Agent-based simulation for gas and dust emissions assessment during construction: A case study in Vietnam

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Abstract. Construction activities account for a significant amount of greenhouse gases (GHG) and fine particulate matter (PM\(_{10}\)) emissions, particularly in developing countries with expeditious urbanization. To achieve sustainability in the construction phase, researchers have made considerable efforts to estimate the emissions accurately. Although several building-level emission databases and related calculation systems have been set up in developed countries, there unfortunately remains a vacancy in Vietnam. This study aims to integrate Agent-based simulation (ABS) and process-based life cycle assessment (pLCA) based on construction norms and environmental data available in Vietnam to evaluate the GHG and PM\(_{10}\) emissions under the uncertain and dynamic conditions of on-site construction and supply chains. This method is developed and applied in the case study of a 20-storey building in Hanoi. The results indicate that, among all of the construction equipment, the off-site and on-site transport equipment are the dominant cause for GHG and PM\(_{10}\) emissions. The formwork-related material contributed the most to GHG among the auxiliary materials.

1. Introduction
At present, air pollution in big cities in Vietnam, such as Hanoi and Ho Chi Minh City is becoming more and more severe due to the rapid urbanization process [1]. Construction activities in the inner city are one of the leading causes of greenhouse gas (GHG) and dust emissions [2]. Meanwhile, research on the environmental impacts of construction projects in Vietnam has not been given due attention. Minimizing the environmental impacts is a challenging task to achieve sustainability in construction industry in developing countries. The construction phase, when compared with the operation and maintenance phases, is short-termed and occurs mostly at overcrowded regions. However, the environmental impacts of construction activities can be severe at aggregated levels [3] and have a significant impact on the communities and must be properly assessed and mitigated. A quantitative assessment of the environmental impact of construction activities can help decision-makers to identify major environmental impact factors and make environment-friendly construction plans in the early stages of construction [4]. A comprehensive evaluation of the impacts requires the consideration of all construction activities, construction resources, and the type and operation time of construction machines that will be used in the construction phase.

To reduce the life-cycle emissions from construction processes, researchers have performed numerous attempts to estimate the emissions accurately. The process-based life cycle assessment (pLCA) has been increasingly applied to the environmental impact assessment (EIA) to quantitatively
measure the environmental impact of construction [5]. However, pLCA has some limitations in supporting environmental assessment in a construction context. A process-based LCA method that relies on static inventory data while construction processes are performed in uncertain and dynamic environments that change rapidly, such as altered on-site conditions, labor productivity fluctuation, and construction machine malfunction. Besides, external factors, such as rush-hour traffic conditions, influence the transportation of material supplies to the site. These factors can lead to process duration overruns, task rework, and emissions fluctuations [6]. Therefore, it is essential to improve pLCA to capture uncertain and dynamic factors in the evaluation of the environmental performance of construction processes. Several researchers, including Zhang [7], Li [4], González[8] combined discrete-event simulation (DES) and LCA to assess the environmental impact of construction processes. The DES can capture the variability of events in complex systems, thereby increasing the ability of the evaluation [9]. However, activity durations in DES model are calculated based on primitive methods such as interpolating existing durations of similar activities in previous projects. Therefore, model elements behave in a predetermined manner, ignoring particular operational real-life scenarios that occur due to resource constraints. These limitations often lead to inaccuracies in emission evaluation. This study aims to propose an innovative method to integrate agent-based simulation (ABS) and pLCA to make environmental performance assessments of construction operations in uncertain and dynamic environments. Multi-agent system (MAS) is a flexible technique with the ability to simulate uncertainty and dynamic factors, where an agent-based model, including smart, adaptive agents, is developed [10]. Each agent has a statechart, a set of static, and dynamic properties to direct its interactions with the environment and other agents.

The proposed method in this paper provides a predictive MAS-tool for contractors to evaluate and compare the environmental performance of alternative construction plans. The GHG and dust emission will be estimated bases on construction norm and available environment data in Vietnam.

2. Integration ABS and LCA in the GHG and dust emission assessment during construction

2.1. Environmental impact sources

The goal of the assessment in this study is to evaluate the construction-related GHG and dust emission. Construction processes cause environmental impacts by equipment and auxiliary material usage alongside the off-site materials supply chains and on-site construction. These impact sources are a part of the contractors’ execution planning, while other major building materials are determined by the upstream design stage. Thus, a boundary for construction includes (1) upstream auxiliary materials extraction, processing, and production; (2) off-site construction materials transportation (major and auxiliary materials); and (3) the on-site construction operation process.

![Figure 1. Cast-in-place construction process breakdown structure](image)

Construction must be broken down into unit tasks so that LCA can be applied, and the essential environmental factors involved in the complex construction process can be identified [11]. For instance, the process of constructing a cast-in-place concrete slab includes several sub-processes such
as formwork, reinforcement, and concrete. Each sub-process can be divided more specifically into unit tasks (Figure 1).

Thereby, a unit task is only performed by one type or suite of construction crews or an equipment. Any work transition during a construction task, such as a change in equipment or type of worker, is regarded as the boundary between different unit tasks. Once the construction process has been broken into unit tasks, it is more convenient to determine the impact sources relating to the equipment and materials used in each unit task (Table 1). These impact sources will then serve as the input data for the simulation tool, which will output the environmental impact evaluation.

### Table 1. The resource allocations for unit tasks of the cast-in-place construction process

| ID | Unit Task          | Product                  | Resources                |
|----|--------------------|--------------------------|--------------------------|
| 1  | S-off-site transport | Unprocessed steel bar    | Diesel trailer           |
| 2  | S-straightening     | Processing steel bar     | Electric bar straightener|
| 3  | S-cutting           | Processing steel bar     | Electric steel bar cutter|
| 4  | S-bending           | Processing steel bar     | Electric steel bar binder|
| 5  | S-on-site transport | Processed steel bar      | Electric crane tower/lift|
| 6  | S-installation      | Steel bar in component   | Iron wire                |
| 7  | F-off-site transport | Unprocessed formwork     | Diesel truck             |
| 8  | F-cutting           | Processing formwork      | Electric cutting machine |
| 9  | F-on-site transport | Processed formwork       | Electric crane tower/lift|
| 10 | F-installation      | Assemble formwork        | Auxiliary material       |
| 11 | F-stripping         |                          |                          |
| 12 | C-off-site transport | Premixed concrete        | Mixer truck              |
| 13 | C-pumping           | Fresh concrete           | Concrete pump/crane      |
| 14 | C-vibration         | Onsite concrete          | Electric vibrator        |
| 15 | C-curing            | Concrete component       | Water, PVC               |

Note: C-, S-, and F- stand for concrete, steel, and formwork, respectively.

Because the method of calculating the environmental impact of each type of resource is different, they are classified into groups with similar specifications (Figure 2).

### Figure 2. Classification of construction resource

#### 2.2. Case-specific and Environmental-specific data.

Case-specific and environmental-specific data are the inputs required for the simulation model. Case-specific data comprise the information about the impact sources of a specific construction project, such as the quantity of construction materials and the required equipment shifts. On the other hand, environmental-specific data describes pollutants per quantity of the impact sources. Thereby, case-
specific data for equipment are derived from the working time of equipment. In contrast, the environmental-specific data describe the emitted pollutants per unit time. For material consumption, case-specific data are the quantities of main and auxiliary materials, whereas environmental-specific data describe the impact per quantity of materials.

The case-specific data can be calculated from construction documents and the database of Vietnamese construction engineering quota [12]. This quota reflects the consumption level of construction activities in the local area where the construction site is located. Environmental-specific data can be derived from existing environmental impact databases of professional organizations and the research results of published studies.

2.3. Greenhouse gases (GHG) and fine particulate matter (PM10)

The Kyoto Protocol defined GHGs as CO2, N2O, CH4, HFC, PFC, and SF6. However, as HFC, PFC, and SF6 are seldom emitted from construction projects, only three GHGs, CO2, N2O, and CH4, are taken into account in the construction industry [13]. Table 2 shows the global warming potential (GWP) values of these GHGs [14]. Carbon dioxide equivalency is a quantity that describes, for a mixture of these greenhouse gases.

Table 2. Global warming potential of GHGs

| GHGs | GWP value(kg CO2/kg) |
|------|----------------------|
|      | 20 years  | 100 years | 500 years |
| CO2  | 1         | 1         | 1         |
| CH4  | 72        | 25        | 7.6       |
| N2O  | 289       | 298       | 153       |

The developed model is used to estimate the quantity of GHG emissions of different impact sources. The emission (Ei) of process i-th is evaluated from Equation (1):

\[ E_i = E_m + E_e = Q_m e_m + Q_e e_e \]  

(1)

where Qm and Qe denote the quantity of impact sources from materials and equipment of process i, respectively; and em and ee represent the GHG emissions per unit quantity of impact sources (emission factor), which can be obtained from data of Vietnam’s Ministry of Natural Resources and Environment or previous international studies.

Table 3. The impact sources data for the evaluation

| Impact Sources | Unit | CO2, eq (kg)\(^a\) | Reference |
|----------------|------|-------------------|-----------|
| Diesel         | liter| 2.680             | [15]      |
| Gasoline       | liter| 2.270             | [15]      |
| Electricity    | kWh  | 0.865             | [16]      |
| Water          | m\(^3\)| 0.213             | [17]      |
| PVC            | kg   | 0.247             | [15]      |
| Plywood        | kg   | 1.049             | [15]      |
| Steel tube     | kg   | 3.589             | [15]      |
| Joint          | kg   | 3.589             | [15]      |
| Bolt           | kg   | 3.589             | [15]      |
| Batten         | kg   | 1.049             | [15]      |
| Iron wire      | kg   | 3.151             | [15]      |

\(^a\)CO2, eq is carbon dioxide equivalent

The engines of construction transport and onsite equipment run on fossil fuel or electricity. According to the Fuel and energy consumption norms [18] of Vietnam’s Ministry of Construction, the energy consumption using fossil fuel can be calculated by Equation (2) [19]:

\[ E_f = E_m + E_e = Q_m e_m + Q_e e_e \]  

(2)
\[ Q_e = EC \cdot PD \]  

where \( PD \) is the process duration simulated by the simulation, and \( EC \) is the energy consumption per work shift (8 hours) for a specific equipment according to [18].

The emission of fine particulate matter (PM\(_{10}\)) for the circulation of vehicles on unpaved roads, dry paved road and the load material process were estimated by applying Equation (3), (4) provided by Environmental Protection Agency (US EPA) [20].

\[
E_1 = k_1 \cdot \left( \frac{s}{12} \right)^a \left( \frac{W}{3} \right)^b
\]  

where:

\[ E_1 ( \text{ pounds/miles}), E_2 ( \text{ g/VKT}) = \text{PM}_{10} \text{ emission factor} \]

\[ k_1 = 1.5, k_2 = 0.62, \text{ multiplicative factor} \]

\[ s = 4.80, \text{ content of silt } (\%) ; W = \text{ average vehicle weight (tons)} \]

\[ a = 0.90 \text{ coefficient function of the particulate size}; b = 0.45 \text{ coefficient function of the particulate size.} \]

\[ \text{SL} = \text{ content of powdery material (sandy/silty) on the road (g/m2)} \]

Build the simulation model For the operating machines in construction site, the emission factors of PM\(_{10}\) is 0.01 kg/h [20].

2.4. Agent-based simulation (ABS)

An agents in a agent-based model can be defined as self-contained program, which controls its own decisions, acts according to its perception of the environment, and operates according to one or multiple objectives. According to [21] a smart agent has three principal criteria, of which two must be satisfied.

- Autonomy – Agents operate without human guidance chasing specific objectives. An essential element is pro-activeness, i.e., the initial ability to operate itself rather than merely reacting.
- Cooperation – Interaction between individual agents is compulsory for ABS.
- Learning – From reactions and/or interactions with their environment, intelligent entities learn, so they can act ideally in similar situations.

| Real world | Conceptual world | Simulated world |
|------------|------------------|-----------------|
| On-site transportation, off-site transportation, material processing, on-site construction | Unit task | Population of gents |
| Workforce | Resource | Population of agents |
| Auxiliary materials | Resource | Population of agents |
| On-site transport equipment | Resource | Population of agents |
| Off-site transport equipment | Resource | Population of agents |
| Processing equipment | Resource | Population of agents |
| Constraints between unit tasks | Constraint | Population of agents |
| Resource allocation | Order | Agent type only |
| Uncertainties, dynamic conditions | Factor | Variable |
| Construction engineering quota | Reference data | Database table |
| Existing environmental impact databases | Reference data | Database table |

This study uses the Anylogic simulation tool (Personal Learning Edition) [22] to create an agent-based model to transform the conceptual model into the simulated world (Table 4). An agent in each agent population can represent a unit task, a resource, a constraint in the conceptual model. All necessary data to create the agent-based model are stored in a relational database (Figure 3). Each agent population is generated based on a data table.
2.5. Task agent and resource agent

All of the unit tasks are represented by an agent population holding their necessary information. Besides a clear identification key, each agent has various attributes such as required resources, workload, set of predecessors, and successors are provided. All of the required information of each unit task has imported from the database and designed as parameters (Figure 4). Each agent processes this information, calculates task duration, priority index, manipulates its state, and operates accordingly. The priority index is calculated based on the longest path following, which stands for the accumulated maximum duration of all successors. For this purpose, a recursive function was implemented, which determines the longest path through the network by self-referencing. Consequently, tasks close to the critical path tend to have a higher priority index so that this bottleneck is primarily served.

![Figure 4. An example of resource agent](image)

Each resource group defined in Table 4 is designed as an agent population with their necessary data for environmental impacts assessment such as emission rate, fuel consumption per work shift, and capacity. All of this information has imported from the database. Table 5 illustrates the different states of task agent and resource agent with its corresponding operations. Figure 4 shows an example of resource agent (off-site transportation resource).

![Figure 4. An example of resource agent](image)

| State       | Description               | Operations                          |
|-------------|---------------------------|-------------------------------------|
| Preparation | Preconditions not met     | Automatic check preconditions        |
| Call resource | Preconditions met     | Send resource orders to control center |
| Operating   | Resources allocated and working | Operate or consume resource |
| Finish      | Task finished            | Release resources, update finished task list |
| Available   | Resource is available    | Send available status to control system |
| Working     | Resource is allocated for task | Using resource, calculating emission |
| Waiting     | Disruption appears       | Wait                                |

![Figure 5. Data model of the implemented database](image)
2.6. Operation of the simulation model

The control system updates the available status of all resource agents and the execution state of the project through a complete task list. Each task agent automatically checks the finish events of all their prerequisites in the complete task list. If the prerequisites are met, the task agent will send resource requirements to the control system. If the corresponding resources are available, the control system will calculate and allocate these resources to the task, which has a high priority index. The pull-driven sequencing mechanism is applied in this case. As soon as the resource agents receive orders from the control system, they change their status to the operating state and send the signal to change the task’s status to the operating state. When each resource agent completes its workload, it sends the finished signal to the task agent, which calls this resource and changes its state to available. The control system will again update the resource status and the complete task list. Thereby, this process is repeated until all the tasks have been completed (Figure 5). The results of this process are project duration, total CO$_2$, and PM$_{10}$ emission.

Figure 4. a) State chart of task agent; b) State chart of off-site transport agent

Figure 5. Operation mechanism of simulation model
3. Application

3.1. Case study in Vietnam

A real office building that is located in Hanoi was selected as a case study to validate the developed method. The collected data from the case study consisted of design and construction documents. The building has a reinforced concrete frame structure with a 20-storey typical floor part, and a 2-storey basement. The total floorage is approximately 55,000 m². The construction of the frame structure of the 20-storey typical floor part was selected to test the developed method. This project is chosen as the case study because its reinforced concrete frame structure is widely applied in buildings in Vietnam; so, this project could test the general applicability of the proposed method.

The distributions of work productivity for the construction operations were based on the manager’s experience. A typical floor of the case study building will take 7 (±1) days to complete, depending on, e.g., the workers’ learning curve and the requirement to meet the deadline of the contract. Thus, this study uses a triangular distribution of (0.85, 1, 1.15) to represent the minimum, most likely, and maximum work productivity probability for a typical floor. The triangular distribution is regarded to be a simplistic and effective description of an input variable (input modeling) for ABS if the minimum, most-like, and maximum of the input variable can be estimated through field measurement or knowledge and experience [23].

For the studied case, premixed concrete was supplied from a ready-mixed concrete supplier that was approximately 19 km away from the construction site under the hypothesis that half of the roads outside the worksite are unpaved. Since transportation to the site can occur at any time of day or whenever construction progress requires it, the following assumptions have been made. The average transportation speed is 20 km/h during busy traffic conditions, i.e., between 08:00 and 18:00. During idle traffic conditions (00:00~8:00, 18:00~24:00) the average transportation speed is 25 km/h. The constructor was able to choose from two types of formwork: plywood form with steel tube support and steel formwork with steel tube support.

3.2. Result and discussion

In the case study, auxiliary material consumption during construction contributed to the highest CO₂ emissions (71%) among all impact sources in the construction phase (Figure 6.a). Off-site transports by mixer trucks, the use of a crane tower, concrete pump for on-site transports, and the use of machines for rebar processing have the high CO₂ emissions among the equipment (Figure 6.b).

![Figure 6. a) CO₂ emission of different impact sources; b) CO₂ and PM₁₀ emission of equipments](image-url)
The PM$_{10}$ emission is significantly lower than CO$_2$ emissions, which is approximately 14% of the CO$_2$ emission of machinery (Figure 7.a). The main reason is that excavation is not considered in this case. Therefore, PM$_{10}$ emission is mainly from material transportation on the unpaved road. Figure 7 depicts the emission comparison between using plywood formwork (option one) and steel formwork system (option two) in the case study. These results indicate that the total CO$_2$ emission of auxiliary material consumption in option two is considerably smaller (15.1%) than option one, while CO$_2$ emission from equipment and total PM10 emission witness similar in both cases. This difference can be explained by the fact that steel formwork can be reused many times compared to wooden formwork. In both options, the plywood and metal-related materials such as iron wire, bolt, joint, steel plate, shaped steel, and nail contributed the most to CO$_2$ emission among the auxiliary materials (Figure 7.b).

![Graphs showing emissions comparison between plywood and steel formwork](image)

**Figure 7.** Compare emissions between using plywood formwork and steel formwork

4. **Conclusions and further work**

In this paper, an innovative method that integrates LCA into ABS in order to evaluate the GHGs and PM$_{10}$ emission of the construction project under the uncertain and dynamic conditions in the construction phase is introduced. An office building with a reinforced concrete frame is used as a proof of the concept to validate the developed method. The results provide useful results about the environmental burdens during the construction phase, not only in terms of magnitude but mainly referring to the activities and processes that must be carefully planned and organized in order to control the adverse effects. By using this method, the constructor can assess the environmental impact and compare construction scenarios to select the best scenarios for impact reduction. The proposed ABS-pLCA is an effective tool for environmental assessment. However, the presented method faces serious difficulty in acquiring LCA data from the Vietnamese construction industry. Some of the data have to be either acquired from different data sources or supplemented with similar data from published international literature. Therefore, more systematic and comprehensive environmental data need to be developed and provided to achieve reliable results in the future. In the new context of rapid-developing building information modeling (BIM) technology that contains product and process information, the proposed method can be extended to connect with BIM. Extracting data from BIM would simplify the ABS-pLCA method in collecting input data and expanding its potential applications.
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