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ROLE OF WORK FLOW IN REDUCING LIFE CYCLE ENERGY CONSUMPTION IN CONSTRUCTION

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ABSTRACT

Lean construction aims to improve the construction industry by focusing on flow and value and eliminating waste. Reducing waste can also meet environmental goals by reducing greenhouse gas emissions (GHGs) and improving environmental performance. Many green building rating systems have emerged over the last three decades as instruments to incentivize the production of buildings that minimize the impact on the environment and human health. However, those approaches are oriented toward the end product only, leaving builders without guidelines on effective processes to reduce operational waste. This research reviews and evaluates opportunities to mitigate GHGs and improve environmental performance through lean construction. It measures the effects of lean principles on reducing GHGs by improving the flow. Case study research was used to measure the quantity of diesel used for heating two construction projects in a cold climate; one is a traditionally managed project and the other is managed using Virtual Design and Construction (VDC) and the Last Planner System (LPS). Results show that the floor cycle time reduced from 189 days to 115 days in the lean-VDC project, a reduction of 64%. Also, the total embodied GHGs reduced from 1,037-tons CO_2e to 629-tons CO_2e, a reduction of 408-tons CO_2e.

KEYWORDS

Lean construction, life cycle assessment (LCA), energy consumption, flow, transformation-flow-value

INTRODUCTION

The construction industry is responsible for a significant amount of energy consumption and greenhouse gas emissions (GHGs) (IEA, 2019). Construction waste in Israel represents major source of waste. It contains different construction materials like steel, blocks, tiles, plastic materials, gravel, and soil (Katz and Baum, 2011). In 2016, the amount of construction waste rose to 7.5 million tons, (Tal, 2016).

Lean construction aims to eliminate different types of wastes by focusing on flow and value. Waste in construction, understood from the lean point of view, comprises not only physical waste but any exhaustion of resources that does not satisfied value to the customer (Womack and Jones, 2003). Bølviken et al., (2014) studied the wastes in construction from the Transformation-Flow-Value theory (TFV) point of view. They proposed a definition of waste as the use of more inputs than needed and unwanted output. This definition can cover aspects

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inside production, including exhausting more than is needed and to producing unwanted things. They classified the transformation waste as physical material waste, non-efficient use of material, and non-optimal use of machinery, energy, or workers. For the flow waste, they mentioned waste in the workflow and the product flow. Workflow waste includes the unnecessary movement of people, waiting and inefficient work, while product flow waste includes, materials not being processed, and unnecessary transportation of material. Finally, for the value waste, they classified them in two waste categories: main product and by-product. The main product waste is lack of quality and intended use. By-product waste consists harmful emissions or injuries and work-related sickness.

Green building rating systems aim to provide healthy facilities, designed and built in a resource-efficient manner (Kibert, 2007). According to Robichaud and Anantamula (2011), there are several pillars of green buildings: the reduction of environmental impact, the increase of health conditions of facility users, the economic returns to investors, and the total life cycle impacts on the project phases. There are different green building rating systems that are well known. These rating systems aim to take a holistic perspective on a building's full life cycle. Yet, there are gaps in how these rating systems capture all processes within the cradle-to-grave context of buildings.

Many researchers studied the effects of lean construction on reducing construction waste and improving environmental performance. Saggin et al. (2015) examined the relationship between lean and LEED in a case study. They calculated the amount of physical waste reduced in a LEED-certified project managed using a lean management approach. They calculated the total volume of waste and normalized it by square meter. Results show that the waste was reduced from 13.53 cm/m^2 in the traditional management project to 10.93 cm/m^2 in the lean project, a reduction of 20%. Koranda et al. (2012) studied the integrity of lean construction and sustainability in six different construction projects in the Midwestern United States. They used qualitative methods, interviewing project managers to identify the waste sources for sustainability and lean. They concluded that sustainability practices result in reducing physical waste generated during construction which lean also aims to eliminate. However, they identified several differences between the two concepts. Lean construction aims to eliminate the different types of physical, process, and operational wastes, while green building rating systems like LEED and BREAM focus on reducing physical waste.

Maraqa et al. (2022) studied the effect of lean construction in minimizing physical and operational waste. The researchers studied three construction projects with different management approaches. One was managed traditionally, the others were managed using VDC and the Last Planner System. The researchers analysed the partition wall activity since it represents one of the main finishing activities during the construction phase. They found that the embodied GHGs in the lean-VDC project per meter square of partition area were 12 kg CO2e/m^2 compared to 58.4 kg CO2e/m^2 in the traditionally managed project. The reduction of GHGs in the lean-VDC project demonstrates the potential of lean practices in improving environmental performance. A further study examined the effect of lean and VDC practices in improving the process and reducing associated operations waste (Maraqa et al. 2021). The researchers monitored block worker activities and divided them into value-adding and non-value-adding activities. The results showed that lean and VDC implementations raised the value–adding activities to 68.4%, compared to 35.8% in a traditional project.

Other studies measured the effect of lean implementations on improving process and operation flow in construction. Maraqa et al. (2021) studied the role of implementing BIM and lean to improve the flow in eighteen construction projects with different combinations of management approaches. Based on a 10-point scale, their results showed that lean and BIM implementations improved the workflow to 8.12, compared with 4.91 in projects that implemented traditional management. However, this study measured the impact of lean and

BIM in improving the workflow from a management perspective without considering the environmental impacts.

Green building rating systems have been criticised because they do not address the environmental problems across the life cycle of a building, and for their transformational checklist approach, which lacks a methodological basis for efficient implementation of green practices during the construction phase. Carneiro et al. (2012) claimed that green building rating systems like LEED does not allow the flexibility valued by lean construction, and it recommends the implementation of environmental interventions without concern time and cost minimization. They argue that while LEED and lean construction practices contribute to the pillars of sustainability, since both focus on the waste elimination concept, the two methods differ in their application. Other researchers claimed that there are some contradictions between green building rating systems and lean construction practices. In some cases, implementing lean construction practices such as the just-in-time delivery concept can consume more energy sources and emit GHGs (Green, 1999).

The objective of this research is to evaluate the potential for improving the construction workflow and reducing the project cycle time in cold climate areas. The research analyses two hypothetical projects with different management approaches: traditional and lean management. Also, three scenarios - Original, Process (location flow) optimization, and Operations (crew flow) optimization - were modelled to evaluate the amount of energy consumed in each, which helps the project manager make better decisions in managing the sub-contractors to guarantee the achievement of general optimization rather than local optimization. These decisions can have an adverse impact on the amount of GHGs emissions resulting from the project during the construction phase. The researchers selected the cold climate areas since the projects in these areas need to be heated during the wintertime which is not required in temperate or hot climate areas.

FRAMEWORK TO MEASURE ENVIRONMENTAL EFFECTS IN THREE DIMENSIONS: TRANSFORMATION, FLOW AND VALUE

Most researchers focus on green building rating systems from a transformational perspective. They focus on the embodied GHGs in the products (construction materials) and the transportation of the product from the source to the project. However, they neglect the processes and their associated operations effects, so they miss the impact of the wastes related to flow and value. Lean thinking guides the process of construction in a complementary way. It deals with construction as a production system that has three dimensions: transformation, flow, and value. Within those dimensions there is an opportunity to improve environmental performance. We developed a framework to measure the environmental effects of construction projects from these three dimensions (transformation, flow, and value) (Figure 1). The framework integrates the transformation, the flow, and the value for all the processes executed in the project and it considers the environmental impacts resulting from not achieving the value within the required time frame. The framework highlights the missing elements in the current state of the green building rating systems. Those missing elements relate to flow and value. Missing flow aspects are waiting, inspection, rework, construction method, and weather conditions. Missing value aspects include value delay (not achieving the value within the required time frame due to project schedule overrun), not achieving the value at all, and overdesign of parts (e.g. excessive slab thickness, steel reinforcement) and of building systems (HVAC, elevators, etc.).

We compare the effects of the flow dimension in two construction projects with contrasting management methods executed in cold climates. One of them is assumed to be managed traditionally, and the second to be managed using lean and VDC management approaches. The aim is to test the impact of location cycle time on the environment by consuming different types of fuels for heating during the winter. The two cases highlight the importance of reducing the waiting time between the different construction processes during the construction phase to improve the environmental performance of the construction process in cold climate areas.

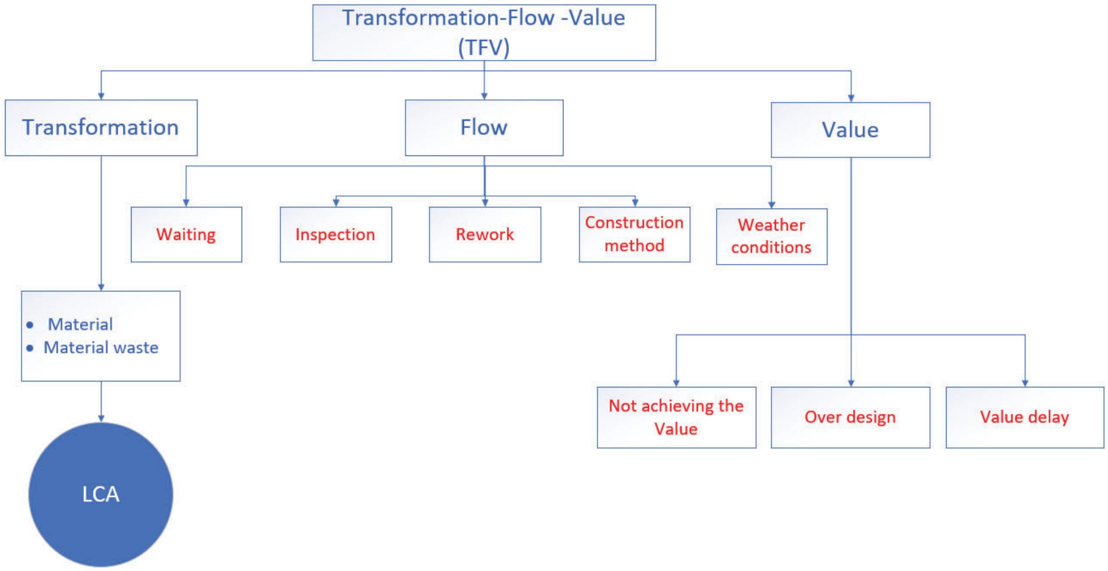

Figure 1. Framework to measure the environmental impacts based on the TFV theory. The boxes with red text represent missing elements in current assessment methods.

METHODS AND DATA

A case study research method was used to study the flow effects on the project's energy consumption. Detailed data, which include start and finish dates for each floor for two high-rise residential construction projects, were collected from the control department of a construction company in a temperate climate region but simulated in a cold climate region by calculating diesel consumed by heaters for heating the project. The two identical projects selected represent two different construction management approaches. The first project was a traditional project without any BIM or lean implementations, while the second project was managed using VDC, 5S and the last planner system (LPS).

The start and finish dates for each floor were used to draw the flow line charts for the two projects using Excel. Two hypothetical cases were evaluated: location optimization to remove the location waiting and crew optimization to remove the crew waiting. The cycle time is defined as the total time from the start of processing of a product until completion. This allows assessment of the marginal impact of implementing VDC, 5S, and LPS in reducing the cycle time. The diesel consumption for heating the construction projects was calculated based on the cycle time for the three scenarios in the hypothetical cases.

LCA following ISO (14040/ 44, 2006) was used to quantify the GHGs results from heating the construction project. Life cycle assessment (LCA) is a framework for evaluating the environmental impacts of products and materials (ISO, 2006). Many researchers used this framework to assess the environmental impacts of products within the economy, including building materials and construction projects (Junnila et al. 2006; Miller et al. 2019; Tian and Spatari 2022). The embodied GHGs were calculated for heating the construction projects in the different flow scenarios to test the flow effects from an environmental perspective.

CASE STUDY DESCRIPTION

The first author has worked in cold climate areas, and observed the amount of diesel consumed by heaters to heat the construction project. During the winter, temperatures declined to around

30 ºC below zero, which means all construction activities, equipment, and cranes must be stopped unless the construction site is heated to create safe working conditions, which required increasing the ambient indoor temperature to 5 ~ 10 ºC above zero. Heating is required before, during, and after casting concrete (to enable the chemical reactions) as well as for the different finishing activities and mechanical, electrical, and plumbing (MEP) system installations (to prevent cracking or breakage of fittings and pipes). These activities consume tremendous amounts of energy to guarantee appropriate work conditions, and the losses are very high because the heating is required for open spaces which are not enclosed or insulated, or enclosed with temporary materials.

The fuel used by heaters is diesel, which has a very high carbon footprint. The cradle to grave GHGs, which include extraction, processing, transport and distribution, and combustion, in one liter of diesel fuel is 3.31 kg CO_2e (One Click LCA, 2023). Each diesel heater consumed 18 liter/hour, and there were tens of heaters around the construction site. Some of these heaters worked 24 hours before and after casting the concrete. Hence, the space cycle time has a strong effect on the environment in cold climate areas, which is neglected within the green building rating systems, and the potential importance of optimizing construction workflow to improve environmental performance during the construction phase.

Detailed data for the start and finish dates for each activity in each location were collected from the control department of a construction company for two identical residential projects completed by the same construction company in a temperate climate zone. The data were used to build line of balance charts for the projects and calculate the space cycle times and the space waiting times.

The first project is a residential construction project consisting of 23 floors with six typical apartments on each floor with an area of 600 m^2. The activities studied are the structural system and six finishing activities: the partitions, electrical, plumbing, HVAC, plaster, and flooring. Virtual design and construction (VDC) using Revit and lean construction principles like LPS and 5S were applied in the project. VDC produced highly detailed models for the partitions, electrical, plumbing, HVAC, plaster, and flooring systems, which accounted for all interactions between these systems and optimized their arrangement. During preparation of the VDC model, the VDC manager shared the ideas with the different crews, who in turn removed the clashes between trades' systems, to plan and optimize the activities sequence. VDC played an important role in reducing the scope and frequency of changes that result from a lack of coordination between different design disciplines. Also, the VDC model helped the construction manager, and engineers in supplying the right quantities to the right location at the right time. Also, in this project, the company applied LPS including look-ahead planning and weekly work planning meetings to improve the workflow and reduce location and crew waiting.

The second project is a residential construction project, which consists of 23 floors with six apartments on each floor with an area of 600 m^2. The activities studied are the same as the first project. This project was built and managed traditionally without any lean or VDC implementations. This project was built and managed by the same company in a period before they started their BIM and lean journey. So, this project was used as a benchmark to test the marginal impact for implementing the lean and VDC practices in reducing the space cycle time and waiting time.

We assumed that diesel heaters were used for heating the construction project in each case to guarantee the appropriate temperature inside the construction project. The heating was assumed to be used mainly for the structural systems, the mechanical and electrical works, and the finishing works. While this paper presents a case study in cold climate areas, the work acknowledges that in temperate and hot climate areas, construction companies do not heat construction projects.

FINDINGS AND RESULTS

The as-performed data from the two construction projects were used to compute the floor cycle times and the associated diesel consumption for heating in cold climate areas. Two additional hypothetical scenarios were considered using simulation:

a) Process optimization, in which tasks from the original schedule were considered to be performed as soon as possible, resulting in continuous work in the locations and minimum cycle-time.
b) Operations optimization, in which the crews were assumed to have continuous work.

Table 1 lists the cycle time for each floor for the two projects with their hypothetical scenarios. The results reveal considerable differences in the cycle time between the traditional project and the lean-VDC project. The average actual cycle time was reduced from 189 days in the traditional to 115 days in the lean-VDC project, a reduction of 64%. Figures 2 and 3 present the flow line charts for the lean-VDC project and the traditional project for the three scenarios (original, location optimization, and crew optimization).

Regarding the hypothetical scenarios, the difference in the cycle time between the original state and the location optimization state for the lean-VDC project is 6 days with a percentage of 6%. However, in the traditional project, the difference is 88 days with a percentage of 87%. These results demonstrate that the location waiting in the lean-VDC project is significantly lower than that of the traditional project. This reduction is mainly due to implementing the Last Planner System (look ahead planning and the weekly work planning), which considered reducing the waiting for both the location and the crew and this shows that the general contractor succeeds to manage the subcontractors to achieve global optimization rather than local optimization.

In the lean-VDC project, the difference in the cycle time between the actual and the crew optimization is 101 days with a percentage of 88% (Figure 4). This means that if the general contractor leaves the subcontractors to manage themselves, the project duration will be extended dramatically. However, applying LPS from the phase planning to the weekly planning meeting results in balancing the work packages between the different subcontractors. In the traditional project, the difference in the cycle time between the actual and the crew optimization is 143 days, with a percentage of 75%. This implies that the subcontractors in this case managed the project from their perspective to achieve local optimization.

From a fuel consumption point of view, the amount of diesel consumed for heating the spaces was measured for the traditional and lean-VDC projects (Table 2). The amounts of diesel were calculated for each floor along its cycle time and then normalized per meter square of the finished building. The average amount of diesel consumed for heating one floor in the traditional project is 13,624 litres, whereas the lean-VDC is 8,264 litres, a reduction of 65%. In the traditional project, the average amount of diesel required for heating a floor in the ideal state (location optimization) is 7,294 litres. The difference between the actual state and the ideal state is 6,330 litres, or 87%.

Table 1: The floor cycle time (CT) in workdays for the different scenarios: original, location optimization, and crew optimization in the Lean-VDC and the traditional approaches.

Floor number	Lean and VDC management			Traditional management		
	Original	Location optimization	Crew optimization	Original	Location optimization	Crew optimization
	CT	CT	CT	CT	CT	CT
23	95	113	229	197	117	254
22	96	102	224	204	126	262
21	89	108	223	193	100	264
20	111	121	234	202	93	274
19	112	111	229	173	94	278
18	101	105	231	180	93	285
17	119	113	237	185	92	291
16	125	109	233	192	111	299
15	126	104	226	170	115	308
14	124	111	226	177	93	316
13	117	105	218	202	103	342
12	104	93	208	207	87	349
11	117	105	212	190	87	353
10	127	111	207	190	136	354
9	114	98	199	196	84	361
8	114	101	202	198	88	364
7	125	117	208	179	78	367
6	119	104	202	179	128	368
5	131	127	209	172	88	372
4	133	106	206	177	102	378
3	139	117	208	186	100	388
2	112	108	202	192	105	394
1	90	112	203	211	110	415
Average	**115**	**109**	**216**	**189**	**101**	**332**

In the lean-VDC project, the average amount of diesel required for heating a floor in the ideal state is 7,829 litres, and in the actual state is 8,264 litres. The difference is 435 litres, or 6%. This shows that the actual state in the lean-VDC project is not too far from the ideal state. The total GHGs in the Lean-VDC project is 629-ton CO_2e, while in the traditional project it is 1,037 tons CO_{2e}. The difference between the traditional and the Lean-VDC project is 408 tons CO_{2e}, a reduction of 65%.

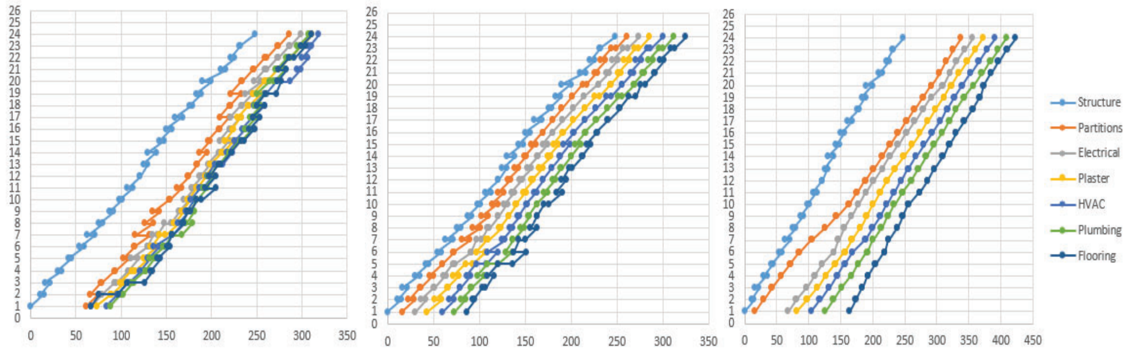

Figure 2: Flow line charts for the lean-VDC project with three scenarios: original, location optimization, and crew optimization (from left to right).

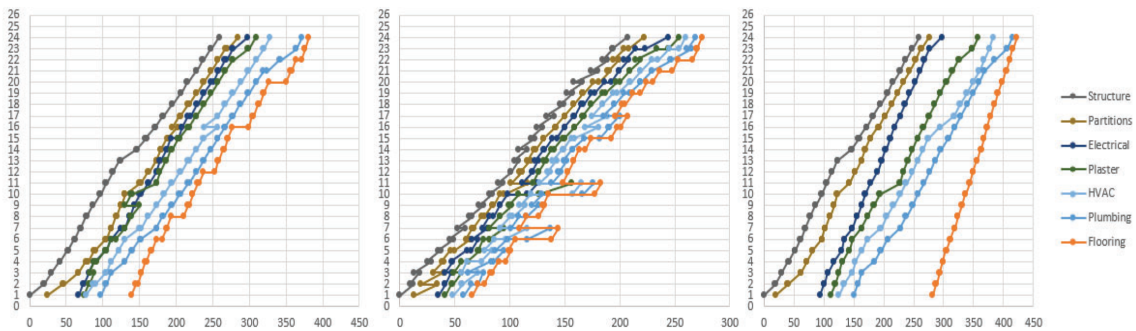

Figure 3: Flow line charts for the traditional project with three scenarios: original, location optimization, and crew optimization (from left to right).

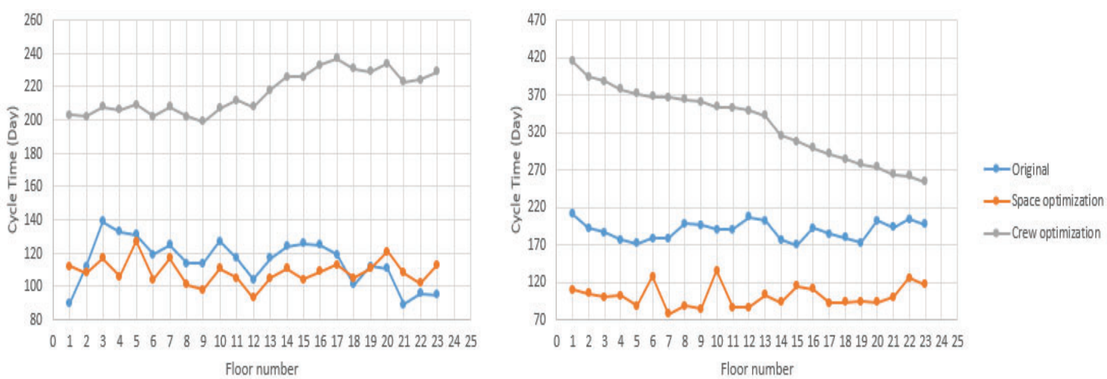

Figure 4: Cycle time for the different floors in the different scenarios for the lean-VDC (left) and traditional (right) projects.

Table 2: The amount of diesel for the different scenarios: original, location optimization, and crew optimization, in the Lean-VDC management and the traditional management approaches

Floor number	Lean and VDC management			Traditional management		
	Original	Location optimization	Crew optimization	Original	Location optimization	Crew optimization
	Diesel (litre)	Diesel (litre)	Diesel (litre)	Diesel (litre)	Diesel (litre)	Diesel (litre)
23	6,840	8,136	16,488	14,184	8,424	18,288
22	6,912	7,344	16,128	14,688	9,072	18,864
21	6,408	7,776	16,056	13,896	7,200	19,008
20	7,992	8,712	16,848	14,544	6,696	19,728
19	8,064	7,992	16,488	12,456	6,768	20,016
18	7,272	7,560	16,632	12,960	6,696	20,520
17	8,568	8,136	17,064	13,320	6,624	20,952
16	9,000	7,848	16,776	13,824	7,992	21,528
15	9,072	7,488	16,272	12,240	8,280	22,176
14	8,928	7,992	16,272	12,744	6,696	22,752
13	8,424	7,560	15,696	14,544	7,416	24,624
12	7,488	6,696	14,976	14,904	6,264	25,128
11	8,424	7,560	15,264	13,680	6,264	25,416
10	9,144	7,992	14,904	13,680	9,792	25,488
9	8,208	7,056	14,328	14,112	6,048	25,992
8	8,208	7,272	14,544	14,256	6,336	26,208
7	9,000	8,424	14,976	12,888	5,616	26,424
6	8,568	7,488	14,544	12,888	9,216	26,496
5	9,432	9,144	15,048	12,384	6,336	26,784
4	9,576	7,632	14,832	12,744	7,344	27,216
3	10,008	8,424	14,976	13,392	7,200	27,936
2	8,064	7,776	14,544	13,824	7,560	28,368
1	6,480	8,064	14,616	15,192	7,920	29,880
Average	**8,264**	**7,829**	**15,577**	**13,624**	**7,294**	**23,904**

CONCLUSIONS

The two hypothetical construction projects analysed herein show that lean principles like VDC and LPS play an important role in reducing the project duration and the location cycle times, which is a crucial issue in cold climate areas. The average original project cycle time was reduced from 189 days in the traditionally managed to 115 days in the lean-VDC managed project, a reduction of 64%. Also, the difference between the average cycle time in the original scenario and the location optimization is six days which means that the general contractor succeeds to manage the subcontractors to achieve global optimization rather than local optimization. However, in the traditionally managed project, the difference in the average cycle time between the original scenario and the location optimization scenarios was 88 days, which means that the sub-contractors achieved local optimization rather than global optimization, resulting in extending the project cycle time.

From an environmental point of view, the amount of diesel consumed in the lean-VDC managed project is 8,264 litres, while in the traditional managed project it is 13,624 litres, a variance of 5,359 litres (65%). The amount of energy used for heating the construction project, which has a significant impact on the environment, could be reduced due to implementation of lean and VDC management approaches.

We conclude that lean practices like LPS and VDC play an important role in improving the workflow and reducing the project cycle time by achieving global optimization rather than local optimization. This contributes to dual benefits for the sub-contractors and the general contractors (win-win relation). Also, the results show the importance of reducing the project cycle time in cold climate areas. The total GHGs reduced from 1,037 tons CO_{2e} to 629 tons CO_{2e}, a reduction of 65%.

These results underscore the importance of reducing the project cycle time from an environmental perspective in cold climate areas. However, this is not the case in temperate or hot climate areas since there is no need to heat the project. Other environmental factors should be investigated in these areas, such as workers' transportation from and to the construction project, or the camp energy consumption in cases where workers live at the construction site.

This research focuses on the effect of heating construction projects during the construction phase. It focuses on cold climate areas since it is needed in these areas, and there is no need for heating in temperate and hot areas. Other issues like workers traveling from and to the construction site, energy sources used for operating equipment, and machines like cranes, elevators, etc, should be considered in the different climate areas. Although these issues are not quantified in this paper, the researchers suspect that they will have considerable impacts on the environment and will be shared between cold, temperate, and hot climate areas. Considering all these emissions will amplify the results. Further research should include these emission sources to visualize the process effect from an environmental perspective.

RESEARCH LIMITATIONS

This paper explored the effect of heating construction projects in cold climate areas by using hypothetical case studies from temperate climate areas and assessing them in cold climate areas. Recently, the researchers have begun collecting data from a project in a country classified as a cold climate area, and in the future, more representative results from the cold climate areas will be published.

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