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Framework for Selecting a Construction Scenario for Bridges Using Simulation-based Optimization

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Abstract: Planning and scheduling is a major step in the success of bridge construction projects and it demands a considerable amount of work due to the complexity of these projects. This paper presents a simulation-based optimization framework that can be used by project planners to plan bridge construction projects and to evaluate the various construction scenarios. A construction scenario consists of the construction method and the decision variables related to it. The framework consists of the following main modules: project information input, database, optimization engine, simulation engine, and reporting and visualization module. The optimization engine uses a fast messy Genetic Algorithm (fmGA) to minimize project cost and/or duration depending on the decision maker requirements. The fmGA considers several decision variables and constraints to produce several populations of solutions. The simulation engine uses discrete event simulation to model the construction processes of constructing a bridge. Simulation is used to find the duration and cost of each solution generated by the optimization engine. The visualization module integrates the output of the simulation engine with a 3D model of the structure to generate a 4D model. The 4D model is used for the visualization and analysis of bridge construction projects, which can help in resolving constructability and work zone planning issues.

1 Introduction

In complex projects, planners and project managers are faced with great challenges due to the huge number of decisions that have to be made. Such decisions if not well studied would have a significant negative impact on the project. Some of these decisions are related to the selection of the construction method, and the number of resources to perform a certain task. In addition, evaluating the impact of these decisions on meeting the project objectives is not a straightforward process. Examining all the possible solutions can be a very time consuming and costly process. Previous research proposed using the Analytic Hierarchy Process (AHP) (Youssef et al., 2005) and Fuzzy AHP (Pan, 2008) to select the appropriate construction method for bridge construction. However, the proposed methodologies are subjective since they were based on qualitative analysis. In addition, these models are restricted by the region where the surveys used to build those models were conducted. Furthermore, they ignore the uniqueness and constraints of each bridge construction project. Consequently, the following questions, pertaining to the management of bridge construction projects, are addressed: What construction method should be used? What is the optimal number of crews for a project? What is the optimal number of equipment for a project? How this selection is affected by the contracting method, and overtime policy? Therefore, there is a need for a new framework that is capable of selecting the near optimal construction method, and number of crews and equipment that will minimize project cost, duration or both. Moreover, this framework should take the contracting method, the casting yard, and the overtime policy into consideration while making the abovementioned decisions.

2 Literature Review

This section briefly introduces construction simulation, fast messy Genetic Algorithm, simulation-based optimization, and 4D modeling.

2.1 Construction Simulation

Simulation is a powerful tool that can be used to mimic the behaviour of real-world systems over time (Law and Kelton, 1991). Simulation can determine the output of a system based on the variations in the input to a system (Halpin and Riggs, 1992). Simulation in construction is used for planning and resource allocation, risk analysis, site planning and productivity measurement (AbouRizk et al., 1992; Wainer, 2009). The construction processes that have a repetitive and cyclic nature can be planned and analysed using simulation (Touran, 1990). Simulation is also used to compare the outcomes of different scenarios and alternative construction methods (Oloufa, 1993). Many examples of using simulation can be found in the literature such as earthmoving operations (McCahill and Bernold, 1993), selection of an earthmoving operations fleet (Marzouk and Moselhi, 2003), the construction process of fiber reinforced polymer bridge deck panels and partial-depth precast concrete decks (Hong and Hastak, 2007), the construction of bridge deck using cantilever carriage (Said et al., 2009), and the construction of pre-cast concrete box girder using the full-span launching gantry method (Mawlana et al., 2012). However, the previous work did not optimize the construction processes of bridges. Therefore, simulation must be integrated with an optimization technique in order to optimize the construction processes of bridges.

2.2 Fast Messy Genetic Algorithm

The fast messy Genetic Algorithm (fmGA) was developed by Goldberg et al. (1993) to overcome some of the problems faced while using the simple Genetic Algorithm and the messy Genetic Algorithm. The fmGA operates by iterating within two loops which are the outer and inner loops. This process is summarized in Figure 1. The fmGA starts from the outer loop by random initialization of the competitive template. Each outer loop, which is called an *era*, perform an inner loop. The inner loop consists of three phases namely the *initialization*, the *primordial*, and the *juxtapositional* phases. The *initialization* phase starts by generating an initial population of size *N* using the probabilistically complete initialization (PCI) technique. Each generated solution is evaluated to measure its fitness. The *primordial* phase uses thresholding selection and building block filtering to increase the proportion of the better solutions by filtering out the worse solutions. All filtered solutions are evaluated at this phase. This process is repeated until the *primordial* termination criterion is met. Finally, the *juxtapositional* phase applies thresholding selection, and two operations namely cut and splice, and mutation. All generated solutions are evaluated in this phase. This process is repeated until the *juxtapositional* termination criterion is met. The template of the new *era* is set to the best solution found at the end of the *juxtapositional* phase. The outer loop stops when the termination criterion is met. The fmGA has proven to be effective in optimizing decision making in construction operations (Feng and Wu, 2006; Cheng and Wu, 2009). However, it is difficult to formulate the objective functions of construction operations using closed form formula. Therefore, fmGA must be coupled with simulation in order to calculate the value of the objective functions.

2.3 Simulation-based Optimization

Obtaining optimal or near-optimal results using simulation requires performing a vast number of replications of experiments to try different input values or alternatives. Simulation-based optimization can be defined as the process of using a heuristic algorithm to guide the simulation analysis without the need to perform an exhaustive analysis of all the possible combinations of input variables (Carson and Maria, 1997). Combinations of simulation with optimization methods such as Particale Swarm (Zhang et al., 2006), Genetic Algorithm (Alberto et al., 2002), and Tabu Search (Glover et al., 1996) have been used to find near-optimal solutions. Marzouk et al. (2009) proposed a framework for optimizing bridge construction using launching girders; however, the proposed framework optimizes a single construction method. Therefore, a framework is needed to select the near-optimum construction scenario. Figure 2 shows a schematic of the integration of simulation and optimization. The process starts by generating candidate solutions by the optimization engine. These solutions are then sent to the simulation engine to be evaluated. Finally, the performance of each solution is reported back to the optimization engine.

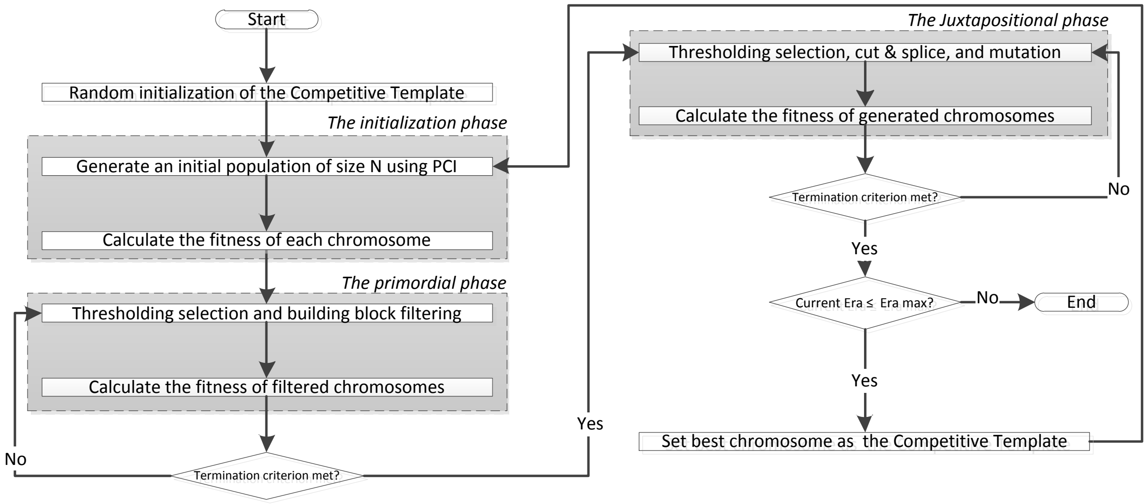

Figure 1: Flowchart of Fast Messy Genetic Algorithm

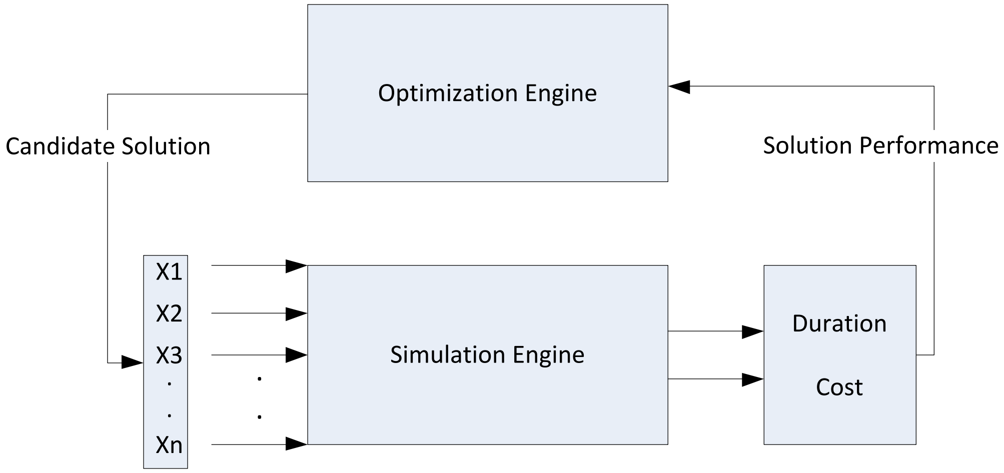

Figure 2: Integration of Optimization Engine and Simulation Engine

2.4 4D Modeling

4D modeling is one of the recent computer technologies that have emerged into the Architecture, Engineering and Construction (AEC) community. A 4D model can be defined as a 3D model linked to the construction schedule (Koo and Fischer, 2000). A 3D model is linked with the desired schedule through specialized software. Navisworks (Autodesk Incorporated, 2012) and ProjectWise Navigator (Bentley Systems Incorporated, 2012) are examples of such software that provide a collaborative environment to extend, review, and modify the 3D model. Prior research efforts have investigated the application of 4D modeling for resource management (Akinci et al., 2003), coordination of mechanical, electrical, plumbing, and fire protection systems (Khanzode et al., 2005), and constructability analysis in building projects (Ganah et al., 2005). In addition, 4D has been used for visualization and analysis of highway construction projects (Liapi, 2003; Hammad et al., 2012; O'Brien et al., 2012; Doriani et al., 2013). Visualization is used to facilitate the communication of project information to project stakeholders (Platt, 2007). The analysis is used to examine the constructability and safety issues. Moreover, time and space coordination can be checked to virtually eliminate workflow issues at the planning stage (Kwak et al., 2011).

3 Proposed Framework

A framework for planning, scheduling and optimizing bridge construction operations is proposed in this paper. This simulation-based optimization framework (Figure 3) can be used by decision makers to enhance and improve the current practice of decision making in bridge construction operations. The aim of the framework is to select a near-optimal construction scenario that satisfies predefined objectives. The construction scenario in this context consists of two main elements. The first element is the construction method that is used to construct a bridge. The second element is the decision variables related to that construction method. These decision variables are different from one construction method to another. The number of stressing crew, the number of equipment, the overtime policy, and the location of casting yard are examples of these decision variables.

The proposed framework consists of five modules which are: (1) project information module, (2) databases of construction cost, resources and methods module, (3) optimization engine module, (4) simulation engine module, and (5) reporting and visualization module. Each of these modules is described in detail in the following subsections.

3.1 Module 1: Project Information

Detailed planning, scheduling, and cost estimating of any construction project require: (1) a complete set of construction plans and specifications; (2) knowledge of the construction methods; (3) information of the cost, productivity, and availability of construction resources; and (4) information about the contract provisions.

3D CAD models are data rich and parametric digital representation of a structure (Samphaongoen, 2010). For that reason, they are used to generate the quantities of work to be performed and the type of materials to be used. This information is used later for estimating the cost of the project. Moreover, the number of structural elements is extracted from the 3D model to be used as input to the simulation models. In addition, 3D models can be used to determine the available space in which the construction work can take place.

Different contracts yield different project cost and duration. Three main types of contracts that are used in highway projects are: (1) cost plus time, (2) incentives/disincentives, and (3) lane rental. Cost assessment models are formulated to take contract type into consideration in order to be able to estimate the project cost.

3.2 Module 2: Databases of Construction Cost, Resources and Methods

A database is an entity that stores data digitally that enables easy access and update to its content. In this framework three databases are used which are cost database, labor and equipment database, and construction methods database.

Construction cost estimating requires a lot of data on structural elements, material, equipment, labor, and other related information. Cost Database stores all the data required for estimating the cost of constructing a bridge. The data needed for estimating the direct cost include labor, equipment, and material costs. The cost information includes indirect cost per day or per project, contingency and profit.

Labor and Equipment Database contains information about the construction labors and equipment. Each construction task requires a certain combination of labor and equipment. The labor’s information includes different trades and their productivity. The equipment information includes the necessary information for each type of equipment such as the equipment capacity, the minimum and maximum speed, and the cycle time.

Several construction methods pertaining to the construction of bridges are modeled using discrete event simulation. These simulation models are stored as templates in this database. Although each template is pre-modeled, it is modeled in a generic format which expands its applicability to any bridge built using that specific construction method.

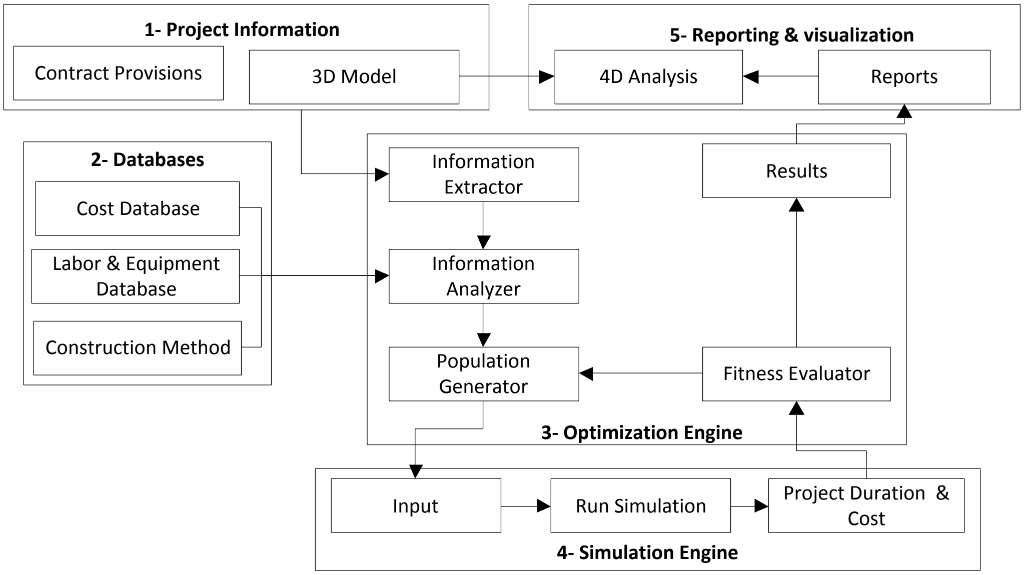

Figure 3: Selecting a Construction Scenario Framework

3.3 Module 3: Optimization Engine

Darwin optimization framework (Wu et al., 2011), which utilizes an fmGA, is used to solve the optimization problem. The algorithm searches for a near-optimum construction scenario that minimizes project total cost or duration. Therefore, the objective function of this algorithm can be single objective (i.e. cost or duration), or multi-objective (i.e. cost and duration).

As shown in Figure 3, this module starts by extracting the necessary information from the Project Information module. Information Extractor extracts the structural type of the bridge (e.g. box-girder) from the 3D model. In addition, Information Extractor extracts the number of the bridge elements (e.g. beams, columns) and their dimensions. This information is used later to calculate the quantity of work to be done. Indirect cost, productivity factors, type of contract, and overtime policy are extracted from the Project Information module.

Information Analyzer is used to analyze the information extracted from the 3D model. The Information Analyzer determines the appropriate construction methods applicable to the bridge. The applicable construction methods determine the type of resources to be used. In addition, Information Analyzer uses this information to get costs and other resources related data from the databases. Based on the characteristics of the construction method, several decision variables are identified to be used later on in the Population Generator. Each construction method has a set of decision variables that differs from another construction method. For example, constructing a full-span pre-cast concrete box girder bridge using launching gantry method has the following decision variables: (1) the number of delivery trucks, (2) the number of onsite trolleys, (3) the distance of the casting yard from the access of the construction site, (4) the number of rebar cage molds, (5) the number of inner molds, (6) the number of outer molds, (7) the number of preparation crews, (8) the number of stressing crews, (9) the number of steel crews, (10) the number of casting crews,(11) the curing method, (12) the overtime policy, (13) the yard storage capacity, and (14) the storage time of the span in the casting yard. The simulation-based optimization of this construction method is demonstrated (Mawlana and Hammad, 2013).

Next, Population Generator generates a set of sub-populations of size M where each sub-population (*j*) represents a specific construction method. Therefore, the number of sub-populations is equal to the number of applicable construction methods. Each sub-population goes through the steps of the fmGA as shown in Figure 4. The process starts by selecting the simulation template corresponding to the construction method *j*. Each sub-population consists of number of eras (k_{max}) where each *era* (*k*) consists of the three phases of the Inner Loop of the fmGA. At the beginning of the first era (k = 1), a competitive template is randomly initialized. Afterwards, an initial population of size *N* using the probabilistically complete initialization (PCI) technique is generated in the *initialization* phase. Simulation is used to evaluate the fitness of the generated solutions. In Figure 4, this is referred to as the Simulation Cycle. These generated solutions are used as the input to the simulation engine. The simulation engine modifies the simulation template based on value of decision variables of each solution as described in Module 4. The simulation engine reports the performance of each solution to the Fitness Evaluator. After all the solutions have been evaluated, thresholding selection and building block filtering in the *primordial* phase take place. All filtered solutions go through the Simulation Cycle to be evaluated. After the termination of this phase, thresholding selection, cut and splice, and mutation is applied in the *juxtapositional* phase. The template of the new *era* is set to the best solution found at the end of the *juxtapositional* phase. The sub-population is terminated when the current number of *era* (*k*) is larger than k_{max}. This process is repeated for all the other sub-populations.

Finally, the group of solutions that were accepted by the fitness function is either presented in a rank system in case of a single objective problem, or as a Pareto chart in case of multi-objective problem. The solution of interest for the decision maker is analyzed further as described in Module 5.

3.4 Module 4: Simulation Engine

Discrete event simulation is used to develop the simulation models for the construction operations of the bridges. Each simulation model (template) represents a specific construction method that's can be used to build bridges. The purpose of using simulation is to find the total duration and the total cost of the project based on the unique constraints inherent to the specific project (e.g., number of stressing crew, number of equipment, etc.). Therefore, the templates are modeled in a generic format to allow for an automatic modification of the constraints. This module is integrated with the Optimization Engine module to calculate the fitness of the generated solutions, also known as chromosomes or individuals, as shown in Figure 4. Each solution, which is represented by a chromosome, encapsulates the constraints of the project. These constraints, also called decision variables, are used to modify the simulation template. The outcome of the simulation for each solution is fed back to the Fitness Evaluator in the Optimization Engine module.

The simulation models are implemented in STROBOSCOPE, an acronym for STate- and ResOurce-Based Simulation of COnstruction ProcEsses, which was designed for simulating construction operations (Martínez, 1996). STROBOSCOPE can accommodate deterministic and stochastic modeling of construction operations. This allows for extensive sensitivity analysis to be carried out which in turn will reduce the risk associated with the project.

3.5 Module 5: Reporting and Visualization

The purpose of this module is to extract and produce detailed schedules, cost estimates, resource utilization plans, and other related information for the selected solution. In addition, the 4D model is generated for the selected solution by integrating the project schedule with the 3D mode, respectively. Leap Bridge and InRoads (Bentley Systems Incorporated, 2012) software are used to build the 3D models. On the other hand, Naviswork (Autodesk Incorporated, 2012) is used to integrate the 3D model with project schedule to generate the 4D model.

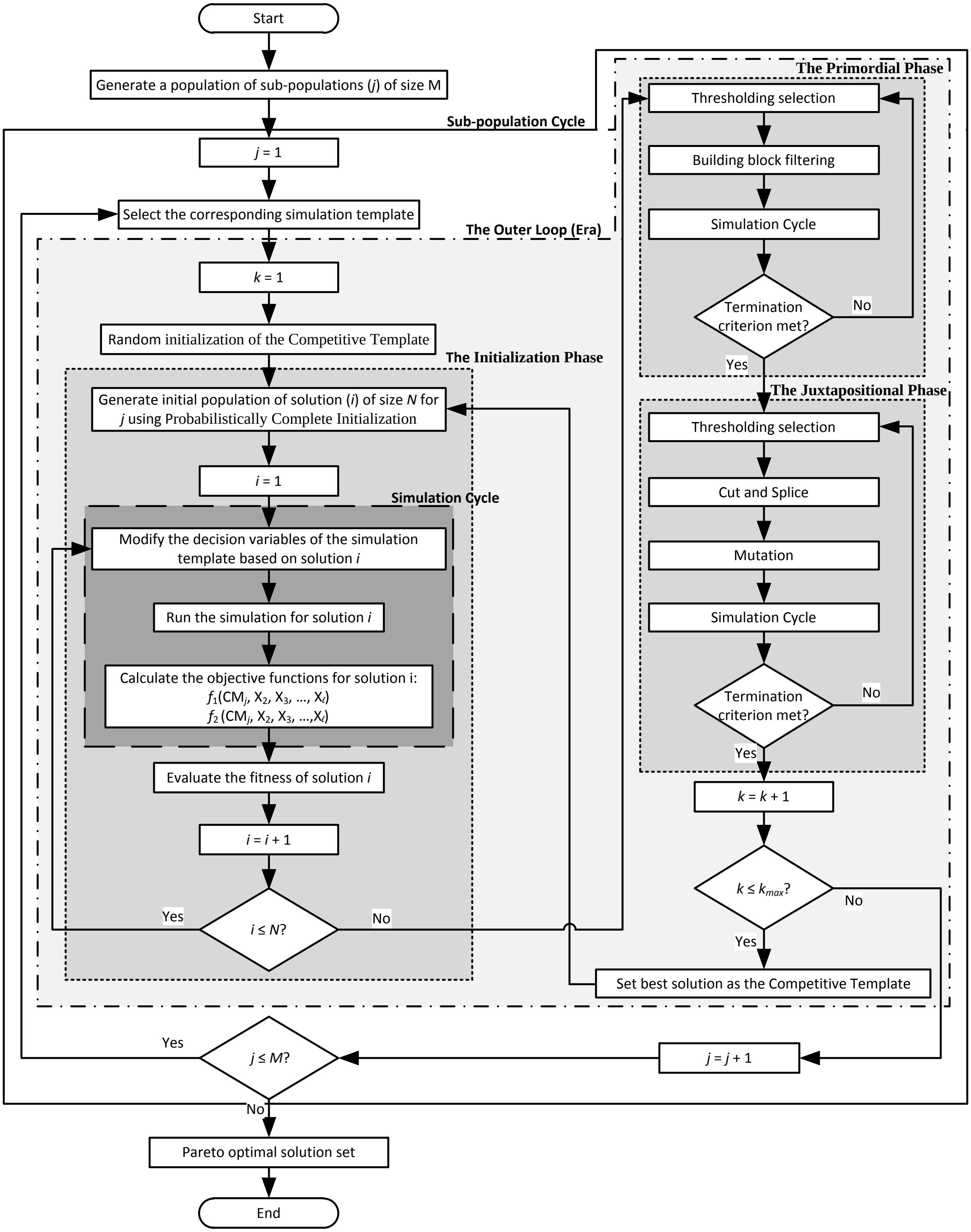

Figure 4: Simulation-based Optimization Model Flowchart

4 Conclusions and Future Work

The proposed framework is designed to support and enhance decision making in bridge construction projects. This framework will aid project stakeholders to select the near optimum construction scenario and to utilize resources more efficiently and therefore minimize project cost and duration. Furthermore, this study is expected to encourage stakeholders to benefit from the advancement in visualization and computing technology. Applying this framework is expected to have a noteworthy impact on: (1) selecting the most appropriate construction method; (2) selecting the number of resources to be used to increase productivity and meet project objectives; (3) reducing project risk; and (4) aiding in setting up the casting yard. Thus, it will provide significant benefits to contractors, construction management firms, and transportation agencies.

Future work of this research will include: (1) building the simulation models for constructing box girder concrete bridge using: (i) precast full-span using launching gantry; (ii) precast full-span using cranes; (iii) precast segmental using overhead gantry and lateral sliding for parallel bridges; (iv) precast segmental using under-slung trusses; and (v) precast segmental using scaffold support; and (2) conducting a survey to collect real data regarding the duration of construction tasks related to the above mentioned construction methods.

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