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HYBRID SIMULATION FOR VALUE STREAM MAPPING TO IMPROVE THE ENVIRONMENTAL PERFORMANCE OF THE CONSTRUCTION PHASE

Danh Toan Nguyen[1] and Walter Sharmak[2]

ABSTRACT

The environmental impact assessment of the construction phase is often not fully considered compared to other phases of the project life cycle. Previous studies on environmental impact reduction have often focused on technical aspects rather than organisational aspects. The value stream mapping (VSM) method has been extended to capture and improve environmental performance by systematically adopting lean methods in the manufacturing process. However, in the construction field, this approach encounters difficulties establishing state maps and considering the interrelationships between different processes in an uncertain and dynamic environment. This study proposes a hybrid approach combining Multi-Agent Systems (MAS) and System Dynamics (SD) based on process patterns to overcome these obstacles. First, process patterns, including activity packages, are developed to assist the VSM in creating state maps and identifying environmental impact sources. Then, construction operations with their state maps and needed resources are modelled as autonomous agents containing causal-effect loops (SD modules) in a MAS model. These agents interact with each other to describe the construction operating mechanism. Finally, different lean methods are analysed to find opportunities to improve environmental performance.

KEYWORDS

Lean construction, value stream, process, environmental assessment, hybrid simulation.

INTRODUCTION

The construction industry has been identified as one of the leading causes of global warming due to its remarkable consumption of resources and energy, and the generation of harmful emissions. According to a report from the International Energy Agency, building construction and operations accounted for the largest share of both global final energy use (36%) and energy-related greenhouse gas (GHG) emissions (39%) (IEA, 2019). However, the Intergovernmental Panel on Climate Change forecasted that the construction field has the largest potential for decreasing GHG emissions compared to

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other sectors (IPCC, 2014). Previous studies on the environmental impact assessment (EIA) of buildings have mainly focused on the product phase (modules A1 to A3 per BS EN 15978: 2011) and use phase (modules B1 to B7), while the construction phase (modules A4 to A5) is often overlooked or incompletely considered (Slosharek et al., 2021). Compared to other phases, construction is a short-term phase and is believed to emit lower emissions, so it has not attracted much research (H. J. Wu et al., 2012). Besides, the uniqueness and uncertainties of construction projects make it difficult to standardise the analysis process. Thus, estimating the environmental impacts of the construction phase is perceived as too burdensome and tedious, especially considering the overall benefits. However, disregarding the construction phase in the EIA leads to a gap in fully understanding the possible sources of environmental impacts of the construction project life cycle.

Value stream mapping (VSM), a commonly used lean method, has been developed to uncover environmental impact sources and identify opportunities to improve environmental performance for production processes. For example, Faulkner & Badurdeen (2014) proposed a sustainable VSM by adding a set of environmental metrics such as raw material usage, energy consumption, and process water consumption. Their developed methodology can apply across various industry sectors by customising and selecting different metrics. The US Environmental Protection Agency (US EPA, 2007) recommends applying VSM to record environmental performance data to develop a future state vision for the production process. Rosenbaum et al. (2014) conducted a case study of the VSM application as a green-lean approach to the construction phase of a hospital. This research confirmed VSM's ability to detect the sources of environmental and production waste, quantify them, and suggest reduction strategies.

Fundamentally, VSM is a method used for the manufacturing industry, which is very different from the construction industry. Therefore, the application of VSM for construction faces the following challenges. First, one of the prerequisites for implementing VSM is the repeatability of processes. In industrial manufacturing, VSM describes the state of a process, which is usually repetitive in an active production system, based on statistical data collected from production lines. In contrast, a construction project presents a unique design and specifications and must be constructed uniquely. Moreover, tracking the construction process is complex and tedious as most of the construction steps are lengthy with the involvement of different stakeholders (Yu et al., 2009). Especially in the execution planning stage, it is impossible to establish the state map because construction activities have not been carried out yet.

Second, VSM relies on static inventory data, so they can not consider the effect of uncertainties and dynamic factors of the construction phase. In addition, the positive effects of implementing lean methods on environmental performance are usually indirect and difficult to evaluate in advance. Many studies combined simulation methods with VSM to overcome these obstacles. For example, the discrete event simulation (DES) method is often applied to enhance VSM in understanding and estimating the impact of randomness and the effect of lean methods on a system (Jarkko et al., 2013; Zahraee et al., 2020). However, previous combinations of VSM and simulation in the construction sector focused only on single processes such as earthwork (Nguyen, 2019), concrete pouring (Zahraee et al., 2020), and steel building erection (Ramani & KSD, 2019). For EIA purposes, all main processes of the construction phase have to be mapped and analysed simultaneously because these processes constantly interact with each other. These process interactions are usually non-random based on rules, terms, and conditions that they meet in explicitly defined networks. Although DES can effectively support VSM in analysing single processes at an operational level, it encounters difficulties when simulating many concurrent processes and capturing causal-effect relations at a holistic level. In contrast, the multi-agent systems method is more appropriate for simulating heterogeneous populations, or agents' networks and their interactions among them and their environment. Besides, system dynamics is a powerful method to complement MAS in modelling feedback processes, demonstrating the interrelationships between project elements at the holistic level (Nguyen & Sharmak, 2021; Swinerd & McNaught, 2012).

This paper proposes a hybrid approach combining MAS and SD based on process patterns to enhance VSM in establishing state maps, identifying environmental impacts and analysing the effects of lean methods implementation on the environmental performance of the construction phase. The paper is organised as follows: The next section describes the VSM application for EIA of the construction phase based on process patterns containing activity packages. Then, the development of a MAS-SD hybrid simulation model and its use to consider the effect of some lean methods on environmental performance are presented. The subsequent section introduces a simulation example of the construction phase of a highrise building to test the developed model. Some conclusions about the contributions of this study are put forth in the end.

PROCESS PATTERNS FOR VSM APPLICATION

Typically, construction projects are unique, differing in architecture, location, function, and structure. However, they can be considered a combination of typical construction processes iteratively. Therefore, several authors suggest that predefined process patterns can conveniently generate the process components for analysis during the planning and scheduling phases (Nguyen & Sharmak, 2020b; I. Wu et al., 2009). A process pattern describes the logic of how a construction operation is organised and performed. Using process patterns can support the VSM method by shortening the mapping time of processes because the practitioner selects only the appropriate method, after which subsequent components are automatically generated.

To apply the VSM for EIA, selecting the appropriate detailed level of mapping plays an important role. Traditionally, the granularity of process patterns used in the construction phase has often been in situ operations such as reinforcement installation, formwork erection, or concrete pouring (Rosenbaum & Toledo, 2014) (level 2 in Figure 1a). However, these processes should be broken down into more granular levels to uncover all activities that affect the environment. For example, the reinforcement should be divided into rebar transport (offsite and onsite), processing (cutting, bending), and installation (level 3 in Figure 1a). In this research, process patterns of the cast-in-place concrete construction process are proposed to facilitate VSM in generating state maps of processes at the "activity" detailed level (level 3 in Figure 1c). The activities of the state maps play an essential role in the identification and assessment of environmental impacts because they are at the atomic level and directly perform specific construction tasks. Activity packages are introduced to minimise the possibility of making errors and omissions in the activity description (Figure 1b). Activity packages depict atomic activities of process patterns with all corresponding data such as constraints, required resources, and environmental impact indicators based on norms and experience. Process patterns and activity packages are stored in databases, which will be queried to generate state maps for VSM. Figure 1 shows value stream maps of construction processes producing vertical components using the cast-in-place concrete method. Each activity can affect the environment in different ways. For example, offsite transport from plant to construction site using trailers or trucks consumes fuel and emits GHGs. Processing activities (cutting, bending) and onsite transport activities from yard to erection site (using cranes, lifts) consume electricity. Installation activities need auxiliary materials such as iron wire, nails, and water (Figure 1c).

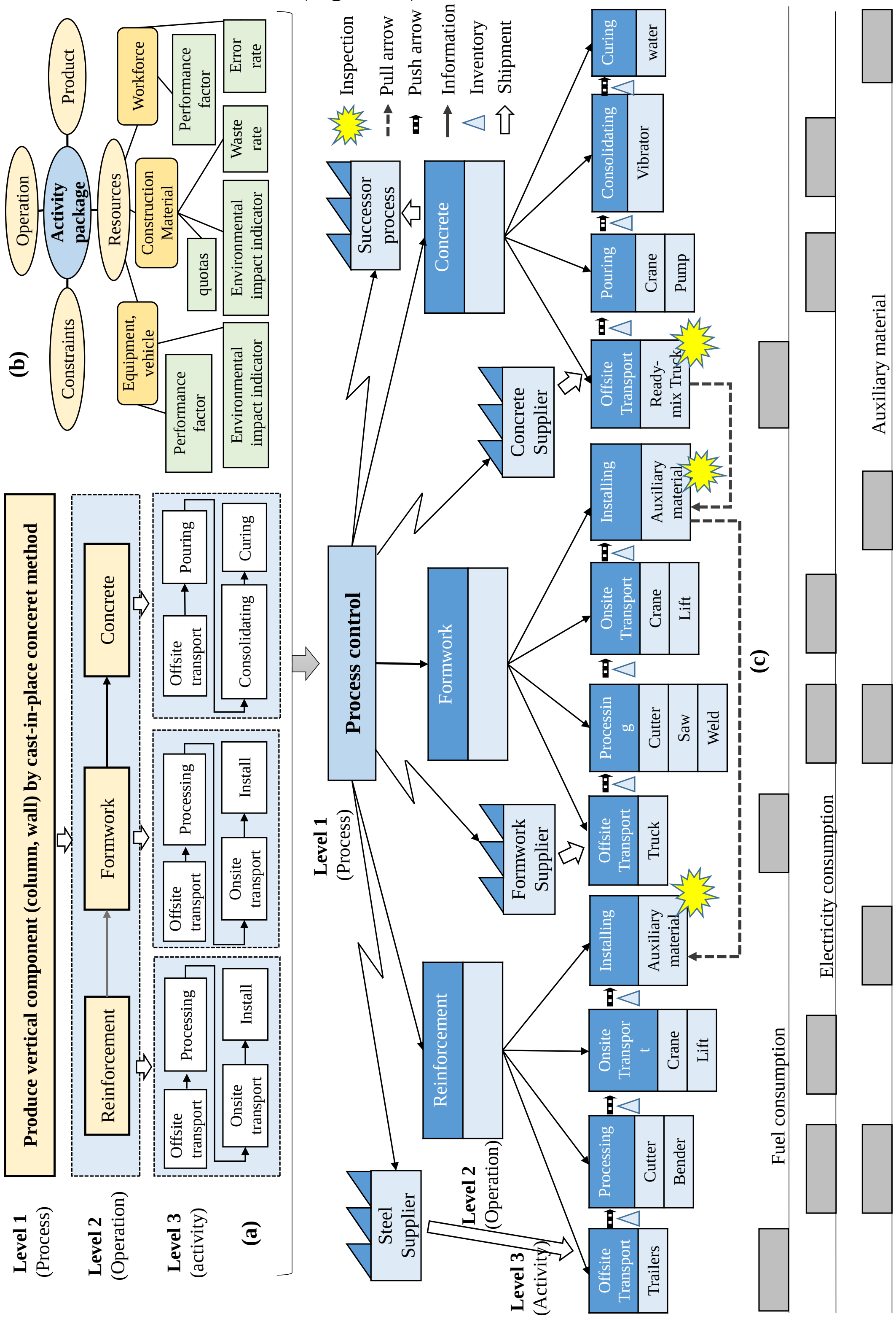

Figure 1: A state map of the construction process using the cast-in-place concrete method.

HYBRID SIMULATION-BASED VSM

HYBRID SIMULATION FRAMEWORK

Since no construction activities have been performed on site during the execution planning stage, planners can conduct the VSM analysis of construction processes based on process patterns and activity packages. First, state maps are established by retrieving needed parts from the process pattern and activity package databases and modelled as statecharts of operation agents of processes in a MAS model. Besides, SD modules are embedded in operation agents to depict the causal-effect loops. In addition, planned resources are also modelled as resource agents in the MAS model (Figure 2). Finally, construction processes are operated through the interaction between operation agents and resource agents according to different organisational and management strategies.

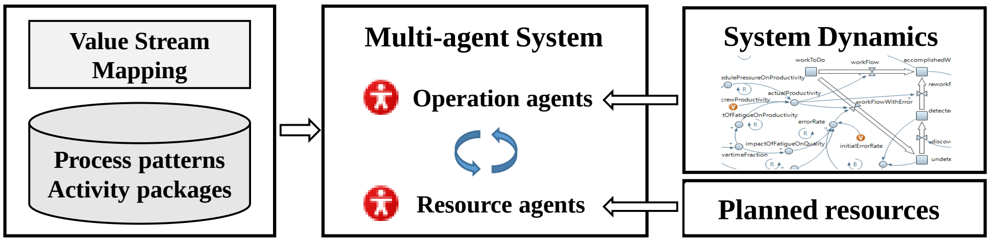

Figure 2: The hybrid simulation framework

MULTI-AGENT SYSTEM

MAS models are based on the bottom-up approach that suits correctly modelling complex systems. The agent-based method is proven helpful in mimicking the system behaviour with autonomous and interactive abilities of agents in a dynamic environment. MAS is defined as intelligent autonomic agents representing real-world parties without global control and unified objectives (Ren and Anumba, 2004). In this paper, both construction operations and construction resources are represented by agents using the AnyLogic simulation engine (Anylogic, 2022).

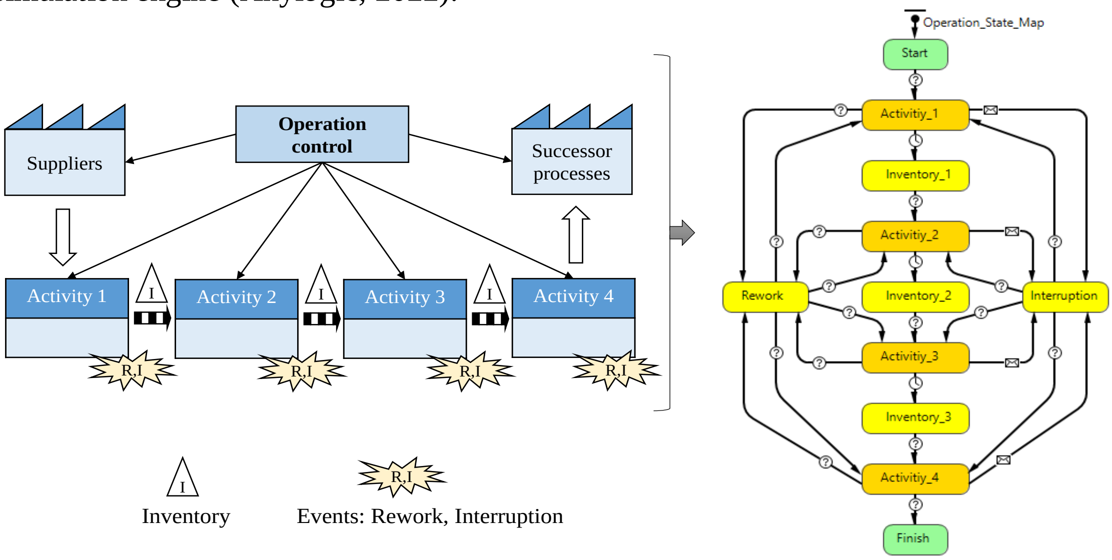

Figure 3: Example of transferring a state map into a state chart in the simulation model

Operation agent

Operations of a construction process are represented by agents containing statecharts to depict all activities of the operation following the VSM method. Figure 3 shows an example of transferring a state map of an operation with four activities into a statechart in the simulation model. According to the flow view of lean principles, processes can be improved by achieving a continuous flow without any interruptions and errors. Therefore, two states, "rework" and "interruption", are added to illustrate the situation when any activity of this flow has a defect leading to rework or is interrupted by external factors. Operation agents contain various attributes such as workload, duration, and due dates. Furthermore, operation agents can self-define their predecessors, successors and needed resources based on process patterns and activity packages. A central control mechanism coordinates communication and interactions between agents that relay information to the respective targets. Each agent process this information on its own, be aware of its state, and behave accordingly.

Resource agent

There are various resources with different functions and variables in the construction phase. Resources are considered autonomous and intelligent agents that can change their state and actively interact with operation agents. For EIA purposes, construction resources should be differentiated into renewable (e.g. machinery, workforce) and non-renewable (e.g. material, water). The consumption of non-renewable resources and the operating time of renewable resources are aggregated to convert into emissions values based on the environmental datasets. Since each resource agent is an instance of a renewable or non-renewable resource, they differ in their attributes and the operations that can be involved. Figure 4 shows state maps of five primary construction resources: workforce, material, offsite transport vehicle, onsite transport equipment, and processing machines.

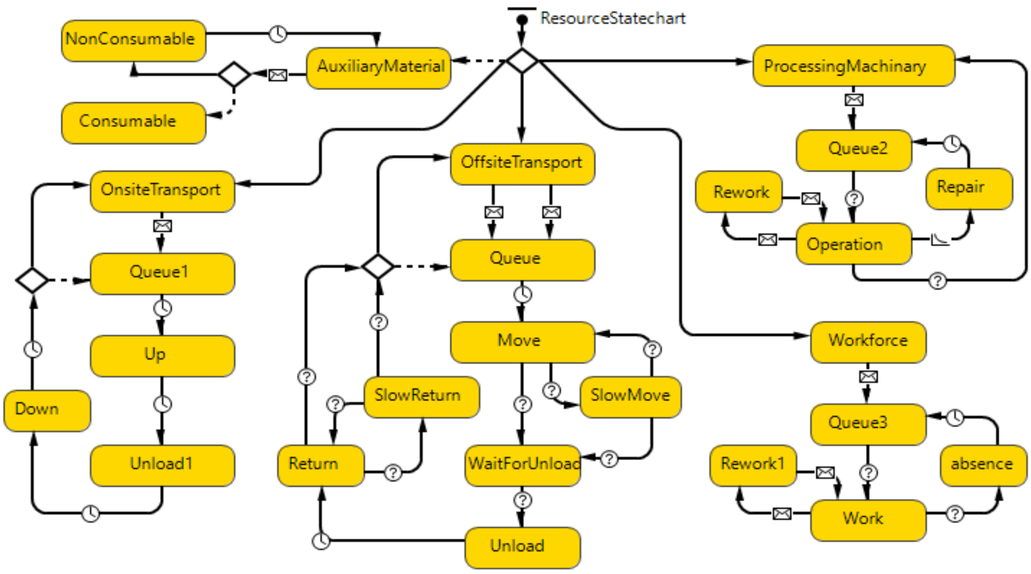

Figure 4: Statechart of construction resources

Agent interaction protocol

In the Multi-Agent System, autonomously active agents interact directly with their predecessors and successors. First, following predefined operating mechanisms, operation agents register their required resource proposals on a central blackboard, a central control system for all agent negotiations. Then, depending on the specific expertise for the registered activity and the availability of resource agents, the control centre processes all the information in a particular protocol and acts respectively to allocate the resources.

INTEGRATION SYSTEM DYNAMICS INTO THE MULTI-AGENT SYSTEM

System dynamics simulation is a top-down approach based on the information feedback to analyse a complex system behaviour between project elements from a macro and holistic perspective within a predefined boundary (Ding et al., 2016). Typically, system dynamics models are structured by stocks-flows diagrams that describe the movement of entities from start to end in a model and causal loop diagrams that capture the chain influences of a cause are traced through a set of related variables back to the original cause. In the literature, many SD models have been developed to analyse the behaviour in the construction field, such as the quality assurance cycle, rework cycle, and errors management cycle (Alzraiee, 2013). In this paper, the feedback processes, including the schedule pressure loop and rework loop, are embedded in the MAS (within the AnyLogic simulation environment) to capture the system behaviour.

Schedule pressure loop

The schedule pressure factor of a construction operation, which represents the discrepancy between the planned schedule and actual progress, is calculated by dividing the required time to complete this operation by the actual remaining time to finish it. If schedule pressure is too low, the productivity will be reduced because performers likely think they have more time to complete their tasks than planned (Alzraiee, 2013). However, excessive schedule pressure can deteriorate productivity considerably. Conventionally, adopting work overtime can decrease the schedule pressure, although it might cause fatigue, lower quality, and generate more errors ().

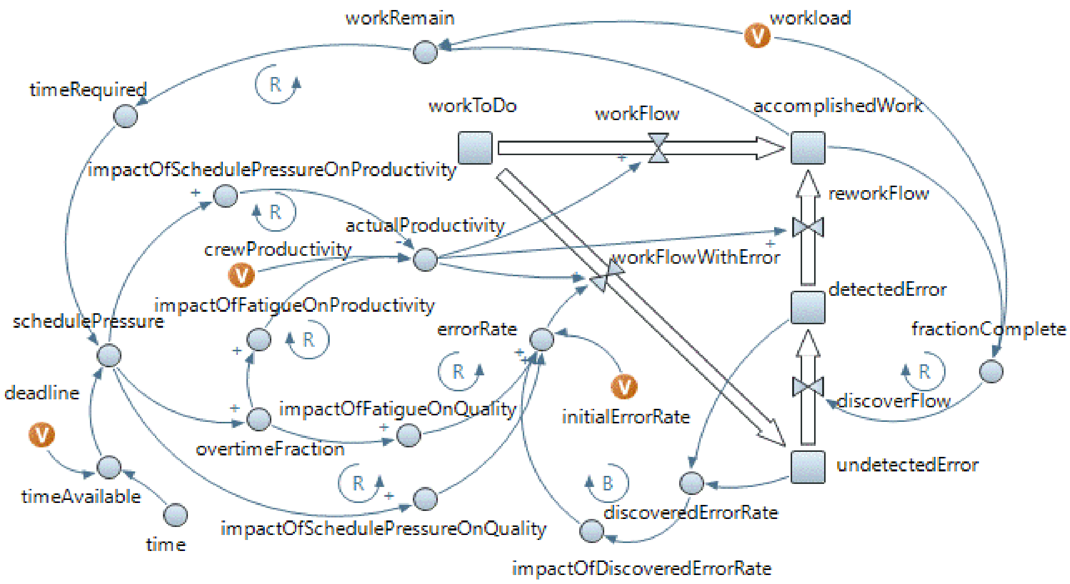

Figure 5: Causal-Effect loops in operation agents

Rework feedback loop

Errors in construction tasks are often inevitable because of the unreliable workflow in an uncertain environment. Errors lead to rework that consumes more resources than expected, so the impact on the environment also increases significantly. In addition, rework can itself be flawed, requiring additional rework in a recursive cycle that can extend project duration and work scope. Several factors that can affect the rework loop, such as labour experience, schedule pressure, and error detection time, usually are omitted by previous environmental impact assessments. The errors can be detected during the working process or by inspection. The crews are usually aware of their mistakes when the work comes nearly to the end, so the error discovery rate depends on the fraction completion of work. When an error is detected, the team can fix it immediately or wait until the ending stage, depending on management policy. By being aware of mistakes, the error rate can be decreased. This relationship is modelled as a cause-effect loop through the impact of the error discovery rate on the error rate in Figure 5.

EFFECT OF LEAN METHODS ON ENVIRONMENTAL PERFORMANCE

The MAS is operated through predefined rules, describing different process management mechanisms. Although many lean methods can be embedded into the developed simulation model by setting up the agent interaction protocol or adding causal loops, this section only mentions some potential lean methods that positively affect the environmental performance of the construction phase.

Last planer system

The LPS can create a stable, highly productive construction environment through reliable planning and efficient control (Ballard & Tommelein, 2021). The LPS tends to plan in greater detail as planned tasks get closer to performing and involves people who are going to carry out the work based on their active coordination and negotiation. In the LPS, activities' duration and due date are set to be consistent with the performer's capacity. Therefore, the schedule pressure of tasks is maintained at an appropriate level to ensure productivity and avoid overtime. Thus, LPS can reduce errors caused by working under high pressure and fatigue due to overtime and indirectly reduce environmental impacts. In the developed simulation model, by setting up pull-driven process management, tasks' deadlines can be adjusted depending on actual demand after each weekly work plan cycle. This effect on construction operations is captured by the schedule pressure loop mentioned in the previous section.

Mistake-proofing (Poka-Yoke)

Researchers suggest that the rework cost in construction projects can range from 10% to 22% of the contract cost (Forcada et al., 2017; Trach et al., 2021). Lean construction tries to prevent errors through simple ways of mistake-proofing. First, tasks in the construction operations prone to errors should be identified. These mistakes could be a quality problem, delays in needed elements supplying, etc. Second, after the problem is recognised, suitable solutions should be researched and implemented to prevent the recurrence of problems in the future. In the proposed simulation model, the effect of different quality inspection strategies is captured by the discovered error loop, which can consider the relationship between the time to detect error and the error rate variation.

Daily huddle meetings

Some construction disruptions are related to the project team's inadequate perception of the project status as a whole, including their work and others' (Ma & Sacks, 2016). This disruption resulted in missing milestones and derailed projects. By contrast, Daily Huddle can connect project teams to synchronise information flow and verify that work is progressing as promised; if not, identify resources for immediate help or adjust schedules. In the MAS, daily huddles were simulated by setting agent meeting events. After the meeting, agents are actively updated with new information from their predecessors and successors. If there is some negative impact on them, these agents can propose solutions to ensure they can operate in the right environment, such as adjusting the due date or requiring more resources to reach the predefined deadline.

SIMULATION EXAMPLE CASE

This section presents a simulation example to test the applicability of the proposed methodology in applying lean methods to improve the environmental performance (this example considers only GHG) of the construction phase. A virtual building of four floors with a total floor area of approximately 8130 m2 in Hanoi, Vietnam, was selected to apply the proposed methodology. The building is a reinforced concrete frame structure built by the cast-in-place concrete method, widely applied in the Vietnamese construction industry. Three primary operations of the cast-in-place concrete method, including reinforcement, formwork, and concrete work, were analysed according to the VSM approach (Figure 1). All necessary data regarding material and resource consumption rates were queried according to Vietnam's construction norms (BXD-VN, 2007). The GHG emissions rates of impact sources were obtained from Vietnam's Ministry of Natural Resources and Environment data or previous international studies (Nguyen & Sharmak, 2020a). The scope of impact sources is within the contractors' area of decision-making, such as vehicles for material transport (construction material and building material), equipment, machinery, and construction material in the construction phase, while the upstream design stage determines other primary building materials.

Four scenarios are analysed using the proposed simulation model to quantify the effect of lean methods on the environmental performance of the construction phase.

Scenario 1: The typical stories of the building are divided into two zones. Construction processes are operated by push-driven process management (so-called conventional process), in which a construction schedule is developed by calculating early, and late activity starts and finishes by applying the critical path method (CPM). Each operation agent always tries to hold needed resource agents to start at their earliest possible time so as not to delay their successors. Process control adheres to the predefined schedule. If an activity is estimated not to meet the deadline, working overtime in night shifts solution is used instead of adjusting the due date. Project member meetings take place twice a week. Quality inspection only focuses on onsite activities such as installing reinforcement and formwork. Other activities in the processing yards, such as cutting and bending rebars, are not regularly checked. (This situation is quite common in most construction sites in Vietnam).

Scenario 2: The typical stories of the building are divided into two zones. The LPS approach is adopted (so-called lean process). In which pull-driven process management distributes resources selectively so that the operation's output is a product needed further downstream in the process. Also, operation agents only start when they are required for downstream operation agents instead of starting as soon as possible. In contrast to scenario 1, the deadline of the activities can be flexibly adjusted to accommodate the available resources updated from daily huddle meetings. In addition, onsite activities and all activities in processing yards are inspected to detect errors as early as possible to prevent a recurrence.

Scenario 3: The operation mechanism of construction processes is the same as in scenario 1, but the typical stories of the building are divided into three zones (the number of zones can be two, three, or four, but this paper only considers the first two cases).

Scenario 4: The operation mechanism of construction processes is the same as in scenario 2, but the typical stories of the building are divided into three zones.

RESULT AND DISCUSSION

The GHG emissions (expressed as carbon dioxide equivalents CO_2eq) and the duration of the four scenarios' performance are shown in Table 1. By applying lean methods, scenarios number two and four can significantly reduce emissions and time compared to scenarios number one and three (conventional processes). For example, with the same number of zones per story, applying lean methods eliminates the GHG emission by 10.7% (34809-31055=3754 kg, compare scenario 1 with scenario 2) and 12.1% (33633-29589=4044 kg, compare scenario 3 with scenario 4). The reason for this reduction is that the application of LPS maintains appropriate schedule pressure, thus indirectly reducing the error rate due to working overtime and fatigue while ensuring labour productivity of crews. In addition, strengthening the quality control of all tasks in process yards can detect errors early, thus avoiding the accumulation of errors for downstream tasks.

Table 1: Simulation results (for one typical story)

Scenarios	Note	CO_2-eq (kg)	Duration (hr)
1	2 zones per story, conventional process	34809	173
2	2 zones per story, lean process	31055	146
3	3 zones per story, conventional process	33633	161
4	3 zones per story, lean process	29589	132

Some previous studies have suggested that reducing batch size in production processes leads to a reduction in project time but does not affect the environmental performance (Golzarpoor et al., 2017). However, this study indicates that increasing the number of construction zones per floor (which means decreasing batch size) can also reduce GHG emissions by 3.3% (34809-33633=1175 kg, compare scenario 1 with scenario 3) and 4.7% (31055-29589=1466 kg, compare scenario 2 with scenario 4). Reducing batch size leads to shorter cycle times for each zone and avoids waiting time for downstream tasks. Therefore, the energy consumption of machinery and equipment in standby mode is eliminated. Besides, reducing batch size also results in minimal inventory levels, thereby reducing defects or deterioration during storage. However, this aspect has not yet been simulated in this example, so the effect of batch size reduction on emissions is relatively low, just under 5%.

CONCLUSIONS

The main contribution of this research is the development of a hybrid simulation method that can enhance the VSM method in estimating environmental impacts and quantifying the effect of lean methods on the environmental performance of the construction phase. By applying process patterns, the hybrid simulation-based VSM can be conducted in the execution planning stage to assist builders in selecting environmentally friendly processes. The simulation example shows that the systematic implementation of lean methods, including LPS, mistake proofing, and daily huddles, can indirectly reduce the GHGs emission by around 12%. Furthermore, it is worth mentioning that reducing the batch size also leads to a decrease in emissions by nearly 5%. In the future, this hybrid simulation model will be further developed to quantify the effect of other lean methods on environmental performance. Moreover, combining this model with the building information model will facilitate adopting lean methods in the construction phase.

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