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Discrete-Event Simulation of Viaduct Construction Methods in Riyadh Metro

Khalid S. Al-Gahtani, Ibrahim A. Al-Sulaihi and Hassan T. Al-Assafi

College of Engineering, Civil Engineering Department, King Saud University, P.O. Box 800, Riyadh 11421, Saudi Arabia

Abstract: The Riyadh metro project is one of the current megaprojects that aim to improve the transit systems in Saudi Arabia. It consists of several metro lines with a total length of 176 km and 85 stations. The viaducts are considered as one of the main construction elements in the metro lines. Four methods for viaducts construction have been used in the Riyadh metro project: precast beam, full span launching method, cast on-site, and segment method (precast segment method and BCM (balanced cantilever method)). The viaducts work consumes a large portion of a project's time and cost. Furthermore, the competitive nature of the construction industry increases the need to improve the efficiency of construction performance. Accordingly, this paper takes the initial steps toward increasing the efficiency of viaduct construction methods through simulation. Simulation of construction processes provides a systematic tool that can be used for determining the resources, time, and cost of these processes. The simulation processes should focus on the main activities affecting this element's execution for viaducts construction, such as segment storage, handling, transporting, and installation. This study highlights the viaducts construction methods and develops general discrete-event simulation models for the most commonly used viaducts construction methods in the Riyadh metro using AnyLogic simulation software. The simulation models visualize and capture the interaction between the different activities and resources in a viaduct construction. Consequently, the construction drawbacks can be identified. Furthermore, the simulation model can be manipulated by adding assumptions to develop more efficient construction methods in terms of time and cost in such projects.

Key words: Simulation, viaduct, construction, AnyLogic, discrete event, Riyadh metro.

1. Introduction

The Riyadh metro project is one of the mega projects under construction for the rapid transit system in the capital of Saudi Arabia. It consists of 6 metro lines which include 85 stations with a total length of 176 km. The project will minimize the need for using cars and reduce car trips, the fuel usage for cars and, therefore, reduce air pollution. The viaduct is one of the main elements in the construction of bridges used in the metro networks and represents an important percentage of the total work in the project. Bridge and rapid transit projects involve fewer crew and activities than building projects. However, the complexity of bridges and transit projects is similar and, in some cases, more complex than the building projects due to the complexity of the management process and the highly competitive environment in this kind of project [1, 2]. In addition, bridge construction includes complex configurations that make the implementation process prone to errors [3]. Accordingly, applying advanced techniques such as innovative information technology approaches for planning this kind of project will help decision-makers make more informed decisions [2]. Developing more realistic plans for construction projects is considered one of the main criteria for success in project performance [4].

The increasing development of information technology tools has enhanced the use of these tools in the construction field. An example of these technologies is using simulation techniques at the planning phase in construction to improve the efficiency and performance of construction processes.

Corresponding author: Khalid S. Al-Gahtani, associate professor, research fields: construction engineering and management.

Construction simulation can be defined as the science of experimenting with construction systems through computer-based tools to understand their essential behavior [5]. In addition, simulation can determine the workforce, equipment, and time required to achieve the different tasks in the project. Different simulation approaches have been used to simulate the construction processes, such as DES (discrete event simulation), ABM (agent-based modeling), and system dynamics simulation. DES ranks the most widely used in the construction field compared with the other simulation techniques [6].

In segmental bridge construction, simulation can play a role in helping to forecast construction processes when using prefabrication and site assembling. The need for simulation in bridge construction comes as size, weight, and transport need for bridge segments are realized as the main factors affecting the construction. It engenders more contextual factors such as handling those factors and the required resources' type and availability. Hence, simulating such a process can aid the improvement and assessment of a bridge construction scenario. In addition, due to the complexity in bridge construction projects, especially inside crowded cities, critical issues of storage area, construction duration, and resources needed can be optimized using simulation. Due to the many advantages of simulation, this study aims mainly to increase the efficiency of viaduct construction approaches in the Riyadh metro through simulation. Increasing the efficiency will help reduce the time, resources, and cost required for such projects. The detailed objectives include: highlighting the several viaduct construction approaches in the Riyadh metro and introducing models for simulating the viaduct construction methods used in the Riyadh metro project. The simulation plan includes manipulating the simulation models and adding some assumptions to develop new construction models that enhance the efficiency of viaduct construction approaches.

2. Background

In recent years, the establishment of megaprojects has been growing continuously due to the development of the global economy. This project's planning, design, and execution are very complicated and involve a complex construction environment [7]. These make it hard for the traditional construction approach to respond to this complicated environment [8]. Therefore, simulation has become a favored tool for modeling complex systems [9].

Construction projects consist of a set of activities that are linked to each other in a logical sequence [4]. This sequence of activities is recognized as a project's activity cycle, which could be opened or closed cycle. The construction of projects requires concerted efforts for storing, transporting, assembling, placing building materials, and installing prefabricated or precast units in the site using specific technology for construction [10]. Six main steps should be performed, representing the framework for applying a simulation system to simulate the project activities [2]. The first step is developing a model for construction processes that should illustrate the start-end times of all activities. The second step is developing a temporary platform for considering the constraints of the proposed model. The next step is assigning the resources required for each activity. The step after that is validating the developed model to check that there is no conflict between the activities and the construction working area (if it fails, go back to the previous steps). The fifth step is validating that there is no collision between plant and equipment. The final step is a generation of the results [2].

Several simulation software for construction processes has been developed in the last three decades, such as CYCLONE (Cyclic Operations Network), DISCO (Dynamic Interface for Simulation of Construction Operation), Micro-CYCLONE, STROBOSCOPE (State & Resource-Based Simulation of Construction Processes), and Symphony [11]. One of the most recent simulation software is

AnyLogic, which uses different types of simulation modeling, including discrete event, agent-based, and system dynamic [6].

The failures that can be faced in bridge construction can be dramatic. Avoiding those failures is based on the effective planning of such construction activities, and the planning can be enhanced when a simulation model is built to assess the construction activity. Many failures in construction can be avoided if we have had the chance to try our methods and approach in specific scenarios. Indeed, this is a powerful tool to avoid high risks when planning a project and resort to a proven construction plan built into a model and simulated. In addition, it helps in reducing costs, enhancing quality, increasing project delivery, and accelerating schedules [5]. The simulation approach enables the planners to experiment with various scenarios from the beginning to the end of the project without setting foot on site.

3. Viaducts Construction Methods

In bridge construction, there are several execution methods for viaducts. In most cases, the viaducts are prefabricated in specialized plants and then transported for installation at the construction site. Using prefabricated viaducts holds many benefits. It first ensures the higher used concrete quality and reduces the associated cost of producing these elements due to optimizing and standardizing manufacturing processes. The construction time is also reduced by reducing site congestion and safety [12]. In the Riyadh metro project, precast concrete is used in most construction methods. A precast yard is dedicated to casting, curing, and storing the concrete spans and segments.

The viaduct system in Riyadh metro is supported via different foundation settings to support loads transferred to pad footing and pile groups. It has been accounted that the design for the pier was executed in 4 categories based on height and loads applied, including the gantry and equipment used to construct the bridges. The viaduct bridges are designed for spans 28, 32, 36, and 40 m. The design faced a critical traffic spot where the bridge intersects with a major highway; therefore, special case spans were introduced, e.g., 64, 72, and 96 m. Four main construction methods have been used in the Riyadh metro. The following subsections will clarify these methods briefly.

3.1 Full Span Launching Method (Long Span) (Span by Span)

The full span launching method is the quickest viaduct construction method. It is also the most automated method and least disrupting the surrounding traffic. The viaducts units are pre-casted in the construction yard and moved to the designated location through rails. After that, the viaducts are installed by a special crane. When the transferred viaduct reaches the installation site, a gantry structure lifts the beam from the conveyor and places the beam between 2 piers, as shown in Fig. 1. This method is suitable for straight streets and can also be used for some curves. It has minimum affection for traffic, but it requires a plot of land and construction alignment. The risk associated with this method is the delay that can be caused due to the diverging of utilities.

3.2 PCB (Precast Beam Method)

Precast beams are usually manufactured using molds at a central plant and then transported to the execution site to be used in the viaducts works. Precast elements have many advantages, including better quality control, shorter time, and being more environmental-friendly [13].

Despite these advantages, the precast elements need proficient planning and management to overcome the difficulties of transporting and installing these heavy and bulky elements.

The PCB is suitable for straight alignments and some large radius curves. This method is slower than the full span method and causes more traffic on the

Fig. 1 Full span lunching method.

Fig. 2 PCB.

construction site. This method required a box girder pre-casted in the yards, transported by trucks to the construction area, and lifted into place using cranes. Fig. 2 illustrates this method.

3.3 Segment Method

The PSM (precast segmental method) is one of the most common methods used worldwide in many projects. It handles each span structure in segments that are cast in a precast yard and then sent to the construction site for assembly. Segmental construction can be defined as a method of construction in which primary load-supporting members are composed of individual members called segments post-tensioned together [14]. The Riyadh metro project selected this method at the planning stage because it can help reduce the laborers, improve quality control, reduce the duration for construction activities, and improve material optimization. This method includes the precast segment method and the BCM (balanced cantilever method).

3.3.1 PSM

The PSM method utilizes what is known as the launching girder, stepping girder, or gantry. This gantry has two support legs and two crossing beams in between, and it is used to lift and assemble segments of the bridge being constructed [13]. The gantry stands balanced on those two crossing beams and uses the legs when it has to move to the next pier. In that case, the gantry moves its structure ahead to the next pier, places the front support leg, and then moves up the crossing beams to the following locations. The gantry has a lifting platform that helps lift all the segments and hold them stable at the level on which the span is constructed (Fig. 3). After lifting all segments, the assembly process takes place, including post-tension rods, gluing, and post-tensioning. Once this is over, the gantry is ready to move ahead to assemble the next span.

3.3.2 BCM

Using the term balanced cantilever construction, we describe a phased construction of a bridge superstructure. The BCM is an assembly method in which the viaduct segments are erected sequentially at the tip of the superstructure [15]. It uses another method of lifting viaduct segments comparing the gantry structure used in the PSM method for lifting and handling concrete segments. To illustrate, the

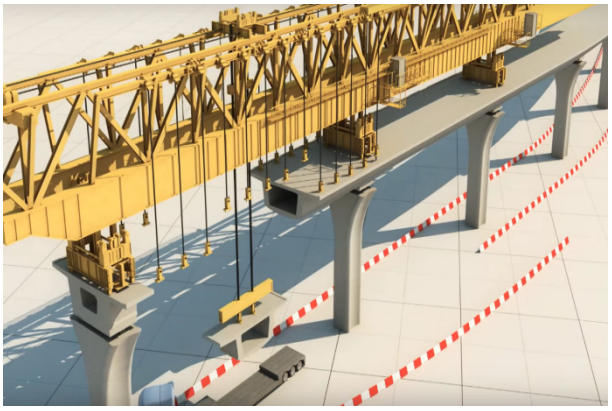

Fig. 3 PSM.

BCM uses two mobile cranes known as lifting frames that start adjacently at the start of the construction atop the first pier. Then they move in the opposite way to the edges lifting segments from ground level sequentially. After each lifting, the same assembly process for PSM occurs for each segment, including post-tension rods, gluing, and post-tensioning. Therefore, the BCM counterweighs the bridge's pier being constructed by concurrently erecting a concrete segment on both sides of the bridge [15]. The construction starts from the piers cantilevering out to both sides. Each phase is tied to the past ones by post-tensioning tendons, incorporated into the permanent structure so that each phase serves as a construction base for the following one [16].

3.4 CIP (Cast-In-Place)

This method is usually used if none of the three previous methods is appropriate. The span viaduct can be CIP rather than the precast solution in this instance. This method is generally more time-consuming and resource-dependent and causes traffic disruptions. However, it is a quick way to overcome the other methods' obstacles.

4. Selecting Viaduct Construction Method

Selecting the bridge construction methods in the Riyadh metro project was based on each method's advantages. Since the project has several bridges that go through various parts of the city, the bridges face various intersections solutions. Thus, each case has its priorities that restrict or limit some methods of construction, which call for an alternative method. For instance, the BCM method is mainly utilized at intersections with highways that complicate the construction of an intersecting bridge. It needs minor traffic control at low traffic hours to transport the concrete segments at working hours. On the other hand, the CIP method is usually used when conjunctions of bridges need special handling. In those cases, the formwork is used to cast concrete on-site. Precast for those segments would consider intricate dimensions, multiple elements to be conjoined, and difficult installation. Thus to avoid all previous situations, on-site CIP is preferred. The PCB method was used in a specified segment of the yellow line in the Riyadh metro. This section is characterized by its length (around 7 km), straightness, and ample road space. This characterization allowed for considering this segment for the PCB in which whole beams are precast on-site and shipped on top of the bridge one by one through a mobile crane. It allowed for the rapid construction of the bridge with minimal obstruction to traffic.

One of the other construction methods used in the Riyadh metro is the full span launching method. This method is suitable for street alignments, and some curves are possible too. It is best used at such roads where a mobile crane transports bridge spans from a yard located at the begging of a metro line. Each mobile crane trip ends precisely at the previously installed span. It has minimum affection for traffic, but it requires a plot of land along the construction alignment. In addition to previous methods, the segmental method is heavily used in the Riyadh metro project since a major part of the metro bridges are located on roads and run on the island. PSM is used in the small curves, and long spans and road access are less favorable. Consequently, the main non-cost factors that affect the selection of viaduct construction methods include: the length of span, the radius of curves, and the impact on traffic. Table 1 compares viaduct construction methods used in Riyadh metro based on these factors.

Table 1 Comparison between the viaduct construction methods.

Viaduct construction method		Span length	Curves radius	Impact on traffic
Full span launching		short	very large	low
PCB		short	large	high
Segment method	PSM	long	small	moderate
	BCM	very long	small	moderate
CIP		very short	small	very high

5. Simulation Models

Simulation has increasingly used the tool in the construction field to improve the performance of construction processes. Simulation modeling includes developing a model that imitates real-world operations over time [17]. Discrete-event simulation is a powerful method to simulate the system behavior in the real world through modeling repetitive processes by considering the stochastic duration and resources impact for the model activates [10]. This method is more commonly used in many fields [9]. AnyLogic is a simulation software that can be used for many industries, including manufacturing, construction, healthcare, mining, etc. This software deals with three methodologies to build the simulation model: discrete event modeling, ABM, and system dynamics. AnyLogic architecture consists of a Windows platform and Java platform [18]. Windows platform includes a code generator and graphical model editor. The model runs on the Java platform via a text-based protocol.

The segment method is one of the most commonly used methods for constructing the viaducts in the Riyadh metro. This method consists of two methods which are PSM and BCM, as discussed in section 3. This section introduces the simulation models for these two methods. The simulation models developed in this section depend on these methods' main general activates.

The construction processes of the balanced cantilever bridge were monitored and recorded to build a simulation model using AnyLogic in which the resources needed can be optimized according to various scenarios. The processes were happening in a sequence in which each process was symbolized in the respective simulation object considering the constraints that govern each construction process, e.g., logistics, resources, and equipment. The model assumes the simulation of the process since the arrival of each concrete segment at the right location under the lifting crane that lifts the segments and holds them till assembly completes. The simulated processes are summarized in Fig. 4.

Building a discrete event model for BCM (shown in Fig. 5) can be summarized in the following processes:

(1) Define the agent, i.e., the concrete segment entering the system and setting the arrival rate.

(2) Build two separate models that represent the construction activities at each side of a balanced cantilever bridge. Both models generate the same agents.

(3) Represent processes, or services, on the model based on the logical sequencing considering each process property, e.g., arrival rate, queue capacity, duration, link to resources, and delay.

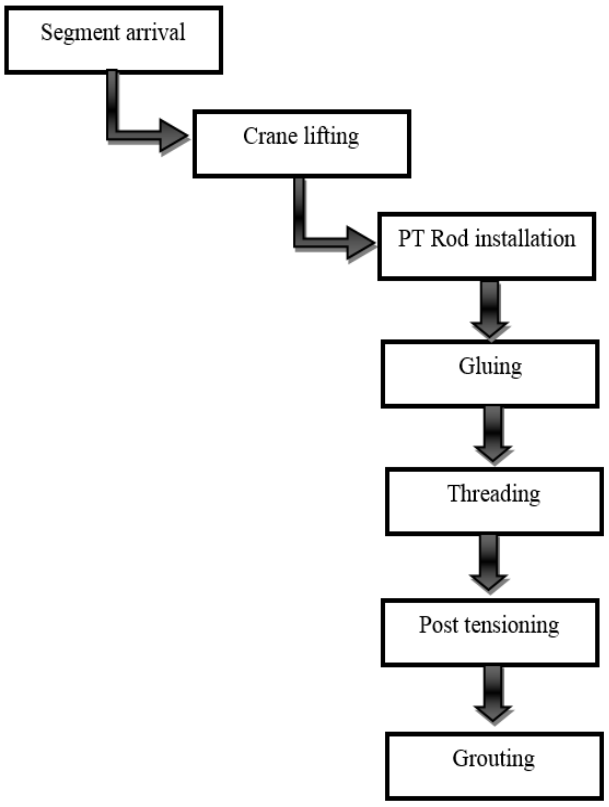

Fig. 4 The main construction processes in BCM.

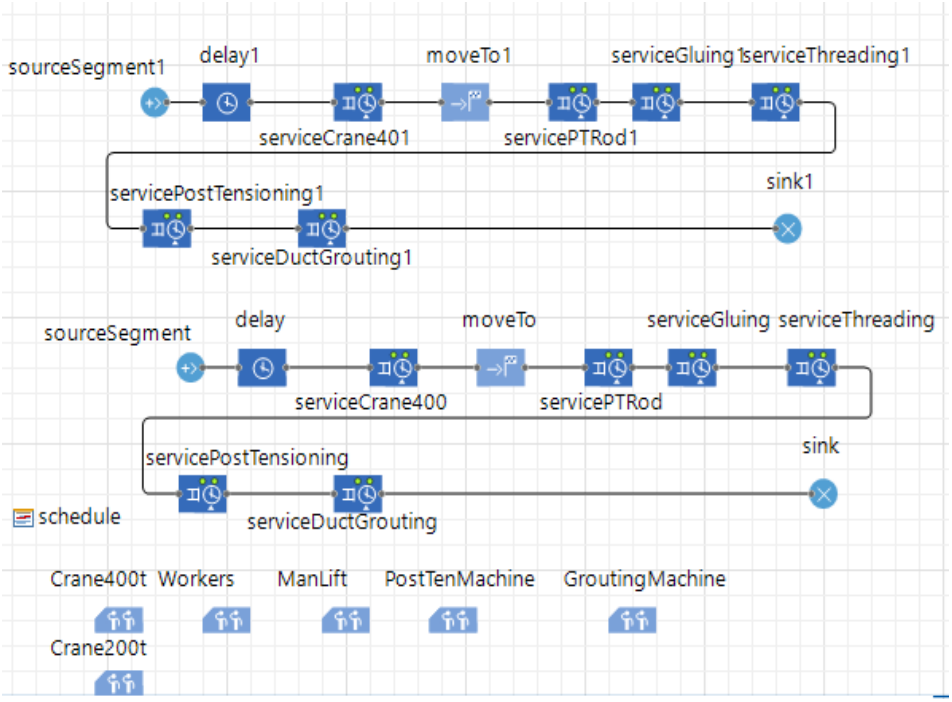

Fig. 5 DES model for BCM using AnyLogic.

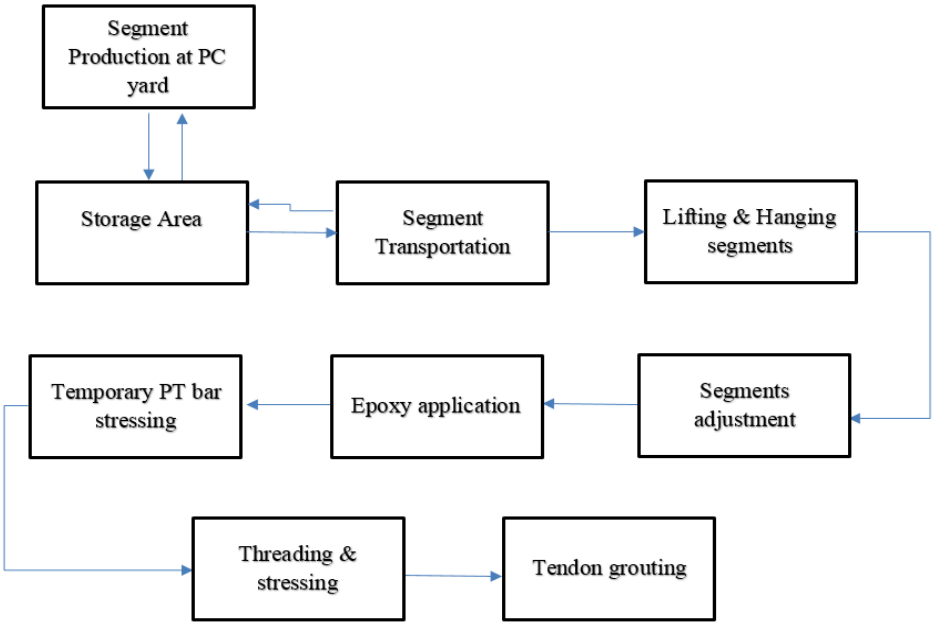

Fig. 6 The main construction processes in PSM.

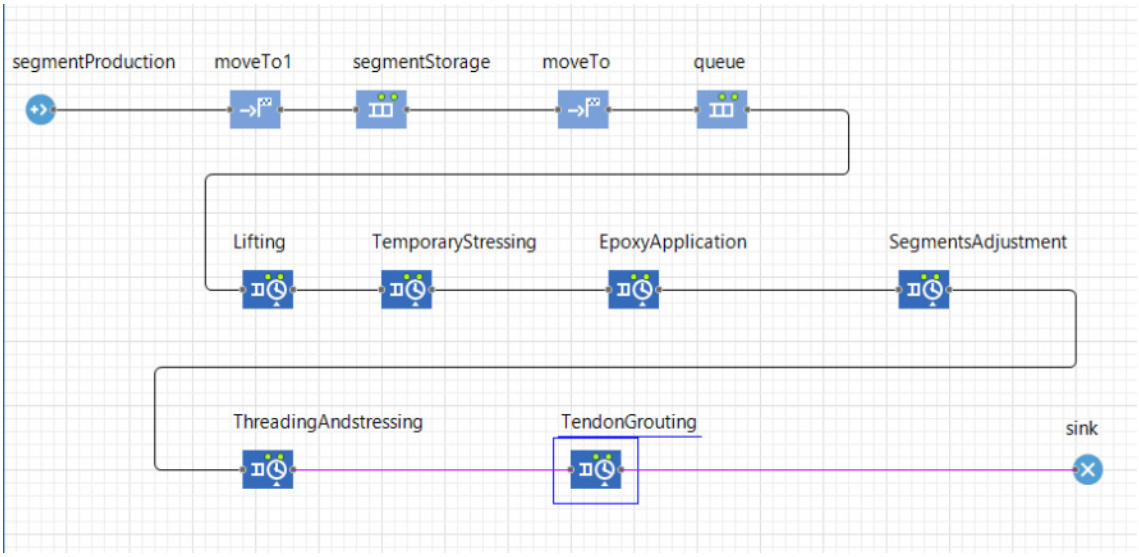

Fig. 7 DES model for PSM using AnyLogic.

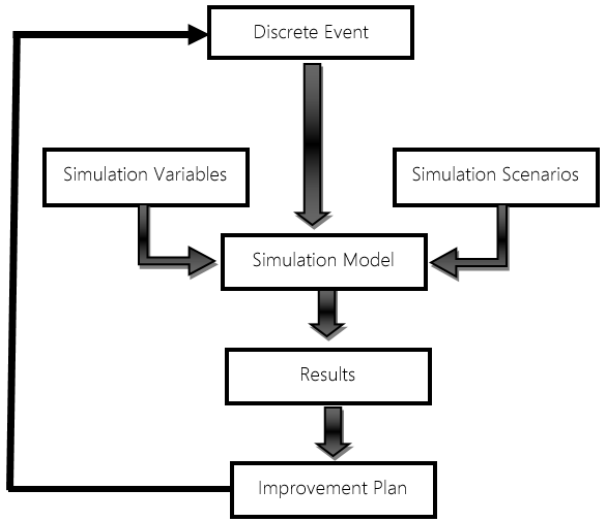

Fig. 8 Improvement plan processes.

(4) Establish the resource pools that enable the model to optimize resources according to the various utilization scenarios of those resources. Each pool can be linked to a model process that requires this type of resource to perform a particular service.

(5) Establish a utilization indicator for a selected resource pool.

The model itself considers the time each segment waits for a mobile crane to take a position and be ready to start the process. A delay block represents this on the model. The simulation model highlights the availability of the resources in this stage by establishing a link to the respective pool of resources, the mobile crane in this case. This pool of resources is restricted to the lifting process in this study at the two lifting sides of a balanced cantilever bridge; however, the more the service is requested, the more optimized use of resources can be achieved through the simulation of this process. Similarly, the processes that follow in order are inserted.

The simulation is now entering the agents and the concrete segments by running the model. Then, it simulates the execution of all the following services that happen to agents. Along with this simulation, the resources assumed for a specific scenario are being under demand, and the utilization indicator shows the fluctuations in this indicator accordingly. Also, the model highlights the duration it takes to perform a full cycle of the installation. Similarly, Figs. 6 and 7 show the main processes and simulation model for PSM.

6. Improvement Plan

After developing the discrete event model and the simulation model via simulation software, as discussed in section 5, these models can be manipulated by changing/adding some new assumptions to develop new construction scenarios as shown in Fig. 8. The factors that can be changed to develop new scenarios can be recognized as the simulation variables, including resources, store

locations, construction plan, supply chain, and many other factors that could affect the simulation results. Each scenario will be simulated to identify the impact on the time and cost. The improvement plan that includes the best scenario will be identified based on the simulation results. Accordingly, the efficiency of the construction process can be increased in the studied project and for similar projects.

7. Conclusion

DES implemented in an AnyLogic simulation environment is a powerful approach to describe the behavior of the systems in the real world. AnyLogic software is a very flexible tool that depends on the Java programming environment. This study tested to use this tool to improve the construction performance in viaduct works in the Riyadh metro. This test was achieved by highlighting the different methods used in building viaducts and developing general initial discrete event models using AnyLogic software. The results highlighted the ability to develop many other scenarios for the construction process. AnyLogic software can test these scenarios to identify the best scenario regarding time, cost, resources, and many other constraints. Accordingly, the efficiency of construction performance can be improved in such projects. Future research work can increase detail in the simulation process to cover all construction methods and relevant processes.

Data Availability

Different research papers and journals were used to produce this paper using common academic databases and search engines. Therefore, raw data supporting the findings of this paper will be available by the corresponding author on request.

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Conflicts of Interests

No conflicts of interest exist. Submitting author is responsible for the co-author's interests.

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