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# Performance analysis of simulation-based optimization of construction projects using High Performance Computing

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ABSTRACT

The complexity and uncertain nature of bridge construction projects require simulation for analyzing and planning these projects. On the other hand, optimization can be used to address the inverse relationship between the cost and time of a project and to find a proper trade-off between these two key elements. In addition, the large number of resources required in large-scale bridge construction projects results in a very large search space. Therefore, there is a need for using parallel computing to reduce the computational time of the simulation-based optimization problem. Another problem in this area is that most of the construction simulation tools need an integration platform to be combined with optimization techniques. To alleviate these limitations, an integrated simulation-based optimization framework is developed within one High Performance Computing (HPC) platform, and its performance is analyzed by carrying out a case study. A master-slave (or global) parallel Genetic Algorithm (GA) is used to decrease the computation time and to efficiently use the full capacity of the computer. In addition, sensitivity analysis is applied to identify the promising configuration for GA and the best number of cores used in parallel and to analyze the impact of GA parameters on the overall performance of the simulation-based optimization model. Using NSGA-II as the optimization algorithm resulted in better near-optimal solutions compared to those of fast-messy GA. Moreover, performing the proposed framework on multiple nodes using the cluster system led to 31% saving in the computation time on average. Furthermore, the GA was tuned using sensitivity analyses, which resulted in the selection of the best parameters of the GA.

## 1. Introduction

Highway infrastructures in North America are relatively old and their deterioration imposes delays on the global economy progress; therefore, there is a need for reconstructing many of the existing highways to ensure their future functionality. ASCE provides a comprehensive assessment of the conditions and needs of the infrastructure in the USA in *Infrastructure Report Card* using a simple A to F school report card format [1]. According to ASCE 2017 *Infrastructure Report Card*, bridges had $C+$ grade with minor improvement from 2009 to 2017. However, $C+$ is still very low and it indicates general signs of deterioration that require attention. According to this report, although the grade regarding the bridges' conditions did not change from 2013, the required cost to improve the condition had increased by 22% [1]. This shows the importance of the reconstruction work on existing bridges to enhance their condition and prevent extra cost imposed to the system due to aging.

These reconstruction or rehabilitation activities have a great impact on traffic flow, workforces, businesses and other community functions [2]. Therefore, decision makers need to trade off the reconstruction duration of the project with the reconstruction cost. To do so, the most near-optimum strategy that satisfies the time and budget along with all other project's constraints should be found considering that the duration and cost of a project have an inverse relationship. This means whenever the duration of a project is shortened, the cost of the project (i.e. the direct cost of labor, equipment, and material) will increase considerably. The time-cost trade-off problem is a classical construction management problem that has been addressed repeatedly. This crucial problem is solved, most of the time, by using optimization methods [3]. Genetic Algorithms (GAs) [4] are a widely-used optimization method in the field of construction management [5]. Because of the conflict between the time and cost in construction projects, they cannot be simply combined to form one objective function to reduce the complexity of optimization problems. Therefore, the time-cost trade-off analysis is categorized as a multi-objective optimization problem.

In addition, the values of the optimization parameters, such as the

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crossover rate and population size, directly affect the performance of the optimization algorithm. Therefore, finding the best configuration of the optimization algorithm and analyzing the impact of these parameters on the overall performance of the optimization are among the challenges that researchers are facing when working with optimization algorithms.

On the other hand, the duration and cost of the construction projects are traditionally assumed to be deterministic. However, construction projects are associated with many uncertainties. Some examples of these uncertainties are design changes in different phases of the project, inflation, execution mistakes of contractors, economic and social stresses, and climate changes to name a few [6]. Therefore, the time and cost of the construction projects usually follow probabilistic distributions that could be determined using historical data, which adds more complexity to the above-mentioned time-cost trade-off problems [3]. To deal with this complexity, stochastic simulation techniques are required to model the uncertainties associated with the construction projects [7]. Micro-CYCLONE [8], STROBOSCOPE [9], COOPS [10], INSIGHT [11], RESQUE [12], and COST [13] are some examples of stochastic simulation tools that are developed based on CYCLic Operation Network (CYCLONE) introduced by Halpin [14]. These tools are especially designed for modeling construction operations with different advantages, limitations, and capabilities.

The integration of simulation models with optimization methods has led to an advancement in the decision-making process. In this type of problems, the optimization objectives are usually minimizing construction projects' cost and time. The resources needed for construction projects are considered as the optimization decision variables, which have an impact on the optimization objectives. Thus, researchers have used simulation, combined with optimization techniques, to evaluate these objective functions [3]. However, this integration is not without some drawbacks. Although GAs are generally capable of finding near-optimal solutions in acceptable time, the run time will increase considerably as the problem becomes more complex. In addition, evaluating the objective functions through simulation will increase the runtime as a function of the number of performed replications and the complexity of the model. Thus, there is a need for applying High Performance Computing (HPC) using either clusters or parallel computing systems. It should be noted that common simulation tools used in construction are not compatible with the Linux environment, which is used in most of the HPC environments. In addition, none of the research works in the literature considered the sensitivity of the proposed models to the optimization parameters and the number of cores used in the parallel process for construction purposes. Thus, the impact of these parameters on the performance of the integrated simulation-based optimization models are left unknown.

Given the above problems, the main goal of this paper is to develop an integrated simulation-based optimization framework for construction projects within an HPC platform and analyze its performance by carrying out a case study. The specific objectives of this paper are: (1) integrating DES with GA multi-objective optimization to find the time-cost trade-off for construction projects using a simulation tool compatible with HPC; (2) tuning the optimization algorithm and finding the best number of cores used in parallel computing by performing sensitivity analysis; and (3) investigating the feasibility of the proposed framework through implementing a case study of a concrete bridge construction project.

## 2. Literature review

This section provides a literature review of several subjects related to this study as discussed in Section 1. The review commences with construction simulations with emphasis on two simulation methods commonly used to emulate construction projects. This is followed by the literature review of genetic algorithms, optimization, and simulation-based optimization approaches for construction projects. Finally, simulation-based optimization approaches using HPC are reviewed. This review shows the shortcomings in this area of research and supports the need for the method proposed in this paper.

### 2.1. Construction simulation

Simulation is a method of analyzing and planning construction projects, especially the ones with repetitive and cyclic nature. It helps managers to make appropriate decisions by providing a better understanding of the interdependencies among construction projects [7,15]. Examples of using simulation in construction include comparing the results of various construction methods, site planning, productivity measurement, planning and resource allocation, and risk analysis to name a few [6,16–18].

Monte-Carlo simulation and Discrete Event Simulation (DES) are two popular methods to simulate construction projects. Monte-Carlo simulation is based on assigning random distributions to the activities' durations based on the network diagram of activities of a project. It generates the cost and time of the project without considering the interaction between activities and resources, such as the queuing of trucks loaded by an excavator in the case of earthmoving operation. To alleviate this shortcoming, DES is used to consider the relationships between activities and resources and to model the behavior of a complex system by defining a sequence of events at the task level. Thus, DES can capture the interaction between the resources of the construction operations, which cannot be done using Monte-Carlo simulation. By using DES, an appropriate selection of resources can be determined by considering an acceptable level of details of the real system [19]. Events progress at discrete points in time by assigning fixed durations (i.e., deterministic) or probabilistic distributions (i.e., stochastic) to the activities' durations [19]. Also, replications are performed to investigate the associated risk with the model. To do so, the simulation model is run for many times (e.g., 1000 times), which results in different performance outcomes for each replication (e.g., time and cost). After running the required number of replications, the means of the simulation outcomes are calculated [20].

### 2.2. Genetic algorithms and applications in construction projects

Optimization problems can be mainly categorized as single objective or multi-objective optimization problems, where the former group has only one objective function and the latter one has more than one objective function. These objective functions are usually in conflict with each other in real-world engineering problems so that the improvement of one of them may lead to worsening the others. Therefore, multi-objective optimization offers the near-optimal set of solutions, which are called Pareto points or Pareto front, rather than a single near-optimal solution. In this set, there is no solution that dominates the others [21].

Among different optimization algorithms, Genetic Algorithm (GA) followed by Particle Swarm Optimization (PSO) are the most used ones in construction management as shown in Table 1. This is due to the capability of GA in solving complex multi-objective optimization problems while maintaining the simplicity of its computational steps. GAs mimic the process of natural selection in order to find proper solutions to optimization problems based on the ideas of the evolutionary theory [4]. PSO algorithm is an evolutionary computation technique, which is motivated by the behavior of bird flocks. Similar to GA, the PSO algorithm generates a population of random solutions called particles. However, unlike GA, each particle is also associated with a randomized velocity. Thus, particles fly around a multi-dimensional search space to find out optimal solutions [22,23]. Based on the literature, while both PSO and GA obtain high quality solutions, PSO finds slightly better optimal solutions compared to GA [24]. However, the number of computational steps for GA is lower than that of PSO, which is due to the communication between the particles after each generation [25].