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ROLE OF LEAN AND VDC IN REDUCING PHYSICAL AND OPERATIONAL WASTE AND ENVIRONMENTAL IMPACT

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ABSTRACT

Lean construction focuses on eliminating process and operational wastes. The reduction of waste improves environmental performance by reducing GHG emissions. This research quantified the impacts of lean construction and VDC in reducing physical and operational wastes related to partition walls. The researchers observed worker activities at construction sites and compared them with observations from past projects. The activities were classified into value-adding and non-value-adding activities. The researchers observed the construction of different block types (gypsum, autoclaved aerated concrete, and concrete blocks) to estimate the operational wastes related to the construction method. The results showed that lean and VDC improved the value-adding activities using gypsum block to 68.4% compared to 25.8% in a traditionally managed project using concrete block, an improvement of 167%. Moreover, the embodied GHG emissions in the lean-VDC project per partition area are 12 kg CO_2e m^{-2} compared to 58.4 kg CO_2e m^{-2} in the traditionally managed project. The reduction in GHG emissions is due to reducing waste in the lean-VDC project and using more sustainable materials.

KEYWORDS

Lean construction, sustainability, waste, Life Cycle Assessment (LCA), Virtual Design and Construction (VDC).

INTRODUCTION

The construction industry is one of the most polluting industries in the world (Choi et al. 2019; EPA 2009; Horvath 2004; Li et al. 2019; UK-GBC 2018; IEA 2019). According to the International Energy Agency (IEA), the buildings and construction industry consumes around 36% of the global energy and releases more than 39% of the global greenhouse gas emissions (GHGs) (IEA, 2019). Those impacts primarily occur during building operation. In the United Kingdom, the construction industry uses more than 400 million tons of material per year, the majority of which imposes major burdens on the environment and large costs for waste management. For example, 60 million tons goes directly to landfill simply due to over-ordering, miss-ordering or poor handling, and

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breakages (UK-GBC 2018). Moreover, the U.S. construction industry accounts for 160 million tons, or 26%, of non-industrial waste generation each year (EPA 2009). It also contributes to 23% of air pollutant emissions, 50% of GHGs, 40% of drinking water pollution, and 50% of landfilled waste (Willmott Dixon Group 2010). Therefore, there is a need to improve the construction industry by implementing new construction paradigms like lean construction and BIM to reduce different types of wastes, which in turn can avoid unnecessary energy consumption and GHGs.

Lean construction focuses on eliminating waste, which represents any exhaustion of time, money, equipment, and energy that does not bring value to the customer (Womack and Jones 2003). Researchers from all over the world studied waste in construction, identifying and attempting to measure this waste and trying to find methods and ways to eliminate it (Lee et al. 1999; Formoso et al. 1999; Koskela et al. 2013; Golzarpoor and González 2013; Sajedeh et al. 2016; Maraqa et al. 2021). Elimination of these wastes plays an important role in providing the customer with the product in an efficient way, by reducing cycle time, time to market, and cost for the whole supply chain. Taiichi Ohno identified seven types of process wastes: transportation, inventory, motion, waiting, over-production, over-processing, and defects (Ohno, 1988).

Virtual design and Construction (VDC) is a practice that uses Building Information Modelling (BIM) for modelling construction products and their related construction processes (Kunz and Fischer 2012). VDC is used to assist multi-disciplinary project teams. It offers an incorporated method to plan production in construction, removing design clashes in the virtual world before they manifest in the real world.

Traditional management focuses on the transformational part of the industry and ignores the process and its associated operations (Koskela 2000). It views waste as the physical waste associated with the product. So, it misses the ability to quantify the process wastes and eliminate them. Lean thinking guides mapping the process and dividing the process' activities into value-adding and non-value-adding activities, which helps to improve the process by reducing the non-value-adding activities or eliminating them.

Life cycle assessment (LCA) is a practical tool and framework that can guide the sustainable design of products, processes, and activities. As a framework, it enables the systematic evaluation of environmental impacts associated with products, processes and activities (ISO 14040/44 2006). For decades, LCA has been used to understand the environmental impacts of products and engineered systems within the economy, including early-stage building materials, civil engineering infrastructure and buildings (Miller et al. 2019; Nguyen et al. 2018; Kendall et al. 2008; Junnila et al. 2006). Moreover, researchers have proposed methods to integrate LCA with BIM tools (Stadel et al. 2011).

During the last decade, many researchers have studied the relationship between lean construction, BIM, and sustainability to find the synergies between them. Koskela et al. (2010) suggested that synergy between BIM, lean, and sustainability is a considerable opportunity to achieve step-changes to address construction problems like delays, cost overruns, shortcomings of quality, and poor safety. However, this requires visionary and decisive action as well as persistence. Sacks et al. (2010) developed a BIM-Lean matrix, finding 56 interactions between the two and showing, through a survey of experimental and practical literature, 48 out of 56 intersections from documented evidence. The BIM-lean matrix can be used as a framework to understand practical issues faced by companies implementing lean and/or BIM.

Saggin et al. (2015) studied the relation between green costs and lean savings in a residential tower in Fortaleza, Brazil. Lean savings showed a reduction in material waste.

Results showed that the waste index in this project reduced to 10.93 cm/m^2 (height unit/area unit) compared with 13.53cm/m^2 in a traditional project without lean implementation, a reduction of 19.24% in construction waste. Carneiro et al. (2012) developed a matrix between lean principles and LEED interventions. They argued that LEED, as a rating system, does not allow the flexibility valued by lean construction, and it suggested the use of often expensive sustainability interventions without concern for process improvement and time and cost reduction. They noted that while LEED and lean construction contribute to the three pillars of sustainability (economic, environmental and social) since both share the waste elimination concept, the two methods differ in their application. Where LEED focuses on sustainability at conception, design, and construction phases, lean construction alternatively focuses on flow and conversion processes, aiming to improve production processes by removing all non-value adding activities. Another difference between lean and LEED is that the former focuses on reducing time and initial cost without specific concern for the environment.

This paper presents an extension of an experiment the researchers started in 2019 (Maraqa et al. 2020). It aims to measure multiple types of partition walls wastes by studying several blocks construction methods with several management approaches. The partitions studied in this work are gypsum block, autoclaved aerated concrete block (AAC), and concrete block. The blocks were studied with different management approaches; lean, lean and VDC, and traditional management. The overall objective is to present the effects of lean construction and VDC in reducing material and operational wastes and to present the role of the product in generating operational waste, which does not exist in other types of products. Also, (LCA) models were built for different types of partitions to evaluate the embodied GHG emissions in the different types.

This paper consists of four main sections. Section 1 describes the problem synopsis and the research objective. Section 2 describes the research method and the case study. Section 3 details the findings and results. Finally, section 4 concludes the paper, synthesizing the major research findings.

RESEARCH METHOD

A case study research method was selected for this research. Data were collected from three construction companies (A, B, and C) to study the physical and operational wastes related to construction of masonry partitions. Company A began implementing lean construction and BIM in 2012 by implementing Last Planner ® System (LPS) and BIM in the design phase, and since then they have made significant improvements in implementing BIM in the big room, virtual design and construction (VDC), 5S principles, centralized mixing, and supply of bulk materials. Companies B and C have worked conventionally without any implementations of BIM or lean construction practices.

This paper extends work described by Maraqa et al. (2020) and applies the same work study-analysis performed by Sacks et al. (2018) in company A's construction projects before the company implemented BIM and lean practices. The same observations and measurements were collected after the company implemented VDC and 5S practices. Recently, a new construction project built conventionally by company C with different block construction methods was studied to visualize the operational waste.

Life cycle assessment (LCA) following ISO (14040/44, 2006) was used to calculate the reduction in GHGs along the material supply chains of projects A3, B1, and C1. Researchers monitored the workers' activities every five minutes and classified the activities into value-adding and non-value-adding activities. The researchers monitored

450 worker-hours in three different projects (A3, B1, C1) under construction. The value-adding activities included: building, gluing, and leveling. The non-value-adding activities included: marking out, moving blocks, shuttering, cutting, moving between floors, steel fixing, cleaning, scaffolding, waiting, reworking, implementing design changes, and others.

A critical analysis was conducted for the raw collected data from the different construction sites. All the activities were classified into different categories, summing the time for each activity, and dividing it by the total time to identify its percentage. The aim was to test the impacts of different construction production systems in reducing wastes and improving environmental performance.

The following section of this manuscript describes the data collection activities for block works. The last section describes an inventory of GHGs designed to calculate the embodied GHGs of the blocks and the plaster layer, from cradle to installation.

LIFE CYCLE ASSESSMENT (LCA) OF THE PARTITION WALL

Life cycle assessment (LCA) following ISO (14040/44, 2006) was used to calculate the embodied GHGs for 1 m^2 of the finished partition wall in projects A, B, and C. To compare GHGs for different types of partition walls, LCA models were built using GaBi for the different types (Figure 1). The models include the block type with the related plaster types. The building materials used were autoclaved aerated concrete block (AAC), concrete block, gypsum block, gypsum plaster, and cement plaster. The embodied GHGs in these products were calculated based on values stored in the GaBi database (Sphera GaBi 9, 2020; Spatari et al. 2001) using the 100-year global warming potential (GWP) based on AR4 of IPCC 2007 (Forster et al. 2007) and measured in carbon dioxide equivalents (CO_2e). The system boundary for the projects studied evaluated the embodied GHGs in the block manufacturing and plaster materials.

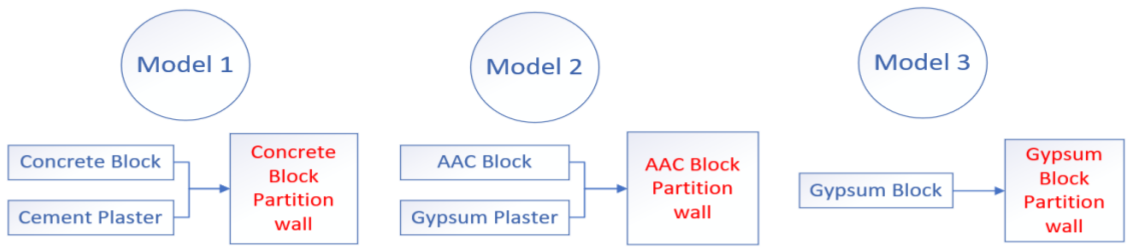

Figure 1: LCA models for different types of partitions using GaBi

CASE STUDY DESCRIPTION

A research team started an experiment for monitoring the block workers' activities in one of the construction sites related to company A in 2007 (A1). The results were interesting and motivated company A to start thinking about waste. Only 31.9% of the workers' activities were value-adding activities, while the rest were non-value-adding activities. The activities are cutting 24.1%, marking out 7.3%, scaffolding 2%, transporting blocks 4.4%, moving between floors 0.4%, design changes 7%, filling grooves 2.6%, and waiting and rework (Sacks et al. 2018).

Company A realized the importance of improving its process. They started to apply value stream mapping (VSM) for the masonry works (A2). They delivered the blocks before placing the concrete slab and avoided stacking two pallets on top of each other. They found that traditional block delivery is very wasteful (Sacks et al. 2018).

From a lean point of view, all these activities except building, gluing, and levelling are waste because they do not add any value to the final product. Avoidance of these activities is a necessity and can be reduced by mapping the process and eliminating these wasted activities. If the blocks are calculated precisely and delivered to the exact locations at the right time without stacking the pallets on top of each other, the workers will spend less time and effort in these waste activities. Also, material waste will be reduced, because stacking two pallets on top of each other increase the pressure on the bottom pallet and damage the blocks.

Block workers' activities were monitored in one of company A’s projects in 2019 (A3) (Maraqa et al. 2020). Company A decided to implement VDC, LPS, and 5S (sort, set in order, sustain, standardize and shine), which is a systematic method for organizing the work environment and keeping the construction site clean and organized. A VDC model was built using Autodesk Revit. The VDC model produced a highly detailed model to optimize the number of block rows and reduce block cutting. Also, it improved the coordination between the different subcontractors and reduced the changes and rework. Three types of blocks were used in this project: autoclaved aerated concrete (AAC) blocks, water resisting gypsum block, and regular gypsum block. Company A decided to use gypsum blocks in their construction projects for many reasons. The blocks are relatively large (50 cm x 67 cm x 10 cm), lightweight, and smooth; thus, they do not need a finishing layer of plaster before being painted. From a construction method perspective, the gypsum block is considered a highly productive solution. VDC models helped in extracting the exact block quantities for each apartment and delivering them to the right location at the right time. Also, the VDC model helped in producing highly detailed partitions layout drawings for the workers. The site superintendent removed all the constraints by preparing the water and electrical connections and distributing the block drawings according to their apartments by hanging them on the wall. Removing the constraints helped the workers get the information from the beginning of the work instead of waiting.

A second project in which company A applied mainly the last planner system without VDC was studied (Maraqa et al. 2020). The reason for selecting this project is to test the marginal impact of different lean and BIM interventions. A third project was studied in 2019 belonging to company B (Maraqa et. 2020) (B1), which worked traditionally without any lean or BIM interventions. The company used AAC block. The blocks were delivered randomly to the different apartments, and block pallets were stacked on top of one another.

Finally, a fourth project was studied in 2021. The project was built by company C using concrete blocks (C1). Company C works traditionally without any BIM or lean implementations. Also, it did not either implement any technological construction method. Today, most construction companies do not use concrete blocks for many reasons. The blocks are relatively small (40 cm X 20 cm X 10 cm), heavy, and rough. Also, the concrete block construction method requires building concrete framing columns and beams. These beams and columns consume a considerable amount of cement and fine and coarse aggregate. Moreover, they need wood for shuttering, rebars for beams and columns, and more effort from workers.

In the fourth project (C1), all the block pallets, fine aggregates, cement, steel, and wood were delivered to the workspace on a temporary balcony after pouring the concrete and removing the shoring from the slabs. The general contractor prepared the balcony for delivery logistics, delivered all the materials, and the block subcontractor moved the materials inside the floor (Figure 2). Delivering the material in this way resulted in additional material relocation steps that wasted the workers' time. Numerous amounts of waste were observed. The workplace was not clean, organized, or even safe. Many of the works constraints were not ready such as drawings, water, and electrical connections. Lack of design visualization resulted in changing some partition wall locations after the workers finished them. Also, the different work packages were not planned well. This resulted in causing the subcontractors to leave and return to the project several times.

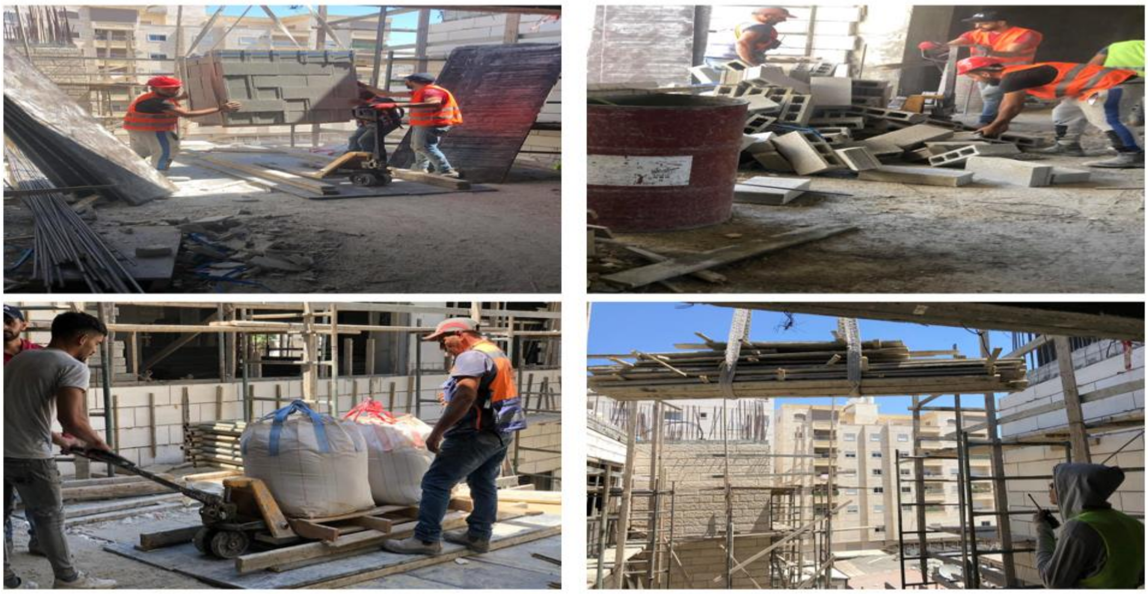

Figure 2: Delivering materials for project C1 using an open balcony

FINDINGS AND RESULTS

The four projects studied were analyzed for different categories: worker activities, material waste, and the embodied GHGs in the materials. Results indicate that lean and VDC interventions have a significant impact in reducing material and operational wastes. Value-adding activities have the highest value for the VDC-lean project with 68.4%, while non-value-adding activities have the highest value for the traditionally managed projects (B1& C1). Figure 3 shows the different projects studied. Project C1 was studied recently for concrete block, projects A1, A2, A3, and B1 studied previously (Maraqa et al. 2020). The value-adding activities in project B1 were 35.8% and in project C1 the results were worse.

In project C1 (traditional 2021), value-adding activities were only 25.8%, and the rest were non-value-adding activities. Non-value-adding activities are related to two aspects: the construction method, and the management approach. In concrete blocks (Project C1), some operational wastes do not exist as they do for the other blocks' types. These operational wastes include shuttering, mixing, drilling, and insulation. Waiting and rework and moving pallets activities were a significant cause of the block works operational waste of approximately 25% of workers' time. Also, the lack of design visualization due to designing the project traditionally resulted in rework. For example, after the workers finished a wall with an area of 25 m^2 between two inner sides of two columns, the client decided to rebuild the wall on the outer side of the columns to increase the room area (Figure 4). This required spending around 20 working hours demolishing the wall. Moreover, the concrete block requires activities that do not exist in the gypsum block or the AAC block. These activities are shuttering 9.2%, mixing 10.6%, steel fixing 4.9%, drilling 1%, placing concrete 6.3%, and insulation 0.3%. These activities form about one-third of the workers' time. Table 1 summarizes the value-adding and the non-value activities in the different projects studied.

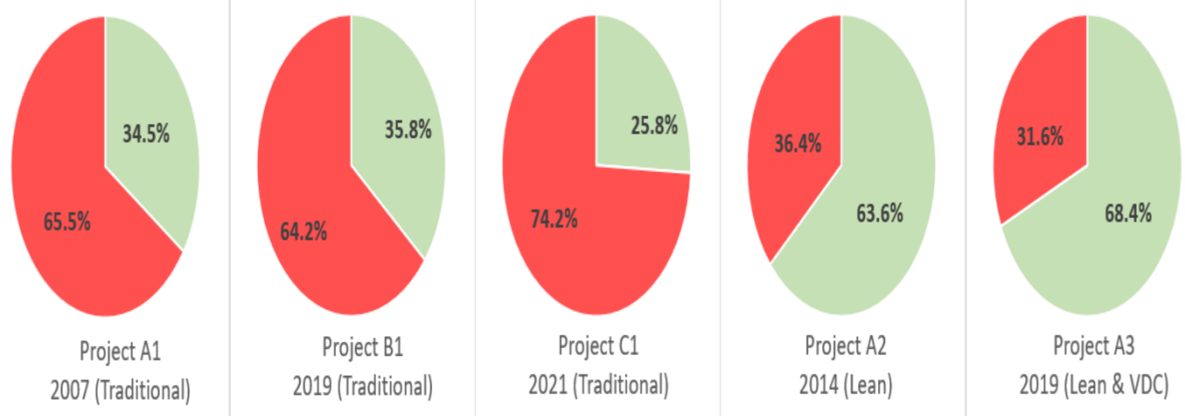

Figure 3: Results for five projects showing proportions of value-adding (green) and non-value-adding (red) activities for masonry construction operations. Charts for company A and B projects were reported previously (Maraqa et al. 2020)

Table 1: Summary of the results of activities observed in five work studies. Values are the percent proportion of the total working time spent on each activity

Worker activity	Project A1 2007 (Traditional)	Project A2 2014 (Lean)	Project A3 2019 (Lean & VDC)	Project B1 2019 (Traditional)	Project C1 2021 (Traditional)
Building, gluing and levelling	34.5	63.6	68.4	35.8	25.8
Cutting	24.1	7.8	1.3	12.6	4.3
Moving pallets	4.4	1.3	4.8	19.0	7.8
Move between storeys	0.4	1.3	1.9	3.7	-
Cleaning	9.9	5.2	4.9	5.7	2.3
Marking out	7.3	11.7	3.5	5.6	1.4
Scaffold	2.0	0.0	0.3	1.2	2.8
Waiting and rework	10.5	3.9	6.1	6.6	15.1
Design changes and others	7.0	5.2	8.8	10.0	8.2
Shuttering	-	-	-	-	9.2
Mixing	-	-	-	-	10.6
Steel Fixing	-	-	-	-	4.9
Drilling	-	-	-	-	1.0
Placing concrete	-	-	-	-	6.3
Insulation	-	-	-	-	0.3
Total	100.0	100.0	100.0	100.0	100.0

Figure 4: Lack of visualization for client review led to rework for a complete block wall

LIFE CYCLE ASSESSMENT AND GREENHOUSE GAS EMISSIONS FOR DIFFERENT TYPES OF PARTITIONS WITH DIFFERENT MANAGEMENT APPROACHES.

This section evaluates the GHGs for three types of partition walls. The partition walls studied consists of the block and the plaster layer. Concrete block with cement plaster was used in the traditionally managed project (C1). Also, AAC block with gypsum plaster was used in the traditionally managed project (B1), while gypsum and AAC blocks were used in the lean-VDC project (A3).

The functional unit studied in this research is 1 m^2 of a ready partition wall. The concrete block partition wall consists of the concrete block and a cement plaster layer. The AAC partition wall consists of the AAC block and gypsum plaster layer, while the gypsum block partition wall consists only of the Gypsum block without any plaster type. The concrete block partition wall has the highest value for the embodied GHGs because it depends mainly on cement. The embodied GHGs per m^2 equal 56.8 kg CO_2e m^{-2}. However, the gypsum block partition wall does not have any plaster, and the gypsum material is environmentally friendly. The embodied GHG per 1 m^2 have the lowest value with 9 kg CO_2e m^{-2}. This analysis showed that the gypsum block is the best alternative among the other three block alternatives. Table 2 presents the embodied GHGs in different types of block and plaster layers.

Table 2: presents the embodied GHGs in different types of block and plaster layers

Partition wall	Block Embodied GHG (kg CO_2e m^{-2})	Plaster Embodied GHG (kg CO_2e m^{-2})	Total Embodied GHG (kg CO_2e m^{-2})
Concrete block	12.7	44.1	56.8
AAC block	17.4	3.2	20.6
Gypsum block	9.0	-	9.0

From an environmental point of view, lean construction and VDC had a dominant influence on reducing waste and GHGs. Table 3 presents the embodied GHGs for the different construction projects studied with the different management approaches. In the traditional management project (B1), the waste percentage is 22%, and in the project (C1), the waste percentage is 12%. However, these wastes were reduced significantly to only

6% in the lean-VDC project. In terms of embodied GHGs per partition, area built, in the lean-VDC project the embodied GHGs is 12 kg $CO_2e\ m^{-2}$, while in the traditional management projects (B1 and C1) are 25.6 kg $CO_2e\ m^{-2}$, and 58.4 kg $CO_2e\ m^{-2}$.

The results show that the embodied GHGs in the traditional management projects (B1 & C1) are greater than those from the lean-VDC project (A3). Some of the GHGs related to the material used in the partition walls, while others related to the management approach. Although the concrete block and the AAC block have higher embodied GHGs used in the traditional project, the lean-VDC project still has the lowest embodied GHGs since it generated the minimum waste.

Table 3: GWP and material waste for two traditional projects and lean-VDC project

Inventoried Data and Performance Metrics	Traditional management B1	Traditional management C1	Lean and VDC management A3		
	AAC Block	Concrete block	AAC block	Gypsum block	Total
Delivered quantities (m^3)	2,225	597	344	1,886	2230
Block volume built (m^3)	1,762	532	334	1,759	2,093
Waste volume (m^3)	463	65	10	127	220
Delivered blocks (ton)	890	597	138	1,603	1741
Blocks built (ton)	705	532	134	1,495	1,629
Block waste generated (ton)	185	65	4	108	112
No. of pallets	1,646	497	251	2357	
No. of truckloads	55	42	9	86	
Distances travelled (km)	5,500	4,200	900	8,600	
Transportation of unused blocks to site (km)	1,000	360	0	500	
Transportation of waste from site (km)	500	180	0	250	
Block embodied GWP (t CO_2e)	387.2	75.8	59.9	168.8	228.7
Plaster embodied (t CO_2e)	56.5	247.4	10.7	0	10.7
Block transport to site (t CO_2e)	6	4	0.9	10.7	11.6
Embodied GWP in transport to landfill (t CO_2e)	0.6	0.2	0.00	0.4	0.4
Total embodied (t CO_2e)	450.3	327.4	71.5	179.9	251.4
Total embodied GWP in waste (t CO_2e)	82.4	8.9	1.7	12.6	14.3
GWP per partition area built (kg $CO_2e\ m^{-2}$)	25.6	58.4	21.4	10.2	12
GWP in block waste percentage (%)	22	12	2	8	6

CONCLUSIONS

Previous research has highlighted the benefits of lean construction in reducing different types of wastes. However, most of this research focused on measuring the environmental impact of reducing physical wastes. In this research, we proposed a case study research method to evaluate both the process and operational wastes. We showed that selecting the product plays a significant role in reducing environmental impacts, not only due to the embodied GHGs in the product but also because it can reduce the operational waste which has embodied GHGs.

The projects evaluated in this study revealed that lean principles and VDC play a significant role in reducing different types of wastes: physical wastes and operational wastes. In the lean-VDC project (A3), the value-adding activities increased to 68.4%, compared to the traditional projects B1 and C1 with 35.8% and 25.8%. Also, this study showed that the construction method itself introduces some operational wastes. The AAC and concrete blocks are both used in traditionally managed projects, but the operational wastes are much higher in the concrete block compared to the AAC block. Concrete block has shuttering, steel fixing, mixing, drilling, and concrete placing, which do not exist in the other block types.

From an environmental point of view, lean and VDC reduced the embodied GHGs significantly compared to the traditional projects. The embodied GHGs reduced in the lean-VDC project (A3) for two reasons; the first, use of an environmentally friendly product and second, reduction of the amount of waste in the blocks. The waste in the lean-VDC project (A3) was reduced to only 6% compared to 22% and 12% in the traditional projects (B1 & C1). The embodied GHGs in the lean-VDC project (A3) is 12 kg CO_2 e m^{-2}compared to 25.6 kg CO_2 e $m^{-2}$and 58.4 kg CO_2 e m^{-2} in the traditionally managed projects (B1& C1).

We conclude that lean and VDC management approaches are dominant in reducing different wastes types (physical and operational waste). The results showed that implementing lean and VDC with environmentally preferable products achieves optimum benefits. The proportion of value-adding activities increased, the block waste decreased, and the total embodied GHGs per partition area decreased.

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