

ASSESSING THE ENVIRONMENTAL IMPACT OF THE CONSTRUCTION PHASE – A SIMULATION-BASED METHODOLOGY.

Danh Toan Nguyen¹ and Walter Sharmak²

¹ University of Kassel, Kassel, Germany

² Technische Hochschule Mittelhessen - University of Applied Sciences, Giessen, Germany

Abstract

The construction industry makes a significant contribution to global resource and energy consumption and the associated CO₂ emissions. The environmental impacts in the execution phase compared to the planning and operating phase have not yet been comprehensively investigated in research for several reasons. This paper presents a methodology for the preliminary calculation of greenhouse gas emissions on the construction site by simulating the nonlinear behavior of the complex and dynamic construction processes. The estimated results will help to optimize the execution planning of the construction processes from an environmental perspective.

Introduction

According to a report by the International Energy Agency, the construction and operating of buildings accounted for the largest share of both global final energy consumption (36%) and energy-related greenhouse gas (GHG) emissions (39%).

However, the Intergovernmental Panel on Climate Change (IPCC) predicted that the construction sector has the greatest potential for significant reductions in greenhouse gas emissions compared to other major manufacturing sectors (IPCC, 2014). Particularly during the operating phase, the building energy requirement will decrease due to the increased requirements for new buildings and renovations of old buildings. Due to this development, the embodied energy will become more important as its share of total energy has increased significantly, based on the calculated life cycle of 50 years. For this reason, studies into sustainable materials like clay are currently gaining great importance in research and development (Tourtelot et al., 2023; Muntari and Windapo, 2020).

Compared with the operating phase, the construction phase is a short-term phase and is believed to have small environmental impacts, so it has not attracted much research (Slossharek et al., 2021). However, to exploit the full potential for reducing greenhouse gas emissions in the construction industry, the execution phase should also be optimized in this regard.

Nonetheless, the complex and dynamic parameters and their relationships on the construction site make it difficult to quantify the environmental impacts in the execution phase. In current practice, only qualitative analyses are carried out to demonstrate the sustainability of the construction site.

The use of simulations can provide a cost-effective and efficient approach to analyzing construction processes and evaluating the resource consumption of different construction methods.

Several researchers have integrated simulation methods such as discrete event simulation (DES), system dynamics (SD) and agent-based simulation (ABS) for various purposes in construction (Xie and Peng, 2012; Xia and Sun, 2013; de Assis et al., 2021). However, such a simulation-based approach is rarely used in the environmental impact assessment of the construction phase.

In this paper, a hybrid simulation model combining ABS and SD is proposed to analyze the environmental performance during the construction phase.

Autonomous agents represent construction processes, and their needed resources can interact with each other according to predefined operating rules. SD provides causal effect loops to simulate the nonlinear behavior of dynamic construction processes. A simple example is presented as well to test the developed simulation model.

Work methodology

The simulation of the processes in the construction phase requires a variety of inputs from different areas for realistic results, such as data on the work schedule, quantities, the planned construction methods and the construction site facilities.

From an IT perspective, the different data structures of the required data represent a major challenge for the simulation. Another challenge is that the construction processes are nonlinear and therefore the traditional discrete event simulation may not lead to reasonable results.

For this purpose, hybrid modelling using multiple interacting agents and system dynamics is used for the simulation in the presented approach of this paper.

Agents are defined in ABS as intelligent autonomous objects that represent real parties without global control and unified goal (Ren and Anumba, 2003).

Autonomously acting agents interact directly with their predecessors and successors. According to predefined operating mechanisms, process agents register their required resources in a central board system that is used for all agent negotiations. Depending on the availability of resource agents, the control centre processes all information in a specific protocol and initiates resource allocation accordingly. Both construction processes and needed resources are represented by agents.

System dynamics simulation is a top-down approach based on information feedback to analyse complex system behaviour between project elements within a predefined boundary (Ding et al., 2016; Ding et al., 2018). Typically, system dynamics models are structured by stock-flow diagrams, which describe the movement of entities from start to finish in a model, and by causal loop diagrams, which capture the chain influences of a cause that can be traced back to the original cause and a set of related variables.

The concept of causal loop diagrams is explained in the simple well-known example related to the human population (Figure 1).

If the human population increases (larger birth rate), this leads in loop 1 (left) to the population continuing to grow in the future. Such a loop is called a Reinforcement Loop (R). Since people need some time after birth before they are able to have children of their own, the loop has a delay, which is represented by two pipes in figure 1. This delay is not deterministic (e.g. 18 years), but depends on many cultural, economic, and other factors. For this reason, this delay should be represented using a suitable probability distribution. Deaths cause the population to decrease. This is shown in the loop on the right (Balancing Loop B). Loop B also has a delay because most people do not die immediately after birth. This delay also has to do with many factors, such as available medical care, exercise or eating habits and cannot be used as a deterministic value (e.g. 75 years), but in this case too a suitable probability distribution should be used.

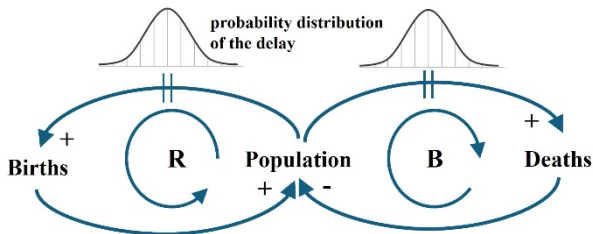


Figure 1: a general example of Causal Loop Diagrams

Another well-known example is related to using work overtime to accelerate the schedule (Figure 2).

Two feedback loops can help decision-makers become aware of both the positive and negative impacts of this management policy. In Figure 2, loop 1 is a reinforcement loop. Indeed, starting with an assumption that Overtime_hours grows and going around the loop counterclockwise (according to the direction of the links going from Overtime_hours through Fatigue, Completed_Work, Remaining_Work and come back to Overtime_hours), we get growth of Fatigue, but at the same time this leads to decrease of Completed_Work, increase of Remaining_Work and again get growth of Overtime_hours, so the same result as the initial assumption. Alternative check by counting the number of

negative links: This loop has two negative links, so it is a reinforcing loop.

This reinforcing loop shows a negative impact of the overtime policy. On the other hand, loop 2 is a balancing loop, which indicates the positive effect of working overtime. The adoption of overtime means an increase in Overtime_hours. Let's go around the loop counterclockwise. The increase of Overtime_hours leads to an increase of Completed_Work, and that by-turn leads to a decrease of Remaining_Work. Consequently, the decreased Remaining_Work will result in the reduction of Overtime_hours, so the result contradicts the initial assumption. Alternative check by counting the number of negative links: This loop has one negative link, so it is a balancing loop.

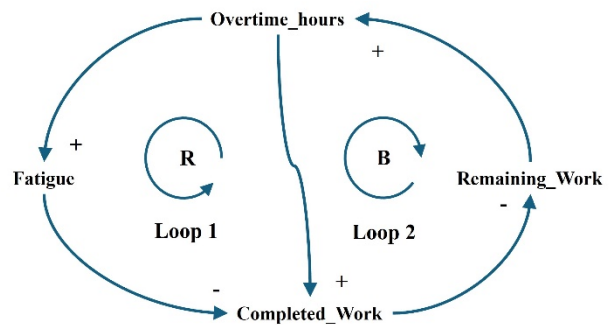


Figure 2: a general example of Causal Loop Diagrams using the Feedback processes related to overtime.

In the presented approach, SD including the schedule pressure loop and the rework loop, is embedded in the processes to capture the dynamic behaviour.

Process patterns are used to facilitate the use of the construction processes in the simulation. A relational database is developed to manage the data of the process patterns. Process patterns are generally used to describe repetitive processes in various construction projects (Dori, 2016; Nguyen, 2024). The process patterns can therefore be used when simulating various projects.

The process pattern structure includes the following elements (Figure 3):

- Description: depicts the process pattern and its application.
- Metadata: contains information about when the process pattern was created, who the author is and some tags to help find patterns.
- Object(s), one or more building object types are created by completing all steps as described in the process pattern, such like walls, columns etc.
- Operations: represent required steps of the process at the second level of granularity.
- Activities: represent required steps of the operation at the third level of granularity.

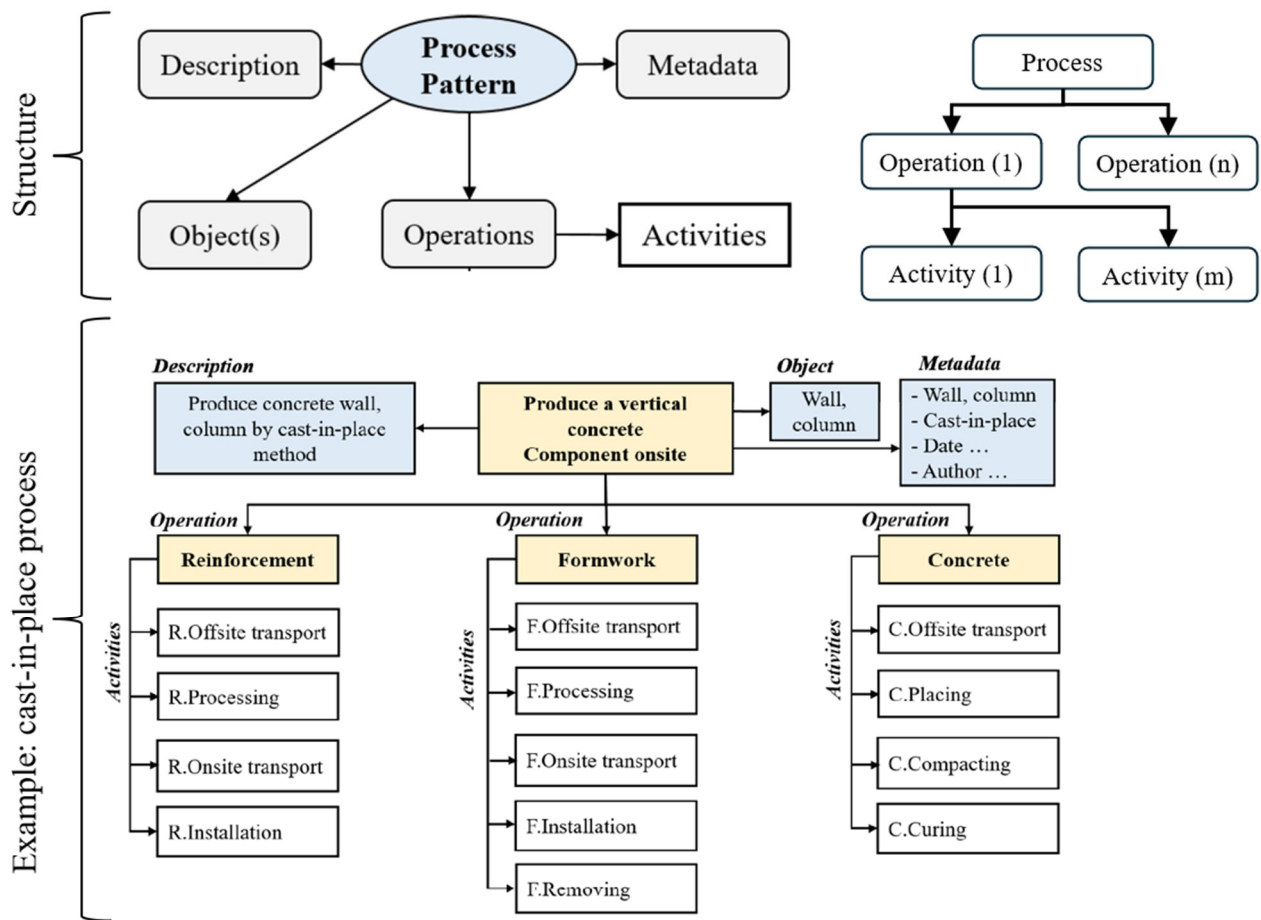


Figure 3: the structure of the process patterns with an example

The necessary information about the building components (such as classification, quantities and dependencies) is extracted from the Building Information Model (BIM). Information about processes and resources is captured by reference to appropriate process patterns. These sources of information are used when initializing agents and populating attributes. In a later step, the required LCA-datasets are queried from a suitable LCA database as a CSV file.

System Dynamics modules are created by combining stock-flow structures and effect-causal loops diagrams. Causal-effect loops are located within the operation agents and consists of reinforcing and balancing loops. A reasonable delay in each loop is considered in the simulation model and its value is represented as a probability distribution using practical experience or literature sources. Examples of the considered dynamic factors in SD Model include overtime and error-related rework. Figure 3 shows schematically the simulation framework planned in the presented methodology.

Figure 4 shows the Error Detection and Rework Loop built in the simulation Software Anylogic. Errors in construction tasks are often inevitable because of unreliable workflow in an uncertain environment

(Alzraiee et al., 2015; SangHyun Lee, 2006). Errors lead to rework that consumes more resources than expected, so the environmental impact also increases significantly. However, errors and rework are often overlooked in previous studies on environmental impact assessment.

The rework cycle is affected by the workforce level, productivity, and quality of the performed work. While undiscovered errors are inherently unobservable, the final stages of a project tend to see a big increase in rework discovery. Indeed, crews are aware of their mistakes when the work comes near the end, so the time of error discovery depends on the completion rate. It is very much like finally putting the pieces of a puzzle together. At the end, it becomes quite obvious which pieces are missing or have the wrong shape.

The suggested rework cycle includes four typical loops that result from management policy. The first loop R1 shows the causal-effect relationship between schedule pressure and work with errors. High schedule pressure increases error rate and flawed work. Consequently, the remaining work or initial scope increases. This adversely impacts and increases the schedule pressure again. The second loop B1 shows that if the management policies increase the productivity rate, the work remaining will decrease. The arrow link with minus symbol connecting

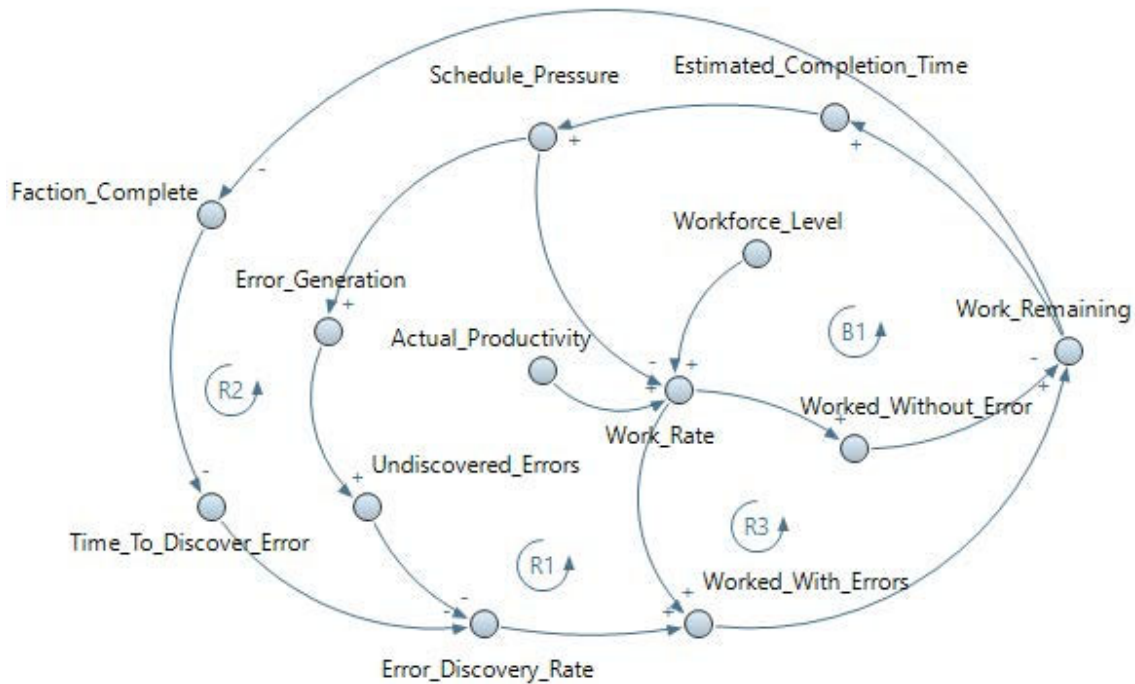


Figure 4: The implemented Error detection and rework feedback loops in AnyLogic.

node Worked_Without_Error and node Work_Remaining has negative polarity (minus symbol) indicating that if node Worked Without Error increases, node Work_Remaining decreases. The third loop R2 shows the fact that the errors are usually detected when the project nears completion. The fourth loop R3 indicates that the increase in work rate could increase the errors, and hence increase the work remaining and schedule pressure.

Case study

To test the applicability of the proposed hybrid simulation methodology for assessing the environmental impacts of the construction phase, a simple process scenario is introduced.

The described simulation environment is implemented in the AnyLogic software. Interfaces to various necessary data, such as the process patterns, are carried out through the SQL interface. Other data, such as LCA data sets or the construction quantities, are prepared in CSV format and imported into the AnyLogic environment.

In the case study, the construction phase of the shell structure of a virtual building is selected to apply the proposed methodology. The building has a reinforced concrete frame structure that is constructed using the in-situ concrete method.

The project delivery method is design-bid-build. The planners select the primary building materials in advance, while the construction companies select the auxiliary materials based on their construction method.

Construction companies and their contractors are responsible for transporting materials to the construction site and carrying out construction work on site. Construction works cause environmental impacts through

the use of equipment and vehicles, consumption and waste of materials.

The range of environmental sources of influence lies within the decision-making area of construction companies, for example when selecting vehicles, equipment, machines and building materials during the construction phase.

Therefore, the scope of simulation in this case study includes the associated material supply chains and on-site construction operations.

All necessary data on resource consumption and greenhouse gas emissions are obtained from available construction standards and open LCA datasets or international studies.

According to the simulation framework shown in Figure 5, the simulation model is designed in three steps. First, the construction phase of the building is decomposed into units, including product units and process units. Secondly, product units and process units are analyzed to select corresponding process patterns. Third, agents are established and enriched by embedding SD models.

In this case, the building consists of two product units. These are vertical elements such as columns and walls and horizontal elements such as floors and beams.

Process entities represent the cast-in-place concrete method, which is applied to produce product entities of the building shell structure. There are two process entities to produce vertical and horizontal product entities. Each process entity includes three main construction operations: reinforcement, formwork, and concrete. Each operation contains several activities which utilize different resources. An operation can be carried out by

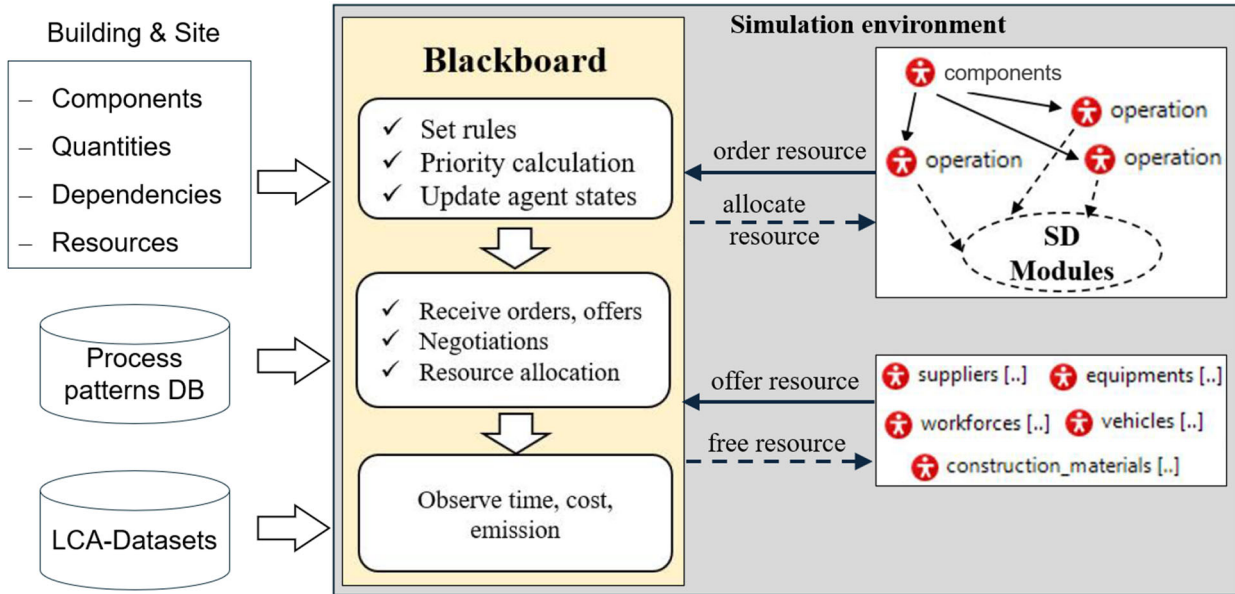


Figure 5: Schematic representation of the planned methodology

different methods. For example, several formwork options can be used to produce one type of concrete structure. When it comes to reinforcement work, reinforcing bars can be processed in the factory or on construction sites.

Depending on the variants selected, modelers can query the process pattern database to identify the specific activities of each process. In addition, the corresponding resources of these activities are determined based on the process pattern.

The abstracted simulation elements of the construction phase are shown in Table 1. For example, building components are defined as product units. Construction-related equipment and building materials that have a direct or indirect impact on the environment are defined as renewable or non-renewable resources.

Table 1: Included Concepts in the simulation model.

Real world	Simulated world
Building components	Product agents
Construction operations	Operation agents
Construction material	Resource agents (non-renewable)
Equipment, workforce	Resource agents (renewable)
Causal-effect relations	Causal-effect loops

Using the proposed simulation model, four scenarios are analyzed to quantify the impact of implemented methods on the environmental performance of the construction phase. The scenarios take into account push or pull controlled processes as well as different resources for the planned construction.

The greenhouse gas emissions (expressed as carbon dioxide equivalents CO₂eq) of the four scenarios using the simulation are shown in Table 2. By applying pull-driven processes, scenarios two and four can significantly reduce emissions compared to scenarios one and three.

Using the ABS simulation without the SD models shows lower greenhouse gas emissions results than the ABS-SD simulation. Understandably, the ABS-SD model assumes that error and rework lead to a higher material consumption, so the greenhouse gas value should be higher than the ABS model results. In addition, the ABS-SD model takes into account overtime during night shifts, requiring vehicles, machines and crews to work in uncomfortable conditions, resulting in longer working hours and higher energy consumption.

The SD components take schedule pressure loops and rework loops into account in the construction processes. These loops are needed to capture the realistic behaviour of the construction processes. By effectively applying lean methods to reduce waste in the processes, the effect of these loops will be reduced, and the results of the hybrid ABS-SD simulation will, in the best case, be identical to those of the ABS simulation.

Notably, material consumption contributed the highest CO₂ equivalent (61%-64%) among all construction phase impact resources. This result is consistent with results from previous studies that found that materials account for approximately 60–80% of the CO₂eq ratio depending on the construction type (Feng et al., 2018; Y. Wang et al., 2017).

Table 2: Simulation results for one typical story.

Scenario	CO ₂ -eq (kg)	
	ABS-SD	ABS
1	34.809	29.239
2	31.055	29.107
3	33.633	28.124
4	29.589	27.978

Conclusions

The proposed methodology in this paper helps to assess the environmental impact of the construction site and contributes to improve the processes on future construction sites from an environmental perspective. It

does not consider only the technical aspect such as the choice of the construction method but also the dynamic changes to the processes. Direct performance measurement on the construction site seems to be difficult because it requires precise documentation of many factors in real-time, which needs a lot of effort and is not justifiable for the construction companies. This makes the target-performance comparison almost impossible. In any case, the proposed simulation-based methodology in the execution planning phase offers a pragmatic solution in this context.

Future development efforts are needed regarding the definition of new patterns for different construction processes and the developing of simulation templates to simplify future use.

The method can also be extended to consider not only the environmental aspect, but also economic and social aspects, which are essential components of sustainable construction.

References

- Alzraiee, H., Zayed, T., & Moselhi, O. (2015) Dynamic planning of construction activities using hybrid simulation. *Automation in Construction*, 49, 176–192. <https://doi.org/10.1016/j.autcon.2014.08.011>
- de Assis, R. F., de Santa-Eulalia, L. A., Ferreira, W. de P., Armellini, F., Anholon, R., Rampasso, I. S., & Santos, J. G. C. L. dos. (2021) Translating value stream maps into system dynamics models: a practical framework. *International Journal of Advanced Manufacturing Technology*, 114(11–12), pp. 3537–3550. doi: 10.1007/s00170-021-07053-y.
- Ding, Z., Yi, G., Tam, V., & Huang, T. (2016) ‘A system dynamics-based environmental performance simulation of construction waste reduction management in China’, *Waste Management*. Elsevier Ltd, 51, pp. 130–141. doi: 10.1016/j.wasman.2016.03.001.
- Ding, Z., Gong, W., Li, S., & Wu, Z. (2018). System dynamics versus agent-based modeling: A review of complexity simulation in construction waste management. *Sustainability (Switzerland)*, 10(7). <https://doi.org/10.3390/su10072484>
- Dori, G. (2016). Simulation-based methods for float time determination and schedule optimization for construction projects.
- IPCC, 2014: Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, R.K. Pachauri, L.A. Meyer (Eds.), IPCC, Geneva, Switzerland, 2014, p. 151. 84.
- Feng, K., Lu, W., Olofsson, T., Chen, S., Yan, H., & Wang, Y. (2018). A predictive environmental assessment method for construction operations: Application to a Northeast China case study. *Sustainability (Switzerland)*, 10(11). <https://doi.org/10.3390/su10113868>
- Muntari, M.Y. & Windapo, A.O. (2020) Clay as Sustainable Building Material and its Benefits for Protection in the Built Environment. *IOP Conference Series: Materials Science and Engineering*, Volume 1144, 3rd International Symposium on Civil and Environmental Engineering (ISCEE 2020) 1st-2nd December 2020, Batu Pahat, Johor, Malaysia
- Nguyen, D.T. (2024) Hybrid Simulation-based Lean Management Methodology to Improve the Sustainability of the Construction Phase. Kassel University Press. ISBN: 978-3-7376-1155-8
- Lee, SangHyun. (2006). *Dynamic Planning and Control Methodology: Understanding and Managing Iterative Error and Change Cycles in Large-Scale Concurrent Design and Construction Projects*. Massachusetts Institute of Technology.
- Tourtelot, J., de Lacaillerie, J., Duc, M., Mertz, J., Bourges, A., & Keita, E. (2023). Strengthening mechanisms of clay building materials by starch, *Construction and Building Materials*, Volume 405, 2023, 133215, ISSN 0950-0618, <https://doi.org/10.1016/j.conbuildmat.2023.133215>.
- Ren, Z., & Anumba, C. J. (2003). Multi-agent systems in construction-state of the art and prospects. *Automation in Construction*, 13(3), 421–434. <https://doi.org/10.1016/j.autcon.2003.12.002>
- Slosharek, B., Dlouhy, J., Schneider-Marin, P., & Lang, W. (2021) Taktung the Sustainability of Construction Processes: An Environmental Assessment Method, *Proc. 29th Annual Conference of the International Group for Lean Construction (IGLC)*, pp. 902–912. doi: 10.24928/2021/0198.
- Wang, Y., Feng, K., & Lu, W. (2017). An environmental assessment and optimization method for contractors. *Journal of Cleaner Production*, 142, 1877–1891. <https://doi.org/10.1016/j.jclepro.2016.11.097>
- Xia, W. and Sun, J. (2013) Simulation guided value stream mapping and lean improvement: A case study of a tubular machining facility, *Journal of Industrial Engineering and Management*, 6(2), pp. 456–476. doi: 10.3926/jiem.532.
- Xie, Y. and Peng, Q. (2012) Integration of value stream mapping and agent-based modeling for OR improvement. *Business Process Management Journal*, 18(4), pp. 585–599. doi: 10.1108/14637151211253747.

