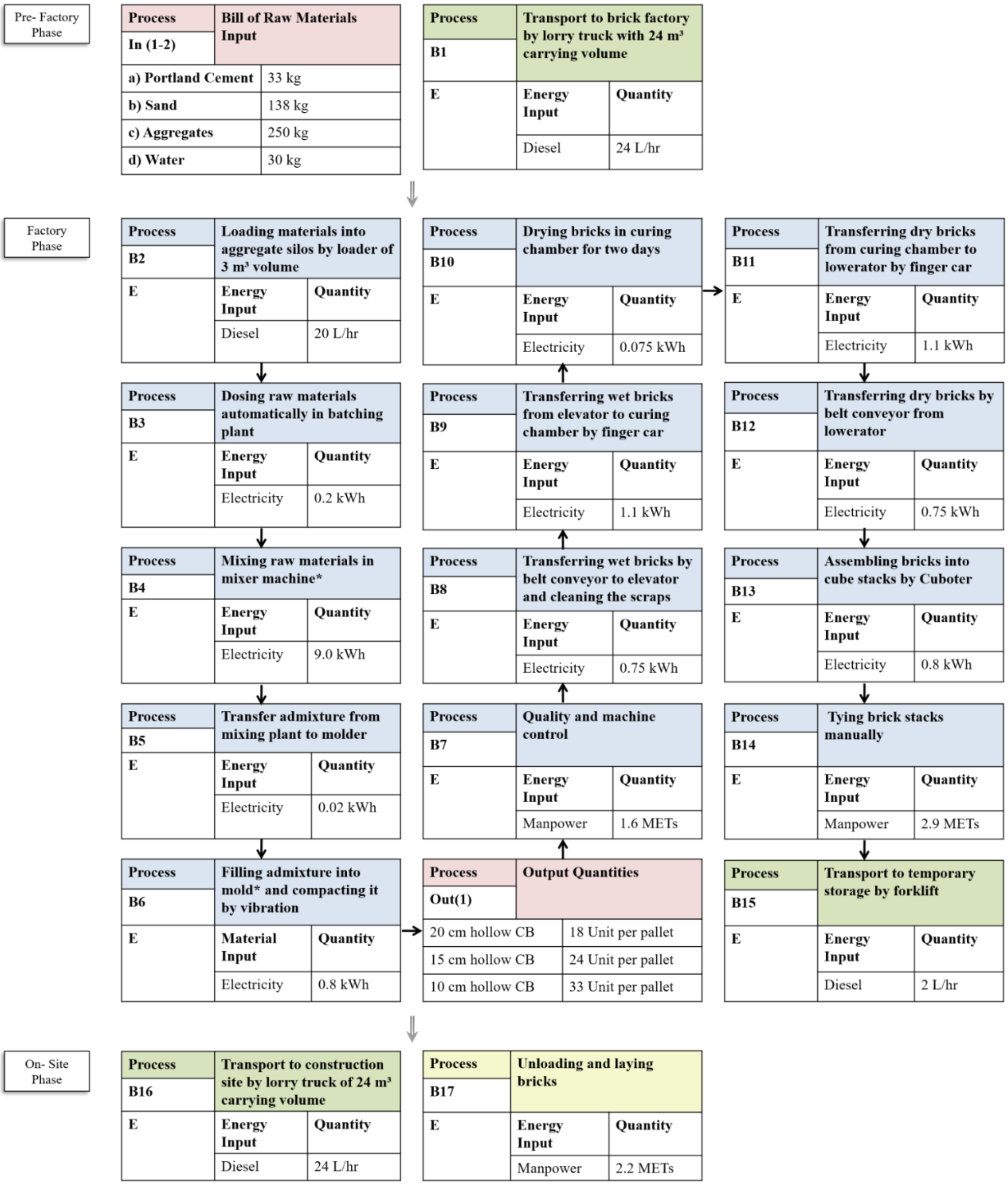
Process	laying bricks into one unit wall in construction site	
B8		
E	Energy Input	Quantity
	Manpower	2.2 METs

Source: Authors, 2023

Figure 5. Systematic flowchart of specific output number of semi-automatic HCB manufacturing process in Jordan including material and energy inputs quantities for each procedure

Source: Authors, 2023

Figure 6. Array of photographs shows full-automatic HCB production from essential materials supply to construction site, refer to table 9



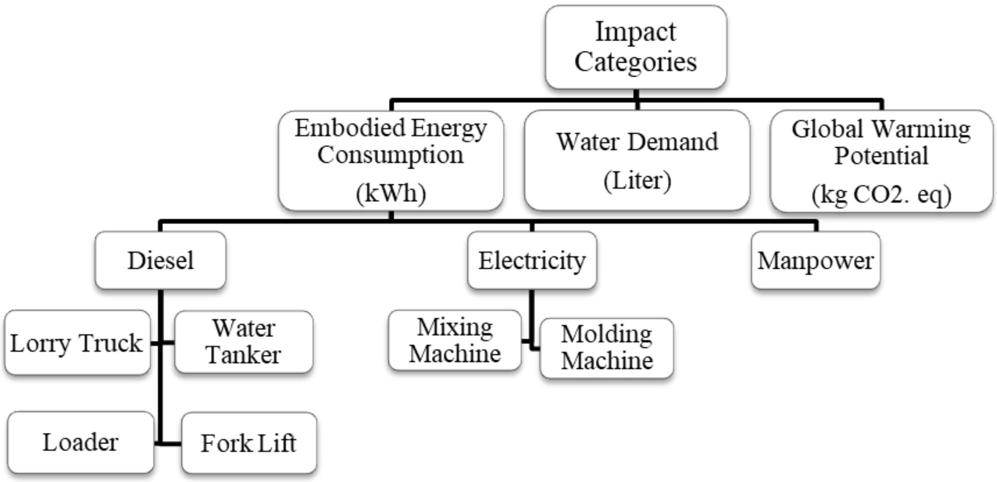
Source: Authors, 2023

Figure 7. Systematic flowchart of specific output number of full-automatic HCB manufacturing process in Jordan including material and energy input quantities for each process

b. Lifecycle inventory and quantifying numerical data

Obtaining the generalized mathematical equation for diesel, fuel energy, and electrical energy consumption; an assumed functional unit of one brick of each size; a kilowatt-hour (kWh) that is the equivalent of 1000 joules per second flowing over one hour amounts to 3.6 MJ is the assigned unit.

Regarding the selected three prevailing impact categories, numerical data has been collected and prepared through a field survey to work on calculations. Figure 8 outlines the work plan as follows:



Source: Authors, 2023

Figure 8. Energy and materials flows considered in this study to be quantified; with their environmental impacts

The total amount of consumed embodied energy by manufacturing concrete bricks is the aggregate quantities as shown in table 3, including all forms of energy used within the identified portion of its life cycle. Reviewing HCB's manufacturing operations indicated that three types of energy were dominant: Diesel power (L/hr.) consumed by carrying raw materials from quarries to the factory, and from the factory to the construction site by lorry trucks, or water tankers; electricity (kWh) consumed by electrical machines used in the factory for mixing, molding, and vibrating bricks; as well as labor embodied energy measured in METs. Worth noting that the estimated energy consumption is determined by a field investigation done by the authors, and is susceptible to a certain error rate attributable to the wide range of machines available and their different types.

Table 3. Raw material weights in for manufacturing HCB in Jordan

Material	Volume (m^3)	Weight (kg)
Cement	1	1515
Sand	1	1500
Aggregate	1	1800
Water	1	1000

Source: Authors, 2023

Diesel fuel energy consumed by transportation: The mathematical equations (1 through 5) below may be followed depending on the manufacturing method that is intended to be employed, with the cut distances serving as the primary variables.

First: Semi-automatic manufacturing method utilizing a 12-m^3 capacity lorry truck that consumes 24 L/hr. transporting various input/output material loads.

$$Ed_{total}\ (L) = b + \sum Ed_i + Ed_j \ldots \qquad (1)$$

where:

Ed_{total}: total value of consumed diesel fuel energy.

b: number of bricks.

Ed_i: fuel energy value consumed by transporting input raw material. i: input raw material.

Ed_j: fuel energy value consumed by transporting output product to the construction site.

But Ed_i can be quantified as follows:

$$Ed_i = S_i\ [24\ (L/\ hr.) \times d_i\ (hr.)] \ldots \qquad (2)$$

where:

Ed_i: fuel energy value consumed by transporting input raw material. S_i: Weight factor (fixed number) refer to table 4.

d_i: distance between input raw material source and the brick factory location in hours.

i: input raw material.

In addition, Ed_j quantified as follows:

$$Ed_j = 1.58 \times 10^{-3}\ [24\ (L/hr.) \times d_j\ (hr.)] \ldots \qquad (3)$$

where:

Ed_j: fuel energy value consumed by transporting output product to the construction site.

d_j: distance between the construction site location and the brick factory location in hours.

j: construction site location.

1.58×10^{-3}: 1/ the average number of multiple sizes of HCB units loaded in lorry truck per trip.

Table 4. Weight factor (S_i), serving as a constant figure in equation (2), according to the input raw material type

Input Material	Input raw material (i)	Weight factor (S_i)
Cement	1	4.5068×10^{-5}
Sand	2	2.28×10^{-4}
Aggregate	3	5.32×10^{-4}
Water	4	0.95×10^{-4}

Source: Authors, 2023

The value of the weight factor (Si) is obtained by:

$S_i = W\ (kg) / F_i \ldots$ (4)

where:

W: The weight capacity of the utilized lorry truck loading.

F_i: The average value in kg of each input raw material weight per one brick of each size (fixed figure), shown in Table 5.

Table 5. The average weight (F_i) in kg of input raw material per one brick of each size, depicted in equation (4)

Brick size	Cement (kg)	Sand (kg)	Aggregate (kg)	Water (kg)
10cm	0.625	3.125	8.75	0.875
15cm	0.833	4.17	11.7	1.17
20cm	1.00	5.00	14.00	1.4
Weight Average (F_i)	0.819	4.098	11.483	1.148

Source: Authors, 2023

Full-automatic manufacturing method utilizing a 24-m^3 capacity.

t_y lorry truck that consumes 24L/hr. in transporting various input/output material loads.

$$Ed_{total}(L) = b\sum_{i}^{4} = 1Ed_i + Ed_j + Ed_k + 1.33\times10^{-3}\dots \quad (5)$$

where:

Ed_{total}: total value of consumed diesel fuel energy. b: number of bricks.

Ed_i: diesel fuel value consumed by transporting input raw material by lorry truck.

i: input raw material.

E_{dj}: diesel fuel value consumed by transporting output product to the construction site.

E_{dk}: diesel fuel value consumed by loading raw materials into aggregate silos by the loader. A value of 1.33×10^{-3} MJ consumed energy average value by forklift adopted from the case study results.

However, Ed_i is quantified as follows:

$$Ed_i = S_i\,[24\ (L/hr.)\times d_i\ (hr)]\dots \quad (6)$$

where:

Ed_i: diesel fuel value consumed by transporting input raw material. Si: Weight factor (fixed number) see Table 6.

d_i: distance between input raw material source and the brick factory location in hours.

i: input raw material.

In addition, Ed_j quantified as follows:

$E_{dj} = 1.00\ \times10^{-3}\ [24\ (L/hr.)\times d_j\ (hr.)]\dots$ (7)

where:

E_{dj}: diesel fuel value consumed by transporting output product to the construction site.

d_j: distance between the construction site location and the brick factory location in hours.

j: construction site location.

$1.00\ \times10^{-3}$: 1/ the average number of multiple sizes of HCB units loaded in a lorry truck per trip.

Table 6. Weight factor (S_i), serving as a fixed figure in equation (6) according to the input raw material type

Input Material	Input raw Material (i)	Weight factor (S_i)
Cement	1	$3.86\ x10^{-5}$
Sand	2	$1.63\ x10^{-4}$
Aggregate	3	$2.46\ x10^{-4}$
Water	4	$5.30\ x10^{-4}$

Source: Authors, 2023

The value of the weight factor (S_i) is obtained by:

$$S_i = W\ (kg)/F_i\dots \quad (8)$$

where:

W: The weight capacity of the utilized lorry truckload in kg.

F_i: The weight average value in kg of each input raw material per one brick of each size, refer to Table 7.

Table 7. The average value (F_i), in kg of input raw material weights per one unit of each size in equation (8)

Brick size	Cement (kg)	Sand (kg)	Aggregate (kg)	Water (kg)
10 cm	1.00	4.18	7.576	0.91
15 cm	1.375	5.75	10.416	1.25
20 cm	1.833	7.67	13.90	1.66
Weight Average (F_i)	1.403	5.867	10.631	1.273

Source: Authors, 2023

In addition, Ed_k quantified as follows:

$$Ed_k = 5.00\times10^{-5}\ [20\ (L/hr.)\times T\ (hr.)]\dots \quad (9)$$

where:

Ed_k: diesel fuel value consumed by loading raw materials into aggregate silos by the loader.

T: loader-working hours/day

$5.00\ \times10^{-5}$: 1/average number of bricks produced in one working day.

c. Consumed electrical energy (kWh) is estimated by multiplying a machine's electrical power (kW) by the amount of time it took to complete a given operation in the brick factory (hours). Correlating each machine with its motor power and its cycle time for each production method is summarized in Tables 7 and 8. As for the semi-automatic production method scenario:

Table 8. Electrical machinery description, used in manufacturing semi-automatic HCB. ().

	Code	Machine	Motor	Horsepower (kw)	Cycle Time (min)
Semi- automatic Brick	B3	Mixing Machine	22.4	30	15 minutes per 80 unit of 10 cm HCB, 60 unit of 15 cm HCB and 50 unit of 20 cm HCB.
	B5	Molding/Vibrating machine (capable of producing two units of 10 cm HCB per press or one unit of 15 and 20 cm HCB per press)	3	4	40-45 second per press

*one horsepower (hp) = 745.7 watts.

Source: Authors, 2023

As for full-automatic production method scenario:

Table 9. Electrical machinery description, used in manufacturing full-automatic HCB

	Code	Machine	Motor Power (kw)	Cycle time
Full-automatic Brick	B3	Dosing system for raw materials.	5.5	2min.
	B4	Mixer machine (3 motors).	45x3=135	4min.
	B5	Admixture transport system from mixing plant to block machine.	2.2	30 sec
	B6	Block making machine (Molder/vibration).	95	28 sec
	B8	Wet side belt conveyor + elevator	15	3min.
	B8+	Product cleaning brush	1.1	3 sec
	B9	Finger car (in) from the elevator to the curing chamber	13	5min.
	B10	Curing chamber 5 fans: air-circulating/ exhaust fans for 2 working days (work Day = 8 working hours.)	0.75x5=3.75	16 hrs.
	B11	Finger car (out) from curing chamber to lowerator	13	5min.
	B12	Dry side return beam conveyor + lowerator	15	3min.
	B13	Cuboter (Automatic HCB collecting Robot with 4-armed rotated head)	23.5	2min.

Source: Authors, 2023

Table 10. Calculating consumed electrical energy values in (kWh) per brick or pallet

Method	(E_e) Consumed electrical energy (kWh) / brick			(E_e) Consumed electrical energy (kWh)/ Pallet		
	10cm	15cm	20cm	10cm	15cm	20cm
Semi-automatic (A)	0.09xb	0.131xb	0.15xb		-	
Full-automatic (B)	0.442xb	0.61xb	0.81xb		14.60xp	

As variables, the approach depends on HCB's LCA results. (Source: Authors, 2023).

The overall cumulative value of electricity consumption for each case study was determined using the equation:

$$E_e = \sum_j^n = 1 E_j \ldots \quad (10)$$

where,

E_e: Total accumulative energy of consumed electricity. E_j: Energy inputs for each manufacturing operation.

j: number of processes required to produce cement bricks in the factory.

To generalize obtaining electrical energy consumption value, two approaches are common in Jordan, Semi-automatic process (A), and Full-automatic process (B), by machinery shown in table 9; both procedures are summarized in table 10, where b: the number of produced HCB units and p: the number of produced pallets.

d. Analysis of water demand

Water demand depends on the input quantity ratio of the concrete admixture, as well as referring to the atmospheric temperature and humidity (for either winter or summer) that affects the moisture of the aggregates in the batching plant.

e. Analysis of carbon footprint/CO_2-Equivalents

Calculating carbon dioxide equivalent (CO_2-eq) emissions quantities in (kg) per unit of fuel (kWh), obtained from the previous (a) and (b) steps above based on their associated conversion factor by applying the following two equations:

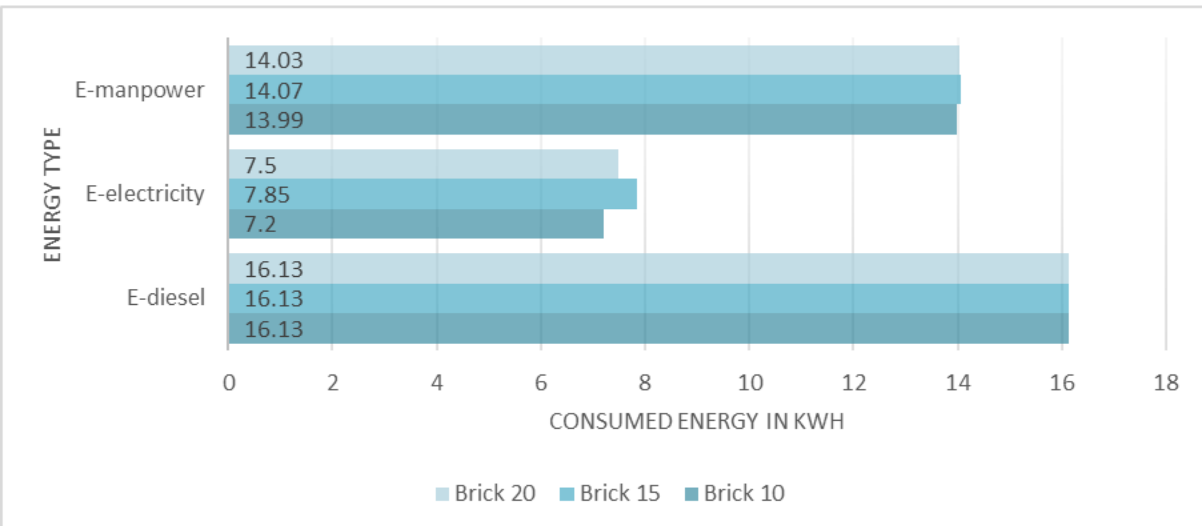
$$(\text{Kg } CO_2\text{-eq}) \text{ for diesel fuel} = E_d \text{ (kWh)} \times 0.253 \quad (11)$$

$$(\text{Kg } CO_2\text{-eq}) \text{ for grid electricity} = E_e \text{ (kWh)} \times 0.544 \quad (12)$$

Conversion factors obtained from UCCCFS (v.1.3) software. The grid Electricity conversion factor varies across countries, the one used in this thesis is a rough estimation across Middle Eastern countries.

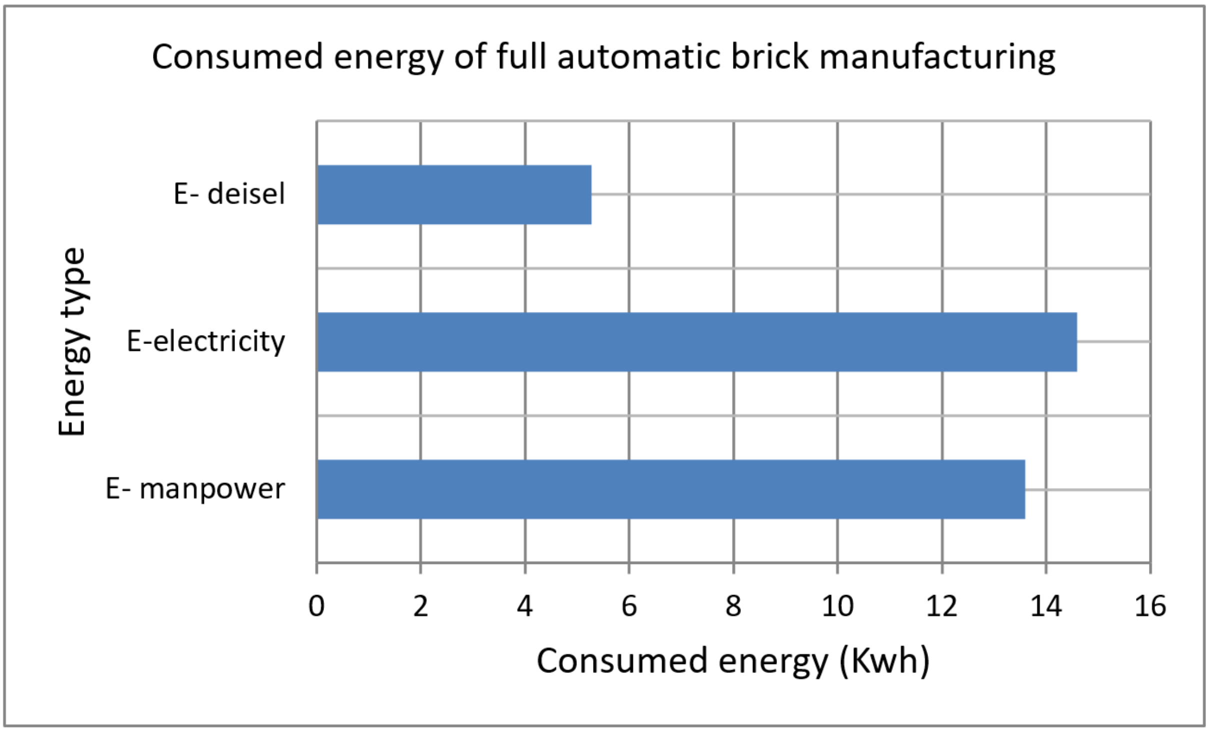
3. Results and Discussion

The proposed calculation approach experimented with a case study of each manufacturing method, the first at Ein al Basha semi-automatic factory, and the second at al Manaseer ready mix full-automatic factory. Results showed that the energy from diesel fuel consumption, with a value of (E_dA = 16.13 kWh) is the highest figure, relating to electrical energy consumption (E_eA = 7.2, 7.85, and 7.5kWh), and labor as energy (Eh A= 13.99, 14.07, and 14.03 kWh) for brick 10, 15, and 20 respectively. However, regarding case study (B) of local full-automatic HCB production, electrical energy was consumed at the highest value, followed by diesel fuel, and manpower energy, which equaled (E_eB = 14.60 kWh), (E_dB = 5.267 kWh), and (E_hB = 13.60) respectively; illustrated in figures 9 through 12.



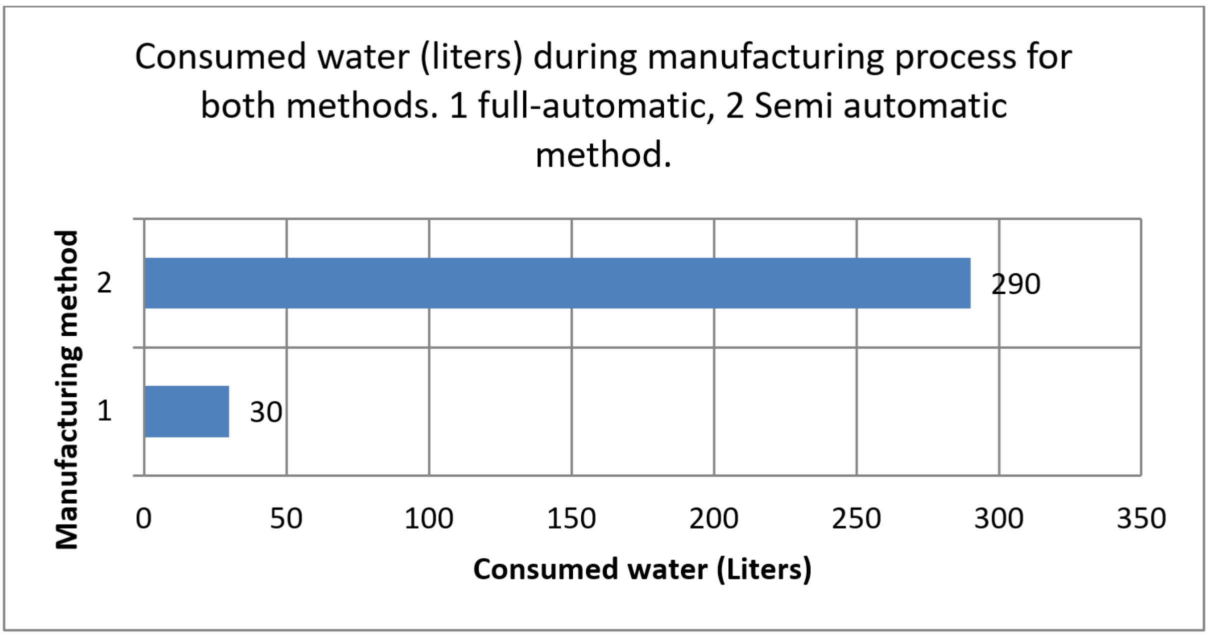
Source: Authors, 2023

Figure 9. Value sinks of consumed three types of energy when manufacturing semi-automatic HCB in Jordan-case study (A)



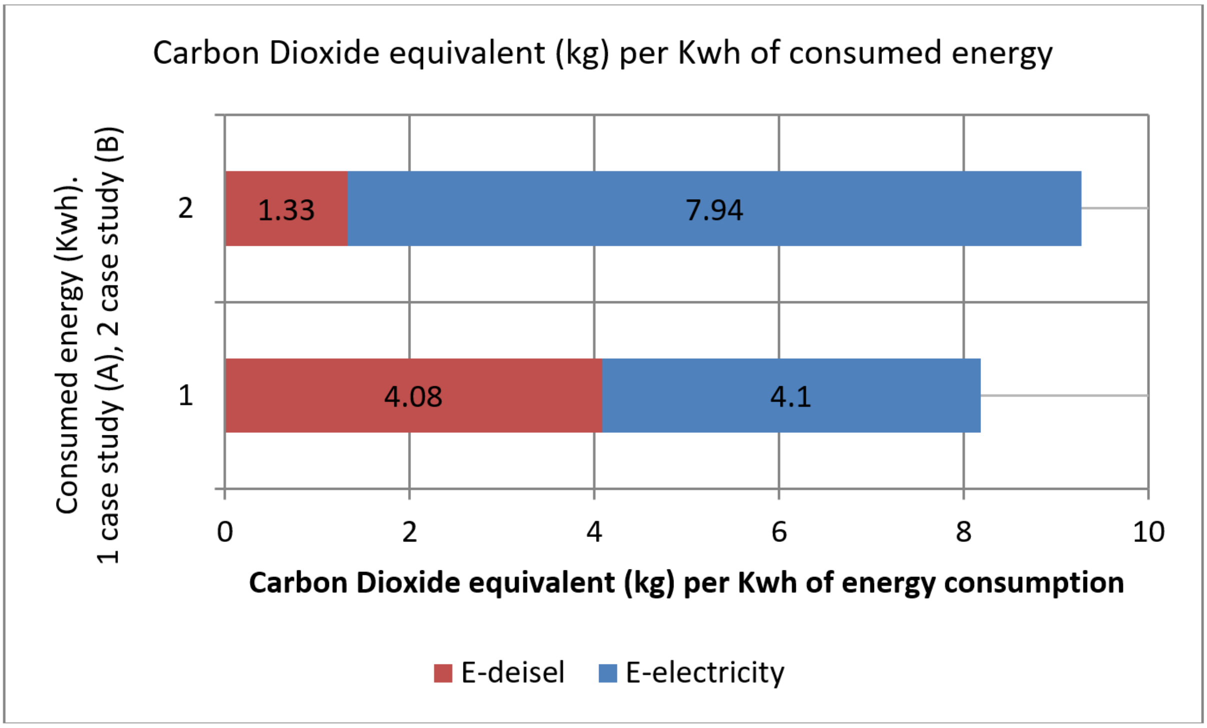
Source: Authors, 2023

Figure 10. Values of consumed types of energy for full-automatic HCB manufacturing in Jordan-case study (B)



Source: Authors, 2023

Figure 11. Quantities of water consumed (liters) throughout manufacturing HCB in Jordan



Source: Authors, 2023

Figure 12. Carbon dioxide equivalent (CO_2-eq) per kWh generated from consuming diesel and electrical energy through manufacturing HCB in Jordan

4. Conclusions and Recommendations

The embodied impact of the manufacturing and supply chain processes of building materials are vital indicators of the building's total environmental impact throughout its entire life cycle when assessing its real sustainability. Implementing the LCA tool to HCB commonly used in the local construction sector, and manufactured building materials in Jordan; manufactured by two different methods depending on the machinery contribution level in the process, semi-automatic and full-automatic as a case study, resulted in obtaining a mathematical equation to generalize the estimation of transportation embedded energy values; in addition to an obtained approach to generalize the estimation of electrical energy values. Kg CO_2-eqs values can be computed automatically by obtaining both diesel fuel and electrical energy consumed values and their corresponding conversion factors.

It is recommended to embrace environmental performance as one of the leading concepts in the building industry, by incorporating LCA methodology into the updated versions of local sustainable assessment tools. And adopting EPDs of building materials into the local context to be used as guidelines driven by national legislation aimed at greening the supply chain, hence achieving sustainability in the long run, and achieving a sustainable environment.

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