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Integrated BIM-based simulation for automated time-space conflict management in construction projects

Mohammad Saleh Dashti [a], Mohammad RezaZadeh [a], Mostafa Khanzadi [a], Hosein Taghaddos [b,*]

[a] School of Civil Engineering, Iran University of Science and Technology, Narmak, P.O. Box 16846-13114, Tehran, Iran
[b] School of Civil Engineering, College of Engineering, University of Tehran, P.O. Box 14395-477, Tehran, Iran

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ABSTRACT

The time-space conflicts may have severe negative impacts on the productivity and safety level in a construction site. However, little attention is paid to propose an automated, integrated system for managing potential time-space conflicts, considering the site space system's dynamic nature. This study contributes to the body of knowledge by proposing a novel integrated approach to manage time-space conflicts automatically. The proposed hybrid approach is based on Discrete Event Simulation (DES), Building Information Modeling (BIM), and Rapidly-exploring Random Tree (RRT) path planning. All types of time-space conflicts during the entire project timeline are automatically detected, evaluated, and resolved based on predefined if-then rules. The proposed approach is applied successfully in a real case study to estimate the project duration considering site space limitations. The results indicate that the proposed system can considerably prevent the negative impacts of time-space conflicts, particularly in congested construction sites.

1. Introduction

Construction projects affect daily lives as they provide all physical spaces and systems for home, work, and travel [1]. On-time completion is a crucial success factor in managing and evaluating the performance of a construction project [2,3]. Thus, effective scheduling is vital to plan and control various processes and time-oriented events in a construction project [1]. Several scheduling techniques are developed in the last decades, including bar charts, Gantt charts, network-based methods such as the Critical Path Method (CPM), and simulation-based scheduling techniques [4–6].

Resources are included in the scheduling of construction projects to represent their actual conditions better [7]. Space is also a constrained resource in construction projects. The total available site space is limitedly shared among the required spaces of the building elements under construction, temporary facilities, laborers, materials, and machinery [8]. However, space is usually neglected in planning construction activities. The traditional network-based scheduling techniques, such as those based on the CPM, only consider the activities' temporal interferences. Creating construction schedules considering space availability is challenging due to the complexity of modeling spatiotemporal relationships among activities. This phenomenon contributes to the occurrence of time-space conflicts [9].

In space management literature, a time-space conflict is faced when the required workspaces of two activities, partially or entirely performing concurrently, interfere. As a general definition, a time-space conflict occurs when two or more types of site spaces, such as the required spaces of the activities, temporary facilities, or machinery, interface with each other in the same period. The negative impacts of time-space conflicts (i.e., loss of productivity, safety hazards, congestion, disputes and quarrels among working crews, access blockage, poor quality of execution, reworks, and delays) are widely mentioned in the literature [8,10–15].

Time-space conflict management in construction projects deals with identifying the time-space conflicts in the entire project duration, evaluating the detected conflicts, and consequently resolving them to prevent their negative impacts [8,10–12,16–18]. Some other expressions such as "time-space analysis", "schedule-workspace management", and "workspace planning" are also used by the previous researchers to describe this process [19,20]. Time-space conflicts in construction sites have three unique features, which challenge their management, as follows: 1) Unlike the other construction resources, which change only

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* Corresponding author.
E-mail addresses: saleh_dashti@civileng.iust.ac.ir (M.S. Dashti), rezazadehmhd@gmail.com (M. RezaZadeh), khanzadi@iust.ac.ir (M. Khanzadi), htaghaddos@ut.ac.ir (H. Taghaddos).

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through the project timeline, space requirements change in four dimensions of x, y, z, and time; 2) They occur temporarily during the project timeline in some specific periods; 3) They occur in different forms due to the diverse types of the space requirements in a site; 4) The diverse forms of time-space conflicts create different problems [21]. Due to such a complex dynamic nature, performing manual time-space planning, particularly in congested construction sites, is challenging even for experienced site engineers. Therefore, an integrated approach that automatically manages all the activities' interfaces (i.e., considering temporal and spatial aspects) is essential in construction projects. Such an efficient site-space management system can improve constructability, reduce waiting and stoppage periods, enhance productivity, increase site safety, decrease conflicts among the workers, prevent costly temporary facilities, reduce reworks, and better protect finished works. Consequently, the mentioned advantages lead to time and cost savings and improved construction quality [11,14,16,22–26].

Several research studies are performed in the area of time-space planning. However, little attention is paid to propose an automated system for managing possible time-space conflicts considering the site space system's dynamic nature. This study presents an integrated framework to detect, analyze, and resolve all the potential time-space conflicts during construction projects by employing BIM and simulation modeling. The proposed system considers the temporal conflicts among all groups of site spaces (e.g., building elements, workspaces, and mobile machinery) in the process-level activities by respecting the spatial constraints.

The rest of the paper includes the following sections. First, a comprehensive literature review of time-space management and the existing research gaps are presented. Then the methodology and the framework of the proposed BIM-based simulation approach are explained in-depth. Afterward, a case study for implementing the proposed method is provided. Once the implementation process is illustrated in-depth, the obtained results are discussed, and conclusions are drawn. Finally, the contributions and limitations of the proposed approach are provided.

2. Literature review

Construction sites have a dynamic nature that is primarily unstable and under change [27]. Therefore, space availability and requirements during the progress of the construction activities are continuously changing. This phenomenon can be due to the construction of the permanent building elements, changes in the temporary facilities' location, and mobile machinery movements. As the site space is limitedly shared between the site objects, some interactions exist among the space requirement changes. This fact contributes to a complicated dynamic space system in construction sites. However, the increasing pressure for shorter delivery schedules makes the contractors increase the activities' resources or execute them simultaneously. Both of these strategies increase the demand for space per time unit, leading to time-space conflicts [21]. Time-space conflicts occur when two activities, executed simultaneously, share a part of the construction site space as their workspace [12]. Time-space conflict management includes detecting possible time-space conflicts and making the best decision for responding to the detected conflicts.

Different approaches are used for detecting and resolving conflicts in time-space management studies. Among the most relevant for this purpose, Thabet and Beliveau [14] developed a simple framework for quantifying workspace demand and availability in multistory buildings. Akinci et al. [21,25,28] proposed a 4D-based framework in which workspace conflicts are automatically detected, categorized, and prioritized. A user is required to define the resolution strategy. Guo [16] introduced a system for identifying workspace conflicts by integrating CAD with a scheduling software application. As conflicts are detected, the project planner must decide and manually implement some resolution strategies considering a series of criteria for analyzing conflicts. Mallasi [10] developed a framework for analyzing and quantifying construction workspace congestion. An add-on to AutoCad is also designed for visualizing workspace congestion in a 4D environment. Winch and North [29] presented a 2D CAD-based decision support system that helps planners in construction space scheduling. Zhang et al. [30] proposed a cell-based simulation approach for detecting time-space conflicts in construction sites. Chua et al. [23] developed a 4D computer-aided design method for quantifying spatiotemporal congestion in construction sites. Bansal [8] proposed a 4D Geographic Information System (GIS) for construction site space topology and geospatial analysis.

Some research studies have proposed mathematical models for time-space planning. For instance, Lucko et al. [31] proposed a mathematical approach based on singularity functions for avoiding tempo-spatial conflicts in two-dimensional floor plane areas. The proposed system minimizes the total project duration by altering the start time of activities. Roofigari-Esfahan and Razavi [17] presented a mathematical framework to optimize linear construction projects' duration besides minimizing their congestions. They introduced the concept of time-space float for taking into account the Spatio-temporal constraints of activities. Isaac et al. [32] employed a network-based scheduling method and singularity functions for spatial scheduling and work-path modeling in construction sites. Tao et al. [33] studied repetitive project scheduling to achieve minimum resource reallocation and congestion. They proposed a multi-objective mixed-integer programming model to minimize repetitive construction projects' time, cost, and congestion. Su et al. [34] presented a research study in which a multi-dimensional mathematic model is developed to plan construction projects regarding space requirements. However, the implementation of the mathematical approaches is limited to research purposes as they demand a high volume of calculations. Many of these approaches cannot be connected to the actual dynamic nature of construction sites. They usually concentrate on only a tiny part of a given construction project [19].

Several researchers have used BIM-based approaches for time-space planning. Among the most relevant studies, Zhang and Hu [35,36] introduced a 4D-BIM framework for conflict management in construction projects. This system detects spatiotemporal conflicts using hierarchical bounding boxes. Su and Cai [37] presented a framework for modeling workspaces according to the dynamic site space requirements. Moon et al. [12] proposed a framework to identify and visualize time-space conflicts using 4D-BIM. The system does not resolve the detected workspace conflicts after their detection. Moon et al. [13] introduced an optimization framework to find an alternative schedule with a minimum level of workspace interfaces in a 4D-BIM environment. The proposed system repeatedly moves the activities within their total floats to minimize workspace conflicts. Therefore, the time-space conflicts are not entirely resolved in this approach. Moreover, the proposed method does not consider the tempo-spatial conflicts of other site spaces, such as mobile resources. Choi et al. [11] proposed a workspace planning framework using a 4D-BIM approach to identify workspace requirements, represent workspace occupations, and identify tempo-spatial conflicts. However, the proposed system only reports the detected conflicts and does not automatically resolve them. Kassem et al. [38] presented a methodology based on Industry Foundation Class (IFC) and 4D modeling for workspace management. As time-space conflicts are detected and visually shown in the system, the project's planner has to resolve them interactively. Rohani et al. [39] introduced a framework for managing time-space conflicts in construction projects based on the combination of 5D BIM and time-cost trade-off analysis. Some strategies are manually implemented in the schedule of the project to resolve the detected conflicts. Getuli et al. [20] proposed a BIM-based approach to automatically create workspaces based on the space syntax analysis. This framework enables the practitioners to analyze the construction sequence scenarios to mitigate time-space conflicts.

Most recently, Getuli et al. [3,40] proposed a novel approach for manual activity workspace planning using immersive Virtual Reality (VR) and BIM technologies. The configuration of the workspaces is eventually improved by analyzing the previously collected active and passive data from the worker's immersive VR activity simulation. Hosny et al. [41–44] developed a 4D-BIM approach for probabilistic modeling of the workspaces and detecting their interfaces in their research studies. The authors indicated the significance of construction workspaces' non-deterministic factors in a qualitative and quantitative evaluation. They recommended modeling the construction workspaces in a bottom-up approach for considering the emergent behavior of crews in workspace collisions. Mirzaei et al. [45] proposed a 4D-BIM time-space system, which identifies time-space conflicts according to the labor crew's parameters movement. This study introduces the best execution pattern by quantifying the severity of conflicts in a set of execution alternatives based on network-based scheduling methods. However, the study does not automatically resolve the time-space conflicts during the construction process. It does not consider the possible dynamic conflicts due to the mobile machinery's movements, either.

3. Research gaps and contributions

Although several studies have been conducted in the area of time-space conflict management, yet the following gaps exist in the literature:

1- Each construction site accommodates several types of spaces (e.g., the building elements space, workspaces, temporary facilities spaces, machinery spaces). Previous studies have mainly concentrated on proposing a time-space planning approach according to only one type of conflicts mentioned above. For instance, some studies have focused on possible conflicts between the workspaces of the activities performed simultaneously. Some other studies have tried to address the potential conflicts among mobile resource machinery. To the best of the authors' knowledge, none of the previous studies have proposed an integrated framework to respect all potential time-space conflicts (e.g., workspace conflicts, mobile machinery conflicts).

2- The construction sites have a dynamic space system with two significant features: the first one is that the space requirements (e.g., required space of the activities, temporary facilities, machinery) are continuously changing due to the progress of the activities and site' changes. The second feature is the deep interactions among the changes in the spatial requirements. Any approach that does not consider the site space system's dynamic nature may not be realistic. To the best of the authors' knowledge, none of the previous studies have proposed a comprehensive time-space planning approach to trace the changes in the site space requirements, considering the entire interactions of this dynamic space system.

3- Most of the previous studies have used conventional network-based scheduling methods for time-space planning. However, these scheduling methods, such as the Critical Path Method (CPM), have some fundamental shortcomings in time-space planning: 1) Space is not considered a constraint resource in scheduling activities in the CPM-based approaches. 2) The network-based scheduling methods are based on defining the sequential relationship between some project milestones. Construction projects' milestones depend on the duration of the primary and logistic activities. The primary activities are those executed in the working areas (e.g., drilling a pile). However, process-level (logistic) activities are those executed between the temporary facilities (e.g., on-site transportation of the materials), usually by some mobile resources such as laborers or machinery [46]. Efficient time-space planning requires investigating changes in the space requirements in both primary and process-level activities. However, network-based scheduling methods do not consider the process-level activities in scheduling construction operations. Therefore, most previous studies have neglected time-space conflicts in process-level activities due to using network-based scheduling methods. 3) Due to the inability to consider the process-level activities, the network-based scheduling methods cannot appropriately consider cyclic activities. Furthermore, they neglect the effects of the laborers' travels and machinery' movements on the project's schedule. 5) The conventional scheduling methods' static nature cannot adequately consider the site space requirements' dynamic changes and their interactions throughout the entire project duration.

4- Based on the explanations mentioned above, there are some significant reasons for inefficiencies of the previous 4D BIM-based approaches proposed by the earlier studies in time-space management. The typical 4D BIM models usually contain only the parametric building elements of the project. Therefore, the other taxonomies of space requirements (e.g., required space for temporary facilities and mobile machinery) are not modeled in usual 4D BIM models. Furthermore, the 4D BIM models are usually developed using a network-based schedule, which only considers the project milestones' temporal information. These milestones are linked to some sets of building elements in a 4D BIM model. Therefore, the usual 4D BIM models do not consider the process-level activities. Thus, although using 4D BIM approaches by the previous studies has partially satisfied some of the time-space management requirements, their mentioned inefficiencies should be resolved.

5- Furthermore, most previous studies have concentrated on merely detecting and reporting the time-space conflicts during the project's timeline. However, one of the main challenges in time-space planning is how to resolve the detected conflicts. In most previous studies, the practitioners should resolve the reported conflicts by revising the project schedule or postponing non-critical activities. None of the previous studies has proposed an automated approach for resolving the detected conflicts to the best of the authors' knowledge.

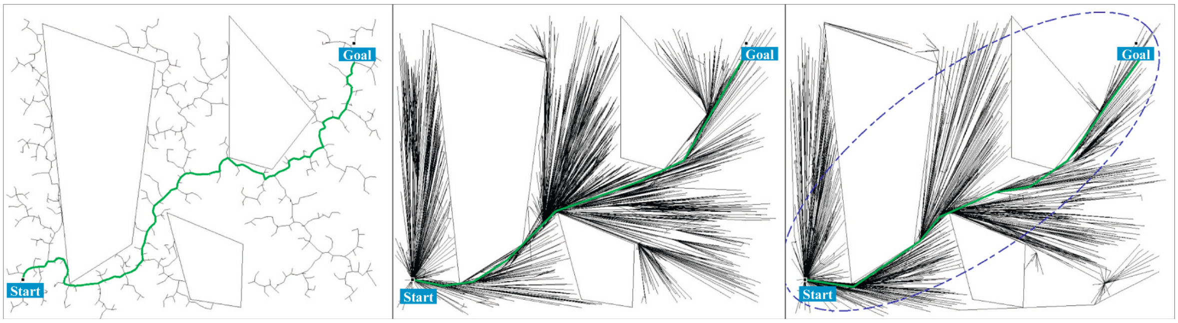
This study contributes to the body of knowledge in the area of time-space management in construction projects by proposing an integrated approach, which has the following capabilities: 1) The proposed approach considers the dynamic changes in the space requirements of the process-level activities and their entire interactions using a simulation-based scheduling engine. 2) The introduced framework manages all the possible Spatio-temporal conflicts among different site space requirements (e.g., the space for the building elements, activities, machinery, temporary facilities) in one general framework. 3) The system automatically generates the required site spaces using the BIM model for time-space planning. 4) The proposed system can automatically detect, evaluate, and resolve the time-space conflicts and modify the project's schedule. 5) The motions of the mobile resources during the construction process are also simulated. 6) An integrated framework based on 4D BIM, Discrete Event Simulation (DES), and Rapidly-exploring Random Tree (RRT) path planning algorithm is provided in the proposed approach.

4. Background

This section provides a brief background about the DES and the RRT algorithm as the primary bases for the proposed framework.

4.1. Discrete event simulation

Several scheduling techniques have been developed in the last decades, ranging from bar charts to network-based methods such as the Critical Path Method (CPM) [4]. DES as a well-known simulation approach can eliminate the mentioned deficiencies of the network-based scheduling methods in time-space planning. The process-level activities, sequential relationships, and cyclic interactions are modeled by some graphical elements in this approach. Once the simulation model is developed, the practitioner can test various scheduling scenarios of the construction process by changing a vast range of parameters, such as the



(a) Generated path by RRT algorithm after 1500 iterations

(b) Generated path by RRT* algorithm after 1500 iterations

(c) Generated path by RRT* informed algorithm after 1500 iterations

Fig. 1. Performance of the family of RRT path planning algorithms.

number of resources, duration of the activities, and project environment. One of the main advantages of the simulation-based scheduling methods is their ability to consider the site space as a constraint resource, which leads to more realistic project schedules.

Many researchers have used DES as a widely accepted and efficient approach to plan and schedule construction projects [47–54]. Several DES-based tools are also developed over the last decades after the adventure of CYCLONE [55] as the first tool in the construction industry, such as STROBOSCOPE [56], EZStrob [57], Simphony.NET [58], and COSYE [59]. Therefore, DES is used as the scheduling engine of the proposed integrated BIM-based simulation approach in this study for automatic management of the time-space conflicts.

4.2. Rapidly-exploring Random Tree (RRT) algorithm

Rapidly-exploring Random Tree (RRT) as a well-known stochastic path planning algorithm can deal with a non-holonomic high degree of freedom problems such as path planning of the mobile machinery in the dynamic nature of construction sites. The RRT algorithms' family is implemented successfully in different fields of studies, such as motion planning of intelligence vehicles [60] and autonomous mobile robot path planning [61].

The basic version of the RRT algorithm gradually generates a tree from the start point to the path's endpoint. In each iteration, a new node called Xrand is randomly generated. If Xrand is not colliding with any obstacle, it is then linked to the nearest existing node. The link is limited to a specific amount of distance (d). Therefore, if the length of the link is more than the defined distance (d), a line from the nearest node with the length of (d) is created toward the Xrand. After that, if the link's line is not colliding with any obstacle, it is added to the tree as a new branch. At the initiation process of random branch generation, the tree contains only one node (i.e., the start node of the path). This iterative procedure extends the tree to explore the environment until the endpoint is reached by a branch [62]. Fig. 1(a) shows a sample process of pathfinding using the RRT algorithm after 1500 iterations.

Since introducing the basic version of the RRT path planning algorithm, many developments have been proposed for different applications. Karaman and Frazzoli [63] demonstrated that almost all the paths created by the basic RRT algorithm are sub-optimal as the created branches of the tree always stay in their initial form. They improved the basic version of the RRT algorithm and called the new one RRT*. Using RRT*, the generated tree is continuously modified and smoothed through each iteration leading to a shorter path (Fig. 1(b)).

The informed version of the RRT* algorithm has the same performance as the RRT* until a solution is found. However, this algorithm only generates new random nodes in an area where the previously found path may be improved. Fig. 1(c) depicts a sample process of pathfinding using the RRT* informed algorithm developed in the current study after 1500 iterations. Once a path is fined, further random points are only located in an ellipse. The previous studies show a high efficiency for this algorithm in various optimization domains [64]. Thus this algorithm is used in the proposed framework for path planning of mobile machinery in construction sites.

5. Methodology

This chapter proposes a generic framework for the automatic management of time-space conflicts in the pre-construction planning phase (i.e., prior to the actual work on the site). The proposed method considers the dynamic changes in the site space requirement and their deep interactions. All types of possible time-space conflicts are automatically detected, analyzed, and resolved in a hybrid 4D BIM-based simulation environment. The proposed integrated system is composed of three major modules and one engine, including (Fig. 2):

- Workspace generation module
- Scheduling module
- Motion planning module
- BIM-based collision detection and evaluation engine

The main modules of the system intensively benefit from BIM and simulation concepts. The collision detection and evaluation engine is utilized in the first triple modules (i.e., workspace generation, scheduling, and motion planning modules) to provide an integrated BIM-based framework. Each module is illustrated in-depth in the following sections.

5.1. Workspace generation module

Space is a fundamental construct of the time-space conflict management area of knowledge. All objects in a construction site (i.e., the building elements, temporary facilities, materials, equipment, machinery, and individuals) occupy space. The first step in managing time-space conflicts is defining what spaces can exist in a construction site. Defining these taxonomies enhances the visual interpretation of site space requirements and lays a foundation for time-space conflict analysis [3]. Previous studies have proposed different taxonomies for site space requirements [10,11,16,22,28,29]. In this study, the site space requirements are classified into five major groups, including “Site object space”, “Building element space”, “Workspace”, “Temporary facility space”, “Machinery space”, and “Safety clearance space”. The definition of each site space taxonomy is provided in Table 1. For simplicity, the required space for laborers, equipment (lightweight tools), and working materials required during the execution of an activity are not classified in a separated group. Instead, they are all considered in the activities' workspace taxonomy.

Once different space types in a construction site are determined, the next step is defining how to model and consider this limited resource in

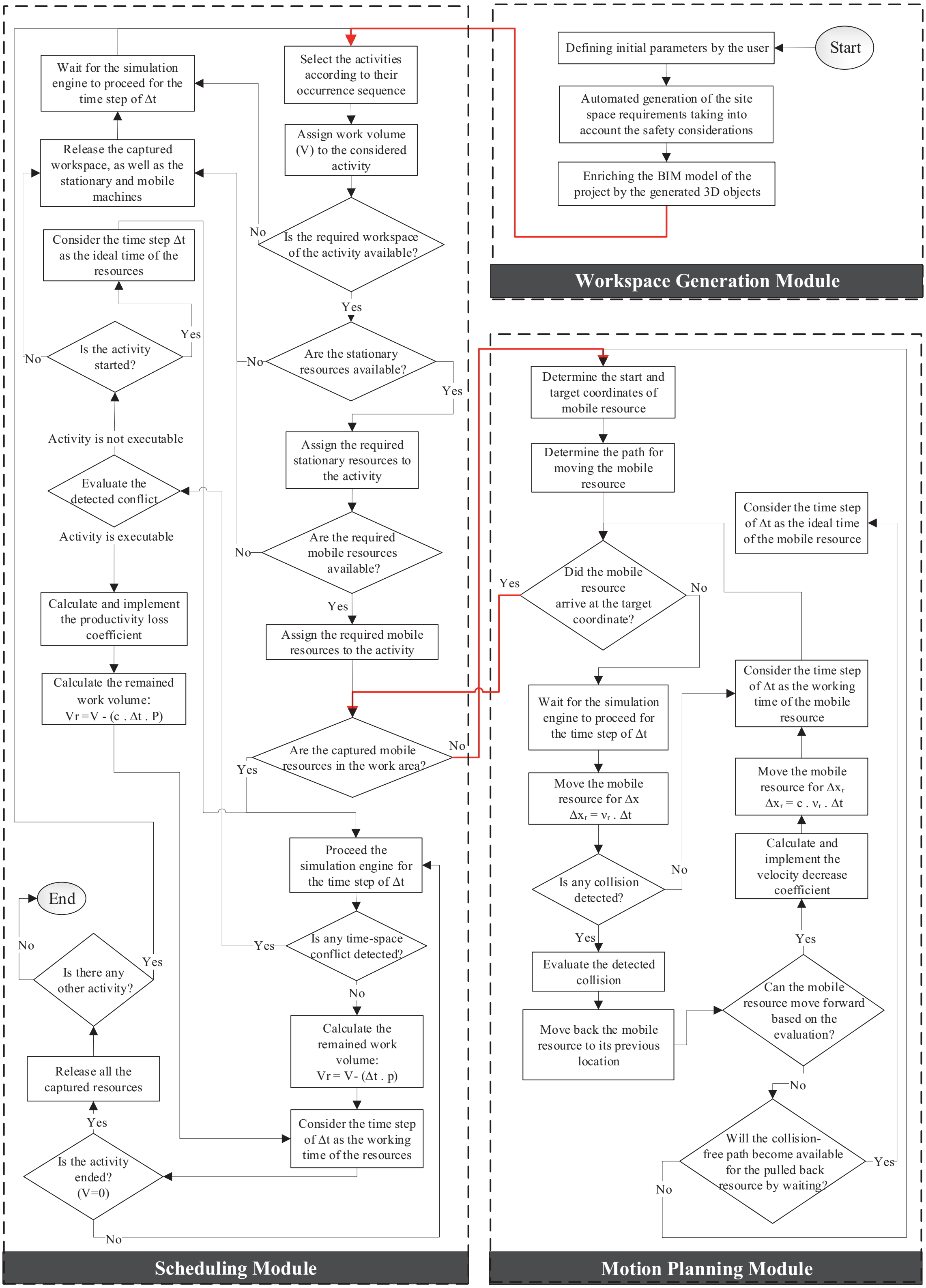


Fig. 2. The general framework of the proposed automatic time-space management system (The black flow lines show each module's intrinsic data flow, while the red flow lines indicate the dataflow between the modules of the system). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

time-space conflict analysis. The traditional network-based scheduling methods, such as the Critical Path Method (CPM), have some deficiencies in considering space as a significant limited resource. Therefore, the previous studies have used different approaches to model space in time-space planning, such as gridding the site area [30,34], determining different spatial layers [14], or using CAD and BIM models [10,11,65,66].

The well-known Building Information Modeling (BIM) approach is

Table 1
The proposed general classification system for site space requirements.

Taxonomies of site space requirements	Definition
Site object space	The space of permanent objects in a construction site such as trees or other buildings
Building element space	The space of building elements which are constructed during the project
Workspace	The space required for performing an activity that accommodates the required work materials, laborers, equipment, and machinery during an activity
Temporary facility space	The space for temporary facilities such as storage areas
Machinery space	The bounding space of existing machinery (heavy construction equipment)
Safety clearance space	The additional required space for protecting the other groups of space such as building elements, machinery, and temporary facilities from possible hazards during the construction process

used in this study as the best method for modeling site space. BIM models can collect all the required spatial information for time-space conflict analysis in a parametric platform. The common BIM models usually contain only the parametric building elements of the project [67]. However, other types of space requirements during the execution of construction projects may not be reflected in a BIM model, such as the spaces of the temporary facilities and mobile machinery (Table 1). Therefore, this study proposes enriching the common BIM models with the other space taxonomies. An enriched BIM model for time-space

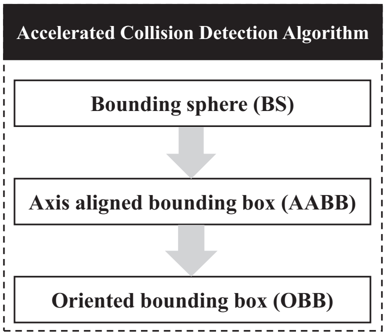
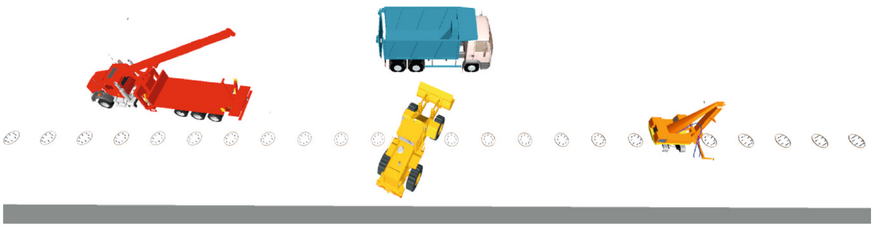


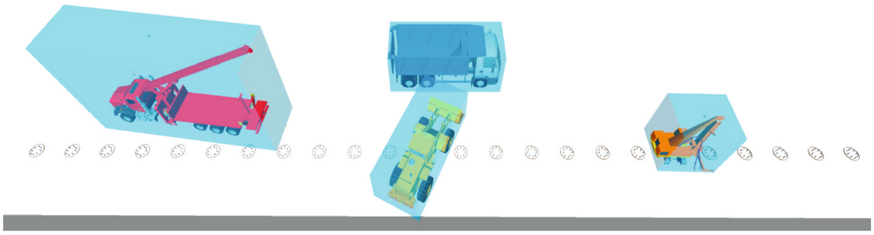
Fig. 4. The proposed three-step algorithm to accelerate the collision detection process in the BIM environment.

a) Project's BIM Model

b) Project's BIM Model enriched by the 3D models of the machinery



c) Project's BIM Model enriched by the 3D models of the machinery and their bounding boxes



d) Project's BIM Model enriched by the 3D models of the machinery, their bounding boxes and the activities' workspaces

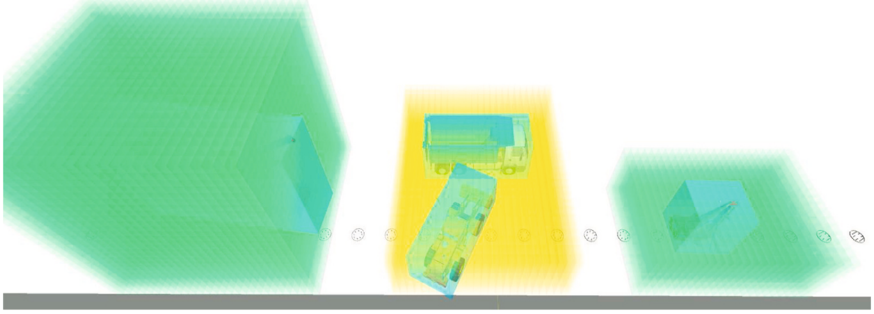


Fig. 3. Generating site space requirements in 3D by enriching the project's BIM model.

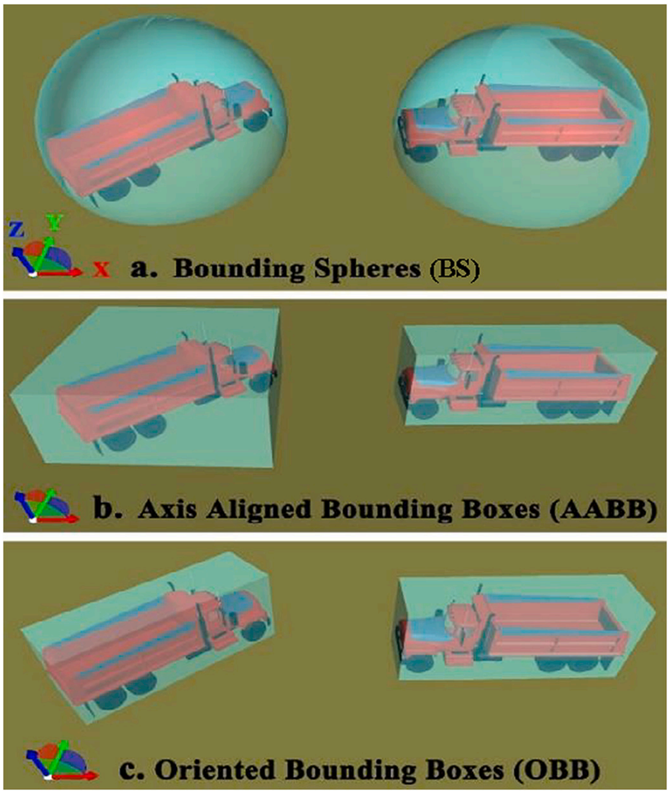


Fig. 5. The imaginary bounding volumes of the site objects.

conflict analysis includes the 3D models of site objects, building elements, activities' workspaces, temporary facilities, and machinery. Before running the system, the site objects, building elements, and temporary facilities are modeled in a BIM environment. The other space taxonomies, including activities' workspaces, machinery space, and safety clearance space, are added to the BIM model using the space generation module. An Application Programming Interface (API) in Autodesk Navisworks Manage is developed as the BIM engine of the system. While the system runs, the process of space generation is performed in three major steps as follows:

1. The project's BIM model, which includes 3D models of site objects, building elements, and temporary facilities, is imported in the first step.
2. In the second step, the 3D models of the foreseen machinery and their clearance from the other space groups are imported. The system automatically adds the imported 3D models to the project's BIM model using the API in the BIM environment (Fig. 3 (b)). The mobile types of machinery are considered as some rotating cuboids during time-space conflict analysis. Therefore, some bounding boxes are automatically created in Autodesk AutoCAD 3D and then added to machinery's 3D models using the space generation module (Fig. 3 (C)).
3. In the third step, the activities' workspaces are automatically generated as rectangular boxes. The length, width, and height of each activity's workspace, as well as its clearance from the other space groups, should be defined. The accuracy and reliability of estimating workspaces' dimensions are highly dependent on the construction manager's experience and knowledge and the information provided by the subcontractors and laborers involved in executing the activities [3]. The size of each workspace should be large enough to accommodate the required machinery, laborers' required working area, working materials, etc. The system automatically generates all the workspaces of the activities using an Autodesk AutoCAD 3D API. The generated workspaces are modeled as 3D cuboids divided into sub-cuboids (Fig. 3 (d)). Once the workspaces are developed, they are also automatically appended to the BIM model.

5.2. *Simulation-based scheduling module*

After generating the site spaces and enriching the BIM model, the project is simulated based on the DES-based scheduling module utilizing the Simphony. Net simulation engine's core services. The system proceeds the simulation time in equal steps of Δt, and it checks for

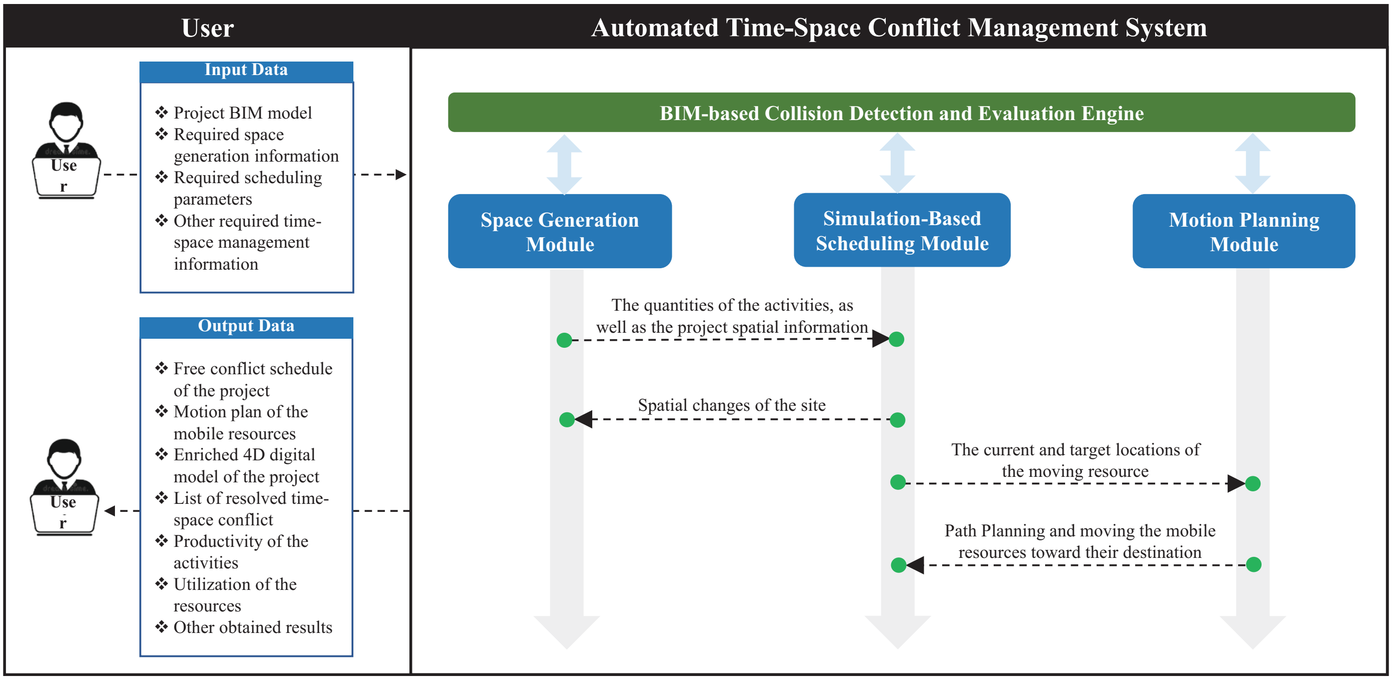


Fig. 6. The overall chronological data interactions among the user, the triple modules, and the collision detection and evaluation engine.

Fig. 7. Schematic plot and Google Earth aerial photo of the project (Yazd, Iran).

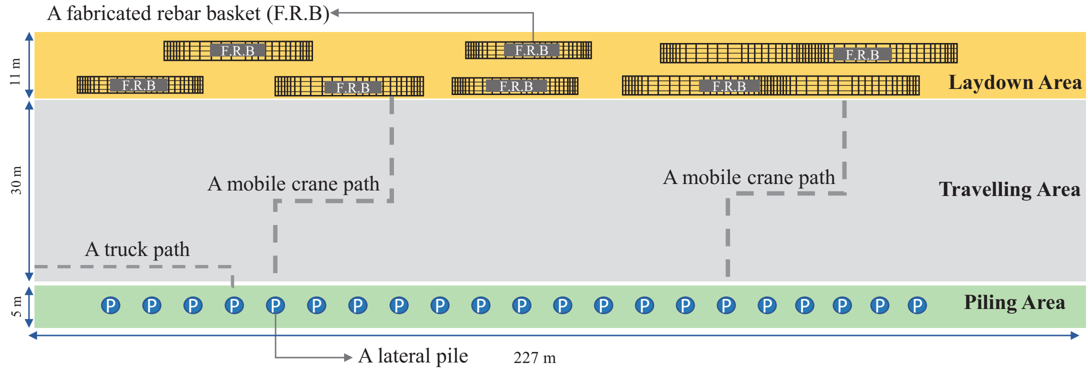


Fig. 8. Site layout plan for constructing the lateral piles.

scheduled events in each time step [68,69]. Once the user populates the required scheduling parameters (e.g., the available number of resources, the productivity of laborers and machinery, moving speed of mobile resources), the project's activities are scheduled in sequence based on the DES engine. The quantities associated with activities are automatically taken off from the BIM model of the project and saved in a pre-design database. Subsequently, the activities are selected based on their occurrence order. The volume of each activity (V) and its productivity (*p*) are assigned using the database (Fig. 2).

In the next step, the availability of the workspace of the activity is checked. Suppose the required space for performing the activity is not available. In that case, the activity will be delayed until the simulation engine's proceeding for the time step of Δt, when the availability of its required workspace is rechecked. Otherwise, the other required resources' availability is checked if the required workspace for initiating the activity is free (Fig. 2).

Two types of resources (i.e., stationary and mobile) are considered for each activity in the current study. Stationary resources (e.g., lightweight tools without the need for planning their movements) are supposed to be available in the activities' working area. However, mobile (i.e., the movable) resources such as heavy machinery may require walking due to initial inaccessibility to the activities' working area. In the proposed system, first, the availability of each stationary resource is checked. Once the resource is available, it is assigned to the activity. Otherwise, the activity is delayed until the proceeding of the simulation engine for the time step of Δt. The availability of mobile resources is

Fig. 9. Installation of a fabricated bar basket using a mobile crane.

Table 2
Diameters and depths of the lateral piles.

Pile type	P1	P2	P3	P4	P5	P6	P7
Diameter (m)	0.8	0.8	0.9	0.9	1	1	1
Depth (m)	2	6	10	14	18	22	26
Number	13	13	13	13	13	13	13

checked one by one in the next step. Once a required mobile resource is not available, the activity is delayed until the proceeding of the simulation engine for the time step of Δt. Otherwise, the activity captures it (Fig. 2).

After that, the current location of the mobile resource is checked too. If the available mobile resource is out of the activity's working area, it will be transferred to the working area using the motion planning module. When all the required resources, including the workspace, the stationary resources, and the mobile resources, are captured by the activity, the simulation engine proceeds for the time step of Δt. In this step, the time-space conflicts between the activity's workspace and all other workspaces are checked. In the case, which no time-space conflict is detected, the activity progresses for ΔP, as shown in Eq. (1):

$$\Delta \mathrm{P} = (\Delta \mathrm{t}^* \mathrm{p}) \tag{1}$$

where p represents the productivity of executing the corresponding

Table 3
Scheduling parameters of fabricating and installing the bar baskets.

Parameter	Value
Number of drilling machine(s)	1
Movement speed of the drilling machine(s) (m/s)	0.65
The productivity of the drilling machine(s) (m/h)	1.7
Number of available loader(s)	1
Loading productivity of the loader(s) (m^3/ min)	1.6
Movement speed of the loader(s) (m/s)	1.2
Number of available truck(s)	2
Hauling capacity of each truck(s) (m^3)	5
Travel speed of the loaded truck(s) (m/s)	8.1
Dumping duration of the truck(s) (min)	3
Return speed of the truck(s) (m/s)	10.8
Number of the available fabricating laborer (s)	6
The productivity of the fabricating crew (m/h)	2.7
Number of available mobile cranes	1
Number of available crane laborer (s)	2
Picking up duration for each fabricated rebar basket (min)	20
Movement speed of the mobile crane(s) (m/s)	1.2
Installation duration for each fabricated rebar basket (min)	20

activity. The system considers Δt as the working time of stationary and mobile resources. The remaining activity volume (V_r) is calculated using Eq. (2):

$$V_r = V - \Delta \mathrm{P} \tag{2}$$

However, if any time-space conflict is detected, the system evaluates the conflict's volume and compatibility. Once the activity is executable under the detected time-space conflicts, then a loss coefficient (c) is implemented to its productivity based on the collision percentage and some predefined If-then rules. Therefore, in this situation, the activity progresses for ΔP_c, as depicted in Eq. (3):

$$\Delta \mathrm{P_c} = (\Delta \mathrm{t}^* \mathrm{c}^* \mathrm{p}) \tag{3}$$

The system considers Δt as the working time of stationary and mobile resources. The remaining activity volume (V_r), in this case, is calculated using Eq. (4):

$$V_r = V - \Delta \mathrm{P_c} \tag{4}$$

Suppose the activity is not executable due to the detected time-space conflict. Two scenarios can occur: 1) If the activity is started before, the time-space conflict stops the activity. Then it does not progress in the time step of Δt. However, the activity cannot release its captured stationary and mobile resources after its initiation. Therefore, the time step of Δt is considered the ideal (waiting) time of the resources. The activity is delayed until the proceeding of the simulation engine for the next time step of Δt. 2) If the activity is not started yet, it releases the captured resources. The initiation of the activity is automatically delayed until the proceeding of the simulation engine for the next time step of Δt.

This procedure is continued until the end of the activity in each time step progress of Δt. When the activity is executed entirely, it releases all the captured resources. The same procedure is being performed for all the activities of the project. In each step of simulation engine progress, all the activities are checked, whether they can be started based on the sequential relationships or not (Fig. 2).

5.3. Motion planning module

As explained in the previous section, before initiating any activity in the proposed approach, the mobile resources, which are not in the activity's working area, should be transferred to the activity's zone using the motion planning module. Therefore, at the first step, the coordinates of the mobile resources' current and destination positions, which should be transferred, are determined using the BIM model of the project by an API in the BIM environment (Fig. 2). The start and target coordinates are sent to the RRT* informed algorithm for path planning. A path is generated for moving each mobile resource from its current position to the target position, taking into account the static obstacles in its way. After determining the mobile resource's moving path, it waits until the Δt progress step of the simulation engine. When the simulation engine progresses in the time step of Δt, the mobile resource is moved toward its destination for Δx_r, obtained from Eq. (5):

$$\Delta \mathrm{x_r} = \mathrm{v_r} \Delta \mathrm{t} \tag{5}$$

where v_r represents the velocity of the mobile resource, which is read from the system database.

As the mobile resource is moved for Δx_r, the collision of its bounding box with the other groups of site spaces is checked. Once no collision is detected, the time step of Δt represents the busy (i.e., working) time of the mobile resources. Otherwise, if any collision is detected, the system recognizes the mobile resource's movability by evaluating its collision. It moves back the mobile resource to its previous location, which is recorded in the database. After evaluation, if the mobile resource can move toward its destination under the detected collision, a loss coefficient (c_v) is calculated and implemented to its velocity based on the collision percentage and some predefined If-then rules. This situation, called "soft collision", happens when the distance of the mobile resources from each other or the other space taxonomies (e.g., activities' workspaces or building elements' spaces) is less than the maximum allowed safety clearance distance. Therefore, in the time step of Δt, the mobile resource travels toward its destination for Δx_{rc} obtained from Eq. (6). The time step of Δt is considered as the working time of the mobile resource (Fig. 2).

$$\Delta \mathrm{x_{rc}} = \mathrm{c}^* \mathrm{v_r}^* \Delta \mathrm{t} \tag{3}$$

Suppose the mobile resource cannot move toward its destination. This situation, which is called "hard collision", happens when the distance of the mobile resources from each other or the other space taxonomies (e.g., activities' workspaces or building elements' spaces) is less than the minimum allowed safety clearance distance or their main bounding boxes have a collision with each other. Two scenarios can occur in this situation: Once the collision can be resolved by waiting for a few minutes, the mobile resource waits for the next Δt progress of the simulation engine. The time step of Δt is considered as the ideal time of the mobile resource. Otherwise, the collision-free path may not become available for the mobile resource by waiting. For example, in the case that another mobile resource with a higher priority has blocked the path and will not move soon. In this scenario, the mobile resource will be replaned to find a new path, and the procedure will be iterated. The system automatically makes the best decision based on some previously defined rules.

While the project is simulated, in each time-step of Δt, the mobile resources' locations are checked to see whether they have arrived at their destination or not. If a mobile resource has arrived at its workspace, the moving process is stopped to send the results to the scheduling module. Otherwise, the explained procedure is iterated (Fig. 2).

As it can be inferred from the above explanations, the proposed approach can simultaneously and automatically plan several mobile resources' on-site motions. It can automatically manage the mobile resources' possible collisions with the other groups of the site space. Once the entire project is simulated using the proposed BIM-based simulation approach, a post-simulation 4D model is generated using the database's recorded data.

5.4. BIM-based conflict detection and evaluation engine

The capabilities of the BIM-based platforms' 3D modeling engine can detect and analyze the time-space conflicts during the project's simulation. Therefore, this study considerably benefits from the BIM approach's advantages in detecting and evaluating time-space conflicts. A BIM-based collision detection engine is developed in the proposed approach using an API in the Autodesk Navisworks Manage

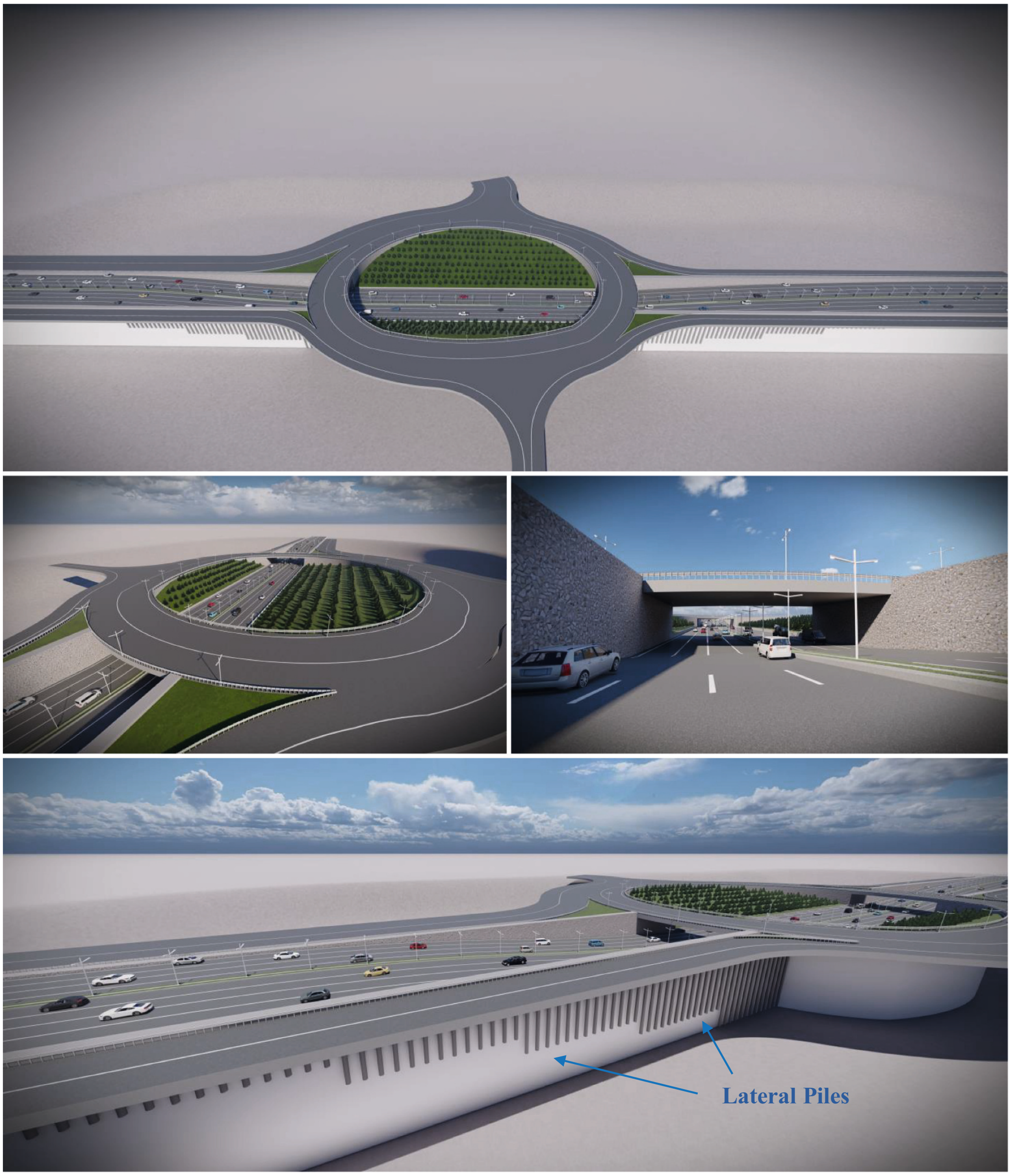


Fig. 10. The BIM model of the project.

Table 4
Samples of the if-then rules used for the evaluation of the detected time-space conflicts.

Row	If-Then rules
1	*In the case of detecting hard collision between the mobile machinery,* **if** *a mobile crane has a conflict with a dump truck,* **then** *the crane has a higher priority*
2	*If two dump trucks have a conflict with each other in the case of detecting a hard collision between the mobile machinery,* **then** *the loaded one has a higher priority.*
3	**If** *the collision percentage of the workspace of an activity is equal to or more than 70 in the case of detecting a compatible time-space conflict,* **then** *it is not executable anymore*
4	**If** *the collision percentage of an activity's workspace is less than 70 in detecting a compatible time-space conflict, it can be continued by implying the productivity loss coefficient. The relationship between the collision percentage of an activity's workspace and its productivity loss coefficient is supposed to be linear (inspired by Thabet & Beliveau* [14]*)*

environment. The three modules of the system utilize the engine to provide an integrated BIM-based framework (Fig. 2). As the project is simulated, the collision detection and evaluation engine checks all the possible conflicts and collisions among different site space requirements in each simulation time step of Δt. Executing this process in a 3D BIM environment demands a large volume of computations, which is highly time-demanding. However, in some situations during the project's simulation, some spaces have long distances from each other. Therefore, they can be quickly removed from the provisional list of potentially colliding spaces using some accelerating techniques.

Using bounding volumes can significantly reduce the computational efforts to accelerate the collision detection process. Bounding volumes are developed as some simple shapes enclosing the entire body of a 3D object. Detecting collisions between two bounding volumes demands significantly less computational effort than the real 3D shape of objects. Various types of bounding volumes have been introduced, such as bounding spheres (BS), axis-aligned bounding boxes (AABB), and oriented bounding boxes (OBB) [70]. A three-step algorithm is proposed in

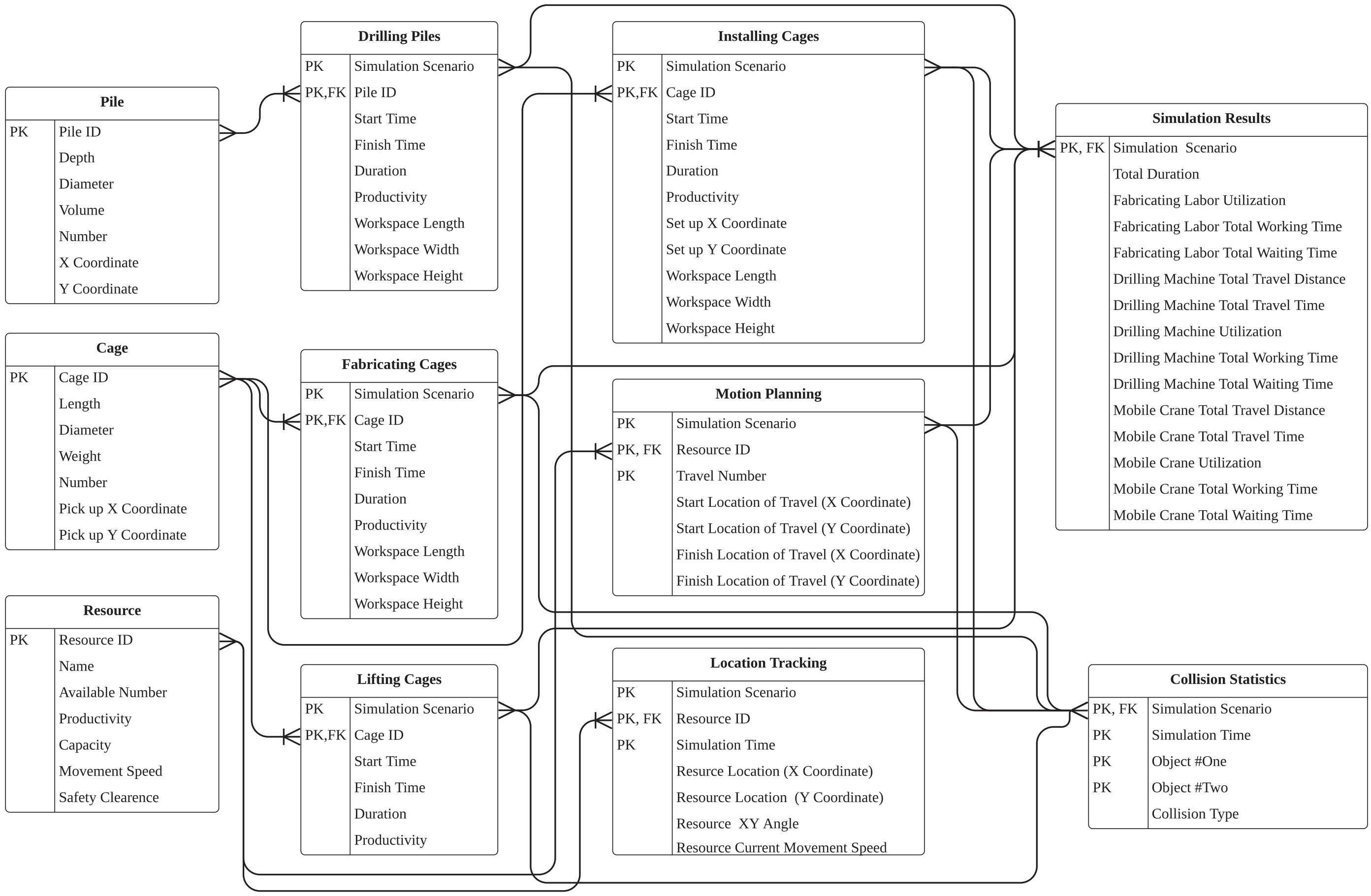


Fig. 11. The Entity-Relationship Diagram (ERD) for the database of the system.

the current study to accelerate the collision detection process in the BIM environment, as depicted in Fig. 4.

As the first step, some imaginary spheres enclosing each type of site space requirements (i.e., object space requirements) are checked against each other using the collision detection and evaluation engine. The sphere's radius equals the longest distance from each space's center to any of its points. If the distance between the center of two objects is more than the sum of the radius of their spheres (plus the possible safety distance), they will not collide. Thus, they are removed from any further collision detection computations. Fig. 5 (a) illustrates an example of the bounding spheres.

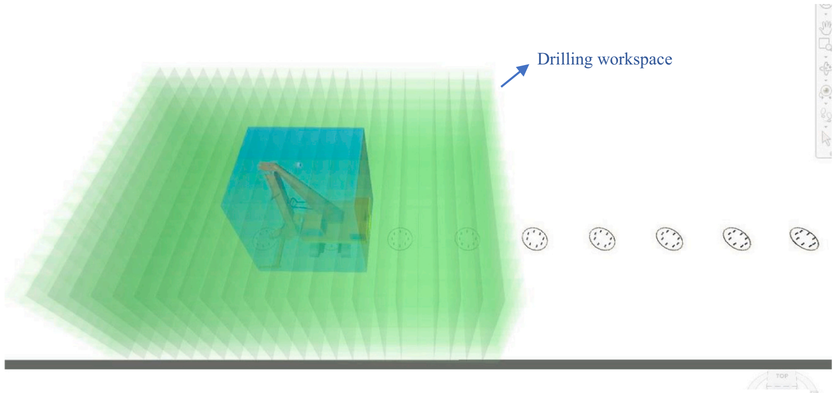
In the second stage, some imaginary AABB volumes of the spaces passing the first stage are checked to remove those with no chance to collide. The minimum and maximum dimensions of the AABB are computationally checked against each other. Once the axis-aligned bounding boxes of two objects collide in all axes of the XYZ coordinate system, they are considered colliding. In cases where the safety clearance distance should be considered for a space requirement, its associated AABB is enlarged. Fig. 5 (b) shows an example of AABB. Note that the illustrated figures of BS and AABB are imaginary created to clarify their concepts.

The last two steps swiftly remove many of the site spaces from further collision detection analysis. In the third step of the proposed BIM-based collision detection approach, the oriented bounding boxes of those spaces that have passed the two first steps are checked for collision detection using the BIM engine. The site spaces, such as the mobile machinery's spaces, can be assumed as rotating cuboids using oriented bounding boxes. This step is the most accurate step of the collision detection approach, which acquires the most computational efforts. Fig. 5 (C) illustrates an example of the OBB. As explained in the previous sections, OBBs are automatically created in Autodesk AutoCAD 3D and then added to the project's BIM model using the space generation module. The created volumes move precisely with mobile machinery during the project simulation.

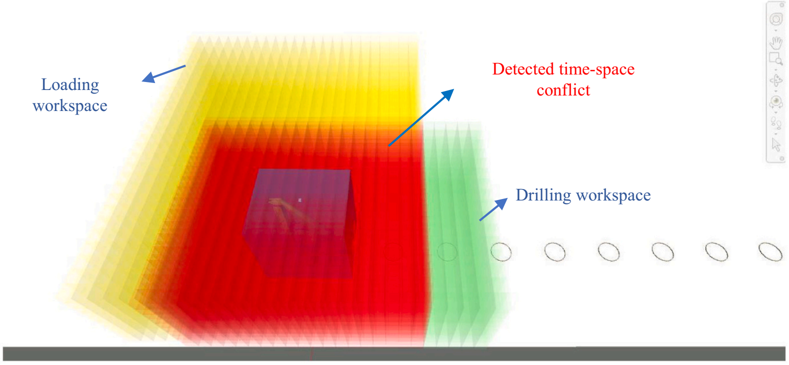
Once the system detects a time-space conflict, it evaluates the conflict and automatically decides to resolve it. As mentioned before, the proposed approach generates all the site spaces and divides them into some sub-cuboids using the workspace generation module before initiating the project simulation (Fig. 3). As the system detects a collision between two site spaces, it computes their collided percentages by dividing the collided cuboids' number into their total number of cuboids. The system automatically makes the best decision for resolving the detected conflict based on the calculated collision percentage and some If-then rules that can be previously defined and coded in the system. The if-then rules can be customized according to each project's activities and mobile resources, site situations, and site experts' opinions. For instance, If the collision percentage of the workspace of an activity is equal to or more than 70 in the case of detecting a compatible time-space conflict, then it is not executable anymore.

5.5. *Summary of the proposed framework*

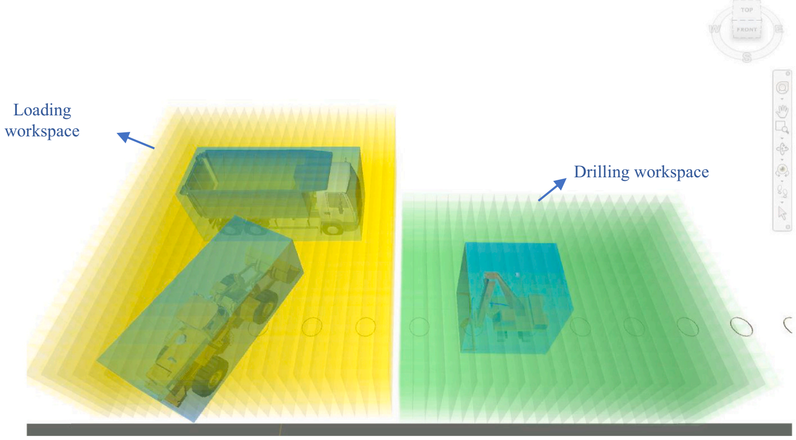
Based on the explanations in the last parts, the overall chronological data interactions among the user, the triple modules, and the collision detection and evaluation engine are shown in a top-down order in Fig. 6. This figure provides an overall understanding of the system's functioning. However, the internal processes of each module are neglected in this figure for simplicity.



a) Drilling pile#1 in its assigned workspace (simulation time = 0 - 1.80 h)



b) Detected conflicts between the required workspace for loading the excavated dirt of pile#1 and the required workspace for drilling pile#2 (simulation time = 1.80 h)



c) Collision free workspace for loading the excavated dirt of pile #1 (simulation time = 6 h)

Fig. 12. Automatic management of the conflicts between excavation and loading activities.

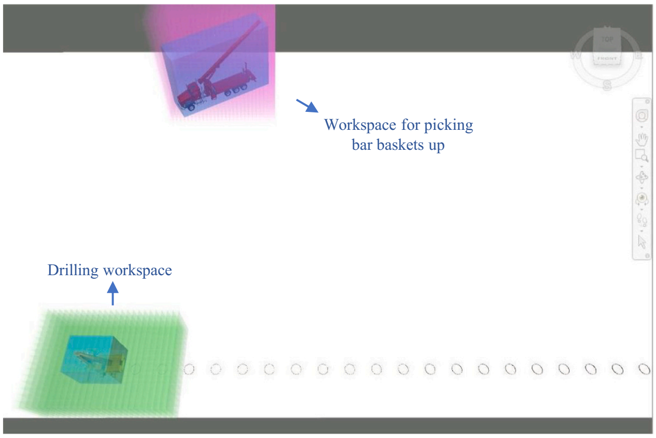
6. Case study

6.1. Description

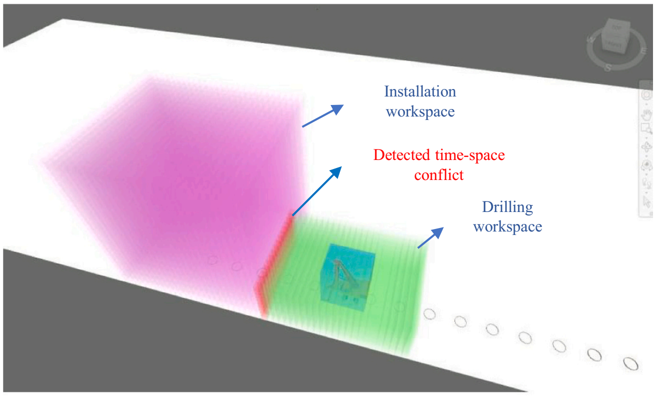
The proposed integrated approach is implemented in a real underpass construction project executed in Yazd province (in Iran) to evaluate its performance. Fig. 7 shows the Google Earth aerial photo of the project. Two highways, which are usually under heavy traffic, intersect with each other at a traffic circle. The city managers decided to construct an underpass on the west-east highway to decrease traffic congestion and the risk of accident occurrence. The construction site is established in the middle part of the west-east highway (the green areas in Fig. 7). The vehicles are temporarily steered to both sides of the highway (the red regions in Fig. 7), which increases daily traffic jams. Fig. 7 depicts that this project is executed in a congested urban area, under time and space limitations.

Based on the contractor's project managers' points of view, the project's critical milestone, which significantly influences its completion time, is constructing a set of 91 concrete piles on each side of the underpass ramps. The piles are built for stabilizing the lateral routes of the underpass ramps. The construction process of the lateral piles is described briefly in the following section.

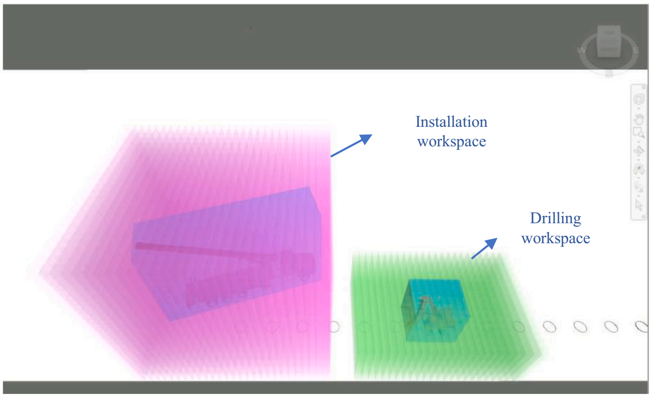
Fig. 8 depicts the schematic layout of the construction site during the construction of the lateral piles. As shown in the figure, based on previous experiences, the project managers divide the construction site into three major areas: the laydown area, traveling area, and piling area. The construction process begins in the piling area by drilling some piles using a hydraulic drilling machine. Once the piles are drilled, the



a) Picking bar basket #1 (simulation time = 0.91 h)



b) Detected conflicts between the required workspace for installing bar basket#1 and the required workspace for drilling pile#6 (simulation time = 6.33 h)



c) Collision free workspace for installing bar basket#1 (simulation time = 7.50 h)

Fig. 13. Automatic management of the conflicts between loading and installation activities.

excavated soil is loaded into some dump trucks by a loader and then hauled to an offsite location through the traveling area. Concurrently with drilling the piles, several laborers fabricate some reinforcing rebar baskets at the laydown area. While the piles are drilled, their excavated dirt is hauled, and their related rebar baskets are manufactured, then the rebar baskets are moved and installed in their corresponding piles, one by one.

In lifting the bar baskets, a mobile crane stays in front of the laydown area, in the direction with the center point of a rebar basket to pick it up (Fig. 8). After picking the rebar basket up, the mobile crane moves toward the corresponding drilled pile through the traveling area. Once the mobile crane arrives, it stays in front of the drilled pile and installs the rebar basket. Fig. 9 shows a mobile crane during the installation process of a rebar basket. Some laborers are also required to pick the rebar baskets up, lift, and install them. The same process is iterated for installing all the rebar baskets of each section in their bored piles. Once all the rebar baskets are installed, concrete is poured into the bored piles as the final stage of constructing the lateral piles.

Table 2 shows different types of lateral piles on each side of the underpass ramps. They are classified into seven groups based on their depths and diameters. The major scheduling parameters of fabricating and installing the bar baskets are demonstrated in Table 3.

In this project, the project managers decided to execute the main activities of constructing the lateral piles in parallel to decrease the project's completion time. Such a strategy prevents social discontent due to project operations. Consequently, three main activities are executed simultaneously: drilling the piles, fabricating and lifting the rebar baskets, and installing them in the drilled piles. However, the time-space conflicts between different space requirements for performing the activities may increase due to the limitation of the available site space in this situation. The chance of clashes occurring among the mobile resources moving through the site's traveling area also increases. All these possible time-space conflicts and clashes may influence the project's completion time due to a decrement in the productivity of executing the activities or lead to some on-site safety hazards. Therefore, the open issues that the project managers are faced with are included but not limited to the following:

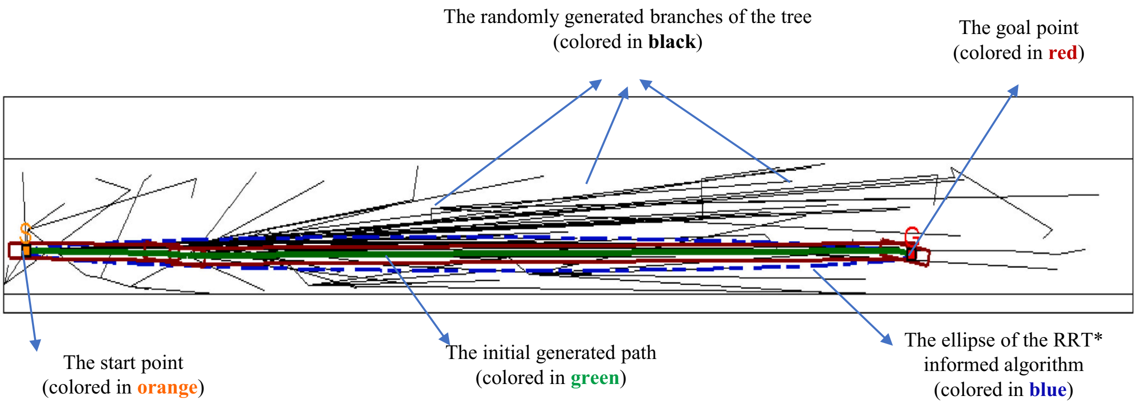
- Is there any integrated solution for planning the execution of the main activities of constructing the lateral piles in such a congested site, which can automatically manage all types of possible time-space conflicts?
- Is it possible to automate the processes of detecting, evaluating, and resolving all the mentioned conflicts?
- Could it be possible to consider the impacts of the detected conflicts on the project's completion time?

6.2. Implementing the automated time-space conflict management system

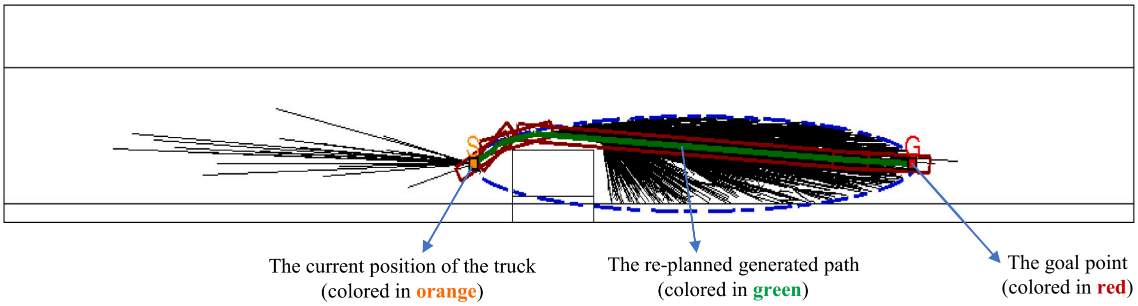
The integrated BIM-based simulation approach for automated time-space conflict management is implemented in the case study to evaluate its capabilities. In doing so, a software application is developed in the.Net framework as an add-on for Autodesk Navisworks Manage. It is programmed using C# language in Visual Studio 2015 environment.

In the first step, the underpass project's BIM model is developed using Autodesk Revit (Fig. 10). The 3D models of all the required machinery (e.g., the drilling machine, the mobile crane, the dump trucks, and the loader) are also prepared. The BIM model of the project and the 3D models of the machinery are then imported to the system and identified by the add-on. After that, the user is asked to input all the initial parameters, such as those required for site space generation and the project's scheduling (Table 3). In the following step, the workspaces of the activities (e.g., drilling the piles, loading the excavated dirt, picking the rebar baskets up, and installing the rebar baskets), and the bounding volumes of the machinery, are automatically created in Autodesk AutoCAD 3D. They are then appended to the BIM model of the project using the workspace generation module. Consequently, the BIM model of the project is enriched by all types of site space requirements.

Once the underpass's BIM model is enriched, the project is simulated using the system's integrated modules. All the activities of the project are coded in the simulation-based scheduling module. The materials' quantities are automatically taken off from the project's BIM model to calculate the activities' volume. In simulating each of the activities, the availability of the mobile and stationary resources is considered. The path planning module plans the mobile machinery movements (i.e., the loader, dump trucks, and the crane). All the time-space conflicts among the site space requirements (e.g., the workspaces of the activities and the bounding boxes of the machinery) are checked and identified in each time step of Δt using the collision detection and evaluation engine. The



a) The initial path generated for traveling a truck



b) The re-planned path generated for traveling the truck

Fig. 14. A sample in-site motion planning of the mobile resources during the simulation process.

three-step algorithm of checking Bounding Spheres (BS), checking Axis-Aligned Bounding Box (AABB), and checking Oriented Bounding Boxes (OBB) is used to accelerate the collision detection process. The collision percentage of each workspace is computed by dividing the number of collided cuboids into its total number of cuboids. Some if-then rules are introduced to evaluate the detected time-space conflicts based on the site engineers' opinions. Table 4 shows samples of these if-then rules. The appropriate resolution method is automatically implemented for each identified time-space conflict until the project simulation finishes. The final simulation results are recorded in the database of the system.

After simulating the project, the system's post-simulation 4D digital model is generated using the database's recorded data. Some options are provided in the developed add-on to animate the construction process in the desired manner. For instance, the user can play, pause, or stop the 4D model during the simulation process to visually check the work sequences. He\she can also choose the number of frames for updating the scene per second to provide a smooth animation or change the 4D model's speed. The proposed system is integrated with a database in Microsoft Access for facilitating the management of the data. Fig. 11 shows the Entity-Relationship Diagram (ERD) for the database of the system.

7. Results and discussion

During the simulation run, all the process-level activities are simulated in detail using the DES scheduling module. The motions of the mobile resource during the construction process are also simulated. All the time-space conflicts between all types of site space requirements are automatically detected, evaluated, and resolved during the project's simulation process. The final duration for performing the selected milestones obtained from the proposed system equals 753 h (i.e., 94 days).

In this section, the results of simulating the process-level activities in installing the first bar basket are explained to illustrate the system's performance in the automatic management of time-space conflicts. While the simulation process is initiated, the drilling machine starts drilling pile #1 in its assigned workspace (Fig. 12(a)). Pile #1 is entirely drilled in the simulation time of 1.80 h. Once pile#1 is drilled, the drilling machine moves to the next pile. Therefore, the workspace of drilling the first pile is released, and the workspace of drilling pile#2 is assigned. Instantly after completing the drilling of pile#1, the simulation engine schedules the truck's loading. All the resources for loading the excavated dirt, including the loader and the trucks, are available in this time step. However, the system detects a time-space conflict between the required workspace for loading the trucks and the workspace needed for drilling pile#2 (Fig. 12 (b)). The detected conflict is subsequently evaluated. This type of collision is previously considered to be incompatible due to safety considerations. Therefore, the system automatically delays the activity of loading the trucks for the subsequent Δt progress of the simulation engine. This condition does not change until completing drilling pile#5 in the simulation time of 5.88 h. Then the required workspace for loading the trucks becomes completely available (Fig. 12(c)). While the loader loads the trucks, the motion planning module determines their traveling path to the offsite location and their returning path to the site. The excavated dirt of pile#1 is wholly hauled to the outside in the simulation time of 6.33 h.

On the other hand, the bar basket of pile#1 is already fabricated in the simulation time of 0.57 h. Subsequently, a workspace is assigned to the mobile crane for picking bar basket#1. After that, the motion planning module moves the mobile crane to the workspace from its

Table 5
The type and number of the detected time-space conflicts (i.e., compatible (colored in green) and incompatible (colored in red)) among the site space requirements during project simulation.

Site space requirements		**Activities' workspaces**				**Machinery**					**Temporary facilities**
		Drilling the piles	Loading the trucks	Picking the baskets up	Installing the baskets	Drilling Machine	Loader	Truck 1	Truck 2	Crane	Fabrication areas
The workspaces of the activities	Drilling the piles	-	0	0	0	0	0	0	0	0	0
	Loading the trucks	**82**	-	0	0	0	0	0	0	0	0
	Picking the baskets up	0	0	-	0	0	0	**2**	**3**	0	0
	Installing the baskets	**78**	**85**	0	-	0	0	0	0	0	0
Machinery	Drilling Machine	0	0	0	0	-	0	0	0	0	0
	Loader	0	0	0	0	0	-	0	0	0	0
	Truck 1	0	0	0	**5**	0	0	-	0	**32**	0
	Truck 2	0	0	0	**8**	0	0	**2**	-	**36**	0
	Crane	0	0	0	0	0	0	**44**	**45**	-	0
Temporary facilities	Fabrication areas	0	0	0	0	0	0	0	0	0	-

Table 6
The total travel distance of the machinery during the project.

Mobile resources	Total travel distance (m)
Drilling machine	236
Loader	236
Dump truck1	11,362
Dump truck2	11,115
Mobile crane	6158

Table 7
Utilization of the resources during the project.

Resources	Utilization (%)
Fabrication laborers	62.7
Drilling machine	99.6
Loader	1.6
Dump truck1	7.2
Dump truck2	7.1
Mobile crane	8.2

previous location. The mobile crane picks bar basket#1 in the simulation time of 0.91 h (Fig. 13(a)). Once the excavated dirt of pile#1 is wholly hauled, the simulation-based scheduling module calls the activity of lifting and installing bar basket #1 in its drilled pile. All the required resources of this activity are available in the simulation time of 6.33 h. However, its required workspace conflicts with the workspace of drilling Pile#6 (Fig. 13(b)). The detected conflict is evaluated and considered to be incompatible due to the safety considerations. Therefore, the system automatically delays moving and installing bar basket #1 for the simulation engine's subsequent Δt progress. This condition does not change until completing drilling pile#6 in the simulation time of 7.06 h. At this time, the required workspace for installing bar basket#1 becomes available. Therefore, the mobile crane is moved to the workspace by the motion planning module, and it installs bar basket #1 in the simulation time of 7.85 h (Fig. 13 (c)). A similar process is iterated for completing the installation of all the bar baskets in their drilled piles.

All the in-site motions of the mobile resources are planned during the simulation process. Once any time-space conflict among volumes of the mobile machinery or other site space requirements is detected, the detected conflict is automatically resolved. All the motion paths of the mobile resources are stored in some image files. These images help significantly to understand, evaluate, and validate the process of motion planning. For instance, Fig. 14(a) shows the truck's generated path from the site entrance position with the coordinates of (−15, 10) to the workspace of a loading activity with the coordinates of (181, 9.5). The start (S) and goal (G) points in the motion path are displayed in orange and red colors. The ellipse of the RRT* informed algorithm is shown in blue. The final path and the branches of the tree are colored in green and black, respectively. While the truck moves toward its target point in each time step of Δt, it collides with the workspace of installing a bar basket. Therefore, the moving path of the truck is re-planned. Fig. 14(b) shows the new path created for the truck from the coordinates ((83.97,9.5) to the coordinates (181,9.5)).

Table 5 shows the type and the number of those detected time-space conflicts among the space requirements of the temporary facilities, activities, and machinery. The upper triangular part of the table (colored in green) shows the detected conflicts, which are evaluated to be compatible. This kind of conflict is resolved by implementing productivity or velocity loss coefficients. The lower triangular part of the table (colored in red) shows the detected conflicts that are evaluated as incompatible. This kind of conflict is automatically resolved based on appropriate methods such as postponing an activity, interrupting the machinery's movement, and re-planning their motion paths.

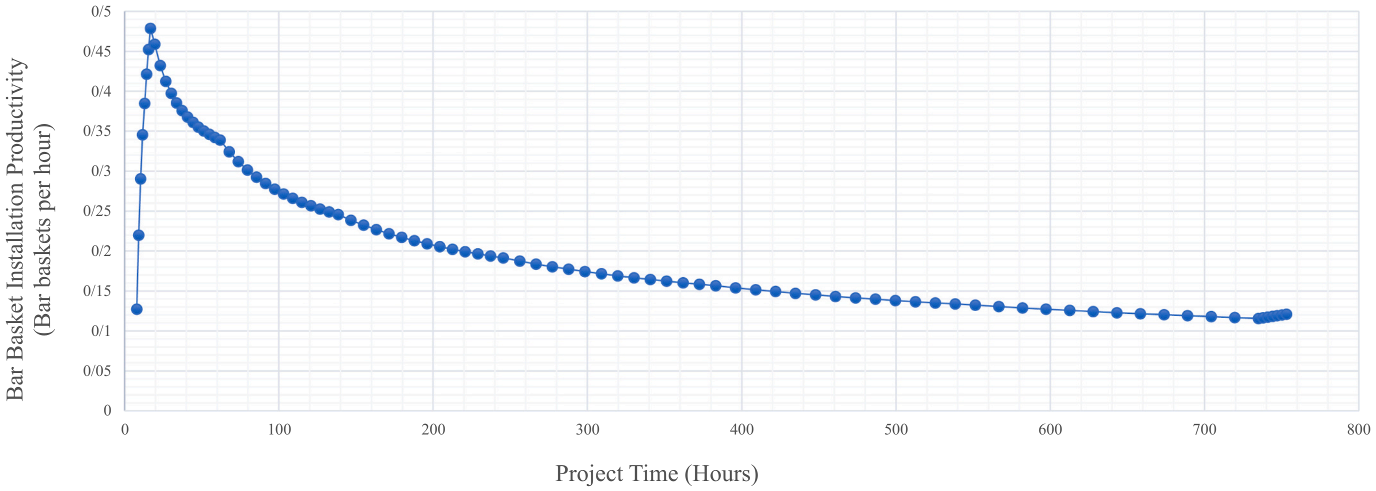


Fig. 15. The production rate of installing the bar baskets in their drilled piles throughout the entire project duration.

As shown in Table 5, the workspaces of drilling the piles conflicted with workspaces of loading the trucks 82 times during the project. Due to the predefined incompatibility between these two activities, loading the trucks is automatically postponed in these situations during the project simulation. Fabricating of the bar baskets is performed in some temporary facilities located at the site's laydown area. Thus, no conflict is detected between the spaces of these temporary facilities and other site space requirements. The spaces of picking the bar baskets and installing the bar baskets conflicted with the dump trucks moving through the traveling area 18 times. In 5 situations, this type of conflict has reduced the dump trucks' moving speed or delays in their travel. The system has automatically made this decision by evaluating the detected conflicts by calculating the conflict percentage and the predefined if-then rules. However, this conflict has led to re-planning the dump trucks' moving path in 13 situations.

The drilling machine is supposed to have the highest priority over the other machinery. It moves straight and continues drilling the piles without having any conflict with the other machinery. The loader is used in the loading activity's workspace, behind the drilling activity's workspace throughout the entire project. Thus, the loader's bounding volume does not collide with the other space requirements during the project. The trucks collided with each other two times during the project simulation. In both situations, these conflicts led to re-planning the moving path of the trucks. The trucks also conflicted with the mobile crane 157 times. In 68 situations, the distance of the mobile crane and the truck have been less than the maximum allowed safety clearance distance (Occurrence of soft collision). The mobile crane has a higher priority than the trucks due to the safety considerations of transferring the bar baskets. Therefore, in 68 situations, this conflict reduced the dump trucks' moving speed. However, in 89 situations, the distance of the mobile crane and the truck have been less than the minimum allowed safety clearance distance (Occurrence of hard collision). Consequently, this type of conflict led to an interruption in the trucks' travel or changes in their moving path in 89 situations (Table 5).

Based on the above explanations, as the system detects the time-space conflicts during project simulation, it automatically takes a suitable decision to resolve them based on the conflict percentage and the predefined if-then rules. The system automatically makes a wide variety of decisions, such as postponing an activity, decreasing the productivity of performing an activity, interrupting the execution of an activity, lowering the moving speed of mobile machinery, interrupting machinery's movement, and re-planning the motion paths of machinery. The system implements the effects of the made decision on the total project duration. The estimated project's duration in the cases of not time-space conflicts considering and considering using the proposed system equals 711 h and 753 h, respectively. The estimated project's duration has been increased by 5.58% in the case of considering time-space conflicts. It illustrates the proposed system's capabilities in having a more realistic estimation for the project's duration.

The combination of simulation-based scheduling (based on the process-level activities) and RRT* informed path planning method enables the proposed system to plan and trace the site's mobile resources' motions. This issue is usually ignored in network-based scheduling methods. Table 6 shows the on-site travel distance of the mobile machinery during the project. Using the proposed approach, the site engineers can plan the start point, goal point, safe travel path, travel start time, travel finish time, and the travel distance of all the machinery in each journey on the site. Detailed planning of all these movements in such a congested site, under automatic management of the possible time-space conflicts, considerably increases safety and prevents site incidents.

Simulating the construction process enables the practitioners to trace two main categories of statistics during the project, including intrinsic (time-dependent) and non-intrinsic (time-independent). Utilization is an intrinsic statistic that shows the utilization of the activity's resources over time [71]. Table 7 demonstrates the utilization of resources during the construction process. The drilling machine has maximum utilization during the construction process. This result hints to the project managers that increasing this resource may decrease the project's duration.

Production rate is a non-intrinsic statistic that shows the ratio of count and the simulation time [71]. The production rate of installing the bar baskets in their drilled piles is depicted in Fig. 15. The installation rate has increased dramatically at the beginning of the project, as it reached 0.48 in the simulation time of 16.71 h. After that, it has gradually decreased until the end of the project. The drilling machine's productivity is high at the beginning of the project, as it drills the piles with less depth. The fabricating laborers also have higher productivity at the beginning of the project as they fabricate short baskets. As the project progresses, the depth of the piles and the baskets' length increase, which in turn reduces the productivity of the drilling machine and the fabricating laborers. Therefore, the production rate of installation increases initially but decreases gradually as the project continues.

Once the project is wholly simulated using the proposed BIM-based simulation approach, a post-simulation 4D model is generated using the database's recorded data. The generated digital model is developed to enrich the project's BIM model with all the required data for the project's time-space management. All types of spatial requirements are parametrically modeled in 3D, taking into account safety considerations. These parametric objects are also enriched with temporal information, including their exact appearance and disappearance time in the construction site. The practitioners gain insights into the sequence of performing the activities using the provided 4D BIM model. Working crews can visually trace when and where to complete the job without interruption due to unforeseen time-space conflicts. Furthermore, all the motions of the mobile machinery are also visualized in a 4D environment.

8. Conclusions

Time-space planning in construction projects involves identifying time-space conflicts in the entire project duration, evaluating the detected conflicts, and resolving them to prevent their negative impacts. Several research studies have been performed in the area of time-space planning. However, none of them have proposed an automated system for managing possible time-space conflicts between all types of space requirements, which can entirely consider the site space system's dynamic nature. Therefore, this study contributes to the body of knowledge in the area of time-space management in construction projects by proposing an integrated approach, which has the following capabilities:

1) The proposed approach considers the dynamic changes in space requirements of the process-level activities and their entire interactions using a simulation-based scheduling engine. 2) The proposed approach considers all the possible temporal conflicts between all types of site spaces (e.g., the spaces of the building elements, activities, machinery, temporary facilities). 3) The system automatically generates the required site spaces using the BIM model for time-space planning. 4) The proposed system can automatically detect, evaluate, and resolve the time-space conflicts and modify the project's schedule. 5) The motions of the mobile resources during the construction process are also simulated. 6) An integrated framework based on 4D BIM, Discrete Event Simulation (DES), and Rapidly-exploring Random Tree (RRT) path planning algorithm is provided in the proposed approach.

The integrated BIM-based simulation approach for automated time-space management is implemented in a real case study to evaluate its capabilities. A software is developed in the.Net framework as an add-on in Autodesk Navisworks Manage environment for implementing the approach. A three-step algorithm based on using various bounding volumes (i.e., Bounding Spheres (BS), Axis-Aligned Bounding Boxes (AABB), and Oriented Bounding Boxes (OBB)) is used to accelerate detection of the time-space conflicts during the project simulation. Once the time-space conflicts are detected, the system automatically takes a suitable decision for resolving them based on the conflict percentage and some predefined if-then rules. Implementing the proposed system illustrates its automatic management capabilities of the time-space conflict during the entire project duration. It realistically takes into account the impacts of space limitations on the estimation of the project duration. Combining simulation-based scheduling (which can consider the process-level activities) and RRT* informed path planning method enables the proposed system to plan and trace the site's mobile resources' motions. The proposed approach's simulation-based scheduling engine also allows practitioners to track project resource utilization and construction processes' productivity rate. The system also generates a post-simulation 4D digital model based on enriching the project's BIM model with all the required time-space management data. The results indicate that the proposed approach can considerably prevent the negative impacts of the time-space conflicts on productivity and safety, especially in congested construction sites.

9. Limitations and future developments

Some limitations of the proposed system and future research directions are provided as follow:

- One of the most critical steps in time-space management is modeling workspaces. Estimating the dimensions of the workspaces based on the experiences of the project managers and the working crews is a limitation of this study. Future research studies can improve the system's performance by using more accurate workspace modeling methods.
- The required spaces for laborers, equipment (lightweight tools), and working materials are not separately generated in this study. Instead, they are all considered in the activities' workspaces taxonomy. Future research studies are required to eliminate this limitation.
- Quantifying the negative impacts of congestion in the working areas is a long-lasting issue that is highly dependent on factors such as the type of activity and site situations. Inspired by Thabet and Beliveau's research study [14], the relationship between the collision percentage of the workspace and the productivity loss coefficient is supposed to be linear in this study for simplicity. More empirical studies are required to scrutinize the relationship.
- The on-site movements of the laborers are not considered in the proposed approach. Combining the developed framework with the other simulation approaches such as agent-based modeling can be investigated to consider the laborers' on-site movements.
- The productivity rate of the activities in the presented case study is considered to have a constant value. However, the simulation engine can consider a wide range of statistical distributions (e.g., triangular, uniform, and exponential) for the productivity of the activities. Future research studies can investigate the performance of the system in probabilistic conditions.
- One of the main contributions of this study is proposing an integrated framework for scheduling construction projects which can consider space as a constrained resource. The authors believe that there is a large potential to improve the proposed system by considering the other scheduling concepts. For example, the proposed system schedules construction projects in a resource-constrained condition. However, the system can be combined with optimization algorithms to solve the well-known time-cost trade-off problem. In other words, the proposed integration method provides a platform to consider the effects of site space limitations on different scheduling issues.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] G. Lucko, L.G. Araújo, G.R. Cates, Slip chart–inspired project schedule diagramming: origins, buffers, and extension to linear schedules, J. Constr. Eng. Manag. 142 (2016), 04015101, https://doi.org/10.1061/(asce)co.1943-7862.0001089.

[2] A.P.C. Chan, D. Scott, E.W.M. Lam, Framework of success criteria for design/build projects, J. Manag. Eng. 18 (2002) 120–128, https://doi.org/10.1061/(ASCE)0742-597X(2002)18:3(120).

[3] V. Getuli, P. Capone, A. Bruttini, S. Isaac, BIM-based immersive virtual reality for construction workspace planning: a safety-oriented approach, Autom. Constr. 114 (2020) 103160, https://doi.org/10.1016/j.autcon.2020.103160.

[4] S.M. Abourizk, Y. Mohamed, Optimal Construction Project Planning, Proceedings of the 34th Winter Simulation Conference: Exploring New Frontiers, IEEE, San Diego, California, USA, 2002, pp. 1704–1708, https://doi.org/10.1109/WSC.2002.1166454.

[5] M. Taghaddos, H. Taghaddos, U. Hermann, Y. Mohamed, S. AbouRizk, Hybrid multi-mode simulation and optimization for subarea scheduling in heavy industrial construction, Autom. Constr. 125 (2021) 103616, https://doi.org/10.1016/j.autcon.2021.103616.

[6] S.M. Bagheri, H. Taghaddos, A. Mousaei, F. Shahnavaz, U. Hermann, An A-Star algorithm for semi-optimization of crane location and configuration in modular construction, Autom. Constr. 121 (2021) 103447, https://doi.org/10.1016/j.autcon.2020.103447.

[7] D.M. Franco-Duran, J.M. de la Garza, Performance of resource-constrained scheduling heuristics, J. Constr. Eng. Manag. 146 (2020), 04020026, https://doi.org/10.1061/(asce)co.1943-7862.0001804.

[8] V.K. Bansal, Use of GIS and topology in the identification and resolution of space conflicts, J. Comput. Civ. Eng. 25 (2011) 159–171, https://doi.org/10.1061/(ASCE)CP.1943-5487.0000075.

[9] H.M.M. Said, G. Lucko, Float types in construction spatial scheduling, J. Constr. Eng. Manag. 142 (2016), 04016077, https://doi.org/10.1061/(asce)co.1943-7862.0001202.

[10] Z. Mallasi, Dynamic quantification and analysis of the construction workspace congestion utilising 4D visualisation, Autom. Constr. 15 (2006) 640–655, https://doi.org/10.1016/j.autcon.2005.08.005.

[11] B. Choi, H.S. Lee, M. Park, Y.K. Cho, H. Kim, Framework for work-space planning using four-dimensional BIM in construction projects, J. Constr. Eng. Manag. 140 (2014) 1–13, https://doi.org/10.1061/(ASCE)CO.1943-7862.0000885.

[12] H. Moon, N. Dawood, L. Kang, Development of workspace conflict visualization system using 4D object of work schedule, Adv. Eng. Inform. 28 (2014) 50–65, https://doi.org/10.1016/j.aei.2013.12.001.

[13] H. Moon, H. Kim, C. Kim, L. Kang, Development of a schedule-workspace interference management system simultaneously considering the overlap level of parallel schedules and workspaces, Autom. Constr. 39 (2014) 93–105, https://doi.org/10.1016/j.autcon.2013.06.001.

[14] W.Y. Thabet, Y.J. Beliveau, Modeling work space to schedule repetitive floors in multistory buildings, J. Constr. Eng. Manag. 120 (1994) 96–116, https://doi.org/10.1061/(ASCE)0733-9364(1994)120:1(96).

[15] N. Kayhani, H. Taghaddos, A. Mousaei, S. Behzadipour, U. Hermann, Heavy mobile crane lift path planning in congested modular industrial plants using a robotics approach, Autom. Constr. 122 (2021) 103508, https://doi.org/10.1016/j.autcon.2020.103508.

[16] S.J. Guo, Identification and resolution of work space conflicts in building construction, J. Constr. Eng. Manag. 128 (2002) 287–295, https://doi.org/10.1061/(ASCE)0733-9364(2002)128:4(287).

[17] N. Roofigari-Esfahan, S. Razavi, Uncertainty-aware linear schedule optimization: a space-time constraint-satisfaction approach, J. Constr. Eng. Manag. 143 (2017), 04016132, https://doi.org/10.1061/(ASCE)CO.1943-7862.0001276.

[18] A. Mousaei, H. Taghaddos, A. Nekouvaght Tak, S. Behzadipour, U. Hermann, Optimized mobile crane path planning in discretized polar space, J. Constr. Eng. Manag. 147 (2021), 04021036, https://doi.org/10.1061/(ASCE)CO.1943-7862.0002033.

[19] V. Getuli, Ontologies for Knowledge Modeling in Construction Planning, Firenze University Press, 2020, https://doi.org/10.36253/978-88-5518-184-6 (ISBN 978-88-5518-184-6).

[20] V. Getuli, P. Capone, Computational workspaces management: a workflow to integrate workspaces dynamic planning with 4D BIM, in: Proceedings of the 35th ISARC International Symposium on Automation and Robotics in Construction and International AEC/FM Hackathon: The Future of Building Things, IAARC Publications, Berlin, Germany, 2018, pp. 1117–1124, https://doi.org/10.22260/isarc2018/0155.

[21] B. Akinci, M. Fischen, R. Levitt, R. Carlson, Formalization and automation of time-space conflict analysis, J. Comput. Civ. Eng. 16 (2002) 124–134, https://doi.org/10.1061/(ASCE)0887-3801(2002)16:2(124).

[22] Y. Song, D.K.H. Chua, Detection of spatio-temporal conflicts on a temporal 3D space system, Adv. Eng. Softw. 36 (2005) 814–826, https://doi.org/10.1016/j.advengsoft.2005.03.025.

[23] D.K.H. Chua, K.W. Yeoh, Y. Song, Quantification of spatial temporal congestion in four-dimensional computer-aided design, J. Constr. Eng. Manag. 136 (2010) 641–649, https://doi.org/10.1061/(ASCE)CO.1943-7862.0000166.

[24] N. Dawood, Z. Mallasi, Construction workspace planning: assignment and analysis utilizing 4D visualization technologies, Computer-Aided Civil Infrast. Eng. 21 (2006) 498–513, https://doi.org/10.1111/j.1467-8667.2006.00454.x.

[25] B. Akinci, M. Fischer, J. Kunz, Automated generation of work spaces required by construction activities, J. Constr. Eng. Manag. 128 (2002) 306–315, https://doi.org/10.1061/(ASCE)0733-9364(2002)128:4(306).

[26] I.D. Tommelein, P.P. Zouein, Interactive dynamic layout planning, J. Constr. Eng. Manag. 119 (1993) 266–287, https://doi.org/10.1061/(ASCE)0733-9364(1993)119:2(266).

[27] M. Khanzadi, F. Nasirzadeh, M.S. Dashti, Fuzzy cognitive map approach to analyze causes of change orders in construction projects, J. Constr. Eng. Manag. 144 (2018), 04017111, https://doi.org/10.1061/(asce)co.1943-7862.0001430.

[28] B. Akinci, M. Fischer, J. Kunz, R. Levitt, Representing work spaces generically in construction method models, J. Constr. Eng. Manag. 128 (2002) 296–305, https://doi.org/10.1061/(ASCE)0733-9364(2002)128:4(296).

[29] G.M. Winch, S. North, Critical space analysis, J. Constr. Eng. Manag. 132 (2006) 473–481, https://doi.org/10.1061/(ASCE)0733-9364(2006)132:5(473).

[30] C. Zhang, A. Hammad, T.M. Zayed, G. Wainer, H. Pang, Cell-based representation and analysis of spatial resources in construction simulation, Autom. Constr. 16 (2007) 436–448, https://doi.org/10.1016/j.autcon.2006.07.009.

[31] G. Lucko, H.M.M. Said, A. Bouferguene, Construction spatial modeling and scheduling with three-dimensional singularity functions, Autom. Constr. 43 (2014) 132–143, https://doi.org/10.1016/j.autcon.2014.03.008.

[32] S. Isaac, Y. Su, G. Lucko, D. Dagan, Work-path modeling and spatial scheduling with singularity functions, J. Comput. Civ. Eng. 31 (2017), 04017008, https://doi.org/10.1061/(ASCE)CP.1943-5487.0000650.

[33] S. Tao, C. Wu, Z. Sheng, X. Wang, Space-time repetitive project scheduling considering location and congestion, J. Comput. Civ. Eng. 32 (2018) 1–19, https://doi.org/10.1061/(ASCE)CP.1943-5487.0000745.

[34] Y. Su, S. Isaac, G. Lucko, Integrated temporal-spatial model for construction plans with boolean logic operators, J. Constr. Eng. Manag. 144 (2018), 04018009, https://doi.org/10.1061/(ASCE)CO.1943-7862.0001450.

[35] J. Zhang, Z. Hu, BIM- and 4D-based integrated solution of analysis and management for conflicts and structural safety problems during construction: 1. Principles and methodologies, Autom. Constr. 20 (2011) 155–166, https://doi.org/10.1016/j.autcon.2010.09.013.

[36] Z. Hu, J. Zhang, BIM- and 4D-based integrated solution of analysis and management for conflicts and structural safety problems during construction: 2. Development and site trials, Autom. Constr. 20 (2011) 167–180, https://doi.org/10.1016/j.autcon.2010.09.014.

[37] X. Su, H. Cai, Life cycle approach to construction workspace modeling and planning, J. Constr. Eng. Manag. 140 (2014) 1–12, https://doi.org/10.1061/(ASCE)CO.1943-7862.0000855.

[38] M. Kassem, N. Dawood, R. Chavada, Construction workspace management within an Industry Foundation Class-Compliant 4D tool, Autom. Constr. 52 (2015) 42–58, https://doi.org/10.1016/j.autcon.2015.02.008.

[39] M. Rohani, G. Shafabakhsh, A. Haddad, E. Asnaashari, Strategy management of construction workspaces by conflict resolution algorithm and visualization model, Eng. Constr. Archit. Manag. 25 (2018) 1053–1074, https://doi.org/10.1108/ECAM-08-2016-0183.

[40] V. Getuli, P. Capone, A. Bruttini, Planning, management and administration of HS contents with BIM and VR in construction: an implementation protocol, Eng. Constr. Archit. Manag. 28 (2020) 603–623, https://doi.org/10.1108/ECAM-11-2019-0647.

[41] A. Hosny, M. Nik-Bakht, O. Moselhi, Workspace planning in construction: non-deterministic factors, Autom. Constr. 116 (2020) 103222, https://doi.org/10.1016/j.autcon.2020.103222.

[42] A. Hosny, M. Nik-Bakht, O. Moselhi, Chaos and Complexity in Modeling and Detection of Spatial Temporal Clashes in Construction Processes, Proceeding of Construction Research Congress 2018, American Society of Civil Engineers, New Orleans, Louisiana, 2018, pp. 639–648, https://doi.org/10.1061/9780784481271.062.

[43] A. Hosny, M. Nik-Bakht, O. Moselhi, Towards agent-based modeling for operational clash detection in construction operations, in: Proceeding of Construction Research Congress 2018, CSCE, Vancouver, Canada, 2017, pp. 1439–1450. https://www.csce.ca/elf/apps/CONFERENCEVIEWER/%0Aconferences/2017/pdfs/CONSPEC/FinalPaper_37.pdf (Accessed September 02, 2021).

[44] A. Hosny, M. Nik-Bakht, O. Moselhi, Workspace management on construction jobsites: an industry survey, in: Proceedings of the 7th CSCE/CRC International Construction Specialty Conference, CSCE, Laval, Canada, 2019 (pp. CON125–1–9), https://www.csce.ca/elf/apps/CONFERENCEVIEWER/conferences/2019/pdfs/PaperPDFversion_125_0527093430.pdf (Accessed September 02, 2021).

[45] A. Mirzaei, F. Nasirzadeh, M. Parchami Jalal, Y. Zamani, 4D-BIM dynamic time-space conflict detection and quantification system for building construction projects, J. Constr. Eng. Manag. 144 (2018), 04018056, https://doi.org/10.1061/(ASCE)CO.1943-7862.0001504.

[46] S. Razavialavi, S.M. Abourizk, Simulation applications in construction site layout planning, ISARC, in: Proceedings of the International Symposium on Automation and Robotics in Construction, IAARC, 2013, pp. 275–284, https://doi.org/10.22260/ISARC2013/0030.

[47] H. Taghaddos, M.S. Dashti, Simulation-based constructability analysis of an RCC dam, in: Proceedings of the 6th CSCE/CRC International Construction Specialty Conference, CSCE, Vancouver, Canada, 2017 (pp. CON271–1–10), https://csce.ca/elf/apps/CONFERENCEVIEWER/conferences/2017/pdfs/CONSPEC/FinalPaper_271.pdf (Accessed September 02, 2021).

[48] J. Larsson, W. Lu, J. Krantz, T. Olofsson, Discrete event simulation analysis of product and process platforms: a bridge construction case study, J. Constr. Eng. Manag. 142 (2016), 04015097, https://doi.org/10.1061/(ASCE)CO.1943-7862.0001093.

[49] S.M. Abourizk, R.J. Wales, Combined discrete event/continuous simulation for project planning, J. Constr. Eng. Manag. 123 (1997) 11–20, https://doi.org/10.1061/(ASCE)0733-9364(1997)123:1(11).

[50] F. Peña-mora, S. Han, S. Lee, M. Park, Strategic-operational construction management: hybrid system dynamics and discrete event approach, J. Constr. Eng. Manag. 134 (2009) 701–710, https://doi.org/10.1061/(ASCE)0733-9364(2008)134:9(701).

[51] O. Frough, A. Khetwal, J. Rostami, Predicting TBM utilization factor using discrete event simulation models, Tunn. Undergr. Space Technol. 87 (2019) 91–99, https://doi.org/10.1016/j.tust.2019.01.017.

[52] J. Du, M. El-gafy, D. Zhao, Optimization of change order management process with object-oriented discrete event simulation: case study, J. Constr. Eng. Manag. 142 (2016), 05015018, https://doi.org/10.1061/(ASCE)CO.1943-7862.0001092.

[53] S. Abourizk, D. Halpin, Y. Mohamed, U. Hermann, Research in modeling and simulation for improving construction engineering operations, J. Constr. Eng. Manag. 137 (2011) 843–852, https://doi.org/10.1061/(ASCE)CO.1943-7862.0000288.

[54] S. Abourizk, Role of simulation in construction engineering and management, J. Constr. Eng. Manag. 136 (2010) 1140–1153, https://doi.org/10.1061/(ASCE)CO.1943-7862.0000220.

[55] D.W. Halpin, CYCLONE-method for modeling job site processes, J. Constr. Div. 103 (1977) 489–499, https://doi.org/10.1061/JCCEAZ.0000712.

[56] J.C. Martinez, P.G. Ioannou, General purpose simulation with stroboscope, in: Proceedings of Winter Simulation Conference, IEEE, Lake Buena Vista, FL, USA, 1994, pp. 1159–1166, https://doi.org/10.1109/WSC.1994.717503.

[57] J.C. Martinez, V. Tech, EZStrobe-General-purpose simulation system based on activity cycle diagrams, in: Proceeding of Winter Simulation Conference, IEEE, 2001, pp. 341–348, https://doi.org/10.1109/WSC.2001.977485.

[58] D. Hajjar, S.M. Abourizk, Unified modeling methodology for construction simulation, J. Constr. Eng. Manag. 128 (2002) 174–185, https://doi.org/10.1061/(ASCE)0733-9364(2002)128:2(174).

[59] S.M. AbouRizk, S. Hague, An overview of the COSYE environment for construction simulation, in: Proceedings of Winter Simulation Conference (WSC), 2009, pp. 2624–2634, https://doi.org/10.1109/WSC.2009.5429307.

[60] D. González, J. Pérez, V. Milanés, F. Nashashibi, A review of motion planning techniques for automated vehicles, IEEE Trans. Intell. Transp. Syst. 17 (2015) 1135–1145, https://doi.org/10.1109/TITS.2015.2498841.

[61] N. Sariff, N. Buniyamin, An overview of autonomous mobile robot path planning algorithms, in: 4th Student Conference on Research and Development, IEEE, Selangor, Malaysia, 2006, pp. 183–188, https://doi.org/10.1109/SCORED.2006.4339335.

[62] S.M. Lavalle, Rapidly-Exploring Random Trees: A New Tool for Path Planning, Computer Science Department, Iowa State University, 1998, pp. 1–4. https://www.cs.csustan.edu/~xliang/Courses/CS4710-21S/Papers/06%20RRT.pdf (Accessed September 02, 2021.

[63] S. Karaman, E. Frazzoli, Incremental sampling-based algorithms for optimal motion planning, in: Proceedings of Robotics: Science and Systems Conference, 2010, pp. 1–8 (Zaragoza, Spain), http://www.roboticsproceedings.org/rss06/p34.pdf (Accessed September 02, 2021).

[64] J.D. Gammell, S.S. Srinivasa, T.D. Barfoot, Informed RRT *: optimal sampling-based path planning focused via direct sampling of an admissible ellipsoidal heuristic, in: IEEE/RSJ International Conference on Intelligent Robots and Systems, IEEE, Chicago, IL, USA, 2014, pp. 2997–3004, https://doi.org/10.1109/IROS.2014.6942976.

[65] A. Nekouvaght Tak, H. Taghaddos, A. Mousaei, A. Bolourani, U. Hermann, BIM-based 4D mobile crane simulation and onsite operation management, Autom. Constr. 128 (2021) 103766, https://doi.org/10.1016/j.autcon.2021.103766.

[66] S. Pooladvand, H. Taghaddos, A. Eslami, A. Nekouvaght Tak, U.R. Hermann, Evaluating mobile crane lift operations using an interactive virtual reality system, J. Constr. Eng. Manag. 147 (2021), 04021154, https://doi.org/10.1061/(ASCE)CO.1943-7862.0002177.

[67] A. Fazeli, M.S. Dashti, F. Jalaei, M. Khanzadi, An Integrated BIM-Based Approach for Cost Estimation in Construction Projects, Engineering, Construction and Architectural Management, 2020, https://doi.org/10.1108/ECAM-01-2020-0027.

[68] D. Hu, Y. Mohamed, Time-stepped, simulation-based scheduling system for large-scale industrial construction projects, in: Proceedings of Winter Simulation Conference, IEEE, Washington D.C, United States, 2013, pp. 3249–3256, https://doi.org/10.1109/WSC.2013.6721690.

[69] D. Hu, Y. Mohamed, H. Taghaddos, U.R. Hermann, A simulation-based method for effective workface planning of industrial construction projects, Constr. Manag. Econ. 36 (2017) 328–347, https://doi.org/10.1080/01446193.2017.1390241.

[70] S. Talmaki, V.R. Kamat, Real-time hybrid virtuality for prevention of excavation related utility strikes, J. Comput. Civ. Eng. 28 (2014), 04014001, https://doi.org/10.1061/(ASCE)CP.1943-5487.0000269.

[71] S.M. Abourizk, S. Hague, R. Ekyalimpa, Construction Simulation: An Introduction Using Simphony, Univ. of Alberta, Hole School of Construction Engineering, Edmonton, AB, Canada, 2016 (ISBN 978-1-55195-357-1).