Mapping simulation optimization requirements for construction sites: A study in the heavy-duty vehicles industry

Abdulkarim Habbab[a,*], Anas Fattouh[b], Bobbie Frank[c], Koteshwar Chirumalla[b] Markus Bohlin[b]

[a] *Mälardalen University / Volvo Construction Equipment, Box 325, 63105 Eskilstuna, Sweden,*

[b]*Mälardalen University, Box 325, 63105 Eskilstuna, Sweden,*

[c] *Volvo Construction Equipment, Box 325, 63105 Eskilstuna, Sweden*

*Corresponding author: abdulkarim.habbab@mdu.se

Abstract

The Construction and mining Industry comprises complex operations and interactions between various actors at different levels. Simulation has emerged as a valuable tool in this domain to better understand the site's behavior and optimize its operation. However, developing a simulation platform that can handle all the operations on the site is challenging due to the computational cost of the digital representation of reality along with the required accuracy level.

This paper aims at extracting and mapping the optimization requirements of construction sites at three main levels: site level, operational level and dynamics level. More precisely, this work seeks to define and map the most important requirements between these levels that ensure simulation credibility and reliability.

Based on interviews with experts in the domain, both from academia and industry, several key insights and recommendations emerged: at the site level, the layout and the key performance indicators, such as productivity, time, cost, number of machines and workers, need to be modeled and simulated. At the operational level, the simulation platform must include the main activities, such as loading, excavating, transporting and dumping. Moreover, the dynamics level should involve machine models and their interactions with the site's environment, such as earthmoving, drilling, excavating and blasting.

1. Introduction

In today's rapidly evolving digital landscape, digitization, as an essential pillar of Industry 4.0, is presented as a great enabler in the industry in terms of efficiency and productivity (Hermann et al., 2016). This is because it allows companies to leverage cutting-edge technologies, such as artificial intelligence, the Internet of Things (IoT), and machine learning, to organize operations and optimize resource utilization. In this context, simulation technology can be a great service to be digitized and presented to a broader range of end-users in the construction and mining industry (Tsai et al., 2016). Quarries, construction and mining sites are vital and dynamic work environments that involve harsh operations such as blasting, digging, excavating, and loading different kinds of materials. In order to optimize the workflow in these sites and maximize productivity while minimizing the cost and meeting environmental constraints, it is vitally important to have a well-designed management and control system in place at each level, site, operations and machines, with well-defined KPIs at each level.

At the site level, the main KPIs of the site related to productivity, time and cost calculations can be determined, which provide a comprehensive overview of the site's overall performance. At the operational level, we can define the main operations that will be ongoing in the selected site, including the type of equipment needed, the manpower required, and the safety protocols that need to be followed. Finally, and most importantly from a software engineering perspective, the machine dynamics level is where we set the proper parameters to represent the machines and facilities on the site, and that includes the type and specifications of used machines, and the modeling of machines' dynamic and their interaction with each other and with the surrounding environment.

By replicating real-world scenarios in a virtual environment, site simulation can be a great help to site designers, managers and engineers to plan, monitor, manage, and predict hazards and potential failures in their sites. However, the use of site simulation is often constrained by a significant bottleneck represented by the computational cost of modeling and simulating all actors operating on the site at different levels. The main challenge is acquiring the required accuracy with the increased number of simulated machines, tasks, and facilities, creating a trade-off between accuracy and feasibility.

This work is motivated by two aspects: first, the current simulation tools are limited in their ability to provide a comprehensive site simulation due to their high computational cost (Guo & Zhang, 2022), and the huge amount of involved elements that can be in a site (Wickberg et al., 2022). Second, the decision-making process for designing and operating construction and mining sites is heavily based on experience rather than data-driven or standard insights.

This study represents an initial exploration in the field of full site modeling and simulation, with the intention of laying a foundation for further research. Subsequent studies will be conducted to expand upon and refine the findings presented herein, in order to contribute to the ongoing advancement of knowledge in this field. Moreover, future research endeavors will also aim to develop and test algorithms that can effectively address the problem explored in this study. These efforts will contribute to the advancement of the field and aid in the development of practical solutions for real-world applications.

The structure of this paper is as follows: Section 2 delves into a review of related literature, followed by an explanation of the research methodology in Section 3. The results are presented in detail in Section 4, and finally, a summary and discussion are provided in Section 5.

2. Related Work

Mapping the optimization requirements is defined as the process of understanding and identifying the key components, constraints, and variables involved in the optimization problem and representing them in a structured framework that can be used for analysis and solution finding.

Scientific software projects often overlook formal requirement engineering, as scientists may not see its benefits and lack knowledge in the field. A recent approach was to use natural language processing techniques, which achieved a high accuracy rate (Li et al., 2015). However, extracting these requirements in practical field is essential part of solving the problem and it requires a deep understanding of the involved processes and factors (Bashir et al., 2023).

In the following subsections, the evolutionary trajectory of earthwork and allocation optimization techniques will be presented, alongside an exploration of the approaches employed for addressing and resolving these optimization challenges.

2.1 Earthwork Optimization: Evolution and Categorization

In the context of construction site optimization requirements, there has been a growing interest in understanding the impact of earthwork optimization on mining and construction site operations. Starting from 1958 with Kantorovich and his proposal of a simple mathematical method to allocate materials to minimize the total cost of transportation of 1 m^3 of material from point A to B, up until 2021 where we start to see that it evolves to become multiple objectives optimization problem (Fernandes et al., 2022).

Delving into the body of literature through a meticulous review conducted by Fernandes et al. (2022), distinct categories within the domain of earthwork optimization emerge, such as:

2.1.1. Earth Allocation Planning:

This category is primarily dedicated to the minimization of costs, often constrained by financial considerations encompassing excavation, hauling, and compaction expenses.

2.1.2. Equipment Fleet Planning:

In this segment, studies gravitate towards multi-objective strategies that extend beyond cost optimization, encompassing concerns related to fuel consumption and emissions reduction.

2.1.3. Earthmoving Operation Routing and Scheduling:

Researchers in this area are committed to optimizing costs, time, and transportation distances through judicious routing and scheduling of earthmoving operations.

Despite the strides taken in earthwork optimization, a critical observation arising from the reviewed studies is the often-peripheral treatment of environmental effects linked to earthmoving operations within optimization objectives. This vital aspect highlights a potential gap in current research priorities.

2.2 Methodological Approaches to Earth Allocation Optimization

Numerous methodologies have been employed to tackle the intricate challenge of earth allocation optimization, such as:

2.2.1 *Genetic Algorithms, Linear Programming (LP), and Mixed-Integer LP:* These traditional techniques serve as the cornerstone. Yet, challenges like discrete domain variables and nonlinear relationships can impede their effectiveness (Burdett & Kozan, 2014; de Lima et al., 2020; Fattouh et al., 2021; Lim et al., 2017; Montaser et al., 2012).

2.2.2 Hybrid Approaches: A notable contemporary trend involves the fusion of algorithms, such as genetic algorithms and LP or combinations like tabu search and simulated annealing (Burdett & Kozan, 2014; de Lima et al., 2020; Fattouh et al., 2021; Lim et al., 2017; Montaser et al., 2012).

2.2.3 Fleet Planning: Evolutionary techniques assume significance in this domain, often synergizing with GPS and GIS methodologies to enhance precision in productivity estimations (Montaser et al., 2012).

It's imperative to acknowledge the limitations intrinsic to each of these algorithms, arising from factors such as discrete domain variables or nonlinear relationships.

2.3 Innovations in Site Layout Planning Optimization

Turning attention to site layout planning, research predominantly leans towards heuristic or metaheuristic models, driven by mathematical constraints in optimization software and the inherently multifaceted nature of site layouts, featuring diverse objectives, laborer and equipment pathways, and facility configurations (Kaveh & Vazirinia, 2018). An underlying premise in optimization algorithms is the alignment between their search paths and the search capability they provide (Xu et al., 2020).

3. Methodology

This research was performed using the case study procedures (Patton, 1990), as the study was designed based on a certain number of workshops and interviews with experts in different levels of the studied case. The selection of the interviewed people was based on their relevance to the involved project, as the selected experts were chosen to cover different operational levels from business to operations and finally technical software modeling and simulation. Table 1 shows the details of the conducted interviews and workshops.

Table 2 shows the participants' designation. The workshops were conducted on a regular basis to discuss the best practices for general construction and mining site optimization solutions.

The interview questions were set to extract the main site design considerations and map them downwards to achieve the most ideal machines, materials and facilities digital representation. The questions were designed to distinguish different site levels (site, operations and machine dynamics), this distinguish comes from the software design needs for more dynamic architectural design of the suggested framework (Fattouh, 2022), as one of its main features is the ability to be expanded always to include new machines, material types and different kind of facilities. The goal of these questions was to get the boundaries on each site level that are essential to keep the site in ideal operation mode, how to achieve that currently and to explore the possibilities of mistakes and problems that can happen on the site and map all this information together to help to build better models of the machines, material their interaction and finally the whole site in general.

We interviewed one site manager, one business development engineer and several modeling and simulation experts. The interviews were conducted online with an approximate timing of 2-3 hours each, while the workshops' timing was approximately 6 hours each.

Table 1: Conducted interviews and workshops.

Description	Interview	Workshop
Number of conducted sessions	6	5
Time/session	2-3h	6h
Total Number of Experts	5	6-12

Table 2: The participants' designation.

Title	Functional Organization	Years of Experience
Simulation Engineer	Product Platform / Wheel Loader	15
Calculation Engineer	Virtual Product Development	17
Research Owner	Emerging Technologies	16
Senior Lecturer	Product Realization Division	5
Business Development Engineer	Stone materials Department	7
Construction Site Manager	Stone materials Department	19

4. Results

The objective of this research is to establish a comprehensive framework for defining and categorizing optimization requirements pertaining to quarries, construction, and mining sites, with the aim of achieving a practical and dependable approach to site modeling and simulation.

Findings from interviews and workshops, particularly with industry experts, indicated that a significant number of design decisions and considerations continue to be influenced by experiential knowledge, business objectives, and regulatory constraints, as these factors define the realistic boundaries within which site operations are conducted

Figure 1.

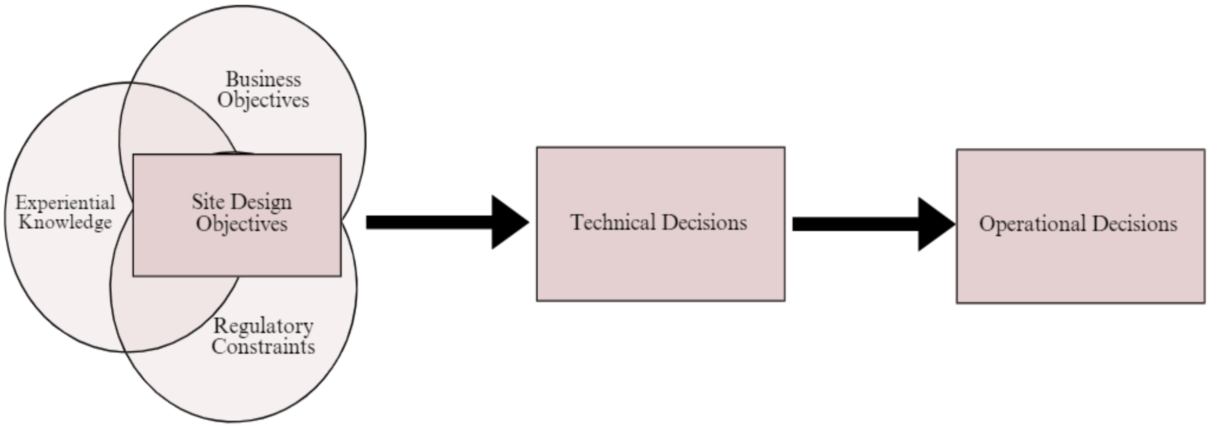

Figure 1 The factors influencing the decision-making processes.

Additionally, from a software perspective, simulating complete construction and mining sites involves significant computational expenses, specifically when considering diverse machinery types, materials, and the presence of static and dynamic objects. The behavior, interactions, and movements of machinery like excavators, bulldozers, cranes, and trucks require complex algorithms. Material simulations encompass forces, deformation, and flow for various materials such as soil, rock, aggregates, and ores. Simulating interactions and collisions between static objects (structures, terrain) and dynamic objects (vehicles, personnel) necessitate sophisticated algorithms and precise modeling of dynamics, kinematics, and spatial relationships.

Consequently, it is imperative to carefully examine the design considerations pertaining to models representing sites, machinery, materials, and machine-material interactions, in order to mitigate the exponential escalation of system complexity.

The resulting requirements and recommendation for simulation optimization can be summarized as follows.

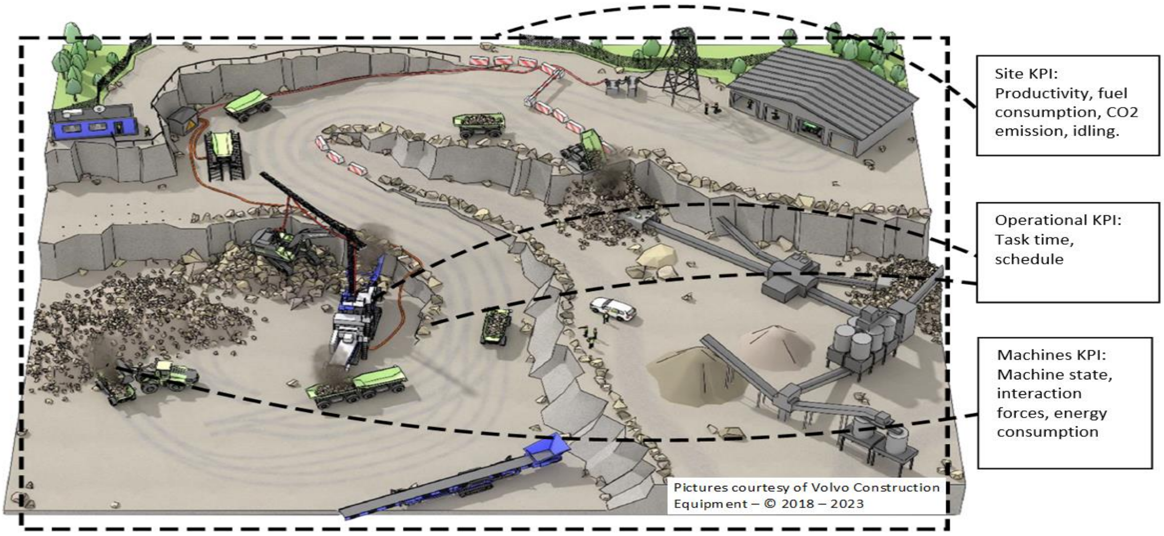

Figure 2: Important KPI at each level in a quarry site.

4.1. General KPI's of the Site

There are several factors that need to be considered when evaluating a site for a project (Figure *2*). These include but are not limited to productivity, cost, time, energy consumption, environmental requirements, and governmental permissions. It is important to mention that these factors are highly dynamic throughout the lifespan of the site and adapting to these factors together could be challenging. Governmental permissions are a critical consideration that can affect various aspects of a project. These permissions dictate working hours, safety measures, noise levels, and environmental constraints. Understanding and complying with these regulations is crucial for legal compliance and avoiding potential penalties or delays. Additionally, governmental permissions can align with business objectives, ensuring that the project meets all necessary regulations while achieving its desired outcomes.

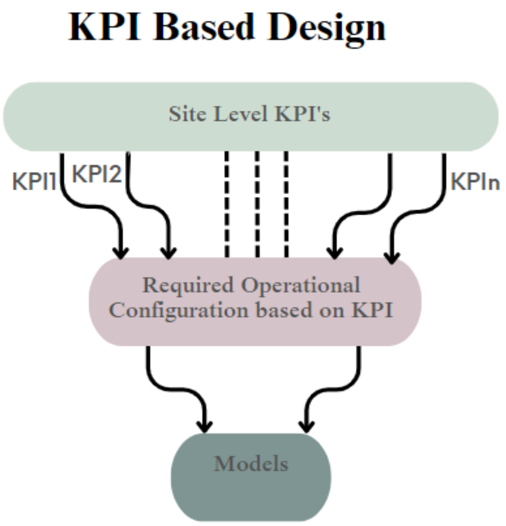

Figure 3 KPI-Based design and models selection

Changes in project goals, market conditions, or regulatory frameworks can introduce new challenges and considerations. Therefore, it is essential from a software perspective to have adaptable characteristics and decision-making processes that can accommodate these evolving factors Figure 3. These characteristics include:

4.1.1. Flexibility and Customizability: to accommodate any change in the targeted KPI or the nature of the site itself based on the need of the project like new routes, increased or decreased number of machines and operators, different kinds of equipment... etc.

4.1.2. Integration: to have a successful, meaningful, and smooth simulation the software must have the ability to integrate and interact with other tools and software.

4.1.3. User Interface: to give the user the ability to set up the simulation in an easy and meaningful manner a user-friendly interface is essential in such an application.

4.2. Design based on Task

Designing the models of machines, material and their interaction in such applications is the most challenging part as this problem can easily grow in complexity to a very high level due to the huge number of parameters needed to represent the site and the activities going on in an accurate way, and due to the nature of these activities that has a huge complexity level in its nature as it is heavily dependable on previous state of the model in each task independently. That is why these models should be designed in a modular flexible way where certain parts of the model can be enabled or disabled based on the nature of the task. The main tasks that we will discuss are the loading and dumping task and the moving task.

During the loading and dumping task, the main factors to estimate the fuel consumption and subsequently the other relevant KPIs like productivity and CO_2 emission are the forces generated from the bucket-material interaction. The machines mainly articulated wheel loaders, or excavators, will be in a relatively stationary state, where the bucket and hydraulic systems are mainly the active systems to perform the loading and dumping processes (Filla, 2005; Frank et al., 2018). Modeling and simulating these processes represent one of the main bottlenecks in the site's simulation. This interaction problem can be approached through various methods, including numerical-based approaches, trajectory-based approaches, and machine learning techniques.

The numerical-based approach in site simulation involves approximating the interaction between the machine's bucket and the material pile as two sides of an equation. The goal is to establish a relationship between the parameters representing the forces involved in the interaction. Although this approach shows feasibility and promise, it encounters a significant challenge when applied to large-scale sites with numerous machines in operation.

Trajectory-based approaches aim to estimate the state parameters of the interaction between the bucket and the material. This method relies on modeling the interaction based on the previous states of the bucket along its trajectory during the excavation process, Notably, the distinct pathways followed by the bucket during excavation lead to the generation of differing forces inherent to this excavation procedure, Figure 4 shows the possible trajectories that could be taken in the excavation process. However, this approach introduces a complexity problem akin to the Travelling Salesman Problem (TSP), as the estimation of forces changes with each new penetration into the material pile. Consequently, this dynamic estimation challenge poses a significant obstacle to overcome in the trajectory-based approach.

Machine learning techniques have become increasingly popular for addressing the interaction problem in site simulation (Egli et al., 2022). By training on large datasets, machine learning algorithms can recognize patterns, learn from past simulations, and predict system behavior. This approach is particularly valuable in complex and dynamic environments where traditional analytical models may be limited. Through machine learning, simulation models can continuously improve and adapt, leading to enhanced accuracy and predictive capabilities.

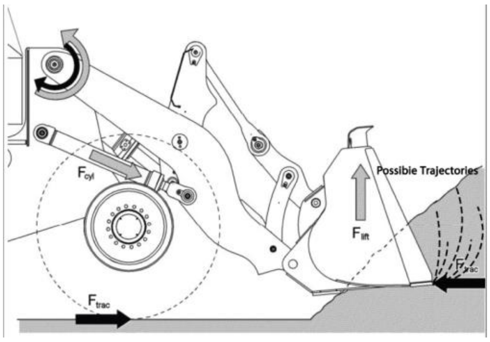

Figure 4: Trajectory-based approach - possible trajectories that can be taken through the excavation process. modified from [(Filla, 2005)].

During the moving task, the machine model exhibits a reduced level of complexity as compared to the model employed in the prior task. Nevertheless, several factors exist that could potentially contribute to increased system complexity. The impetus to minimize this complexity stems from the overarching goal of attaining a comprehensive view of the site simulation environment in this case study. Our findings suggest that a few key parameters, namely the road profile, power train, and axle load, have significant impacts on the energy management calculations during the moving task, Therefore, these parameters should be considered the primary components in the task's model design and subjected to thorough analysis.

The optimization problem faced by specialists in the construction, mining and quarries industries encompasses multiple dimensions and is evident both during the initial planning phase of opening a new site and in daily operations. The inherent limitations of humans make it challenging to effectively solve multidimensional problems, resulting in suboptimal solutions. However, these challenges highlight the need for alternative approaches.

Looking toward the future, it is anticipated that the number of dimensions involved in site optimization will increase further. For example, achieving zero emissions may require the use of battery electric machines, which necessitate more frequent and longer charging times compared to refueled equipment. Additionally, automation is expected to play a significant role, especially in sites with mixed traffic and partial automation, necessitating a different design approach (Frank, 2019; Wickberg et al., 2022).

5. Summary and Discussions

This research aimed to extract and map the simulation optimization requirements among quarries, construction, and mining sites. The study revealed that site design and management decisions are highly influenced by experiential knowledge, business objectives and regulatory constraints. These factors along with the complicated nature of the daily site operations put the site into a suboptimal state and this problem can be solved by simulation. Moreover, simulating complete sites presents its own set of challenges. The dynamic nature of site processes, coupled with the presence of diverse machinery, materials, and static and dynamic objects, introduces significant computational demands.

Different approaches were discussed with experts from the industry to recommend suitable methods to build and simulate sites and optimize the simulation. The study highlighted the importance of adaptable software that can accommodate the dynamic nature of sites, modular design approaches that allow for flexibility and customization, and the consideration of key parameters in the simulation process.

Overall, the research offered valuable insights for effective site simulation optimization. The next step will be to investigate the best machine learning approach to solve the complexity problem and compare that to the performance of numerical approaches.

Acknowledgment

This work is funded by the KK-Stiftelsen via the project (IndTech+) – Industrial Technology Graduate School, grant number 20200132 01 H, and by the Vinnova FFI project TRUST-SOS - TRUSTed Site Optimisation Solutions, grant number 2021-02551.

References

Bashir, S., Abbas, M., Saadatmand, M., Enoiu, E. P., Bohlin, M., & Lindberg, P. (2023, 2023//). Requirement or Not, That is the Question: A

Case from the Railway Industry. Requirements Engineering: Foundation for Software Quality, Cham.

Burdett, R., & Kozan, E. (2014). An integrated approach for earthwork allocation, sequencing and routing. *European Journal of Operational Research*, *238*, 741–759. https://doi.org/10.1016/j.ejor.2014.04.036

de Lima, R., Nobre Júnior, E., & Pinheiro Santos Fernandes, P. (2020). Optimization of Earthmoving Operations Planning: A Novel Approach Considering Interferences. *Journal of Engineering Project and Production Management*, *11*, 158-168. https://doi.org/10.2478/jeppm-2021-0016

Egli, P., Gaschen, D., Kerscher, S., Jud, D., & Hutter, M. (2022). Soil-Adaptive Excavation Using Reinforcement Learning. *IEEE Robotics and Automation Letters*, *7*(4), 9778-9785. https://doi.org/10.1109/LRA.2022.3189834

Fattouh, A. (2022, 9-11 Dec. 2022). An Integrated Simulation Framework for Construction Site Operations. 2022 IEEE 1st Industrial Electronics Society Annual On-Line Conference (ONCON),

Fattouh, A., Bohlin, M., & Sundmark, D. (2021, 23-26 April 2021). A Real-Time Optimization Model for Production Planning in Quarry Sites. 2021 IEEE 8th International Conference on Industrial Engineering and Applications (ICIEA),

Fernandes, P. G. P. S., Júnior, E. F. N., & Prata, B. d. A. (2022). Optimization of earthworks planning: a systematic mapping study. *Canadian Journal of Civil Engineering*, *49*(12), 1781-1795. https://doi.org/10.1139/cjce-2022-0185

Filla, R. (2005). *Operator and machine models for dynamic simulation of construction machinery* Institutionen för konstruktions-och produktionsteknik].

Frank, B., Kleinert, J., & Filla, R. (2018). Optimal control of wheel loader actuators in gravel applications. *Automation in Construction*, *91*, 1-14. https://doi.org/https://doi.org/10.1016/j.autcon.2018.03.005

Frank, M. (2019). *A Step Towards the Design of Collaborative Autonomous Machines - A Study on Construction and Mining Equipment*

Guo, K., & Zhang, L. (2022). Multi-objective optimization for improved project management: Current status and future directions. *Automation in Construction*, *139*. https://doi.org/10.1016/j.autcon.2022.104256

Hawarneh, A. A., Bendak, S., & Ghanim, F. (2021). Construction site layout planning problem: Past, present and future. *Expert Systems with Applications*, *168*. https://doi.org/10.1016/j.eswa.2020.114247

Hermann, M., Pentek, T., & Otto, B. (2016). *Design Principles for Industrie 4.0 Scenarios* 2016 49th Hawaii International Conference on System Sciences (HICSS),

Kaveh, A., & Vazirinia, Y. (2018). Construction Site Layout Planning Problem Using Metaheuristic Algorithms: A Comparative Study. *Iranian Journal of Science and Technology, Transactions of Civil Engineering*, *43*, 105-115.

Li, Y., Guzman, E., Tsiamoura, K., Schneider, F., & Bruegge, B. (2015). Automated Requirements Extraction for Scientific Software. *Procedia Computer Science*, *51*, 582-591. https://doi.org/https://doi.org/10.1016/j.procs.2015.05.326

Lim, A., Rodrigues, B., & Zhang, J. (2017). Tabu search embedded simulated annealing for the shortest route cut and fill problem. *Journal of the Operational Research Society*, *56*(7), 816-824. https://doi.org/10.1057/palgrave.jors.2601900

Montaser, A., Bakry, I., Alshibani, A., & Moselhi, O. (2012). Estimating productivity of earthmoving operations using spatial technologies1This paper is one of a selection of papers in this Special Issue on Construction Engineering and Management. *Canadian Journal of Civil Engineering*, *39*(9), 1072-1082. https://doi.org/10.1139/l2012-059

Optimization of earthworks planning a systematic mapping study. *Canadian Journal of Civil Engineering*.

Patton, M. Q. (1990). *Qualitative evaluation and research methods, 2nd ed*. Sage Publications, Inc.

Tsai, W. T., Zhibin, C., Xiao, W., Paul, R., Qian, H., & Xin, S. (2016). Modeling and Simulation in Service-Oriented Software Development. *Simulation*, *83*(1), 7-32. https://doi.org/10.1177/0037549707079221

Wickberg, P., Fattouh, A., Afshar, S., Sjöberg, J., & Bohlin, M. (2022, 27-29 Dec. 2022). Dynamic Maps Requirements for Autonomous Navigation on Construction Sites. 2022 5th International Conference on Communications, Signal Processing, and their Applications (ICCSPA),

Xu, M., Mei, Z., Luo, S., & Tan, Y. (2020). Optimization algorithms for construction site layout planning: a systematic literature review. *Engineering, Construction and Architectural Management*, *27*(8), 1913-1938. https://doi.org/10.1108/ecam-08-2019-0457