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BIM-based schedule generation and optimization using genetic algorithms

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ABSTRACT

This research presents a transformative framework to tackle challenges within the construction industry, where efficiency is hindered by limited digitalization and disjointed project phases. The framework seamlessly integrates state-of-the-art technologies, such as Building Information Modeling (BIM), Genetic Algorithms (GAs) for schedule optimization, 5D simulation, and a Business Intelligence (BI) Dashboard. By doing so, it effectively enhances productivity while bridging the gap between the realms of management and engineering. A comprehensive literature review underpins the framework's design, focusing mainly on BIM-based schedule generation and optimization. The approach's validity is demonstrated through a compelling case study, showcasing automated BIM model creation, BIM-Based schedule generation limited to structural elements of bottom-up Cast-in-situ construction method, GAs-driven schedule optimization, 5D project simulation, and the integration of the BI dashboard. This research propels operational efficiency and promotes harmonious integration with pre-existing software systems, thus facilitating smoother adoption and adaptation.

1. Introduction

The construction industry holds immense significance in the global economy, playing a pivotal role in infrastructure development. However, it continues to grapple with various daunting challenges, including low productivity, high costs, frequent delays, compromised quality, and safety risks [1]. A study performed by McKinsey Global Institute in 2017 to measure labour productivity in the construction industry in the period between 1995 and 2014 found that it is slowly growing by 1% per year while the manufacturing industries witnessed a rapid increase in labour productivity by 3.6% per year [2]. Astonishingly, large projects across diverse asset classes often exceed their scheduled completion time by approximately 20% and overrun their budgets by up to 80% [3]. Moreover, specific markets have witnessed a decline in construction productivity since the 1990s, leading to low and volatile financial returns for contractors [3]. Examining the results of these studies, Ashcraft [4] spotted low productivity as the main challenge that causes cost overrun and schedule delays and claimed that the gap in labour productivity growth between the construction industry and manufacturing industry is due to the lack of development in construction industry technologies, also the traditional project delivery approach.

A key hindrance to the progress of developing the technologies of the construction industry and implementing Integrated Project Delivery (IPD) as a replacement for the traditional project delivery approach lies in the prevalence of nonhomogeneous and unstructured data within the industry, impeding the seamless integration of various aspects such as management and engineering and severely restrict collaboration, communication, and efficiency among multiple stakeholders. The absence of a unified and automated system for data exchange between engineering and management aspects of the project results in inefficiencies and increases the likelihood of errors and miscommunication. Consequently, essential project information may not be readily accessible to all involved parties, hindering decision-making and preventing the realization of the project's full potential [5–7].

By investigating these two aspects it can be noticed that for instance, the construction schedule is the data source for the management aspect, as it is the key element in tracking and controlling the project. Also, it is the core element for creating an integrated project management system as most of the construction management processes like risk, cost, and communication heavily depend on it. At the same time, the Building Information Modeling (BIM) model serves as the source of data for the

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engineering aspects regarding design collaboration, procurement, quantity surveying, and more. However, these two vital aspects of the construction process remain disconnected and rely on manual development [5].

The construction schedule has a few software tools supporting it, focusing on assisting planners by implementing the Critical Path Method (CPM), generating a Gantt chart, and helping with resource levelling. But at the same time, all the work of creating activities, assigning resources, developing logical sequencing, generating a Work Breakdown Structure (WBS), and manual schedule crashing to achieve the targeted project end date still heavily rely on the planner's experience. The construction industry, unfortunately, lags behind in technological advancements that could enhance this crucial aspect of construction management. This deficiency in technology renders the scheduling process error-prone and exceedingly time-consuming. For instance, in a manual approach to crashing the schedule, planners may arbitrarily select activities with extended durations or rely on their experience to choose the activity. This often leads to suboptimal, cost-inefficient crashed schedules, as not all potential solutions are thoroughly explored. Contrastingly, a system empowered by Genetic Algorithms (GA) can explore a broader spectrum of potential solutions efficiently. Unlike traditional methods, a GA-powered system can swiftly discover optimal crash schedules by evaluating a larger set of possibilities, thereby significantly reducing both errors and time consumption. [5].

On the other hand, while BIM is the core of the engineering aspect of the project, BIM's implementation is still limited specifically in "small and medium enterprises" (SMEs). The study by Vidalakis, et al. [8] on the UK's SMEs found that 85.8% of companies do not know most BIM software packages. The study also found that 70% of SMEs have never used BIM in drafting, 75% have never used it in scheduling/planning, and 62% have never used it in visualization. Moreover, the study found that the low level of BIM use is due to its high adoption cost and software interoperability issues. Moreover, Torres-Calderon, et al. [9] found that studies have emphasized the advantages of utilizing 4D Building Information Modeling (BIM), a combination of 3D spatial dimensions with temporal elements, to enhance construction planning and scheduling efficiency. Only approximately 35 to 40% of leading engineering news-record (ENR) companies have incorporated 4D BIM into their practices, and its application is confined to specific projects within their portfolios. Also, the use of 4D BIM tends to be temporary, often not extending beyond the pre-construction phase. The perceived challenge is the substantial effort required for creating 4D BIM, which raises concerns about its overall return on investment (ROI). As a result, it is evident that there is a need to facilitate shifting to BIM for SMEs and reducing the effort to develop 4D and 5D simulations by automating them.

Along with developing the construction industry process and technologies to automate some aspects of schedules and BIM and create a bridge between engineering and management aspects to facilitate the data exchange within a project and make it easier to implement the IPD, an imperative necessity arises for implementing a robust delivery strategy to alleviate the persistent issues of schedule and cost deviations that frequently afflict capital ventures. A portion of this amelioration prospectus resides in the augmentation of data-centric decision-making within capital projects through utilizing and implementing Business Intelligence (BI) systems. The inventive amalgamation of novel operational paradigms and potent advanced analytical tools presents a compelling occasion for diminishing project expenditures and deviations by a noteworthy margin ranging from 30 to 50% [10].

It is evident that the construction industry grapples with significant challenges, experiencing a notable lag in progression compared to the manufacturing sector. The predominant reliance on antiquated manual processes has led to a decline in productivity, an increase in errors, and limited avenues for seamless integration across various aspects of the industry Recognizing the imperative for change, the construction industry is on the verge of a transformative era (Construction 4.0), embracing automation and interconnectivity. A digital revolution is underway, revolutionizing its processes. Embracing more integrated project delivery methods, such as IPD, and deploying advanced automated systems to manage and optimize projects, the industry seeks highly accurate planning and estimates utilizing cutting-edge technologies and techniques [1,5,7]. Despite the availability of several commercial software solutions, they fall short of fulfilling the technological requisites of the evolving industry transformation. Furthermore, prior research in this domain has presented promising yet constrained feature solutions. These include early attempts to automate schedule generation based on historical data, predating the advent of BIM technology. Subsequent efforts automated schedules based on BIM models but lacked seamless integration with scheduling software and omitted incorporating 4D or 5D simulations. These simulations play a critical role in aligning the efforts of diverse project stakeholders and minimizing operational conflicts at the project site. Furthermore, there were initiatives to create 4D-oriented schedules primarily for simulation purposes. Additionally, other endeavours resulted in frameworks that supported the development of schedules and simulations but lacked essential elements such as standardized activity naming conventions, assignment of resource data to activities, a live link between different framework components, and integration with widely used scheduling software. Consequently, a novel and indispensable framework is necessary to facilitate this transformative shift, automating most tasks within the industry while offering a comprehensive and integrated solution.

This research proposes a new framework that leverages innovative technology to usher the construction industry into a digitally advanced era. The framework is designed to automate critical processes of BIM modeling, schedule generation, schedule crashing and optimization using GAs, project simulation, and project monitoring using BI to propel the industry toward a new era of efficiency and innovation. In addition to enhancing operational efficiency, this framework promotes seamless integration with pre-existing software systems, facilitating smoother adoption and adaptation.

This paper comprises the following sections: Section 2 is a literature review on BIM-based schedule generation and optimization. Section 3 shows the proposed BIM-based framework.

Section 4 implements the BIM-based framework in a prototype example to evaluate its efficiency and feasibility. Section 5 shows the limitations and recommendations for future studies, and Section 6 concludes the study.

2. Literature review

Automating schedule generation has been around for nearly half a century, with research in this field beginning in the early 1960s as Newell and Simon [11] have been working on finding new ways to use computer-based algorithms and applications to make scheduling projects easier. Since then, numerous commercial and academic initiatives have been devoted to developing diverse computer applications. Automating various aspects of the scheduling procedure has been a topic of interest and study for a considerable time. The primary objective of most of these applications is to reduce the time and effort spent recreating this information for new projects. Project-specific information has always been required for these applications to achieve their objectives successfully [12].

In the realm of prior studies, there has been a tendency to categorize these applications into distinct generations. However, the usage of such terminology inadvertently conveys the notion that each succeeding generation supersedes its predecessor, thereby implying a linear progression over time. In actuality, these applications undergo continuous refinement concurrently across various dimensions. This phenomenon is much similar to the four levels of BIM maturity established by

ISO 19650 therefore these applications can be grouped in this study into four levels of maturity based on whether the approach is BIM-based or not and the outputs of that approach.

2.1. BIM-based scheduling maturity level zero

In this maturity level, scheduling processes are automated through various methods, excluding the utilization of Building Information Modeling (BIM) data or the generation of BIM-related products like 4D Simulation. The early stages of this level witnessed the development of multiple approaches, each demanding specific inputs. For instance, the GHOST system relied on the manual listing of design components for rule-based sequencing and analytical purposes [13]. Meanwhile, the SIPE model utilized the hierarchy of physical components as input to construct a network of work schedules, attributing a single activity per component [14]. A prototype described by Fischer and Aalami [15] utilized predetermined sub-networks of activities, accessible from a predefined store based on the selection of higher-level aggregated activities. The proof-of-concept prototype required users to input high-level seed activities, resulting in the creation of detailed-level activities.

On the other hand, the case-based reasoning approach used project features such as structural type, and the number/size of floors, as inputs to reuse past schedules [16]. Using historical schedules, Chevallier and Russell [17] offered a method where construction engineers establish project templates, preserving the correct breakdown structure, logic, and sequencing principles. These templates, saved as rules, are applied to new projects. The system, using physical and process views, solicits project-specific information from the user to adapt to the new project's scope.

Early research at this level predominantly relied on knowledge-based methods, with Case-Based Reasoning (CBR) standing out as the most suitable method [18,19]. However, while aligned with AEC industry needs, CBR still necessitates user inputs, such as manual extraction of project attributes, quantities take-off, and various edits on generated schedules.

More advanced research at this level transitioned to model-based methods, leveraging 3D CAD models generated through computer-aided design (CAD) [15,20–23]. These models significantly reduced the effort required for activity creation and connection to 3D objects [24,25]. However, the implementation of this concept demanded a substantial amount of physical labor.

2.2. BIM-based scheduling maturity level one

This maturity level marks the beginning of BIM-based scheduling, which was introduced with the emergence of BIM technology in the AEC industry. This scheduling system is oriented toward leveraging BIM's rich data and ability to offer better interoperability. At this level of maturity, the data stored in BIM models are extracted and then used to develop a schedule automatically.

Early efforts in this level of maturity created just the algorithms of automatic schedule generation without discussing the ability to export it to any commercial software for further edits. The algorithms used in these efforts depended on using the Open-BIM offered by the buildingSMART [12]. Open-BIM considers BIM data exchange in the industry foundation classes schema (IFC) usable from any software. Leveraging the features of Open-BIM, Kim, et al. [26] extracted elements' attributes from Open BIM for schedule generation, while [27,28] pioneered approaches to determine correct construction sequences. Additionally, Liu, et al. [29] considered schedule panelised construction, while Schwabe, et al. [30] provided a resources-constrained site layout as planning, and Moon, et al. [31] detected the degree of spatial overlap and suggested an optimum solution for project scheduling. Noteworthy efforts by Mikulakova, et al. [32] and Chen, et al. [33] are also examples of this stage, as Mikulakova, et al. [32] developed a system rooted in CBR and IFC BIM Models, extracting data from IFC files and comparing it with a CBR database to generate schedules. Similarly, Chen, et al. [33] engineered a system for automatically generating maintenance schedules based on BIM-Model. However, neither study prioritizes optimization nor facilitates the export of schedules to commercial software.

Recent efforts in this level of maturity did not just create a schedule automatically from the model but also offered a method by which these schedules can be exported into commercial scheduling software. Also, some efforts were made to develop an optimization method after the schedule creation, considering resource or site layout constraints. Such optimization efforts also focused on solving the time–cost trade-off problems. Illustrative examples of this mature level include the endeavours of [6,34–37]. Wang and Rezazadeh Azar [35] constructed a framework utilizing Dynamo programming within Revit to extract BIM model data. Subsequently, two schedules based on CBR were developed and exported to MS Project for any necessary edits. ElMenshawy and Marzouk [6] proposed a comprehensive framework involving extracting BIM model data through Dynamo programming in Revit. This data is then exported to Excel to generate two schedule options and then optimized using Genetic Algorithms (GA). The developed and optimized schedule is then imported into Primavera P6. While, Yu, et al. [34] directed their efforts toward BIM-Based Scheduling optimization for large-span spatial steel structures in airport terminal buildings. Their framework extracted data from the BIM model and Work Breakdown Structure (WBS) packages, storing it in an MS Access Database. Subsequently, a Particle Swarm Optimization (PSO) algorithm was adapted to optimize the sequence between activities, culminating in developing a feasible schedule applicable to the site.

2.3. BIM-based scheduling maturity level two

This level of maturity has targeted visualizing the scheduling data for better communication, which resulted in 4D models that emerged many benefits to the AEC industry by making it possible to review the method by which the project will be executed and correct any possible mistake in the construction plans. Also, it decreases Health Safety and Environment (HSE) risks, besides other potential risks, and saves time and cost.

Early efforts in this level of maturity, which include works of [38,39] produced the 4D simulation. However, linking the construction schedule to the 3D BIM model to create this simulation was left manual, making it error-prone and time-consuming.

Recent efforts in this maturity level focused on linking the schedule with the BIM model to automate the 4D simulation. Such efforts are based on manually created schedules and BIM models or an automatically generated schedule from the BIM model but oriented toward 4D simulation only without considering creating a feasible schedule for site works. The efforts exerted by [9,40–43] are considered examples of work of this level. Torres-Calderon, et al. [9] created a framework to address the problem of lack of implementation of 4D simulation, that uses Machine Learning (ML) to recognize the activities, their locations, and the phase in which they are performed and then match these activities with the corresponding elements in the 3D BIM model, then the 4D simulation is developed. In a related study by Altun and Akcamete [40], a schedule derived from the 3D BIM model was created, coupled with the automated linkage of elements to facilitate the development of a 4D simulation. The framework begins by generating 4D identifiers for distinct 3D model elements, organizing them based on properties for scheduling. The data is then passed to a planner to arrange and supplement activities, creating a manually developed schedule. In the final stage, an automatic linkage between the schedule and the 3D model, using 4D IDs, enables the creation of a 4D simulation, aligning temporal and spatial aspects of the BIM model. Notably, while resulting from an automated process, the schedule is considered manual due to its reliance on a planner using exported data with 4D IDs. Other efforts by, Kang, et al. [41],Chau, et al. [42] have used a shared WBS. While, Mirzaei, et al. [43] have created 4D BIM systems showing an improvement in the dynamic detection of time-space conflict. Additionally, Kim, et al. [44] generated an automated 4D simulation by creating constructible (structurally stable) sequences. This approach robustly incorporates structural data, encompassing nodes and connections, while addressing variations in static indeterminacy.

2.4. BIM-based scheduling maturity level three

This level of maturity is considered the higher as it includes all the previous levels while adding interconnectivity and is oriented toward more automation in all phases of BIM and scheduling management.

At this level, many frameworks have been proposed that build on the first level in developing and optimizing the schedules using BIM and the second level in automatically linking the 3D model elements to the schedule's activities. Also, more advanced studies at this level have customized their frameworks to facilitate the IPD delivery method. At the same time, others included the creation of data structures like ontology and optimizing simulations like discrete-event simulation (DES).

The efforts exerted by ([5,12,45,46]) are considered examples of the work of this level. For instance, Elghaish and Abrishami [5] proposed a Navisworks-based framework to streamline 4D modeling. Starting with 3D model import, the planner selects a Work Breakdown Structure. Design elements are added, and the planner picks an activity from framework suggestions, utilizing diverse methods. GAs propose optimal approaches, but the planner retains the flexibility to choose alternatives. Resource tracking and optimization precede the development of the 4D model and schedule. Another study in this group of efforts was developed by Mohammadi, et al. [47] that extracts BIM model data and develops an ontology based on it. Later, this ontology structure is used to optimize the resources and produce the most optimum schedule. Finally, a 4D simulation is generated to visualize this schedule.

2.5. Comparative analysis

To demonstrate the effectiveness of the proposed framework, Table 1 shows a comparative analysis of the four levels of maturity and the proposed framework.

In Table 1, it is evident that all features present at level 0 are encompassed within level 1. Moreover, all features found in both level 1 and level 2 are incorporated into level 3. However, notable distinctions emerge, as certain features existing at level 1 are not accessible in level 2. This discrepancy arises from the primary focus of level 2, which centres around 4D Simulation and the automated correlation between scheduled activities and the BIM model elements. Consequently, the automation of schedule generation, aimed at producing a practical and real schedule for construction, optimizing resource utilization, and exporting it to a commercial software, assumes a secondary role beyond the primary concerns of most contributors at this level. Consequently, in response to this issue, level 3 seeks to address these disparities by establishing a framework that amalgamates the advantages of level 1 with the automated 4D simulation capabilities provided by level 2.

3. The proposed framework for BIM-based automatic schedule generation, optimization and simulation

This paper introduces a framework that integrates BIM into the processes of generating and optimizing schedules automatically while providing 5D simulations and BI dashboards. The proposed framework consists of nine stages, as shown in Fig. 1:

Stage 1 - BIM Model Generation: in the initial stage, the framework focuses on improving BIM implementation by automating the generation of BIM models. This is achieved by leveraging CAD drawings data or manually filled tables (Excel files) through a dedicated BIM software plug-in.

Stage 2 - BIM Model Data Extraction and Integration: this stage involves extracting BIM model data using another BIM software plug-in and then storing this data in a structured database specifically designed for scheduling software (SQL Database). Proceeding to stage 3 - Resources and activity code libraries creation, in this stage the framework facilitates the creation of libraries for resources and activity codes within the structured database of the scheduling software. Stage 4 - Activities generation with resource and activity code assignment, this stage utilizes a developed algorithm to read BIM model data from the structured database table, generating activities and assigning resources and activity codes accordingly. Stage 5 - Activities sequential order generation and assignment, this stage employs another algorithm to determine the sequential order of activities based on logical and spatial relations, subsequently assigning these relationships to the activities, which ensures a well-structured and organized project schedule. Stage 6 - Schedule optimization using GAs, in this stage the framework extracts the schedule data and utilizes GAs to generate an optimized schedule that aligns with the project's finish date. This optimization process ensures efficient resource allocation and overall project timeline adherence. Stage 7 - Project schedule simulation in an automatically generated 5D simulation, Once the schedule is complete, stage 7 establishes links between the activities and their corresponding BIM elements, facilitating the automatic generation of a 5D simulation. This simulation provides a valuable visual representation of the project's progression and aids in effective decision-making. To enable effective

Table 1
A comparative analysis between schedule generation approaches.

Level Activity	Level 0	Level 1	Level 2	Level 3	Proposed framework
Activity Generation	Automated based on previous schedules or CAD Drawings	Automated based on BIM Models	Automated based on BIM Models or selected by the planner based on BIM model and previous schedules	Automated based on BIM Models	Automated based on BIM Models
Sequencing Activities	Automated based on previous schedules	Automated based on previous schedules	Automated based on previous schedules or left to the planner	Automated based on BIM Model elements relations or coded rules	Automated based on BIM Model elements relations and coded rules
Exporting the schedule to a commercial scheduling software	Not available	Available just in recent studies	Not available	Available	The schedule is developed automatically inside Primavera P6
Schedule Optimization	Not available	Automated	Not available	Automated	Automated
Providing 4D simulation	Not available	Not available	Automated as the main target of the schedule	Automated	Automated
Resources assignment inside the scheduling software	Not available	Not available	Not available	Not available	Automated
BI Dashboards	Not available	Not available	Not available	Not available	Automated
Live updating with changes	Not available	Not available	Not available	Not available	Automated
Single database for BIM data and schedule data	Not available	Not available	Not available	Not available	The core of the developed framework

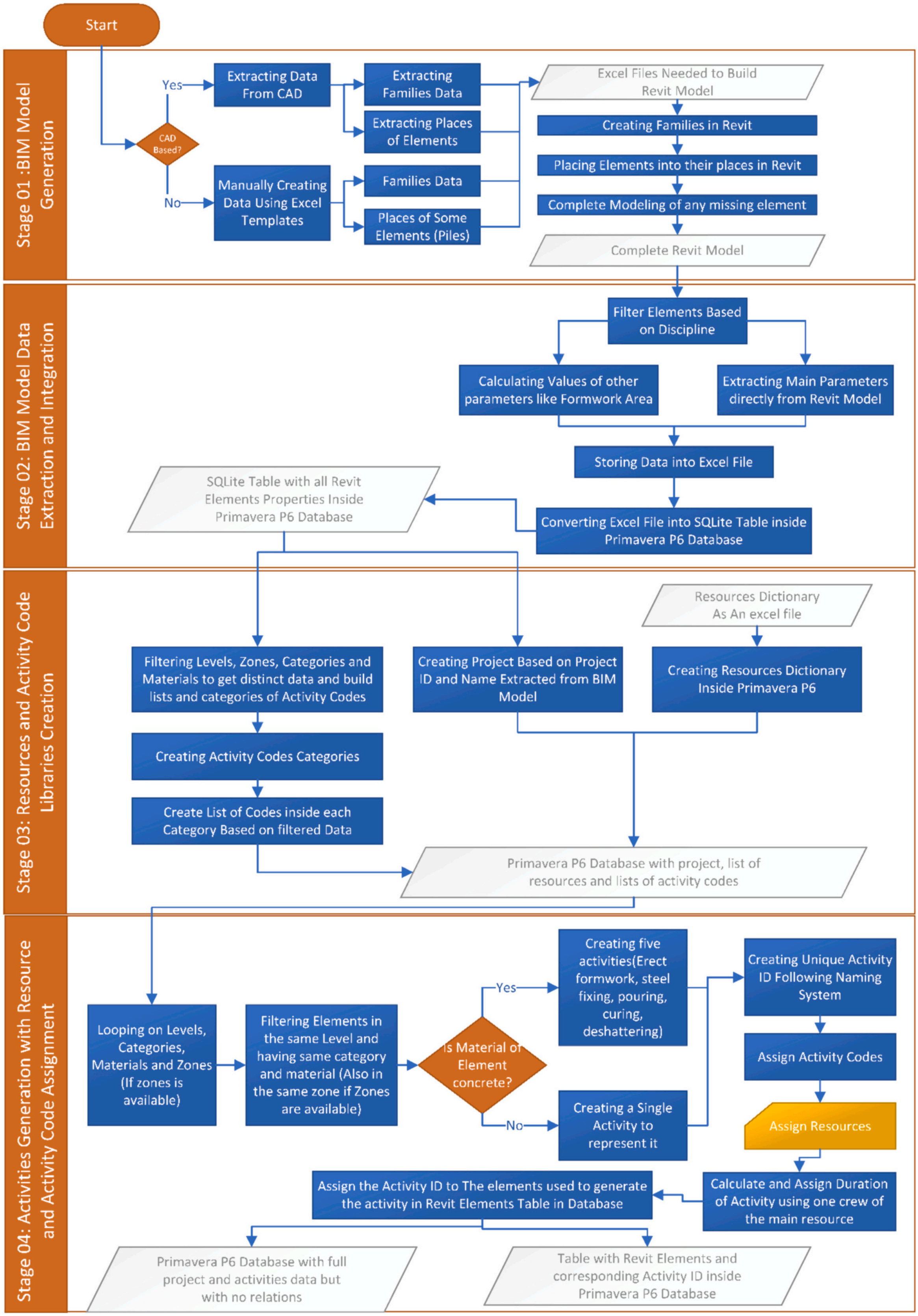


Fig. 1. The proposed BIM-based framework for schedule generation and optimization using GAs.

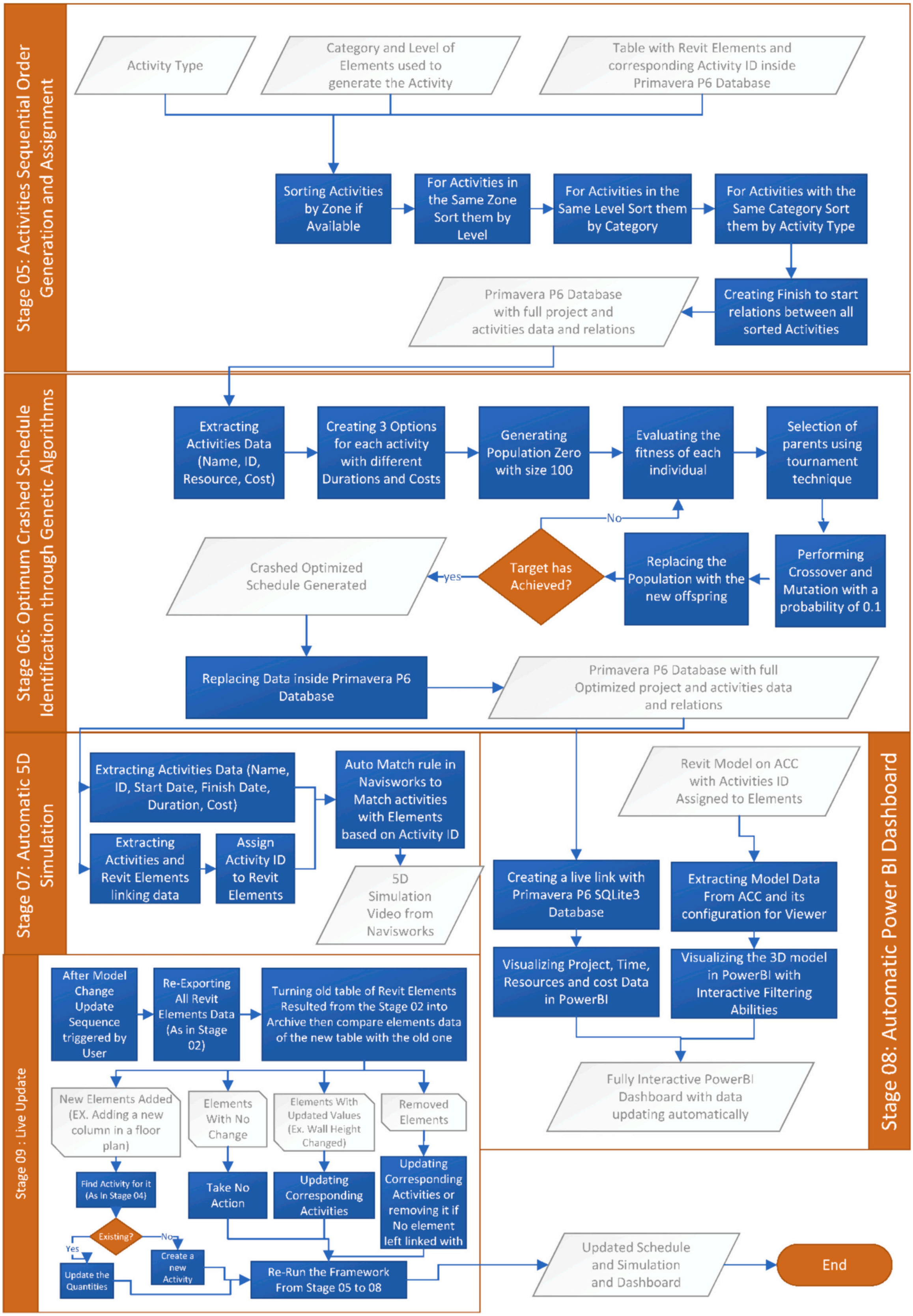


Fig. 1. (*continued*).

project monitoring. Stage 8 - BI dashboard generation for project control, this stage utilizes the data from the structured database of the scheduling software, the BIM model, and the 3D representation of the model to generate a business intelligence dashboard. This dashboard serves as a centralized platform for project control and provides key insights and metrics to project stakeholders. Lastly Stage 9 - Live updates based on BIM, this stage ensures that the framework remains updated with changes in the BIM model. Any modifications made to the model trigger an automatic re-execution of the remaining stages, ensuring that all framework outputs accurately reflect the updated information. This seamless integration of changes allows for efficient project management and adaptability. The detailed descriptions of each of the nine stages are presented in subsections 3.1 to 3.9, respectively.

3.1. BIM model generation

Creating a model with sufficient information and adhering to established best practices is crucial to automatically generating a schedule from a BIM model. However, BIM models are not commonly utilized by SMEs. Therefore, implementing this framework in such companies would require a significant investment of time and potentially additional costs to build the BIM model. Consequently, the framework offers a preliminary stage to enhance BIM implementation before generating the schedule. During this stage, the user has two options: firstly, the user may furnish CAD drawings and additional details as input, which will be subject to analysis by specialized software to detect family types and element locations. These findings will then be exported in the form of Excel files. Alternatively, the user can manually populate Excel file templates to generate families, place elements, and manually model the rest of the BIM model.

After model generation, the user will set the project zones in a shared parameter injected in each element. The zones can be different buildings within the same model or parts of the same building.

3.2. BIM model data extraction and integration

The essential data are extracted for generating the project schedule upon generating the BIM model. This data includes: (1) Project information, encompassing the project name and ID; (2) Elements information, comprising volume, area, material type, location, height, dimensions, category, and type; and (3) Information of non-modelled elements like formwork and insulation. A dedicated BIM plug-in extracts and organizes the data into a table to facilitate this process. The plug-in directly extracts information, such as volume and area, from the elements and stores it in the table. Meanwhile, it unifies other data from different element categories, such as base level, due to variations in nomenclature across various categories within the BIM model (the Base Level of an element in the category of the floor is called Level while in Beams, it is called Reference Level and in walls called base constraint so it needs to get unified under the same name in the extracted data table to be processed later). Moreover, other information is calculated, such as formwork or insulation, based on existing element parameters.

Then, the collected data and the constructed table are stored in the scheduling software's structured database, which enables more accessible establishment of relationships between this data and other relevant information within the database and the automatic reflection of future updates.

It is worth noting that the existing database schema of one of the most widely adopted scheduling software, Primavera P6, is based on a structured database of 124 tables. While these tables contain comprehensive data about activities, projects, codes, relations, and resources, there is no dedicated table for storing BIM model data. To address this, a new table called "REVIT_ELE" is created within the database, specifically designed to store the data extracted from the BIM model, as shown in Fig. 2.

3.3. Resources and activity code libraries creation

Following extracting and storing the necessary BIM model data for schedule generation, the required libraries within the scheduling software are constructed. During this stage, additional inputs are solicited from the user in the form of an Excel file containing resource data, including the ID, name, cost, productivity, and data related to elements used to generate the activity that this resource should be assigned to, including material type association, element type association and structural level of the corresponding elements. Subsequently, using a developed algorithm, data are stored in the respective tables within the structured database.

Simultaneously, while building the resources library, the framework accesses the BIM model data stored in the database to generate categories and lists of activity codes. These codes are then stored in their respective tables within the structured database of the scheduling software. As part of this process, an empty project is initialized using the project ID and name retrieved from the BIM data stored in the database preloaded with essential information awaiting the inclusion of activities.

3.4. Activities generation with resources and activity codes assignment

The activities are generated using the newly created empty project, along with the activity code and resource libraries. Initially, the algorithm utilizes lists of zones, levels, categories, and materials to group model elements. Based on this grouping, a list of activity names is generated, describing the grouped elements. The naming system for activities consists of five parts, as depicted in Fig. 3.

The first part represents the type of work, with predefined values for concrete elements such as "Erect Formwork of," "Steel Fixing of," "Pouring," "Curing," and "Formwork Removal of." For other elements, the type of work is set as "Creating." The second part represents the Material Type, such as "concrete," "steel," "wood," etc. The third part corresponds to the category, such as "Slab," "Ground Beams," "Structural Columns," "Wall," "Structural Framing," and "Foundations." The fourth part denotes the name of the zone, if applicable. Finally, the fifth part signifies the level of the elements.

Once the activities are created with their respective names, the algorithm assigns a unique activity ID. This ID serves as a reference for the activity in any associated documents. The ID begins with three letters, representing the department under which the activity is performed, such as "CON" for Construction, "ENG" for Engineering, and "PRO" for Procurement. Additionally, the algorithm assigns activity codes that reflect the activity classification based on the data of the BIM model elements that were grouped to generate the activity.

Subsequently, another algorithm runs to assign resources to the activities. This algorithm first reads the activity name and relevant data from the activity's associated BIM elements, such as material and category. It then determines the type of activity based on its name. Following that, the algorithm uses this information to determine the necessary material resources to be assigned to the activity and its amount. Meanwhile, it identifies the primary resource (crew) to be allocated to the activity and assigns just one crew to the activity.

Furthermore, the activities' durations are calculated based on the production rates of the resources and the quantities of materials assigned to an activity. The Database ID and the unique activity ID are then stored back in the BIM elements' table in the database. This enables tracking of changes and automatic linking of the generated schedule with the BIM model during simulation.

3.5. Activities sequential order generation and assignment

The relationships among activities are created to form the schedule after generating activities, assigning codes and resources, and determining their durations. In this stage, information about the type of each activity and the BIM elements utilized to construct these activities, including their categories and base levels, is used. The process starts by grouping and sorting the activities. Based on user preferences, one of these logics is applied

1) Finishing level by level in all Zones (Like a single connected building)

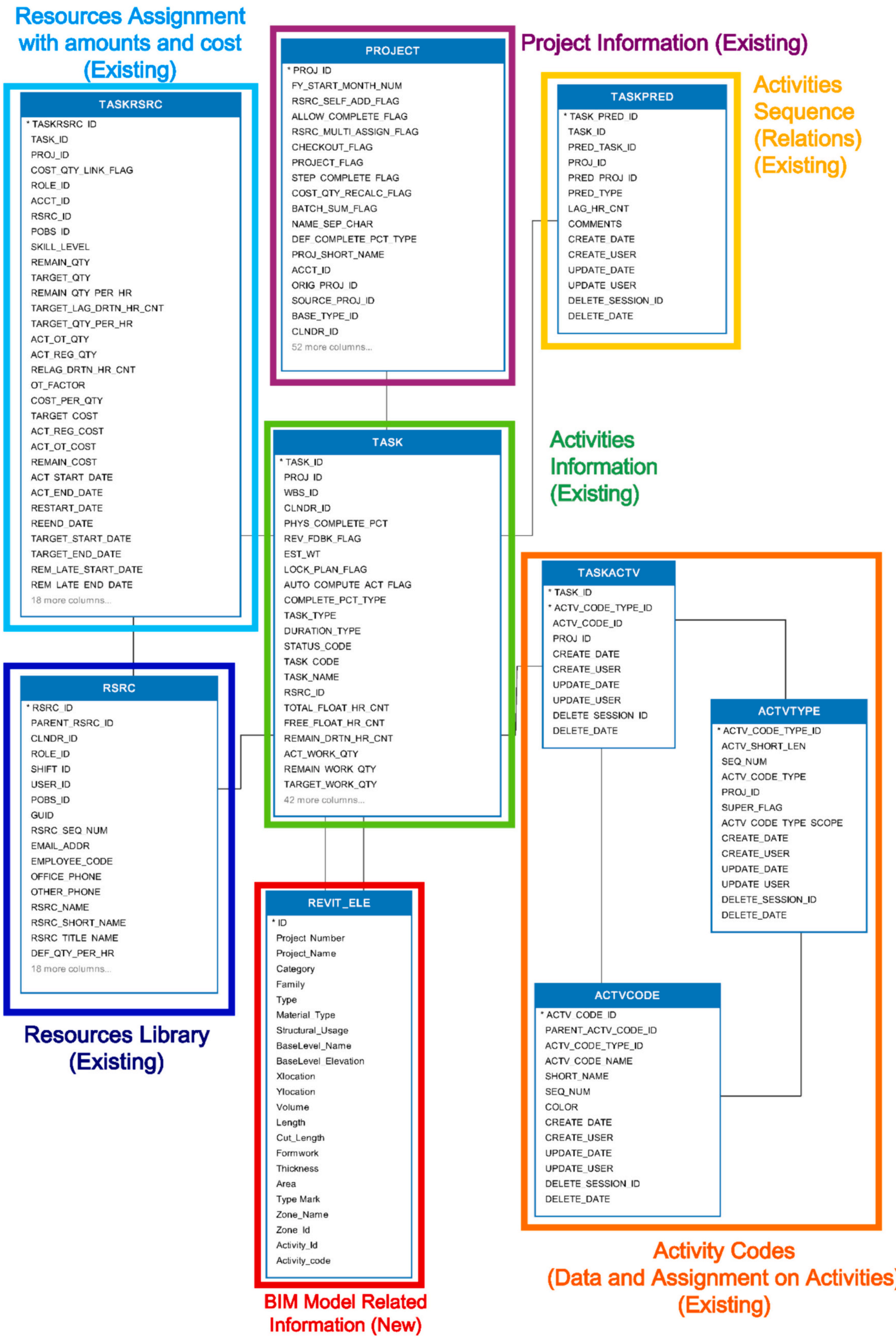


Fig. 2. Main tables of the SQL database.

Part 01	Part 02	Part 03		Part 04	Part 05
Type of Work	Material	Category of Elements		Zone	Level
Erect Formwork of	Concrete	Structural Foundations	In	Zone01	Level Lower

Fig. 3. The naming system of activities.

Initially, activities are sorted by the elevation of the base level of their respective BIM elements using the relation between the activities table (Tasks) and BIM data table (REVIT_ELE); for activities that contain elements within the same level, the algorithm performs sorting based on the category of elements (foundations, then structural framing and slabs together, then structural columns and walls together). Activities with the same category are sorted based on the zone. Then, within the same zone, the algorithm considers the material of elements (Activities of concrete elements are performed before activities of steel elements), followed by the activity type (shuttering, then steel fixing, then pouring, then curing, then Formwork Removal), for activities originating from the same element (e.g., activities associated with concrete elements).

2) Finishing zone by zone at all Levels (Like separated buildings)

Initially, activities are sorted by zone, and then the algorithm prioritizes the elevation of the base level of their respective BIM elements. Furthermore, activities within the same level are sorted based on the category of elements (foundations, structural framing slabs, structural columns, and walls together). Additionally, the algorithm considers the material of elements, followed by the activity type (shuttering, steel fixing, pouring, curing, and Formwork Removal) for activities originating from the same element (e.g., activities associated with concrete elements).

Once the sorting and grouping are completed, the finish-to-start relationship between activities is established. Subsequently, lags are assigned between activities whenever needed.

3.6. Finding the optimum crashed schedule

Upon creating a schedule, the finish date is compared with the contractual finish date. Then, if necessary, the schedule is optimally cashed using GA. Based on the law of diminishing returns, when more crews of workers are added to the project, their original productivity decreases. Meanwhile, the cost may increase to coordinate them. So, to perform the optimization, additional data is collected from the user, including the maximum allowed number of crews for each resource (to ensure that the algorithm will not use crews more than what the space of the project can take or more than what a contractor can recruit), performance index for each resource in each option (an index that is used to decrease the productivity and increase the cost when the crews increase in the site).

3.6.1. Generating construction options (scenarios)

Subsequently, the algorithm generates multiple scenarios in a way similar to ElMenshawy and Marzouk [6]. To highlight their differences, these scenarios can arise from alternative construction methods, which can significantly impact the productivity rate of specific tasks. Additionally, they can result from an increase in the number of crews or different crew formations. The user-inputted performance index is multiplied by that productivity rate, influencing the durations and costs calculated for each scenario. The developed code enables the generation of three schedule scenarios as follows.

Finding the number of crews for each option:

For the first option, the algorithm uses just one crew. In contrast, for the second option, the algorithm calculates 50 % of the maximum allowed number of crews for the resource. Then, it checks the duration of activity resulting from using this number. If it is equal to or more than one day, then it is acceptable; otherwise, if the duration is less than one day, the algorithm finds the number of crews achieving the 1-day duration (to ensure that there are no extra crews more than the needed work). On the other hand, the third option uses the maximum allowed number of crews for the resource and then performs the same check performed in the second option.

Finding the performance index:

If the option uses just one crew, then the performance index of option one is used, while if it uses 50 % of the maximum allowed number of crews, then the performance index of option two is selected. Moreover, if the maximum allowed number of crews is used, then the performance index of option three is selected in cases where the number of crews is not an exact value of these. The nearest index is selected (e.g., if option three uses 60% of the maximum number of crews, as using 100% will make the activity less than one day based on its amount of work, then the performance index of option two will be used as 60% is near to 50% more than 100%).

Calculating the duration and the cost of the activity:

The calculation of duration is based on the following formula:

$$\text{Activity Duration} = \frac{\text{Amount of work*the Performance Index}}{\text{Number of Crews*Crew Production Rate}}$$

While the activity cost is calculated based on the following formula:

$$\begin{aligned}\text{Activity Cost} = (&\text{Number of Crews*Cost of Crew Per Day} \\ &\text{*Activity Duration}) + \text{cost of material}\end{aligned}$$

3.6.2. Optimizing the schedule using GAs

The different scenarios eventually lead to a trade-off problem, solved using GAs. GA relies on three fundamental operations: selection, crossover, and mutation [48]. The implementation of GAs in this framework consists of the following operations:

Initialization:

The algorithm starts by initializing a population of potential solutions, where each solution (chromosome) represents a combination of options for all project activities generated by randomly assigned integers ranging from 1 to 3 (different scenarios). The population size is set based on user input. Then, the project duration is calculated considering the assigned calendar (defined by the user).

Evaluation:

The fitness function evaluates the quality of a solution by computing the total duration and cost based on the selected options. The soft constraint is to minimize the difference between the total duration of selected options and the target duration (contractual end date) and reach zero difference, if possible. While the objective is to minimize the total project cost while achieving this soft constraint. The fitness function uses the following formulas.

The project duration is calculated as follows (assuming all activities are sequential).

$$\begin{aligned}\text{Total Project Duration} = &\sum \text{Duration of the selected option of activity i} + \sum \text{lag between activities} + \text{Total days off} \\ &\text{i} = 1, \ldots\ldots, \text{n (number of activities)}\end{aligned}$$

The total cost is calculated as follows.

$$\text{Total Cost} = \text{Total Direct Cost} + \text{Total Indirect Cost}$$

$$\text{Total Indirect Cost} = \text{Indirect Cost Per Day*Total Project Duration}$$

$$\text{Total Direct Cost} = \sum \text{Cost of the selected option of activity i}$$
$$\text{i} = 1, .., \text{n (number of activities)}$$

Selection (Tournament Selection):

The selection strategy determines which individuals are chosen for reproduction, with the premise that superior chromosomes pass to the next generation to enhance the population [6]. Tournament selection is one of the GA selection methods in which a predefined number of individuals compete against each other, typically with a tournament size of two. This selection is easy to implement and enhances selection efficiency [48,49]. It is worth noting that larger tournament sizes can lead to a loss of diversity, as individuals may not be selected from the beginning or may lose in a tournament against individuals with higher fitness [6].

This algorithm uses a Tournament selection technique with some modifications to select parents for crossover while balancing exploration (finding new potential solutions) and exploitation (choosing the best-known solutions). In each tournament:

1. A subset of n potential parents (the tournament size set based on user input) is randomly chosen from the current population.
2. Each individual in the tournament competes based on their fitness.
3. The individual with the best fitness among the tournament participants is selected for crossover. This ensures that the individual is fit and has a higher chance of contributing favourably to the next generation.

Crossover and Mutation:

Crossover is applied (with a crossover rate defined by the user) to selected parent solutions with random crossover points, creating new offspring solutions.

Mutation introduces random changes to offspring solutions with its probability defined by the user.

Replacement:

The GA proceeds to the replacement step after creating new offspring chromosomes through crossover and mutation. In this step, the old generation is entirely replaced by the new offspring generation. This ensures evolving toward better solutions with each iteration. The number of individuals remains constant throughout the evolution cycles.

Termination Criteria:

The algorithm terminates under the following conditions:

- After reaching the user-defined number of generations.
- The optimization process converges (i.e., the obtained solution does not change through ten consecutive iterations).

Upon completion of the GA, the optimized schedule is retrieved. This final schedule is then stored in a structured database within the scheduling software.

3.7. Generating a 5D simulation

Once the fully developed schedule and the BIM data are available, a 5D simulation of the project could be automatically generated. This process involves extracting activities' IDs and their corresponding element IDs in the BIM model and then using a developed BIM plug-in to attach activity ID information to the respective BIM elements. Then, extracting activities' details such as name, ID, start and finish dates, cost, and duration. So, the Activity ID can be used in an automated matching rule to link the BIM elements to each respective activity, automatically creating the 5D simulation. This simulation plays a critical role in decision-making by aligning the efforts of diverse project stakeholders and minimizing operational conflicts at the project site while helping to discover any issue in the construction method along with reducing safety risks.

3.8. Generating a BI dashboard

By leveraging the fully developed schedule and the BIM model, a specialized dashboard template is created to display project data and incorporates a 3D viewer. A developed data connector is also employed to retrieve model data from the cloud, commonly utilized for collaborative design purposes. The schedule data is obtained by directly connecting to the SQL database. The purpose of this developed dashboard is to serve as a valuable tool for facilitating informed decision-making and actions. As the dashboard maintains a live link with the BIM model and the schedule, it consistently reflects updates as they are recorded, which can help better understand the construction method using interactive simulation in the dashboard. Also, it discovers issues in the planning and cost estimates by showing their link to the actual BIM model elements.

3.9. Performing live update

Upon the occurrence of any alterations within the BIM model, an algorithm is promptly initiated. This algorithm starts by re-exporting all elements data from the BIM model as in stage 2. This data is stored in the same SQL database while the table of the old extracted data gets its name changed to "Old_REVIT_ELE" then the algorithm harnesses the analytical capacities of the SQL database to discern and pinpoint modifications between the new table and the old table. Subsequently, these changes are categorised as (1) Elements added (ex., adding a new column to a floor plan), (2) Elements with no change, (3) Elements with updated values (ex., wall height changed), and (4) Elements got removed. Then, the algorithm removes activities if all BIM model elements associated with it have been removed or update the quantities of material and the duration of activity if some BIM model elements got updated, while if an element added to the model and has no existing activity that it can be grouped under then a new activity is created. These modifications are integrated into the activities embedded within the scheduling software. Consequently, the framework undertakes a reiteration of stages 5 to 8 thereby accommodating the updated dataset.

Concurrently, the algorithm regenerates the 5D simulation, ensuring its fidelity in representing the amended project information. It is pertinent to emphasize that these updates do not influence the dashboard's functionality, as it seamlessly and instantly adapts to changes. The real-time interconnection between the dashboard, the database, and the model facilitates this integration.

4. Proposed system automation and implementation on a case study project

The purpose of the case study is to evaluate the reliability and feasibility of the multi-phase framework. The framework has been developed to work with any structure following the bottom-up (where elements are constructed from lower levels to higher levels) cast-in-situ construction method, so it can be applied to (building construction projects, and infrastructure like bridges) and on any scale as long as they are constructed following this methodology. There is almost no difference between all these categories of buildings in their structural elements in different scales except for the change of using zones with medium and large-scale buildings to split them into smaller phases of construction. As such, the case study project selected is a three-story technical school consisting of three zones. The building includes floors, roofs, beams, columns, piles, trusses, and other components. The structural BIM model of the school is built in Revit, as shown in Fig. 4.

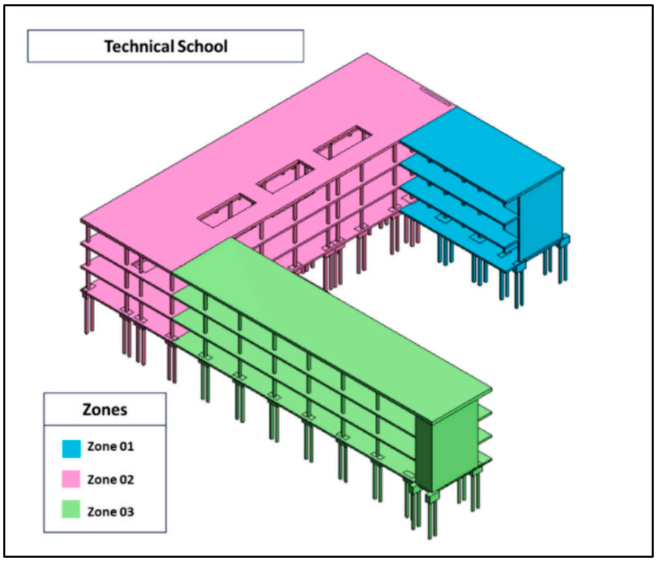


Fig. 4. School BIM model with coloured zones.

4.1. The prototype

To enable implementation and automation of the developed framework, a prototype was developed that uses a developed BIM plug-in in Revit for BIM modeling from Excel. Another developed BIM plug-in in Revit for BIM data extraction, Primavera P6 Professional Project Management (PPM) for building the schedule in a structured database-based scheduling software, SQLite 3 for the database, a developed GA for optimization, Navisworks for the 5D simulation, and Microsoft PowerBI for BI dashboards. The overview of these processes is shown in Fig. 5.

The selection was made to consider a low-cost implementation to fit SMEs. The prototype is implemented only on the structural elements of buildings. It was deployed on a machine with the following specifications: RAM: 16 GB with processor 11th Gen Intel(R) Core (TM) i7-11800H @ 2.30GHz, 2304 MHz, 8 Core(s), 16 Logical Processor(s); Graphics: NVIDIA GeForce RTX 3050 Laptop GPU: software: Autodesk Revit 2023, Primavera P6 PPM (22.12) and Microsoft Excel 365.

Alternative options for schedule management, BIM authoring, and BI dashboards can be used to implement this framework including but not limited to, Primavera P6 (desktop), Primavera P6 EPPM (Server) and Primavera Cloud (Cloud Based) for schedule management, Autodesk Revit, ArchiCAD, Tekla, and IFC files for BIM authoring, and Autodesk Navisworks, Synchro 4D Pro, and Fuzor for simulations. Moreover, Microsoft PowerBI and Oracle BI are among the viable choices for BI dashboards.

Details of the implementation process are outlined in the following subsections.

4.1.1. BIM model generation

A Revit plug-in was developed to generate the BIM model to generate families and place elements based on a set of Excel files. Fig. 6(A) shows the ribbon of this developed plug-in into Revit. It contains a button to generate levels based on Excel files automatically, a drop list of buttons to generate families needed in the Revit model as shown in Fig. 6(B), and another drop list of buttons to place the elements into their place based on another set of Excel files as shown in Fig. 6(C). Using this plug-in, the prototype can either transfer CAD to Revit or assist a BIM modeller in generating the model from scratch using a set of Excel templates.

The levels creation works based on an Excel file that contains names of levels and their elevations in mm so the algorithm can automatically generate a set of levels and their structural plan views based on these data. Fig. 7 shows the Excel file imported into the developed Revit plug-in and the resulting levels generated in the project.

For the families' creation, the algorithm retrieves family parameter data from Excel files. It either imports a custom family included in the plug-in for elements (beams, columns, foundations, and piles), or it duplicates an existing type in the Revit model (slabs, floors, walls) and sets their new values. The parameters in the Excel files vary from one category to another, e.g., beams (name, width, and depth) while piles (name and diameter) and walls (name and thickness). Fig. 8 shows some Excel files used to generate families in the case study and the resulting families in the BIM model.

Finally, for the elements placing part, there are three algorithms governing it; the first one is used on elements needing a single point to be placed (columns, piles, isolated footings), while the second is for elements needing a path (a line) to be placed like (walls and beams) the third and final one is for elements needing a polygon or an area to be drawn like (slabs and floors). After creating elements, the user needs to manually create some elements like stairs and ramps and data like project name and number; then, the model is considered completed and ready to be used in the following steps. Fig. 9 shows the placement of columns in the BIM model based on an Excel file.

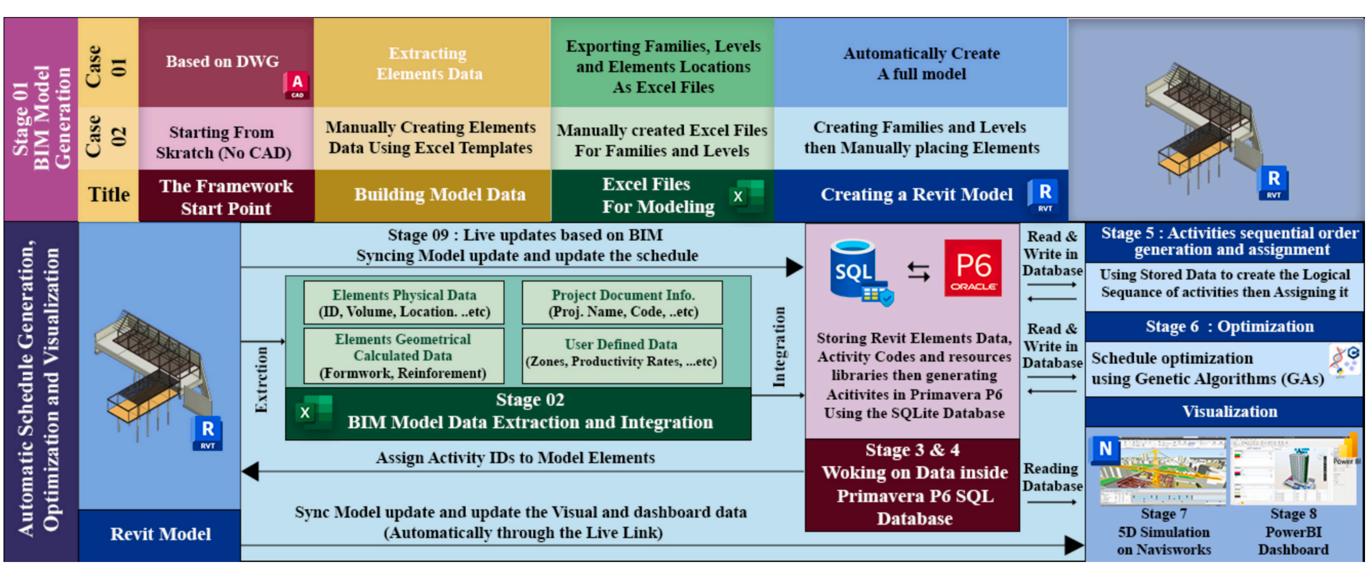


Fig. 5. Prototype processes overview.

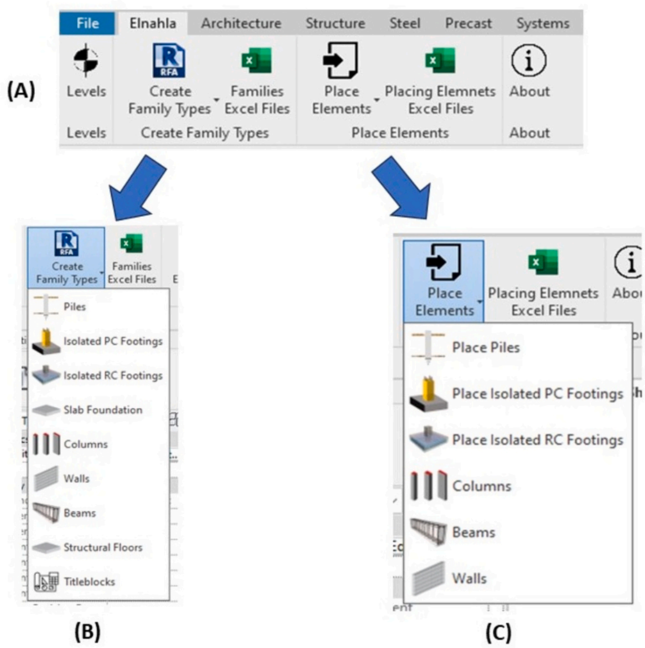


Fig. 6. Revit plug-in to generate the BIM Model.

4.1.2. *BIM model data extraction and integration*

After creating the model, another developed Revit plug-in extracts the model data and builds the schedule. Fig. 10 shows the ribbon of this plug-in.

The plug-in has two options to extract data: as an Excel file to be used as a document of quantity surveys or as a Primavera schedule. When the primavera schedule is triggered, the Excel file template shown in Fig. 11 opens to allow the user to enter data (yellow highlighted fields) not available in the BIM model and needs to create the schedule.

After filling in the data and running the schedule generation, the plug-in extracts the model data into an Excel file. As shown in Fig. 12, the file is converted into a table placed in a Primavera P6 SQLite 3 database that is stored inside the plug-in as a template. The data extracted is either extracted directly (Project Name, Project Number, Element ID, Element Type, Element Category, Element Area, Element Volume, Element Material) or remapped from their original parameter name to the name used in the data collection table like (Level of the element will be mapped to Base Level in the collection data structure) or the value is calculated from other parameters like the side area of the element.

4.1.3. *Resources and activity code libraries creation*

Using user inputs retrieved from the created table of the BIM model elements, lists of activity codes are generated; for example, a category is created for levels, and then a list of these levels is created based on the levels of elements extracted from the BIM model and stored in the database. Afterwards, the resources library in Primavera is generated; this library is based on the Excel file of resources the user provided as input earlier. After generating the libraries, another script starts detecting the name and ID of the project stored in the BIM model and reflects it on a new project inside the database.

4.1.4. *Activities generation with resources and activity codes assignment*

This algorithm runs through the BIM model, starts grouping elements based on zone, level, category, and material, and generates activities' names using these groups. Five activities are created for concrete elements (Erect Formwork, Steel Fixing, Pouring, Curing, Formwork Removal) and one activity for other elements. Then, an activity ID is generated, and the activity is created in the database with codes and resources assigned to it. Meanwhile, the algorithm returns the activity ID and database ID of the activity. Consequentially, it stores each element used in this activity in the BIM data table in the database. Fig. 13 shows the generated activities with codes and resources assigned to them and durations and costs calculated.

4.1.5. *Activities sequential order generation and assignment*

After generating activities, the algorithm starts sorting and linking them based on the selected preferences. In this case study, the finishing level by level in all zones' logic is selected as there is only one building in the project, and it is needed to finish all zones of each level before proceeding to the next level.

4.1.6. *Optimum crashed schedule using GA*

After the automatic schedule generation, the initial schedule finish date was falling beyond the contractual finish date (28th January 2025). the duration variance between the contractual finish date and the initially generated schedule finish date resulted because during the schedule generation, the framework always assigns a single crew for each activity whether the activity has a considerable amount of work. Accordingly, the project duration exceeds the deadline date, and the resulting schedule needs to go through a crashing process.

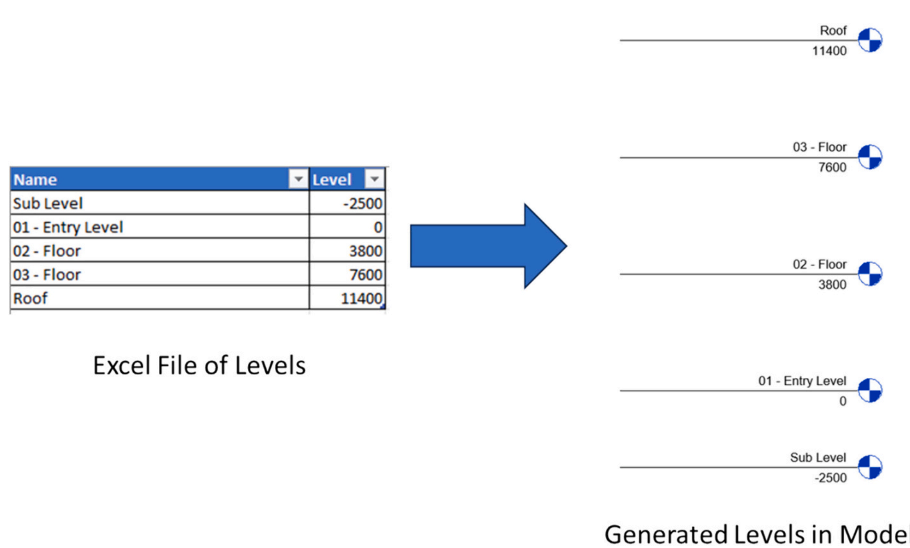
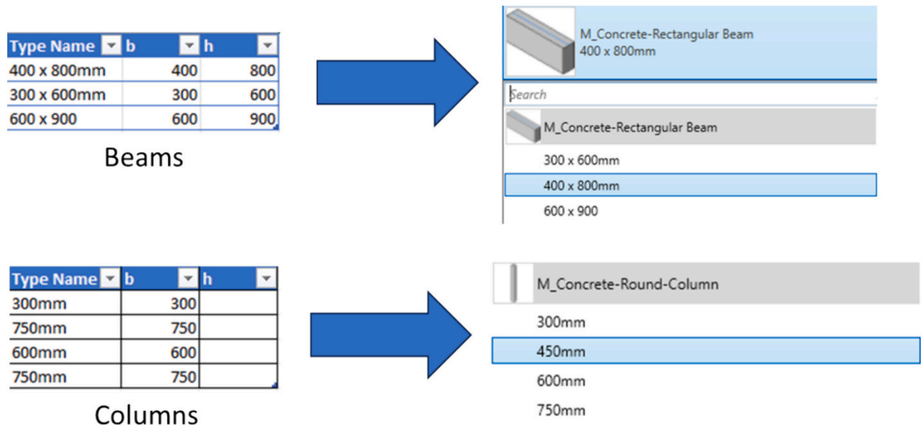


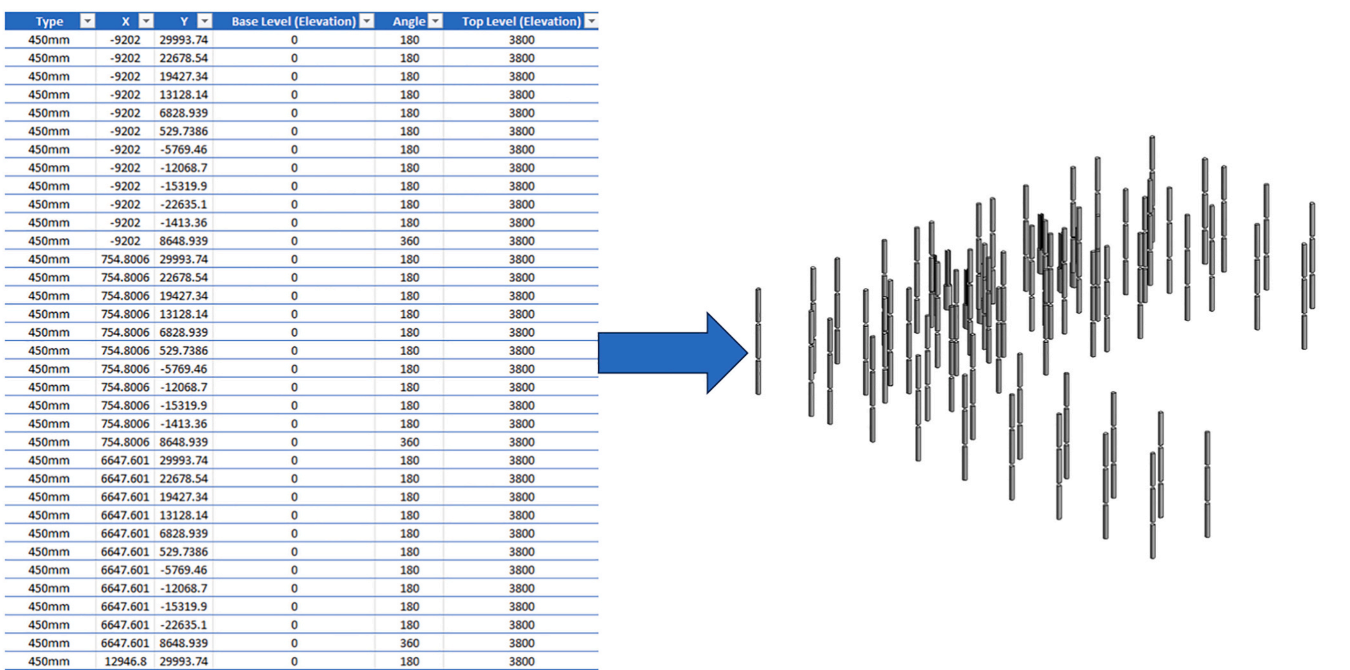
Fig. 7. Levels generation using Excel file.



Type Name	b	h
400 x 800mm	400	800
300 x 600mm	300	600
600 x 900	600	900

Type Name	b	h
300mm	300	
750mm	750	
600mm	600	
750mm	750	

Fig. 8. Excel files of families' generation and the resulting families in the model.



Type	X	Y	Base Level (Elevation)	Angle	Top Level (Elevation)
450mm	-9202	29993.74	0	180	3800
450mm	-9202	22678.54	0	180	3800
450mm	-9202	19427.34	0	180	3800
450mm	-9202	13128.14	0	180	3800
450mm	-9202	6828.939	0	180	3800
450mm	-9202	529.7386	0	180	3800
450mm	-9202	-5769.46	0	180	3800
450mm	-9202	-12068.7	0	180	3800
450mm	-9202	-15319.9	0	180	3800
450mm	-9202	-22635.1	0	180	3800
450mm	-9202	-1413.36	0	180	3800
450mm	-9202	8648.939	0	360	3800
450mm	754.8006	29993.74	0	180	3800
450mm	754.8006	22678.54	0	180	3800
450mm	754.8006	19427.34	0	180	3800
450mm	754.8006	13128.14	0	180	3800
450mm	754.8006	6828.939	0	180	3800
450mm	754.8006	529.7386	0	180	3800
450mm	754.8006	-5769.46	0	180	3800
450mm	754.8006	-12068.7	0	180	3800
450mm	754.8006	-15319.9	0	180	3800
450mm	754.8006	-1413.36	0	180	3800
450mm	754.8006	8648.939	0	360	3800
450mm	6647.601	29993.74	0	180	3800
450mm	6647.601	22678.54	0	180	3800
450mm	6647.601	19427.34	0	180	3800
450mm	6647.601	13128.14	0	180	3800
450mm	6647.601	6828.939	0	180	3800
450mm	6647.601	529.7386	0	180	3800
450mm	6647.601	-5769.46	0	180	3800
450mm	6647.601	-12068.7	0	180	3800
450mm	6647.601	-15319.9	0	180	3800
450mm	6647.601	-22635.1	0	180	3800
450mm	6647.601	8648.939	0	360	3800
450mm	12946.8	29993.74	0	180	3800

Fig. 9. Excel files of elements placement and the resulting elements in the model.

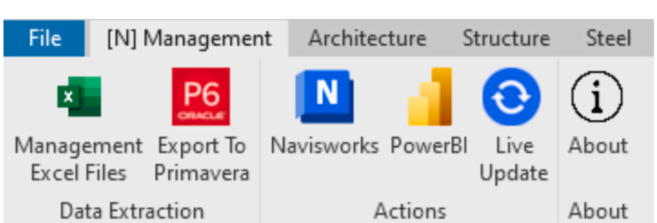


Fig. 10. Revit project management plug-in ribbon.

At the beginning, the algorithm generates three options (scenarios) and exports them as another spreadsheet. Then, the optimization process to reach an optimum crashed schedule starts. First, the days off between the project start date and the contractual finish date are calculated based on user inputs of weekends and vacation dates. Then, different sets of genetic parameter settings are experimented with to find the best set of parameters. Table 2 shows these sets. While Table 3 shows the results of these experiments.

Using the best set of genetic parameters, the algorithm ran through generations to reach the optimum solution that respected the project deadline date resulting in multiple valid solutions. Among the advantages of the GA, the users are presented with a set of solutions where users can choose another solution based on their preference. Table 4 shows a sample of five of these valid solutions resulting from the GA. The fitness shows the total cost, while the numbers between square brackets in the solution show the gene structure of this solution, and each number represent an option selection for each activity in the schedule. While Fig. 14 shows the cost evolution through different generations, where cost of the optimal solution (the solution that achieves the minimum cost and respects the project duration constraint) is plotted against the evolutionary cycle. Instances where the cost remains constant in certain intervals in Fig. 14 indicate the utilization of the best solution from the previous generation, ensuring adherence to the duration constraint, particularly in cases where none of the solutions in the current generation surpass the cost efficiency of the previous generation's best solution while still meeting the specified constraint.

Solution no. 2 shown in Table 4 has the least cost, representing the best solution, reflected in Primavera and automatically modified the

Resource_ID	Resource_Type	Resource_Name	Productivity	Cost	Maximum_Number	Perf_index_01	Perf_index_02	Perf_index_03	Activity Type	Category	Element_Material	Type	Level
R01	Labor	Dewatering Crew	308	174	4	1	0.5	0.5	Dewatering	Earth Work			
R02	Labor	Excavation Crew	406	261	5	1	0.4	0.2	Excavation	Earth Work			
R03	Labor	Backfilling Crew	467	250	4	1	0.5	0.5	Backfilling	Earth Work			
R04	Labor	Compaction Crew	75	114	5	1	0.7	0.4	Compaction	Earth Work			
R05	Labor	Concrete Demolishing Crew	11	266	5	1	0.6	0.6	Demolishing	Demolishing	Concrete		
R06	Labor	Brick Demolishing Crew	23	175	6	1	0.8	0.8	Demolishing	Demolishing	Brick		
R07	Labor	PC Formwork Crew	10	257	4	1	0.5	0.5	Formwork	Structural Foundations	Concrete	PC	Foundation
R08	Labor	PC Pouring Crew	43	243	4	1	0.7	0.5	Pouring	Structural Foundations	Concrete	PC	Foundation
R09	Labor	RC Foundation Formwork Crew	7.6	230	4	1	0.5	0.5	Formwork	Structural Foundations	Concrete	RC	Foundation
R10	Labor	RC Foundation Steel Fixing Crew	10	156	5	1	0.6	0.6	Steel Fixing	Structural Foundations	Concrete	RC	Foundation
R11	Labor	RC Foundation Pouring Crew	21.5	203	6	1	0.4	0.3	Pouring	Structural Foundations	Concrete	RC	Foundation
R12	Labor	RC Columns Formwork Crew	7.6	217	5	1	0.7	0.4	Formwork	Structural Columns	Concrete	RC	
R13	Labor	RC Columns Steel Fixing Crew	10	225	6	1	0.6	0.5	Steel Fixing	Structural Columns	Concrete	RC	
R14	Labor	RC Columns & Walls Pouring Crew	21.5	194	5	1	0.5	0.5	Pouring	Structural Columns & Walls	Concrete	RC	
R15	Labor	RC Walls Formwork Crew	7.6	240	5	1	0.7	0.2	Formwork	Walls	Concrete	RC	
R16	Labor	RC Walls Steel Fixing Crew	10	209	6	1	0.4	0.3	Steel Fixing	Walls	Concrete	RC	
R17	Labor	RC Beams Formwork Crew	7.6	149	6	1	0.5	0.4	Formwork	Structural Framing	Concrete	RC	
R18	Labor	RC Beams Steel Fixing Crew	10	130	4	1	0.4	0.3	Steel Fixing	Structural Framing	Concrete	RC	
R19	Labor	RC Floor Slabs Formwork Crew	7.6	209	6	1	0.5	0.4	Formwork	Floors	Concrete	RC	
R20	Labor	RC Floor Slabs Steel Fixing Crew	10	115	6	1	0.7	0.7	Steel Fixing	Floors	Concrete	RC	
R21	Labor	RC Floor Slabs & Beams Pouring Crew	21.5	185	6	1	0.6	0.5	Pouring	Floors & Structural Framing	Concrete	RC	
R22	Labor	RC Stairs Formwork Crew	7.6	210	5	1	0.8	0.5	Formwork	Stairs	Concrete	RC	
R23	Labor	RC Stairs Steel Fixing Crew	10	160	4	1	0.5	0.5	Steel Fixing	Stairs	Concrete	RC	
R24	Labor	RC Stairs Pouring Crew	21.5	272	6	1	0.7	0.6	Pouring	Stairs	Concrete	RC	
R25	Labor	Foundation Insulation Crew	8	124	6	1	0.5	0.4	Insulation	Structural Foundations & Ground Beams	Concrete	RC	Foundation
R26	Labor	Roof Insulation Crew	9	198	5	1	0.4	0.4	Insulation	Floors	Concrete	RC	Roof
R27	Labor	Basement Insulation Crew	8	230	5	1	0.7	0.5	Insulation	Walls	Concrete	RC	Basement
R28	Labor	Deshattering Crew	20	242	4	1	0.6	0.3	Deshattering		Concrete		
R29	Labor	Steel Structure Crew	15	195	5	1	0.5	0.4	Steel Structure		Steel	Steel	
R30	Labor	Generic Crew	10	122	4	1	0.7	0.5	Unknown	Any			
M01	Material	Reinforced Concrete		203									
M02	Material	Plain Concrete		137									
M03	Material	Formwork		147									
M04	Material	Insulation		197									
M05	Material	Steel Reinforcement		111									
M06	Material	Steel Element		204									

Fig. 11. User data input.

Project Info		ID	Category	Family	Type	Material Type	Structural Usage	BaseLevel		Location (coordinates)		Volume	Length	Cut Length	Side Area
Project Number	Project Name							Name	Elevation	X	Y				
2009-01	Technical School	122477	Structural Columns	M_Concrete-Round-Column	450mm	Concrete	Column	01 - Entry Level	0	-9.202	29.99374	0.556639	3.8	3.8	4.948006
2009-01	Technical School	122478	Structural Columns	M_Concrete-Round-Column	450mm	Concrete	Column	01 - Entry Level	0	-9.202	22.67854	0.556639	3.8	3.8	4.948006
2009-01	Technical School	122479	Structural Columns	M_Concrete-Round-Column	450mm	Concrete	Column	01 - Entry Level	0	-9.202	19.42734	0.556639	3.8	3.8	4.948006
2009-01	Technical School	122480	Structural Columns	M_Concrete-Round-Column	450mm	Concrete	Column	01 - Entry Level	0	-9.202	13.12814	0.556639	3.8	3.8	4.948006
2009-01	Technical School	122481	Structural Columns	M_Concrete-Round-Column	450mm	Concrete	Column	01 - Entry Level	0	-9.202	6.828939	0.556639	3.8	3.8	4.948006
2009-01	Technical School	122482	Structural Columns	M_Concrete-Round-Column	450mm	Concrete	Column	01 - Entry Level	0	-9.202	0.529739	0.556639	3.8	3.8	4.948006
2009-01	Technical School	122483	Structural Columns	M_Concrete-Round-Column	450mm	Concrete	Column	01 - Entry Level	0	-9.202	-5.76946	0.556639	3.8	3.8	4.948006
2009-01	Technical School	122484	Structural Columns	M_Concrete-Round-Column	450mm	Concrete	Column	01 - Entry Level	0	-9.202	-12.0687	0.556639	3.8	3.8	4.948006
2009-01	Technical School	122485	Structural Columns	M_Concrete-Round-Column	450mm	Concrete	Column	01 - Entry Level	0	-9.202	-15.3199	0.556639	3.8	3.8	4.948006
2009-01	Technical School	122486	Structural Columns	M_Concrete-Round-Column	450mm	Concrete	Column	01 - Entry Level	0	-9.202	-22.6351	0.556639	3.8	3.8	4.948006
2009-01	Technical School	122487	Structural Columns	M_Concrete-Round-Column	450mm	Concrete	Column	01 - Entry Level	0	-9.202	-1.41336	0.556639	3.8	3.8	4.948006
2009-01	Technical School	122488	Structural Columns	M_Concrete-Round-Column	450mm	Concrete	Column	01 - Entry Level	0	-9.202	8.648939	0.556639	3.8	3.8	4.948006
2009-01	Technical School	122490	Structural Columns	M_Concrete-Round-Column	450mm	Concrete	Column	01 - Entry Level	0	0.754801	29.99374	0.556639	3.8	3.8	4.948006
2009-01	Technical School	122491	Structural Columns	M_Concrete-Round-Column	450mm	Concrete	Column	01 - Entry Level	0	0.754801	22.67854	0.556639	3.8	3.8	4.948006
2009-01	Technical School	122492	Structural Columns	M_Concrete-Round-Column	450mm	Concrete	Column	01 - Entry Level	0	0.754801	19.42734	0.556639	3.8	3.8	4.948006
2009-01	Technical School	122493	Structural Columns	M_Concrete-Round-Column	450mm	Concrete	Column	01 - Entry Level	0	0.754801	13.12814	0.556639	3.8	3.8	4.948006
2009-01	Technical School	122494	Structural Columns	M_Concrete-Round-Column	450mm	Concrete	Column	01 - Entry Level	0	0.754801	6.828939	0.556639	3.8	3.8	4.948006
2009-01	Technical School	122495	Structural Columns	M_Concrete-Round-Column	450mm	Concrete	Column	01 - Entry Level	0	0.754801	0.529739	0.556639	3.8	3.8	4.948006
2009-01	Technical School	122496	Structural Columns	M_Concrete-Round-Column	450mm	Concrete	Column	01 - Entry Level	0	0.754801	-5.76946	0.556639	3.8	3.8	4.948006
2009-01	Technical School	122497	Structural Columns	M_Concrete-Round-Column	450mm	Concrete	Column	01 - Entry Level	0	0.754801	-12.0687	0.556639	3.8	3.8	4.948006
2009-01	Technical School	122498	Structural Columns	M_Concrete-Round-Column	450mm	Concrete	Column	01 - Entry Level	0	0.754801	-15.3199	0.556639	3.8	3.8	4.948006

Fig. 12. Extracted BIM model data in Excel.

Layout: CaseStudy WBS — Filter: All Activities

Activity ID	Activity Name	Original Duration	Remaining Duration	Schedule % Complete	Start	Finish	Resources	Budgeted Total Cost	Total Float
01 - Entry Level		412	412	0%	28-Apr-23	26-Nov-24		$64,404.40	0
Structural Columns		53	53	0%	06-Aug-24	18-Oct-24		$3,712.40	0
Zone 01		5	5	0%	06-Aug-24	13-Aug-24		$624.00	0
CON1000	Erect Formwork of Concrete Structural Columns In Zone 01 01 - Entry Level	1	1	0%	06-Aug-24	07-Aug-24	Formwork, RC Columns Formwork Crew	$192.00	0
CON1010	Steel Fixing of Concrete Structural Columns In Zone 01 01 - Entry Level	1	1	0%	07-Aug-24	08-Aug-24	Steel Reinforcement, RC Columns Steel I	$240.00	0
CON1020	Pouring Concrete Structural Columns In Zone 01 01 - Entry Level	1	1	0%	08-Aug-24	09-Aug-24	Reinforced Concrete, RC Pouring Crew	$0.00	0
CON1030	Curing Concrete Structural Columns In Zone 01 01 - Entry Level	1	1	0%	09-Aug-24	12-Aug-24	Reinforced Concrete	$0.00	0
CON1040	Deshattering Concrete Structural Columns In Zone 01 01 - Entry Level	1	1	0%	12-Aug-24	13-Aug-24	Formwork, Deshattering Crew	$192.00	0
Zone 02		16	16	0%	19-Sep-24	11-Oct-24		$2,496.00	0
CON1050	Erect Formwork of Concrete Structural Columns In Zone 02 01 - Entry Level	5	5	0%	19-Sep-24	26-Sep-24	Formwork, RC Columns Formwork Crew	$960.00	0
CON1060	Steel Fixing of Concrete Structural Columns In Zone 02 01 - Entry Level	4	4	0%	26-Sep-24	02-Oct-24	Steel Reinforcement, RC Columns Steel I	$960.00	0
CON1070	Pouring Concrete Structural Columns In Zone 02 01 - Entry Level	2	2	0%	02-Oct-24	04-Oct-24	Reinforced Concrete, RC Pouring Crew	$0.00	0
CON1080	Curing Concrete Structural Columns In Zone 02 01 - Entry Level	1	1	0%	04-Oct-24	07-Oct-24	Reinforced Concrete	$0.00	0
CON1090	Deshattering Concrete Structural Columns In Zone 02 01 - Entry Level	3	3	0%	07-Oct-24	10-Oct-24	Formwork, Deshattering Crew	$576.00	0
CON1150	Creating Steel Structural Columns In Zone 02 01 - Entry Level	1	1	0%	10-Oct-24	11-Oct-24	Steel Element	$0.00	0
Zone 03		5	5	0%	11-Oct-24	18-Oct-24		$592.40	0

Fig. 13. The generated activities with assigned codes, resources, durations, and costs calculated.

schedule's data.

4.1.7. Project schedule simulation in an automatically generated 5D simulation

As the schedule has been crashed and optimized, it can now generate the 5D simulation. Fig. 15 (A) shows the data extracted to be used as a schedule inside Navisworks, while Fig. 15 (B) shows the data extracted to match the Revit element automatically to the activities using the data stored during activities generation in REVIT_ELE Table (the custom table added to the database to support BIM elements data).

Another developed Revit plug-in automatically assigns the Activity ID value inside a shared parameter within each element using the table

Table 2
Genetic parameter sets experimented.

Exp. No.	Popu.	Gen.	Crossover Rate	Mutation Rate	Exp. No.	Popu.	Gen.	Crossover Rate	Mutation Rate
1	1000	100	0.9	0.05	21	1000	100	0.7	0.03
2	900	200	0.9	0.05	22	900	200	0.7	0.03
3	800	300	0.9	0.05	23	800	300	0.7	0.03
4	700	400	0.9	0.05	24	700	400	0.7	0.03
5	600	500	0.9	0.05	25	600	500	0.7	0.03
6	500	600	0.9	0.05	26	500	600	0.7	0.03
7	400	700	0.9	0.05	27	400	700	0.7	0.03
8	300	800	0.9	0.05	28	300	800	0.7	0.03
9	200	900	0.9	0.05	29	200	900	0.7	0.03
10	100	1000	0.9	0.05	30	100	1000	0.7	0.03
11	1000	100	0.8	0.04	31	1000	100	0.6	0.02
12	900	200	0.8	0.04	32	900	200	0.6	0.02
13	800	300	0.8	0.04	33	800	300	0.6	0.02
14	700	400	0.8	0.04	34	700	400	0.6	0.02
15	600	500	0.8	0.04	35	600	500	0.6	0.02
16	500	600	0.8	0.04	36	500	600	0.6	0.02
17	400	700	0.8	0.04	37	400	700	0.6	0.02
18	300	800	0.8	0.04	38	300	800	0.6	0.02
19	200	900	0.8	0.04	39	200	900	0.6	0.02
20	100	1000	0.8	0.04	40	100	1000	0.6	0.02

Table 3
Experiments results.

Exp. No.	Population	Generation	Crossover Rate	Mutation Rate	Cost
1	1000	100	0.9	0.05	405,208
2	900	200	0.9	0.05	407,662
.	.	.	.	.	.
9	200	900	0.9	0.05	410,394
10	100	1000	0.9	0.05	403,713
.	.	.	.	.	.
20	100	1000	0.8	0.04	403,887
21	1000	100	0.7	0.03	406,555
.	.	.	.	.	.
30	100	1000	0.7	0.03	408,983
31	1000	100	0.6	0.02	408,145
32	900	200	0.6	0.02	406,126
33	800	300	0.6	0.02	406,318
34	700	400	0.6	0.02	406,387
.	.	.	.	.	.
40	100	1000	0.6	0.02	407,168

of data regarding Revit element mapping to activities in the schedule. Fig. 16 shows an example of an element with an Activity ID assigned to it.

Then, using the Revit model with the activity ID parameter on its elements and the table of data representing the schedule for Navisworks, an auto-match rule attaches each element to the corresponding activity, and the simulation is ready to be rendered. Fig. 17(A) shows this auto-matching rule, and Fig. 17(B) shows a result of attached elements to an activity highlighted in blue.

Providing access to this simulation for various project stakeholders streamlines the coordination of site operations. It allows for a visual representation before execution, facilitating a deeper understanding of the construction methodology compared to relying solely on written instructions.

4.1.8. *Business intelligence dashboard generation for project control*

Using the Primavera P6 database, the extracted data through the previous steps, and a developed custom 3D visual in PowerBI, the framework generates a reach interactive dashboard that can quickly help in understanding the project or improve decision-making while planning. Fig. 18(A) shows a simple example of these dashboards, and Fig. 18(B) shows the filtration and interactive features when selecting a zone or category. Also, the developed 3D viewer can reversely filter data based on element selection, which helps better understand the construction plan.

Table 4
Five of the solutions resulted from the optimization.

Solution No.	Solution	Total Project Cost (Fitness Value)
1	[3, 3, 1, 3, 2, 1, 3, 3, 1, 2, 3, 1, 2, 2, 1, 3, 2, 3, 2, 3, 2, 3, 3, 2, 3, 3, 2, 3, 2, 2, 1, 2, 2, 2, 3, 1, 3, 3, 2, 1, 3, 2, 1, 2, 3, 2, 2, 1, 3, 1, 3, 1, 2, 1, 2, 3, 3, 3, 3, 3, 3, 2, 3, 1, 3, 2, 2, 2, 2, 3, 3, 3, 3, 3, 3, 3, 3, 3, 1, 3, 3, 1, 3, 1, 1, 3, 3, 1, 2, 3, 3, 3, 3, 2, 3, 2, 1, 3, 2, 3, 2, 3, 3]	409,650
2	[3, 1, 1, 3, 2, 1, 3, 3, 2, 3, 2, 1, 2, 3, 1, 3, 2, 2, 1, 2, 2, 3, 2, 2, 2, 2, 3, 2, 3, 3, 1, 2, 2, 1, 1, 2, 2, 2, 2, 3, 2, 2, 2, 2, 3, 3, 2, 2, 3, 3, 2, 1, 2, 1, 3, 2, 3, 1, 3, 3, 2, 3, 3, 2, 3, 3, 2, 3, 3, 2, 3, 3, 3, 3, 2, 2, 3, 3, 1, 1, 3, 1, 2, 3, 1, 1, 2, 2, 2, 2, 2, 2, 3, 1, 3, 3, 3, 2, 1, 3, 2, 2, 3]	403,713
3	[1, 2, 1, 1, 3, 1, 1, 3, 1, 2, 3, 3, 1, 1, 3, 2, 1, 2, 2, 3, 3, 2, 1, 3, 3, 1, 3, 3, 3, 1, 2, 1, 3, 3, 3, 2, 3, 1, 2, 3, 2, 3, 3, 3, 2, 1, 1, 1, 1, 3, 2, 3, 1, 2, 2, 2, 2, 3, 2, 2, 1, 3, 2, 2, 3, 2, 3, 3, 2, 3, 3, 3, 3, 3, 3, 1, 3, 3, 2, 3, 2, 2, 2, 3, 1, 3, 2, 2, 3, 1, 2, 3, 3, 2, 3, 3, 1, 3, 3, 3, 2, 2, 2]	406,672
4	[1, 2, 1, 2, 2, 1, 1, 3, 1, 2, 3, 3, 1, 1, 3, 1, 3, 2, 2, 3, 3, 2, 1, 3, 3, 1, 3, 3, 3, 1, 2, 1, 3, 2, 3, 2, 3, 1, 2, 3, 2, 3, 3, 3, 2, 1, 1, 1, 1, 3, 2, 3, 2, 2, 2, 2, 2, 3, 2, 2, 1, 3, 2, 2, 3, 3, 2, 3, 2, 3, 3, 3, 3, 3, 3, 1, 3, 3, 2, 3, 2, 2, 2, 3, 1, 3, 2, 2, 3, 1, 2, 3, 2, 2, 3, 3, 1, 3, 3, 3, 2, 2, 2]	405,792
5	[1, 2, 1, 3, 3, 1, 1, 3, 1, 2, 3, 3, 3, 1, 3, 3, 1, 2, 3, 3, 3, 2, 1, 3, 3, 1, 3, 3, 3, 1, 3, 1, 2, 3, 3, 2, 3, 1, 2, 3, 3, 1, 2, 3, 2, 2, 2, 2, 1, 3, 3, 3, 1, 2, 2, 2, 2, 3, 2, 2, 1, 3, 3, 2, 3, 3, 2, 3, 2, 3, 3, 3, 3, 3, 3, 1, 3, 3, 2, 3, 3, 2, 2, 3, 1, 3, 2, 2, 3, 1, 1, 3, 2, 2, 3, 3, 2, 3, 3, 3, 2, 2, 1]	406,215

4.1.9. *Live updates based on the BIM model*

Once any change in the model happens, the user can click on the Live update button shown in the plug-in ribbon in Fig. 10. A developed algorithm will use SQL to compare data, determine the change, and then reflect it on the schedule.

4.2. *Prototype evaluation*

4.2.1. *Schedule quality test*

Using Primavera P6 check schedule report to prepare a report of the generated schedule in the case study against the standard test in

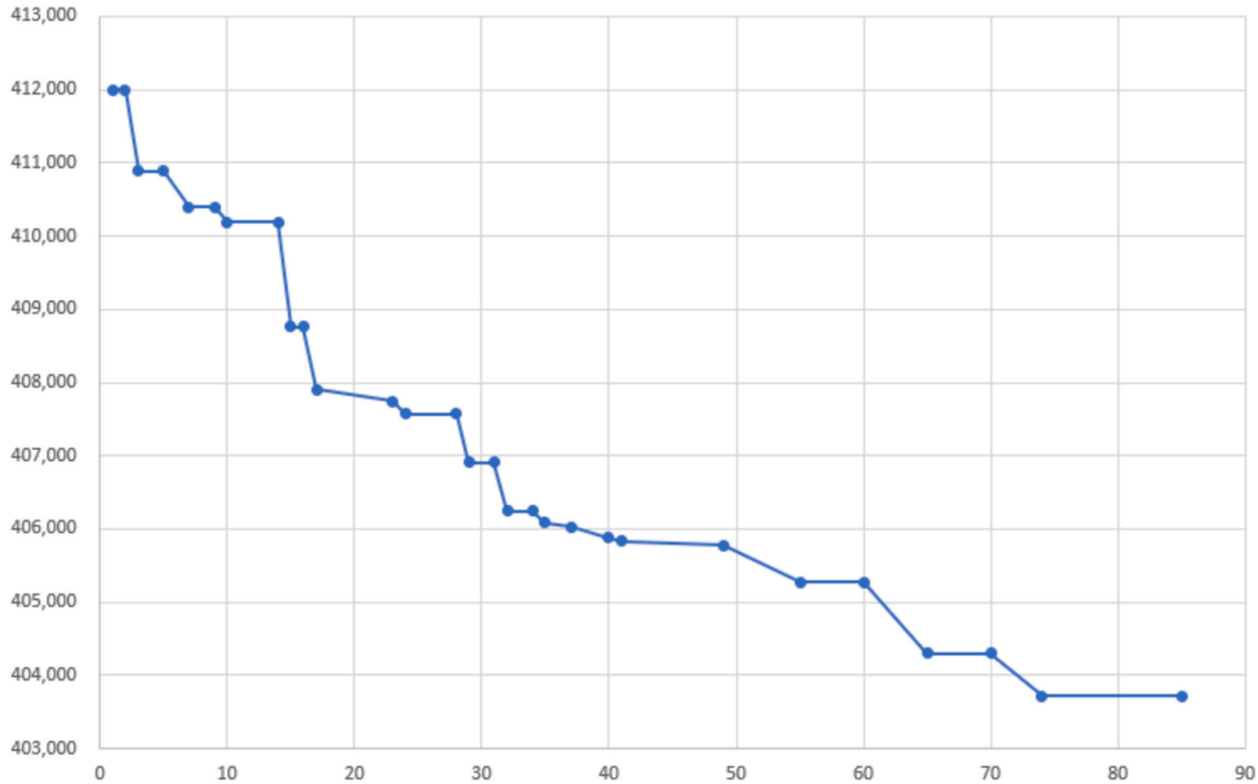
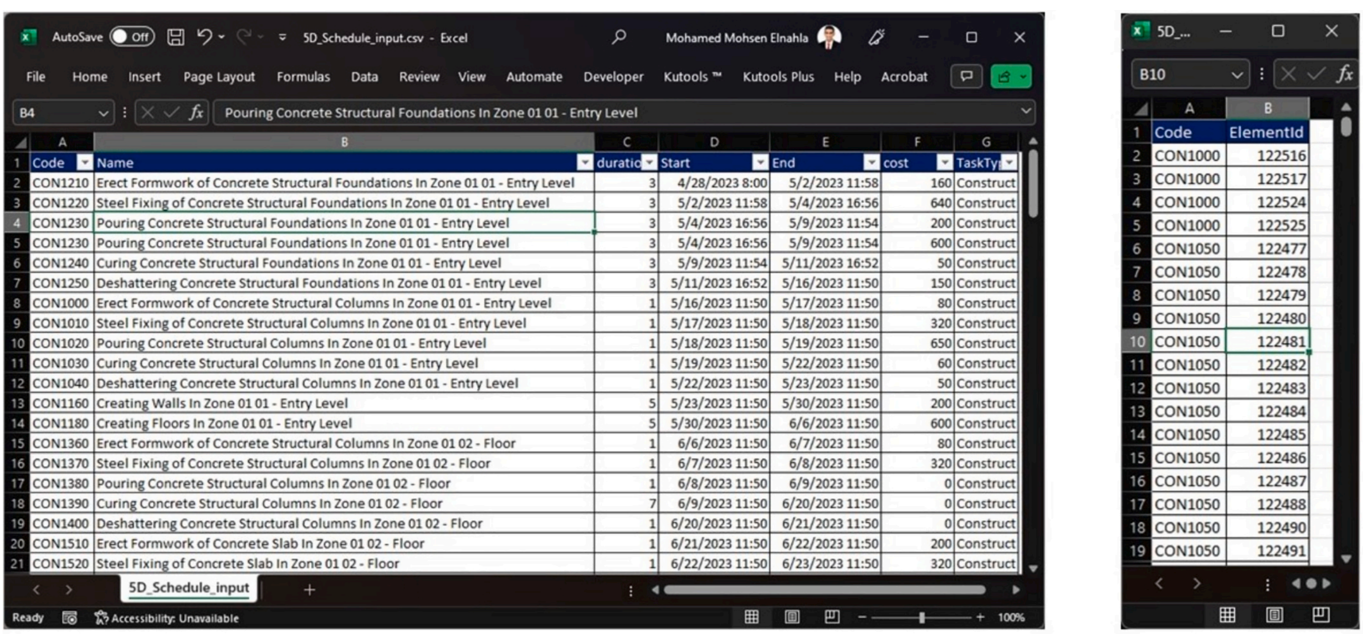


Fig. 14. Cost evolution through generations (X-Axis shows number of generation while Y-Axis shows the cost).



	A	B	C	D	E	F	G
1	Code	Name	duratio	Start	End	cost	TaskTy
2	CON1210	Erect Formwork of Concrete Structural Foundations In Zone 01 01 - Entry Level	3	4/28/2023 8:00	5/2/2023 11:58	160	Construct
3	CON1220	Steel Fixing of Concrete Structural Foundations In Zone 01 01 - Entry Level	3	5/2/2023 11:58	5/4/2023 16:56	640	Construct
4	CON1230	Pouring Concrete Structural Foundations In Zone 01 01 - Entry Level	3	5/4/2023 16:56	5/9/2023 11:54	200	Construct
5	CON1230	Pouring Concrete Structural Foundations In Zone 01 01 - Entry Level	3	5/4/2023 16:56	5/9/2023 11:54	600	Construct
6	CON1240	Curing Concrete Structural Foundations In Zone 01 01 - Entry Level	3	5/9/2023 11:54	5/11/2023 16:52	50	Construct
7	CON1250	Deshattering Concrete Structural Foundations In Zone 01 01 - Entry Level	3	5/11/2023 16:52	5/16/2023 11:50	150	Construct
8	CON1000	Erect Formwork of Concrete Structural Columns In Zone 01 01 - Entry Level	1	5/16/2023 11:50	5/17/2023 11:50	80	Construct
9	CON1010	Steel Fixing of Concrete Structural Columns In Zone 01 01 - Entry Level	1	5/17/2023 11:50	5/18/2023 11:50	320	Construct
10	CON1020	Pouring Concrete Structural Columns In Zone 01 01 - Entry Level	1	5/18/2023 11:50	5/19/2023 11:50	650	Construct
11	CON1030	Curing Concrete Structural Columns In Zone 01 01 - Entry Level	1	5/19/2023 11:50	5/22/2023 11:50	60	Construct
12	CON1040	Deshattering Concrete Structural Columns In Zone 01 01 - Entry Level	1	5/22/2023 11:50	5/23/2023 11:50	50	Construct
13	CON1160	Creating Walls In Zone 01 01 - Entry Level	5	5/23/2023 11:50	5/30/2023 11:50	200	Construct
14	CON1180	Creating Floors In Zone 01 01 - Entry Level	5	5/30/2023 11:50	6/6/2023 11:50	600	Construct
15	CON1360	Erect Formwork of Concrete Structural Columns In Zone 01 02 - Floor	1	6/6/2023 11:50	6/7/2023 11:50	80	Construct
16	CON1370	Steel Fixing of Concrete Structural Columns In Zone 01 02 - Floor	1	6/7/2023 11:50	6/8/2023 11:50	320	Construct
17	CON1380	Pouring Concrete Structural Columns In Zone 01 02 - Floor	1	6/8/2023 11:50	6/9/2023 11:50	0	Construct
18	CON1390	Curing Concrete Structural Columns In Zone 01 02 - Floor	7	6/9/2023 11:50	6/20/2023 11:50	0	Construct
19	CON1400	Deshattering Concrete Structural Columns In Zone 01 02 - Floor	1	6/20/2023 11:50	6/21/2023 11:50	0	Construct
20	CON1510	Erect Formwork of Concrete Slab In Zone 01 02 - Floor	1	6/21/2023 11:50	6/22/2023 11:50	200	Construct
21	CON1520	Steel Fixing of Concrete Slab In Zone 01 02 - Floor	1	6/22/2023 11:50	6/23/2023 11:50	320	Construct

	A	B
1	Code	ElementId
2	CON1000	122516
3	CON1000	122517
4	CON1000	122524
5	CON1000	122525
6	CON1050	122477
7	CON1050	122478
8	CON1050	122479
9	CON1050	122480
10	CON1050	122481
11	CON1050	122482
12	CON1050	122483
13	CON1050	122484
14	CON1050	122485
15	CON1050	122486
16	CON1050	122487
17	CON1050	122488
18	CON1050	122490
19	CON1050	122491

(A) (B)

Fig. 15. Data extracted to be used in 5D simulation.

Primavera P6, it was found that; just the start and end activities are missing a predecessor or successor, which is normal. Also, activities over 352 h are just five, representing 3.79% of total activities, so it is acceptable. Meanwhile, all relations are finished to start, which is the recommended relations. Also, there are no activities with no resources assigned to it. The overall Baseline Execution Index is one. The result of this report is shown in detail in Fig. 19.

4.2.2. *Prototype reliability test*

To ensure the reliability of the prototype the following tests were performed: (See Table 5)

5. Limitations and recommendations for future studies

Despite the success of the current framework in the generation of the

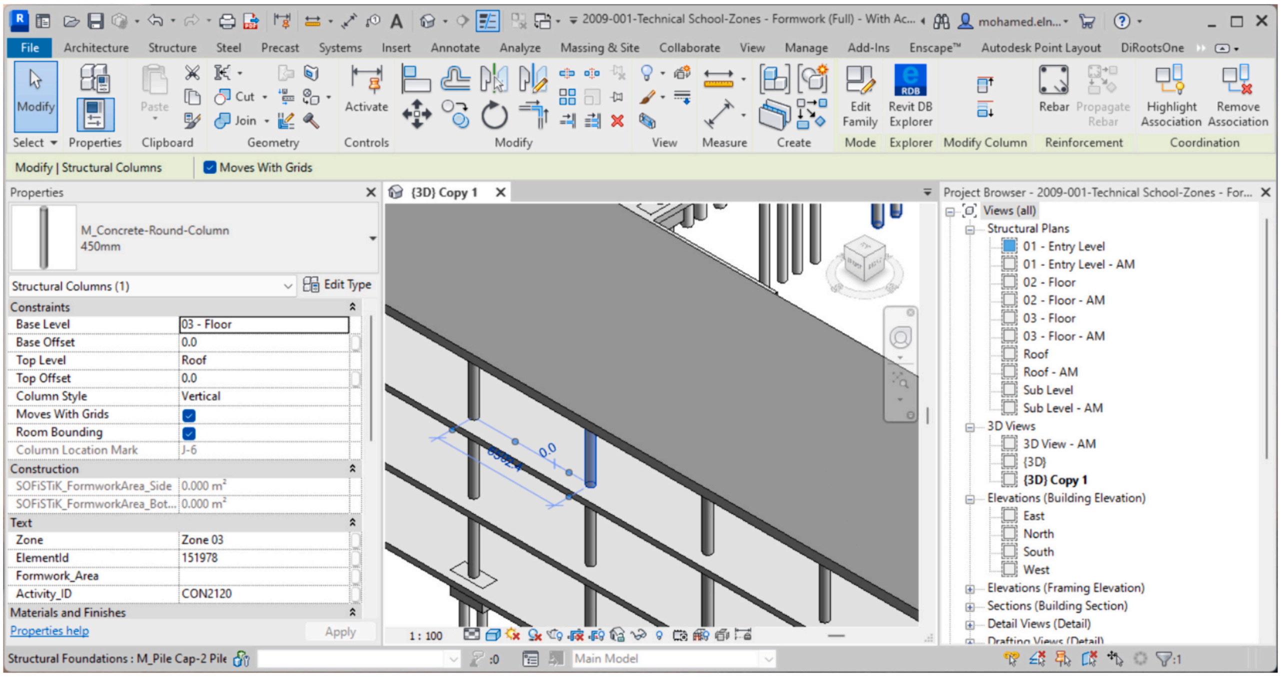


Fig. 16. An example of an element with an activity ID assigned to it.

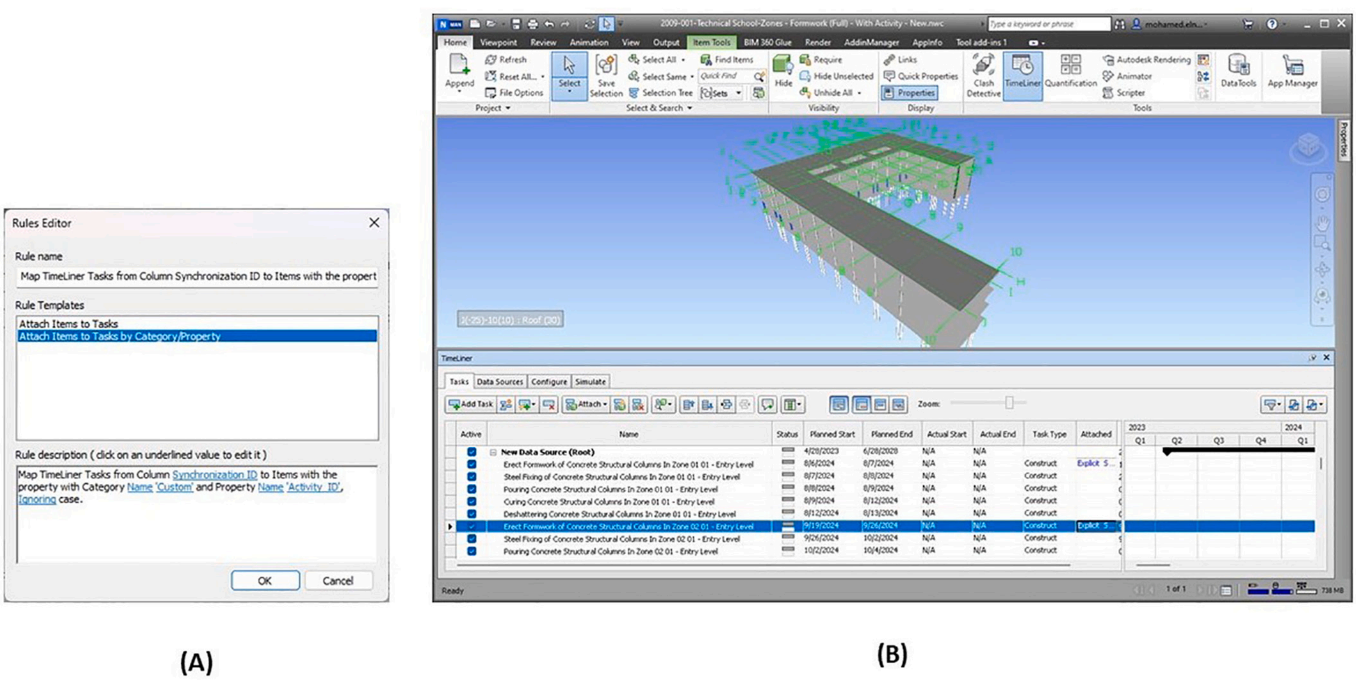
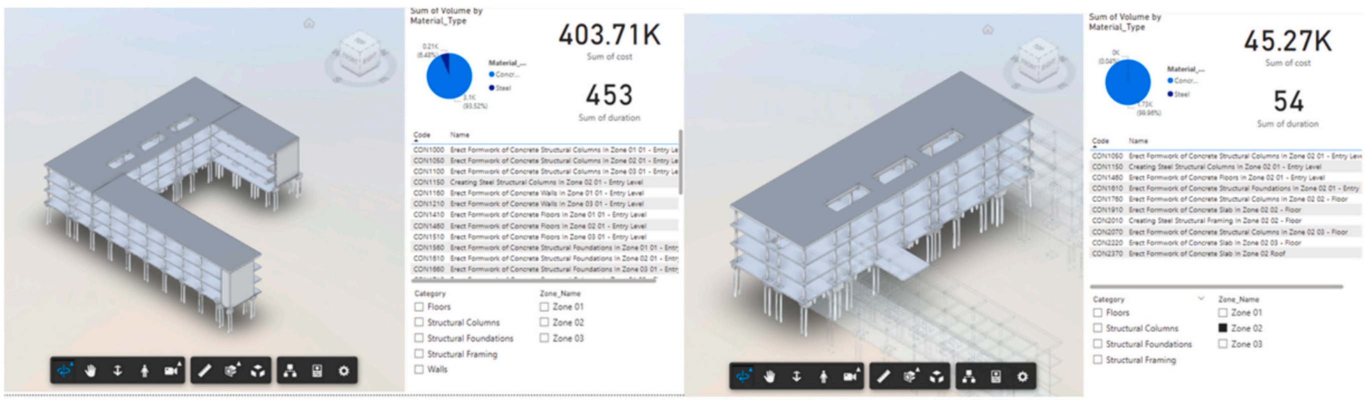


Fig. 17. The automatic 5D simulation on Navisworks.

BIM model and the optimized construction schedule, as well as the 5D simulation and BI dashboard. Nevertheless, this framework has the following limitations, and it is recommended to develop it in further research:

1. The framework cannot automatically generate BIM model elements of stairs, ramps, and all non-structural elements of the building.
2. The current sequence is based on creating finish-to-start relations without considering any branching, so it is recommended that future studies investigate a solution for this critical point to reach a more practical framework.
3. The current sequencing logic is limited to the structural elements of the building, but this sequencing algorithm can be improved to adapt to other disciplines.
4. The framework has been developed to work with any structure following the bottom-up construction method (where elements are constructed from lower to higher levels). Also, it shows greater details with cast-in-situ construction while less details with steel frame construction and needs improvements before being applied to pre-cast construction or composite construction. Thus, it can't be applied on roads, dams, and core-based buildings (where the core is constructed before the rest of the building). so, it is recommended in



(A) (B)

Fig. 18. A simple example of BI dashboards.

Check Schedule Report
15-Aug-23
PM.EXE

▼ Projects Checked

Project ID	Project Name	Data Date	Total Activities	Complete Activities	Internal Relationships	External Relationships
2009-01	Technical School	28-Apr-23	132	0	131	0

▼ Project checked to have links to the following closed projects

Closed Project ID	Closed Project Name	Data Date	Links to/from the closed project

▼ Check Summary

Check	Description	Target	Percent	Found	Total
Logic	Activities missing predecessors or successors	< 5.00 %	1.52 %	2	132
Negative Lags	Relationships with a lag duration of less than 0	< 1.00 %	0.00 %	0	131
Positive Lags	Relationships with a positive lag duration	< 5.00 %	0.00 %	0	131
Long Lags	Relationships with a lag duration greater than 352 hours	< 5.00 %	0.00 %	0	131
Relationship Type	The majority of relationships should be Finish to Start	> 90.00 %	100.00 %	131	131
Hard Constraints	Constraints that prevent activities being moved	< 1.00 %	0.00 %	0	132
Soft Constraints	Constraints that do not prevent activities being moved	< 5.00 %	0.00 %	0	132
Large Float	Activities with total float greater than 352 hours	< 1.00 %	0.00 %	0	132
Negative Float	Activities with a total float less than 0	< 1.00 %	0.00 %	0	132
Large Durations	Activities that have a remaining duration greater than 352 hours	< 5.00 %	3.79 %	5	132
Invalid Progress Before Data Date	Incomplete activities before the data date	< 1.00 %	0.00 %	0	132
Invalid Progress After Data Date	Activities with actual dates after the data date	< 1.00 %	0.00 %	0	132
Resources/Cost	Activities that do not have an expense or a resource assigned	< 1.00 %	0.00 %	0	132
Late Activities	Activities scheduled to finish later than the project baseline	< 5.00 %	0.00 %	0	132

Check	Description	Target	BEI Ratio	Project Activities	Baseline Activities
BEI	Baseline Execution Index	> 0.95	1	-	-

▼ Logic — Activities missing predecessors or successors

Project ID	Activity ID	Activity Name	Predecessor	Successor
2009-01	CON1560	Erect Formwork of Concrete Structural Foundations In Zone 01 01 - Entry Level	No	Yes
2009-01	CON2460	Formwork Removal of Concrete Slab In Zone 03 Roof	Yes	No

Fig. 19. Primavera P6 check schedule report.

futures studies to consider developing other frameworks for each of these types.

5. This framework generates only the construction logic part of the schedule without milestones or other parts like procurement, engineering, testing, commissioning, etc. However, these parts can be added manually after the schedule generation. Therefore, it is recommended for future studies to provide a method to include non-construction activities based on a template for the project type or machine learning system using historical data.

6. Conclusion

This study delved into bridging the gap between a project's engineering and construction management aspects. This was achieved through a comprehensive analysis of existing literature. The study highlighted the necessity for more integrated solutions, advocating for creating a unified data repository as a new common data environment. This repository would be meticulously structured to accommodate all project-related data with their appropriate interconnections. To facilitate the automatic generation and optimization of construction schedules. Meanwhile, the development of simulations and dashboards could

Table 5
Reliability tests.

Test ID	Test Description	Targeted stage	Test Data	Steps to be Executed	Actual Result and Post-Conditions	Test status
1	Comparing the automatically generated with a manually developed BIM model.	Stage 1 BIM model generation.	1) The manually generated model by Autodesk 2) The automatically generated model.	1) Run stage 1 of the framework to generate a BIM model automatically. 2) Comparing elements of the generated model and the manually developed model by Autodesk based on: existence; location; dimensions and data inside the element.	The model matched the original Autodesk model except for the missing reinforcement, stairs, steel columns, steel framing elements, and pile caps.	Pass
2	Comparing extracted BIM model data stored in the SQL database with the original data of elements inside the BIM model.	Stage 2 BIM model data extraction and Integration.	1) The original BIM Model 2) The extracted BIM data inside the SQL database.	1) Run stage 2 to Extract the BIM model data and store it inside the SQL database of the scheduling software. 2) Check table's existence in the database. 3) Comparing the data of each element with the data inside the table in the SQL database.	1) The table was created in the database 2) The data matches with some rounding in decimal digits. 3) Parts of level's related data which the element is hosted should be remapped to a column called base level instead of the name of its original parameter in the model to ease data processing.	Pass
3	Comparing the generated library of resources and codes in Primavera P6 with data from the model and Excel file of resources.	Stage 3 Resources and activity code libraries creation.	1) Excel file of Resources 2) A Primavera P6 project full of library data.	1) Run stage 3 to generate a library of resources and codes in Primavera P6. 2) Compare each resource name and type with resources in the Excel file. 3) Compare codes of levels and zones with the levels and zones in the BIM model. 4) Ensure the project has the exact name and code set in the BIM model.	1) Resource names and types match with the data in the Excel file. 2) All levels and zones in the BIM model have an activity code created with the correct naming for it. 3) The project has the exact name and code set in the BIM model.	Pass
4	Ensuring the data of generated activities.	Stage 4 Activities generation with resources and activity codes assignment.	A Primavera P6 project filled with activities.	1) Run stage 4 of the framework. 2) Check the naming of each generated activity. 3) Compare the number of generated activities with the expected number based on the logic of the framework. 4) Comparing the quantity of materials in each activity compared to its expected quantities from the BIM model. 5) Comparing the codes assigned to each activity with the expected codes. 6) Compare the assigned crew for each activity with the expected.	1) The naming of activities following the developed logic 2) For each concrete-related element five activities are created, while for non-concrete-related elements, just one activity is created. 3) When selecting a of elements in the BIM model that represents a single activity, quantity of materials was equivalent to the assigned quantity on the activity. 4) Each activity has the correct codes regarding its zone and level. 6) Each activity has a main resource represents the crew executing the activity.	Pass
5	Correct relations between activities.	Stage 5 Activities in sequential order.	A Primavera P6 project with activities relations assigned to it.	1) Run stage 5 of the framework. 2) Reviewing the relations between activities assigned to each activity.	All activities have logically valid relations following the same logic developed in the framework.	Pass
6	Testing the Optimization Algorithm.	Stage 6 Finding the optimum crashed schedule.	A primavera P6 project with activities and relations.	1) Run stage 6 of the framework. 2) Check extracted data from the schedule before generating options. 3) Check the generated options before optimization. 4) Check the assignment of the optimum solution inside Primavera P6.	1) The extracted schedule data matches the data in the schedule. 2) The three options were generated correctly within the limits of resources defined and following the developed logic. 3) After optimization, the data updated in Primavera P6 with the cost and duration resulting from the optimization with the cost and resources are updated correctly.	Pass
7	Testing the link between activities and BIM model elements on Navisworks.	Stage 7 Generating a 5D simulation.	1) The BIM model is used to generate the activities. 2) A primavera P6 project with activities and relations with optimized data.	1) Run stage 7 of the framework to assign activities to elements in the BIM model and extract Excel file for Navisworks. 2) Run the matching rule on Navisworks. 3) Check if any activity has no elements assigned. 4) Check if any element is missing in the activity assignment.	All elements in the Navisworks were attached to activities with no elements left. Also, all the attached elements were in the correct activities without any wrong allocation.	Pass

(*continued on next page*)

Table 5 (*continued*)

Test ID	Test Description	Targeted stage	Test Data	Steps to be Executed	Actual Result and Post-Conditions	Test status
				5) Check if any element got assigned to the wrong activity.		
8	The dashboard interactively filters the model.	Stage 8 Generating a BI dashboard.	1) The BIM model generates activities with IDs assigned to elements. 2) A P6 project with activities and relations with optimized data.	1) Run stage 8 of the framework to generate the PowerBI dashboard. 2) Check the relations between tables in the database of the dashboard. 3) Check the interactive filtration between the model and other visuals by selecting the model element or selecting any data from other visuals.	1) All relations between tables in the database are correct. 2) Selecting an element in the model filters the data of all other visuals to show its data. 3) Select data from any visual filters in the model to show the elements related to the selected data.	Pass
9	Changes are reflected based on model updates.	Stage 9 Performing live update.	The BIM model is used to generate the activities with activity IDs assigned to elements.	1) Changing the height of some elements, removing some elements and creating new elements in the model. 2) Run stage 9 of the framework. 3) Check the schedule to measure the changes that happened.	The schedule got updated with the new changes in the model and other parts of the framework linked to the schedule like dashboard and simulation, reflected the update automatically.	Pass

enhance decision-making processes. The underlying focus was ensuring seamless data transition across various project stages without compromising the data integrity.

The proposed framework was intricately crafted to address these imperatives. Its design not only emphasized the theoretical aspects but also emphasized practical implementation. This pragmatic approach aimed to seamlessly incorporate the framework within pre-existing software systems, thereby minimizing user disruption and expediting its adoption. The framework's innovation lay in integrating BIM into the process of automatically generating and optimizing construction project schedules, alongside its provision of 5D simulations and BI dashboards. Comprising nine distinct stages, the framework encompassed BIM model generation, BIM model data extraction and integration, creation of resources and activity code libraries, generation of activities with resource and activity code assignment, establishment of activities' sequential order, identification of optimum crashed schedules through GAs, simulation of project schedule via an automatically generated 5D simulation, generation of a BI dashboard for project, and prove live updates based on BIM data. Notably, the framework was thoughtfully extended to address the challenge of integrating BIM within SMEs, with the initial stage of the framework tailored to confront this obstacle head-on.

All generated products, including the BIM model and schedule, are designed to be editable. They serve as draft versions for various stakeholders, including BIM engineers, planners, and Virtual Design and Construction (VDC) engineers. In the case of a planner, the automated system alleviates the need to construct a schedule from scratch, reducing the likelihood of omitting crucial elements and saving considerable time spent on creating resource libraries, assigning resources to activities, and establishing relations. Meanwhile, the proposed framework addresses the challenge faced by planners in fitting the schedule into the required end date. Unlike the manual approach, where planners might not explore multiple scenarios due to time constraints, the automated system facilitates the crashing of the schedule in a cost optimized way to reach the targeted date of project by using GA which efficiently discover multiple scenarios till finding the optimum one. Furthermore, the BIM engineer got families, levels and most structural elements automatically generated and placed using a set of excel files. Moreover, the VDC engineer benefits from the automated system, as it links BIM elements to the schedule for 5D simulation. This process aids in identifying missing activities, conflicts, and sequencing errors, providing a more accurate representation of the construction process. Stakeholders can easily comprehend the project plan through the automated 5D simulation, saving time and effort compared to the manual linkage of BIM elements. Moreover, the automated BI dashboard, loaded with project data and interactive information, is another key component of the proposed framework. Creating such a dashboard manually, including modeling the required data and establishing connections, would be a time-consuming task. The automated system eliminates this burden, ensuring efficient delivery of project information.

To validate the framework's effectiveness, a compelling case study was undertaken. This endeavour culminated in developing a prototype meticulously designed to evaluate the framework's viability and substantiate its theoretical foundations. The standout accomplishment of this prototype lay in its remarkable capacity to significantly curtail time expenditures during the planning process. It could formulate and optimize project schedules. Furthermore, the prototype seamlessly integrated a 5D simulation, linking BIM model elements with scheduled activities through an automatic procedure triggered during activity generation. Beyond schedule optimization, the framework presents an interactive BI dashboard. This tool markedly augmented project comprehension during the planning phase and became a potent ally for decision-making. The dashboard's real-time connection to project data ensured that updates were immediately reflected.

CRediT authorship contribution statement

Hossam Wefki: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Conceptualization. **Mohamed Elnahla:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Conceptualization. **Emad Elbeltagi:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Conceptualization.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the author(s) used OpenAI's ChatGPT and Microsoft Bing Chat to improve the explanation of some programming codes in an easier way for the reader. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

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.

Data availability

Data will be made available on request.

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