HIGHLIGHTS

- A prototype integrating 4D BIM applications were developed to facilitates real-time concrete joint layout planning.
- The system improves integration of structural design process and eases decision making prior construction phase.
- The system helps reducing structural damages caused by operational shortfalls and supply-chain issues.
- This paper contributes to 4D BIM literature by integrating operational data with design considerations to leverage efficiency.
- Paper discussed how the system can be improved by adopting machine learning, sensors, and data science techniques.

1 INTRODUCTION

Concrete defects (e.g. cracks) can significantly reduce the structural integrity of buildings [54]. Therefore, meticulous attention to detail should be given, during the design and construction phases, to prevent the occurrence of these defects [30]. One risk mitigation approach is to use various types of joints in concrete structures [59]. For instance, expansion joints mitigate the stress resulted by temperature changes in structural concrete, and contraction joints accommodate drying shrinkage of the concrete without engendering cracks [58]. Construction joints are, therefore, unavoidable and must be controlled during both the design and construction phases [42]. When placed incorrectly, these joints can reduce structural integrity and lead to irreparable or costly damages to the structure [27]. Conversely, the correct placement of joints can support structural health [73].

In practice, various factors (beyond structural analysis considerations) control concrete pouring tasks and limit flexibility in the selection of joint positions. These include time considerations such as the speed of erection; human resources limitations such as the prerequisite skills and competencies of workers; and temperature control between the concrete core and its surface [1]. Other major considerations are the accurate identification of locations to cease concrete pouring and the production of an efficient and effective concreting plan and schedule [15,29]. Evidence from the industry reveals that these items have presented major challenges, particularly for structures that require large pours [9]. These challenges could be overcome via the use of automation achieved through digitisation of the design and construction process [19,28]. An inherent benefit of Building Information Management (BIM) is its ability to produce information that supports insightful decision making in structural analyses and designs [24,35]. Such information could include the details of concrete pours and more specifically, that of construction joints [36,68].

Despite this foreseeable need, research that explores the capabilities of BIM within the concrete supply chain has received scant academic attention [4,39]. Hitherto, pertinent studies on the applications of BIM for concrete work have been limited to either improving supply chain management or enhancing the quality of precast components on projects [48,49], or estimating the costs of production and reducing the carbon footprint of concrete structures [23,62]. Hyun *et al.* [41] represented the only study with the closest alignment to the topic and sought to use BIM in designing cast-in-place concrete formwork. At present, there is a notable dearth of research that explores BIM's capabilities for controlling joints, and initial attempts to provide automated procedures still remain in their infancy stages [63,78]. In order to address the identified knowledge gap, this study developed an automated concrete schedule programme using BIM with a focus on planning construction joints, given common limitations affecting concrete pouring activities on construction projects.

2 THE THEORETICAL BACKGROUND

2.1 Construction joints

Uninterrupted concrete pouring is often impractical due to a myriad of reasons, including size and/or complexity of structures, material supply limitations, allowable working times/conditions, and availability of labour [16,27]. Consequently, it is usually necessary to place fresh concrete on the concrete that has already hardened, where the 'contact surface' is termed as a 'construction joint' [34]. Whilst construction joints can be eliminated through increasing reinforcement, the volume of reinforcement needed makes it infeasible for ordinary construction projects [59]. According to Issa *et al.* [42], *"no concrete structure is built without the use of construction joints, whether planned or unplanned."* Yet, construction joints require optimisation to reduce unfavourable impacts, such as increased permeability. In addition, construction joints reduce the loading capacity of respective structural elements, by up to 20% below the computed value [50]. The superlative option is to meticulously plan construction joints to coincide with contraction joints prior to concrete pouring, hence minimising the number of joints in structures [16,26]. Yet, joints are also formed due to unplanned interruptions of concrete supply for a long enough duration for the initial setting of the concrete [16,26]. Thus, the professional designer must specify the joints' location and create a concrete pouring schedule that accounts for determinatives, such as the given daily batching volume [73,79]. Moreover, joint locations must be determined in conjunction with the contractor, to incorporate the maximum volume of concrete placement and mitigate any potential operational constraints applicable to the project [16]. Table 1 reports upon a summary of recommendations for concrete joint location derived from several guidelines and specifications in different countries or regions of economic collaboration.

As inferred from Table 1, relying on various guidelines might result in different solutions. For instance, both British and European standards recommend a special design of joint, whilst other specifications allocate these joints where the shear force is minimum – based on the designers' judgment. Moreover, despite the availability of these clear guidelines, a wide range of variables may affect the planning of joints, e.g. appearance, strength and cost [79]. Cumulatively, a diverse set of standards and variables serve to illustrate that planning the location of joints is a complex task that is prone to human acts, errors or omissions [9]. Therefore, effective planning relies extensively upon the availability of proficient personnel [37], and it is affected by the judgements, competencies, and perceptions of the staff undertaking it [32]. Traditional forms of planning for complex circumstances can produce poor or defective quality structures, because of human input and this present research is founded upon the premise that the intrinsic capabilities of BIM for planning and scheduling concrete pouring should represent viable solutions [20,31,39].

Table 1 - Various guidelines for construction joint placement in concrete

Country (Source)	**Recommendations summary**	**Type of recommendation**
Australia [77]	Construction joints are located to facilitate the placement of concrete; unless otherwise specified, a construction joint shall be made between the soffits of slabs or beams and their supporting columns or walls.	Position of the joint based on the distribution of shear force
Canada [13]	Provision shall be made for the transfer of shear and other forces through construction joints.	Position of the joint based on designers' judgment
Hong Kong [38]	Construction joints in concrete shall be formed only at the specified positions and by the specified method unless otherwise approved by the engineer.	Position of the joint based on the distribution of shear force
Japan [44]	Joints should be located in portions where the shear force is less and, at right angles to the direction of compressive force, according to the requirements specified herein.	Position of the joint based on the distribution of shear force
The EU [80]	Where tensile stresses are expected to occur in concrete, reinforcement should be detailed to control cracking.	The special design of joint
The UK [7]	Construction joint location should be carefully considered and agreed before concrete is placed.	The special design of joint
The USA [34]	Desirable locations for joints: perpendicular to the main reinforcement, at points with minimum shear or points of contra-flexure.	Position of the joint based on the distribution of shear force

2.2 4D BIM for planning and scheduling

BIM is equipped with multiple dimensions for information delivery and data integration [25] and is capable of transforming existing practices across the construction sector [2,18,22,71]. Integration of BIM with other applications is defined as nD modelling [28], where supplementary information is added to three-dimensional models (3D) to create additional dimensions and visualising the process [11,66]. There is consensus within academic literature that linking the time dimension to 3D models (colloquially termed as 4D BIM) is an innovative addition and remedial solution to overcoming the deficiencies of current planning practices [17,32,39]. This entails adding a temporal dimension to 3D models – specifically, linking units of work (based on geometric graphical 3D models) to scheduling details [37,64,66].

Koo and Fischer [51] and later Heesom and Mahdjoubi [37] argued that the fourth dimension of BIM provides construction stakeholders (i.e. designers and contractors) with a useful alternative to traditional project scheduling tools like critical path method (CPM). The use of 4D BIM provides greater control and assists in avoiding time and cost deficiencies - estimated to be 40% more efficient than traditional planning procedures [14,57]. Various 4D applications can cover both activity and operations levels, alike including temporary components such as equipment movements; resource availability and congestion; operational problems; and the layout and dynamic analysis of construction sites [3,40,82]. 4D applications can also improve the quality of the planning process in various ways by providing: augmented vehicle tracking and transportation route planning [18]; improved logistics management, spatial conflict detection and workspace congestion avoidance [10]; enhanced health and safety management [33]; and improved monitoring of construction progress and site layout designs with better resource utilisation [19,39].

Project teams are supported by 4D BIM's inherent ability to identify activities through model interrogation, and use accurate durations and estimations of needed resources, via automated quantity estimation processes [31]. The visualisation element, provided by 4D results in higher productivity, better training and enhanced communications and collaboration in undertaking scheduling and constructability analysis [11,22]. With the above in mind, 4D can be a useful alternative for traditional methods of joint planning for concrete structures [17].

2.3 Research gap and methodological approach

Despite 4D BIM's potential, research into exploring its various applications (such as creating and validating new practices to perform project tasks for the benefit of practitioners) has been limited [11,31,39]. Table 2 reports upon major studies that applied 4D BIM for concrete structures to reveal a limited volume of research undertaking within the literature.

Table 2 - Studies on the use of 4D BIM for concrete structures

Publication	Focus of study	Main method	Findings
Boton [11]	Use of 4D and VR in constructability assessments	Integration of 4D and VR applications	Presenting a procedure for transferring a 4D model into VR for constructability analysis
Wang *et al.* [81]	Precast concrete structure	Integration of BIM and Genetic Algorithm	An optimal assembly sequence is presented to reduce the assembly difficulty of a precast concrete building
Lee and Ham [53]	Formwork systems	Cost optimisation	An automated procedure to optimise the design and layout of formwork, to reduce costs
Wang *et al.* [81]	Temporary structures (formwork)	Automation of temporary structures estimation	An automated procedure to estimate temporary structures requirements
Mansuri *et al.* [56]	Formwork systems	BIM integration with a cascading algorithm	Generating a scheduled formwork reuse plan and calculating the minimum quantity of formwork required for a project
Singh *et al.* [76]	Formwork design	Application Programming Interface (API) of BIM tools	A streamlined formwork design process in the BIM environment
Jiang and Leicht [43]	Constructability checking for formwork	Pursuing automated constructability reasoning	Establishing constructability ontology
Stanton and Javadi [78]	Cost optimisation of a reinforced concrete structure	Cost optimisation with Genetic Algorithm	Cost of reinforced concrete is optimised based on site-based variables like height limitations
Aram *et al.* [4]	Exploring BIM capabilities for concrete structures supply chain	Conceptual study	Recommendations are proposed to align BIM tools with the supply chain of concrete structures
Porwal and Hewage [70]	Reducing the waste of rebar in concrete structures	Use of BIM models to simulate the architectural and structural design	Significant cost saving increases increasing the diameter of rebar
Barak *et al.* [8]	Defining BIM requirements for concrete structures' production modelling	A qualitative study based on experts' views	Providing a set of object schemas, defining relations, methods, and attributes needed for modelling the

	production of concrete structures

These studies are predominantly based upon optimisation objectives regarding formwork required for concrete structures with a view to reducing the workload of designers [53,76].

Current 4D activities on construction projects are of the most labour-intensive parts. Currently, most construction projects rely on human resources for manually planning activities and inspecting and controlling progress. The average share of these activities within a project budget lies up to 40%, as argued by Kropp *et al.* [52]. Therefore, automating 4D BIM application and reducing the now-needed workload of field personnel is of great importance, yet still an underexplored potential of BIM [52].

Investigating typical damaged concrete structures after earthquakes show that the failure of joints is a major contributor to the collapse of concrete structures due to earthquake excitation [46].One such area is 4D activities associated with optimising the layout of joints, which contemporary literature fails to address, despite its importance to structural integrity. This study posits that this might be due to very multidisciplinary nature of the issue and high stiffness of construction practices, when it comes to changing established routines so that this gap hasn't been explored thoroughly yet.

3 RESEARCH DESIGN

To address these theoretical and technical gaps, this study aimed at developing and validating proof of concept prototype for the 4D automated concrete joint layout planning application. The study adopted a two-phased process to cover both technical and theoretical aspects at the same time:

Stage one: prototype development **–** this consists of a three-stage iterative process: i) identification of the factors and variables that affect the concrete pouring schedule; ii) integration of selected software tools and data exchange procedures needed to automate the model; iii) establishment of logic and analytical considerations for concrete pouring.

Stage two: application of the proof of concept – a case study, to demonstrate and validate the approach developed in phase one.

Figure 1 illustrates the two stages of the research design and full details of these stages are presented in Section 4 and Section 5.

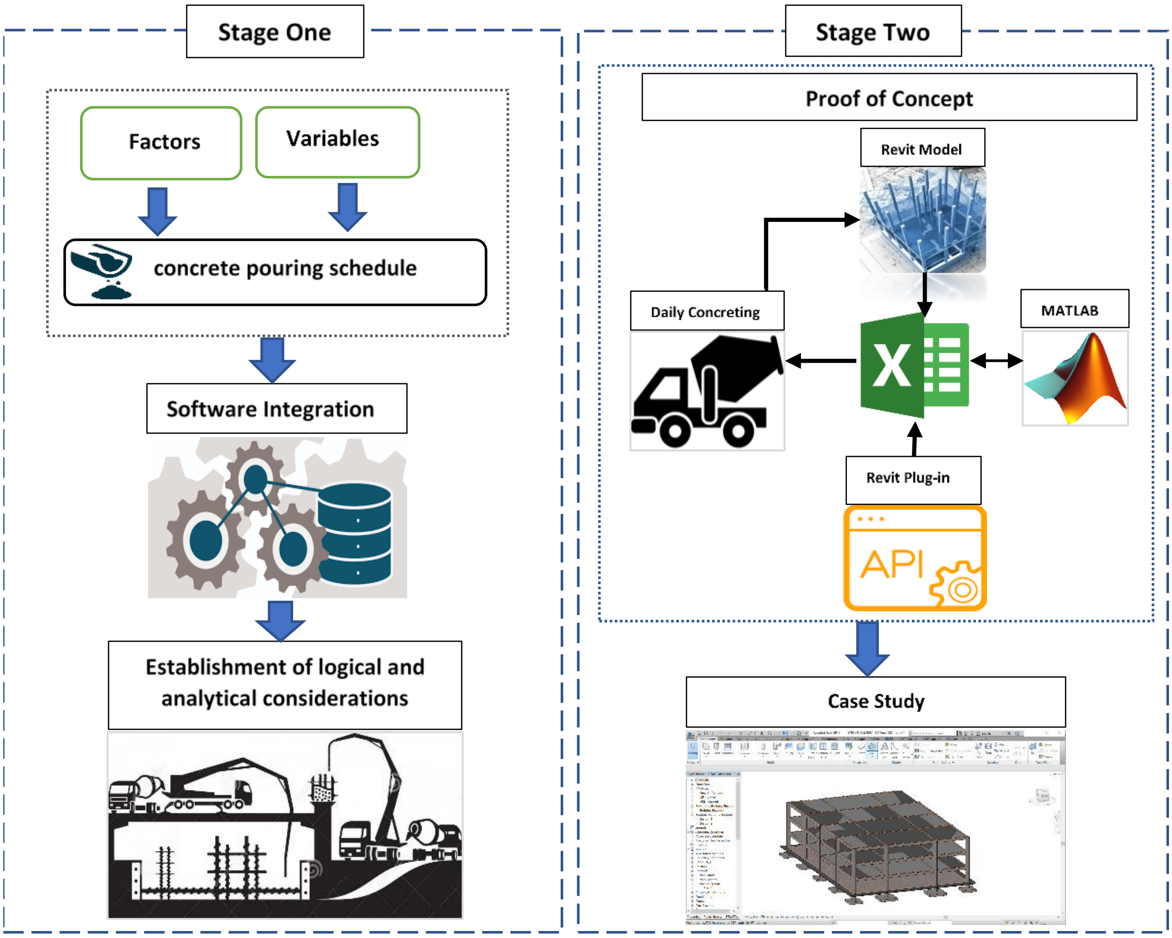


Figure 1. The two-stage research design

4 STAGE ONE: PROTOTYPE DEVELOPMENT

4.1 Assumptions, factors and variables

For the initial proof of concept, several assumptions were considered: the daily allowed concrete remains constant on various working days; structures used have rectangular plans;

and the structural plan is similar across all floors of a building. Holding these assumptions constant enabled the proof of concept's basic design to be developed and tested, however, it is acknowledged that future work is required to increase the application's scope (in terms of different production schedules, material availability and building designs).

Many variables and factors affect the pouring technical requirements, and also the scheduling and planning of the pour [1]. These variables are both context-dependent and unique to a bespoke project. Cumulatively, they place limitations on the pouring procedure, and therefore, must be incorporated into the proof of concept (refer to Table 3).

Table 3 - Factors and variables affecting the concrete scheduling procedure

Factor / Variable	**Associated considerations**
Daily available concrete	Clarifying the limitation for daily concreting available on the project.
Concrete waste percentage	Estimating the amount of concrete waste.
Pour starting point	Clarifying the point of start for the pour.
Pour direction	Clarifying the direction to which poring is heading.
Floor thickness, Points: details of the floors The perimeter of the model	Estimating the concreting volume.
Beams: start and end points	Locating midspan points.
Beams: midspan points	Locating construction joints and stop concreting.
Maximum length and width of the model	Clarifying the point of start for the pour and clarifying the direction to which pouring is heading.

4.2 Project framework and data exchange procedure

This study employed four software applications, to develop the automated procedure within this proof of concept prototype: i) Autodesk Revit© 2018; ii) Dynamo 1.3.2; iii) Microsoft (MS) Excel 2016; and iv) MATLAB 2014. The combination of Revit-Dynamo provides a convenient and automated data exchange procedure for importing data extracted in various forms from a BIM model in Revit [61]. Dynamo is recognised as a user-friendly input-output data interface, enabling users of visual programming to establish bilateral integration between Revit and MS Excel in order to store and manipulate BIM data in spreadsheets [12].

Dynamo's architecture of subroutine definitions and communication protocols provide access to the Revit API (application programming interface) [6]. This enables Dynamo users to interact with a Revit model, query and change element properties, and also add and modify some elements, directly from the Dynamo environment [65]. Data exchange structure and flowchart of how these 4 applications are integrated into the developed prototype are presented in Figure 2.

In the Revit model, the first step was to insert data into the model (refer to arrow 1). The next step was to identify relevant data to export from the 3D model into the Dynamo spreadsheet. To prevent unplanned joints and develop the concreting schedule, the pour volume was needed together with the identification of vulnerable points in beams and the perimeter of the model. For beams, the vulnerable points were located in one-third of midspans, and for floors, the vulnerable points were located at the building perimeter. Accordingly, the coordination details – of beams and floors – were extracted from the model and submitted to the spreadsheet (arrow 2). The data were exchanged between the Revit model and one of the two MS Excel spreadsheets. This data exchange provided the exact location coordinates for beams and floors (arrow 3). Figures 3.a and 3.b illustrate the data flow (of perimeter data) between the Revit model and MS Excel for floors in seven steps.

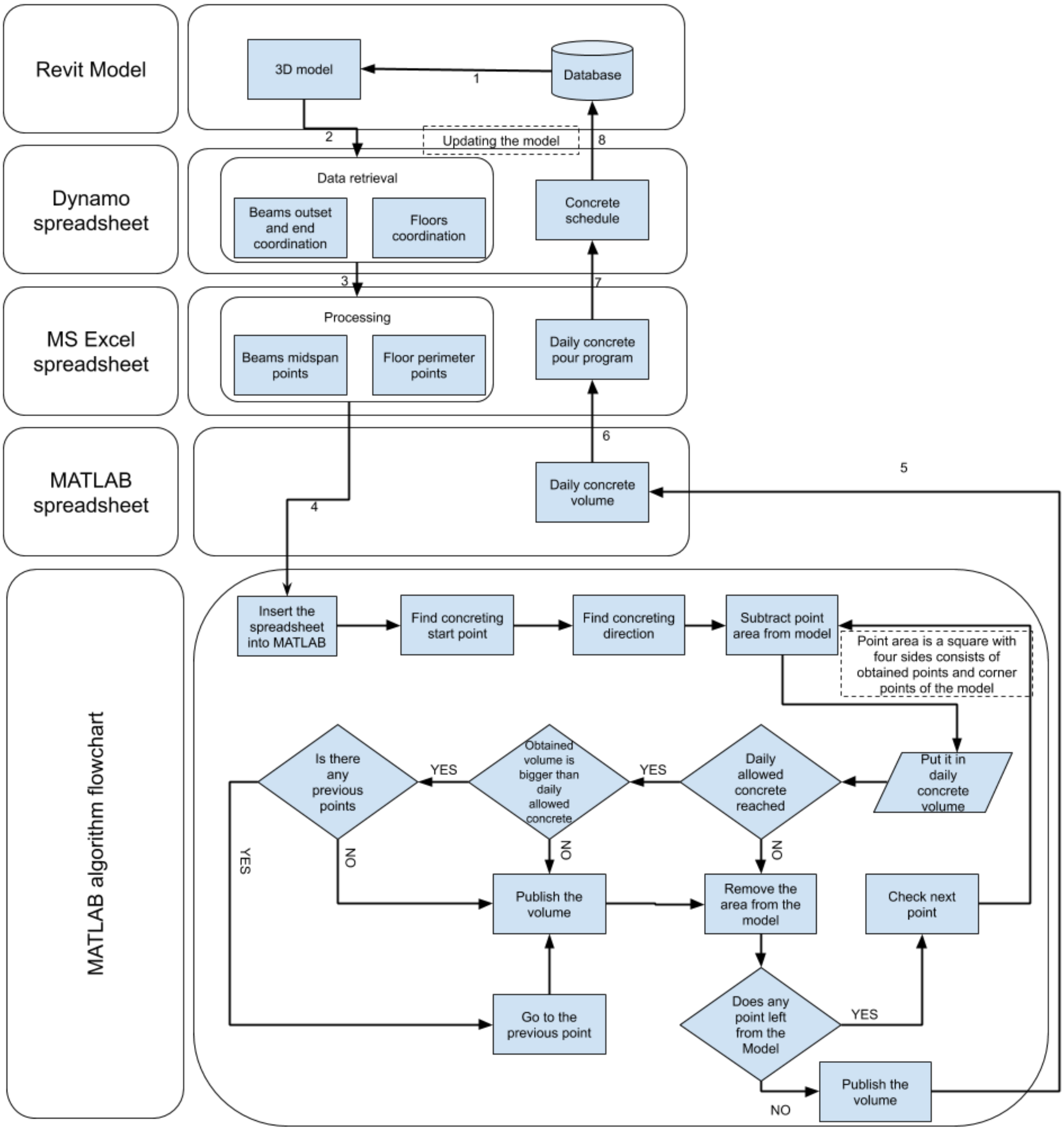


Figure 2. The structure of data exchange

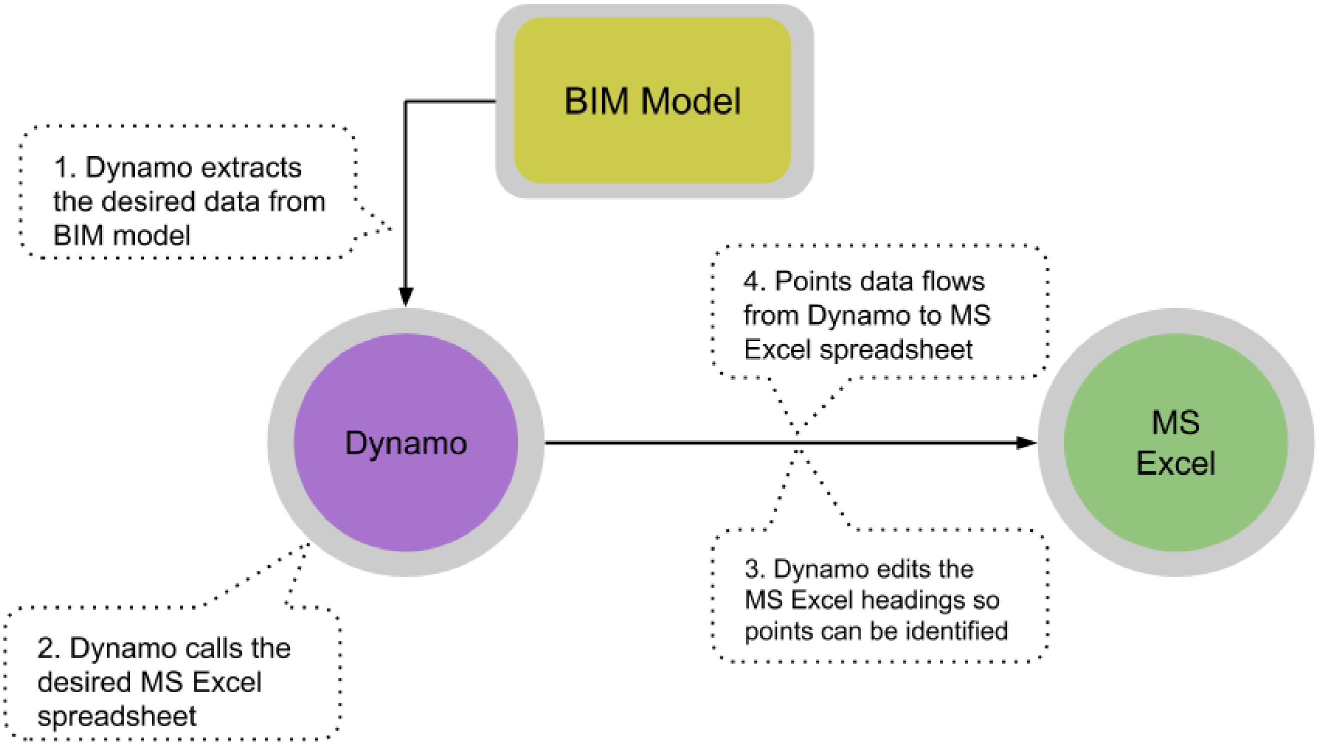
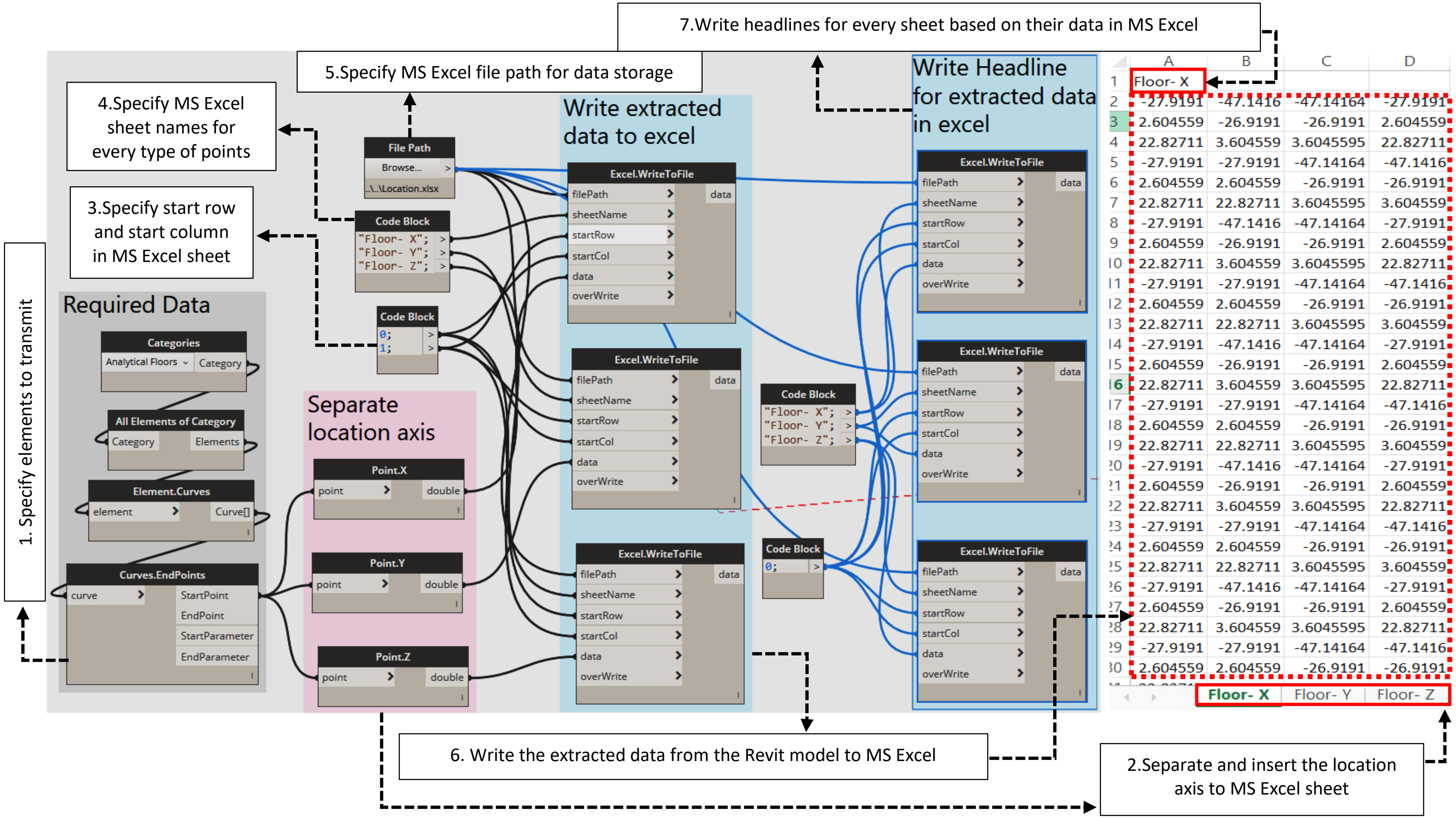


Figure 3.a Data flow from the 3D Revit model to MS Excel, using Dynamo



	A	B	C	D
1	Floor- X			
2	-27.9191	-47.1416	-47.14164	-27.9191
3	2.604559	-26.9191	-26.9191	2.604559
4	22.82711	3.604559	3.6045595	22.82711
5	-27.9191	-27.9191	-47.14164	-47.1416
6	2.604559	2.604559	-26.9191	-26.9191
7	22.82711	22.82711	3.6045595	3.604559
8	-27.9191	-47.1416	-47.14164	-27.9191
9	2.604559	-26.9191	-26.9191	2.604559
10	22.82711	3.604559	3.6045595	22.82711
11	-27.9191	-27.9191	-47.14164	-47.1416
12	2.604559	2.604559	-26.9191	-26.9191
13	22.82711	22.82711	3.6045595	3.604559
14	-27.9191	-47.1416	-47.14164	-27.9191
15	2.604559	-26.9191	-26.9191	2.604559
16	22.82711	3.604559	3.6045595	22.82711
17	-27.9191	-27.9191	-47.14164	-47.1416
18	2.604559	2.604559	-26.9191	-26.9191
19	22.82711	22.82711	3.6045595	3.604559
20	-27.9191	-47.1416	-47.14164	-27.9191
21	2.604559	-26.9191	-26.9191	2.604559
22	22.82711	3.604559	3.6045595	22.82711
23	-27.9191	-27.9191	-47.14164	-47.1416
24	2.604559	2.604559	-26.9191	-26.9191
25	22.82711	22.82711	3.6045595	3.604559
26	-27.9191	-47.1416	-47.14164	-27.9191
27	2.604559	-26.9191	-26.9191	2.604559
28	22.82711	3.604559	3.6045595	22.82711
29	-27.9191	-27.9191	-47.14164	-47.1416
30	2.604559	2.604559	-26.9191	-26.9191

Figure 3.b. Exporting floors location from the 3D Revit model to MS Excel, using visual programming

The next step was to identify the existing floors as structural elements using Dynamo. It then involved separating and inserting the locations of the concrete pour into MS Excel. By specifying the start row and column in the MS Excel sheet, and the names for various types of points, the file path to store the data was defined in the Matlab algorithm. Extracting X, Y and Z coordinates of the floor from the Revit model was the next step. By including the headlines for every sheet of the extracted data in the MS Excel sheet, results were visually seen as X, Y and Z for points, where every X, Y and Z combination had its own headline in the spreadsheet. A similar procedure for the data flow between BIM and MS Excel was applicable to structural beams. The aim of data extraction for floors was to find the perimeter of the model for the whole building, whereas, for beams, the aim was to find the mid-spans. This approach served to identify the points with the minimum negative effects on the structure, where the concreting activity can be ceased.

In order to locate the beams' mid-spans as well as the floor's perimeter, coding was performed in the MS Excel environment using macros and the programming language Visual Basic for Applications (VBA). Macros and VBAs are coding spreadsheets, on which mathematical actions and formula insertion can be conducted. The developed coding has the capability of taking up to 10000 data in every excel column for beams to locate their mid-span.

4.3 Logic and analytical considerations

In order to develop the concrete schedule, the maximum width and length of the model were calculated in MS Excel first to find the starting point location for the pour and the direction towards which the concreting is headed. A common practice within the industry is for contractors to start and continue the concrete pouring process in a direction with the minimum of length, to make the concreting cease controllably. Logical operator 1 (below) illustrates: if the length of the model (Y) is greater than its width (X), then the start point is one of the points with the minimum of (Y). From the aforementioned points, the point with the minimum (X) value would be selected as the start point. If (X) is greater than (Y), then the start point would be one of the points with the minimum (X) and from those points, the point with the minimum

(Y) will be chosen as the start point of the project.

$$A \subseteq Model\ points, A = \{x, y | x, y \subseteq Model\ points, (x, y_{min})\},$$

$$B = \{x, y | x, y \subseteq A, (x_{min}, y)\}$$

$$C \subseteq Model\ points, C = \{x, y | x, y \subseteq Model\ points, (x_{min}, y\},$$

$$D = \{x, y | x, y \subseteq C, (x, y_{min})\}$$

$$Start\ Point\ and\ Direction = \begin{cases} Start\ Point : Set\ B, Directon: Augmented\ X, & X < Y \\ Start\ Point : Set\ D, Directon: Augmented\ Y, & X \geq Y \end{cases}$$

Logical Operator 1

Where A is a subset of B which includes all of the points with the minimum value of Y, and B is a start point if $X < Y$. In addition, C is a subset of D which includes all of the points with the minimum value of X, and D is a start point if $X \geq Y$.

Figure 4 illustrates the process of identifying the corner point of a plan view building as the start of the project.

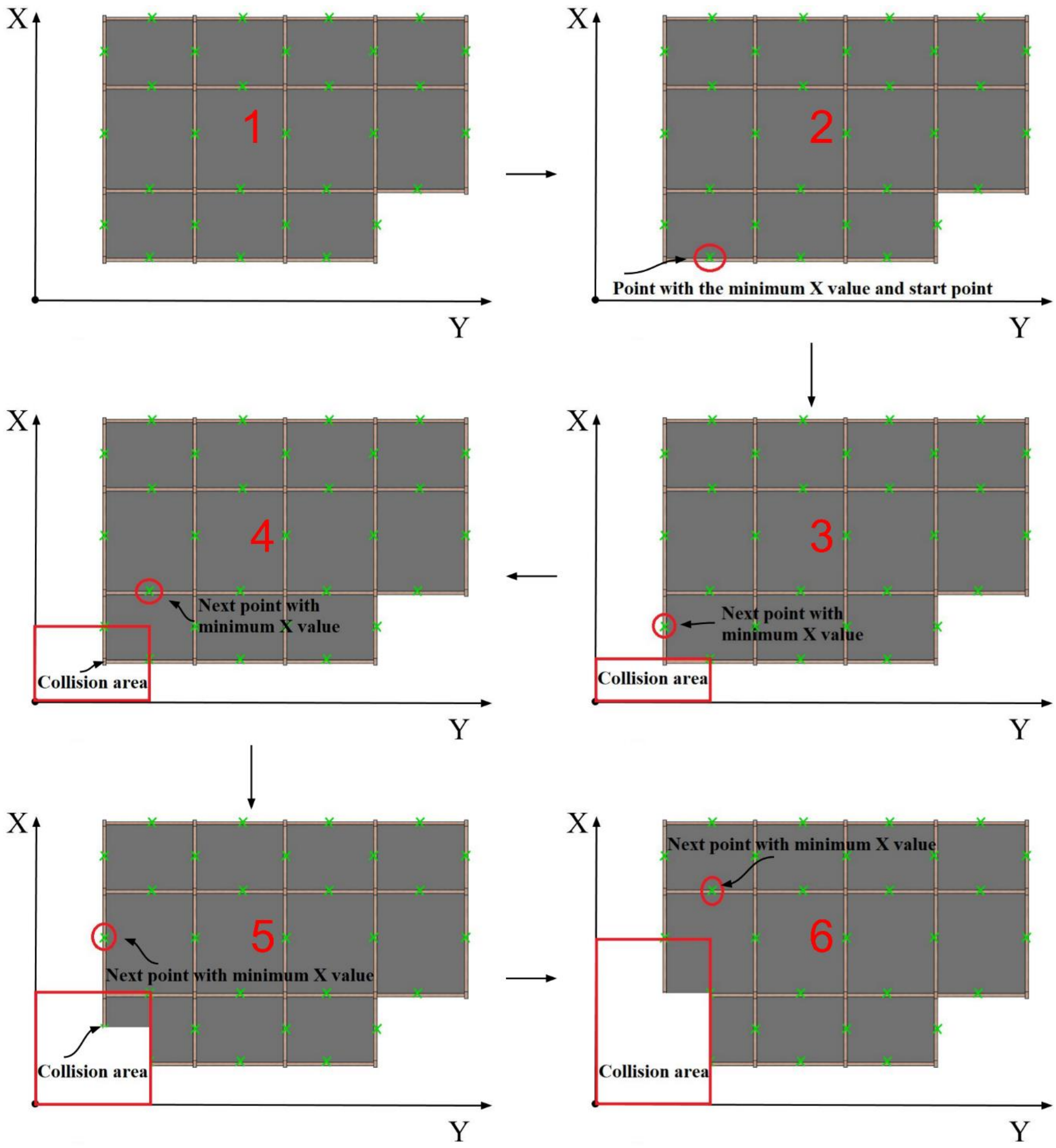


Figure 4. Logic of methodology

To choose the right direction in concreting, as shown in Logical Operator 1, in case the length of the model is greater than the width, the concrete pouring will start at the point with minimum the value of (X), with (Y) value fixed and the next points will head on new (X) and same (Y) respectively. Conversely, concrete pouring would head on new (Y) direction with the fixed (X) value. While on the equal width and length situation, there is no difference in the direction of concreting and the default is set on fixed (Y).

By finding the start point, a rectangular area including this start point and the model's corner points – as the rectangle corners – are identified (see Figure 4, section 4). This collision area is calculated and removed at the next step; afterwards, the next point is checked. The arrangement strategy for this selection is based on the direction of concrete pouring as if the width of the model is greater than the length. The next point is an augmented Y with the fixed X value. Where the value of the model's length is greater than the width value, the next point is augmented X with the fixed Y value. This method will continue up until the complete row is eliminated. Then the new fixed X or Y value are selected as the start point, and the loop will continue until there is no model left on the program.

Available concrete is an important variable that differs across different projects [21]; where this volume depends on resource limitations such as financial resources, access restrictions to the site and human resources restrictions [1]. Hence, each bespoke project has its own unique available concrete [21]. Therefore, a variable representing the available concrete has been inserted into the proof of concept as a default concrete volume number, which will be used as the limitation volume in daily concrete operations. This value is defined as a variable; its value is left, to be defined by individual users working on projects with various conditions affecting them.

Another variable is the concrete waste. During on-site activities, some unavoidable factors (such as material transportation and human resource activities) affect the amount of concrete waste generated. Therefore, a coefficient was included (as a percentage) to estimate concrete waste and determine how this will affect total volume. Determining waste is a complex phenomenon that is almost entirely context-specific and based upon the on-site experiences and records of technicians [45,60]. This coefficient is included in the automated schedule designed for the present study.

The pour schedule data was linked with the Revit model for visualisation purposes. According to Figure 2 (arrow 6, 7 and 8), the pour programme generated through the proposed methodology in MATLAB – showing the results in the MS Excel spreadsheet – must be inserted into the model using Dynamo. The extracted data are attached to the floor element in the Revit model for the concrete pour schedule.

In order to facilitate the automation process and create a user-friendly interface, an Autodesk Revit plug-in was developed, using Revit API (Figure 5). This plug-in can access the daily concrete volume, as well as daily concrete waste, based on experimental and documented records of previous projects and floor thickness when calculating the surface of the pour. By using the structural design of the project and based on the information mentioned above, ceasing concrete pouring in critical points can be properly managed, and structural problems can be avoided.

5 STAGE TWO: APPLICATION OF THE PROOF OF CONCEPT

The developed proof of concept prototype was tested and validated via adopting a real-life case study. All factors and variables, mentioned in Table 3, are used in different stages of this case study. In this regard, available daily concrete, concrete waste percentage, and floor thickness were obtained via a plug-in and used in concreting schedule calculations. Floors' perimeter points and beams' start and end points were obtained from the 3D model and used for calculating concrete volume as well as beam midspan points. Maximum length and width of the model were also calculated based on floor perimeter points, to help calculate concrete pouring directions and starting points.

The case of study was a three-storey educational building (with a uniform design) in Tehran, Iran. The total project budget was USD 345,210, and it was developed over an 18 months' period (from 02/2017 to 08/2018). Using the developed plug-in in the Revit environment, the daily concrete volume and the starting point of the pour are defined (Figure

6.b). Data required for running the plug-in are the available daily concrete volume (as the first limitation to start the project), floor thickness and the percentile concrete waste factor (Figure 6.a). Based on the previous studies on the composition of construction waste, concrete is the second contributor to the whole process of waste generation. According to Poon's investigation, 80% of the work was made from ready-mix concrete. 3-5% wastage of concrete is mainly caused by excessive material ordering, broken formwork, and redoing due to poor concrete placement quality [69]. Given this, in this research, the amount of concrete waste is considered to be 5%.

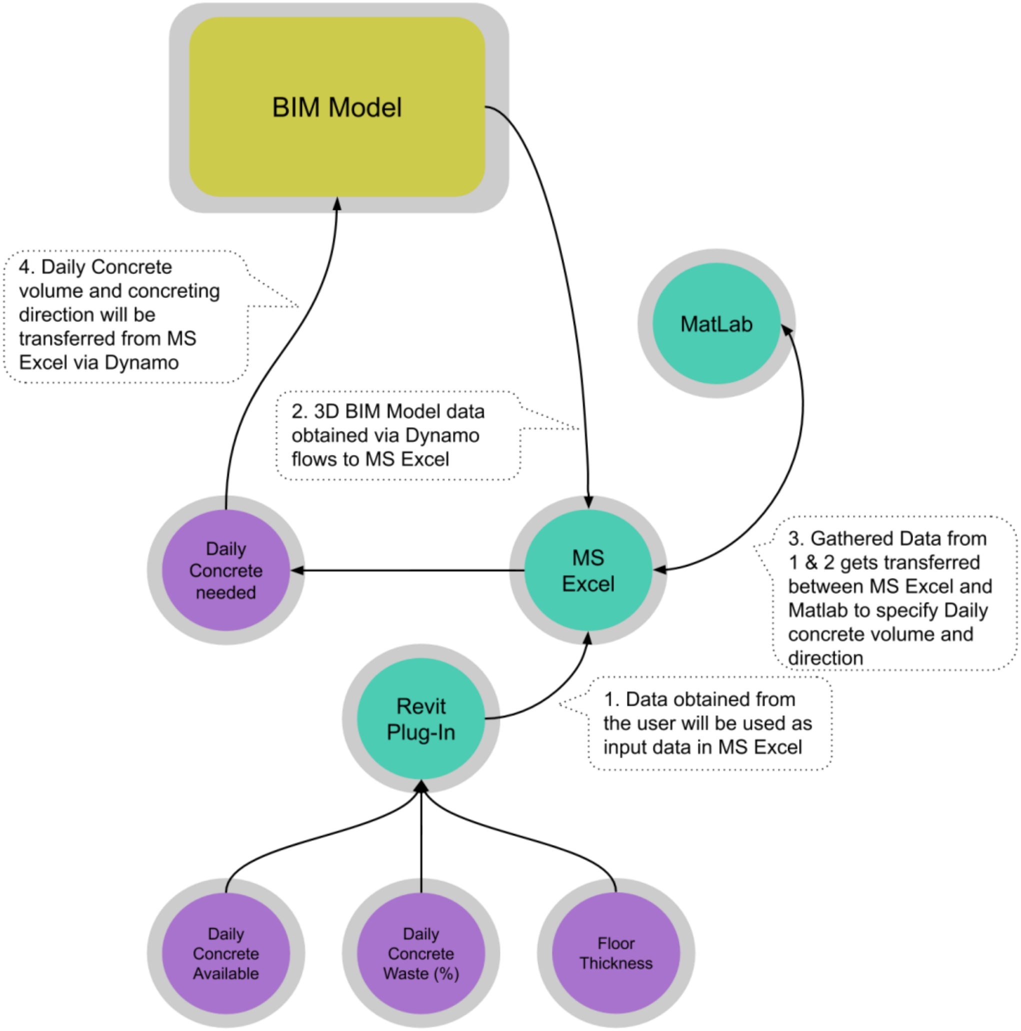


Figure 5. The developed Autodesk Revit plug-in

As illustrated in Figure 6.b, the generated concreting schedule volume was shown in the analytical floor schedule. The first column in this schedule shows the daily concrete volume required during construction. Daily allowed concrete volume, in this case, was 400 ft^3. Yet, the available amount was automatically reduced by 5% to factor in the impacts of waste. The second column shows the start point. The direction of the concrete is calculated automatically using the logic as discussed in Section 4.3; the direction heads to the side with less length.

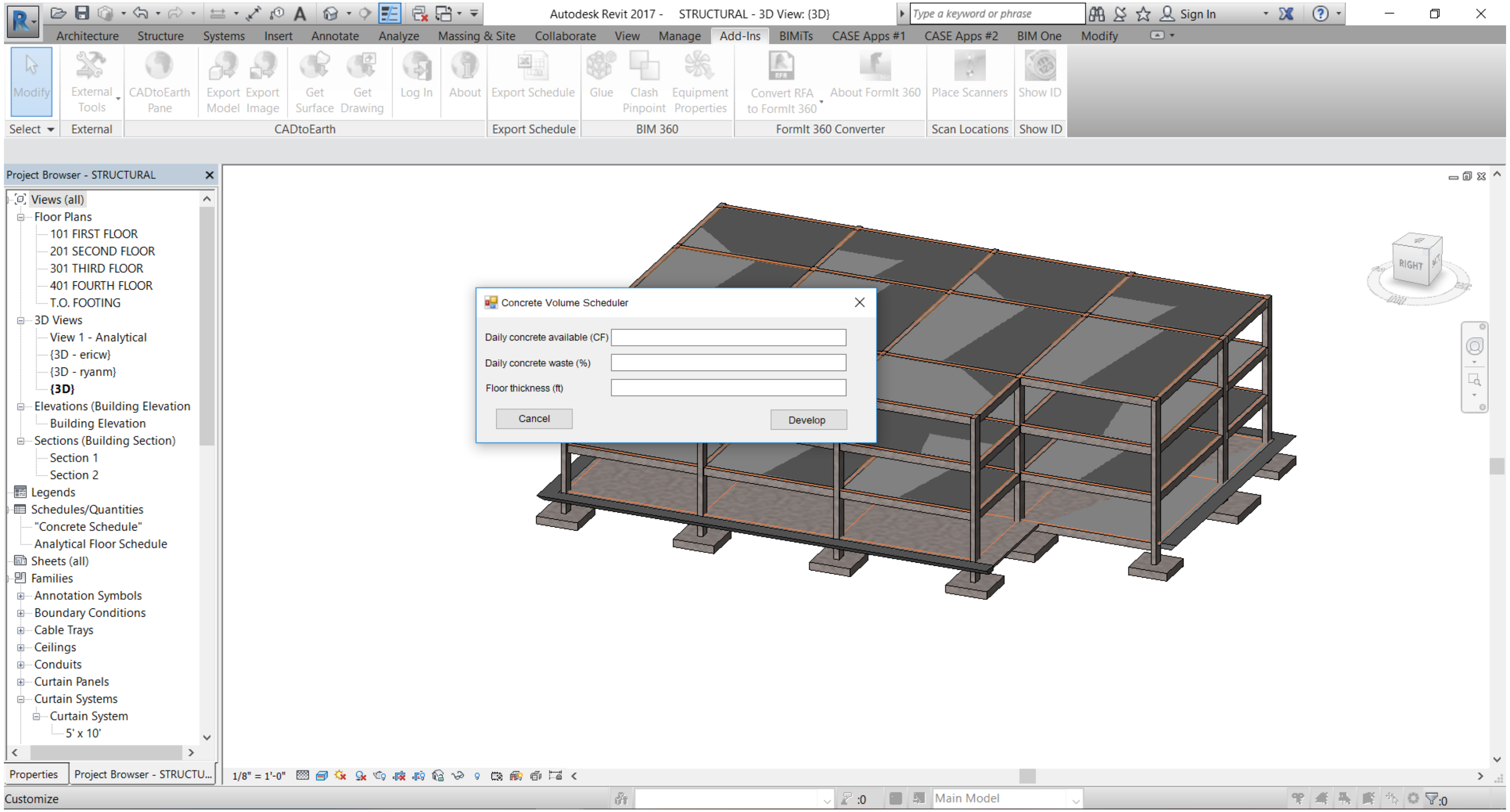
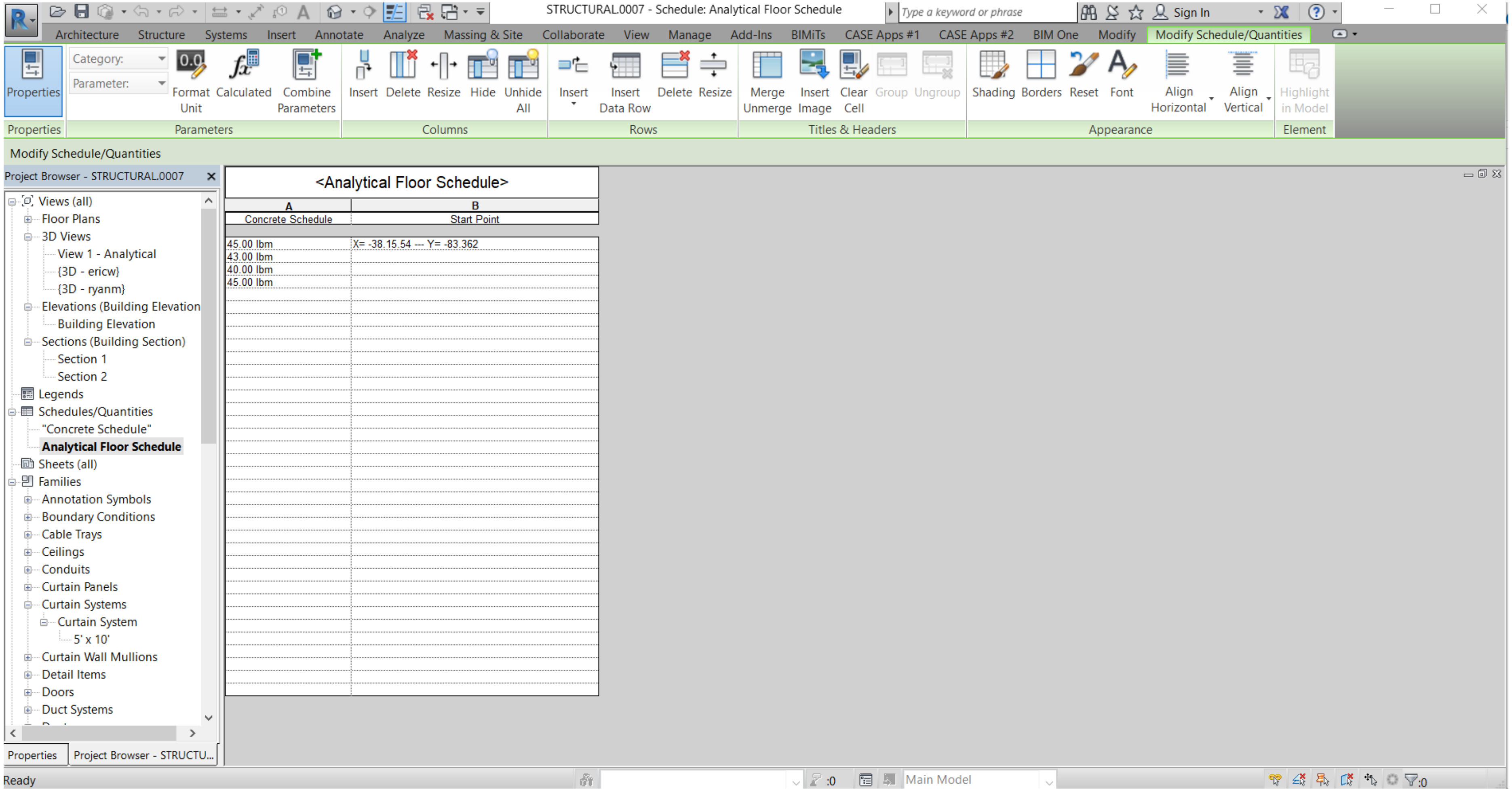


Figure 6.a. Snapshot of the automated concreting schedule plug-in



<Analytical Floor Schedule>

A	B
Concrete Schedule	Start Point
45.00 lbm	X= -38.15.54 --- Y= -83.362
43.00 lbm	
40.00 lbm	
45.00 lbm	

1

Figure 6.b. Snapshot of the developed concreting schedule

The outcomes of applying the plug-in on scheduling the pour are visualised against a scenario in which the pour was planned merely based on the daily available concrete volume of 400 ft ^{3}. The total areas which need concrete are illustrated in Figure 7.

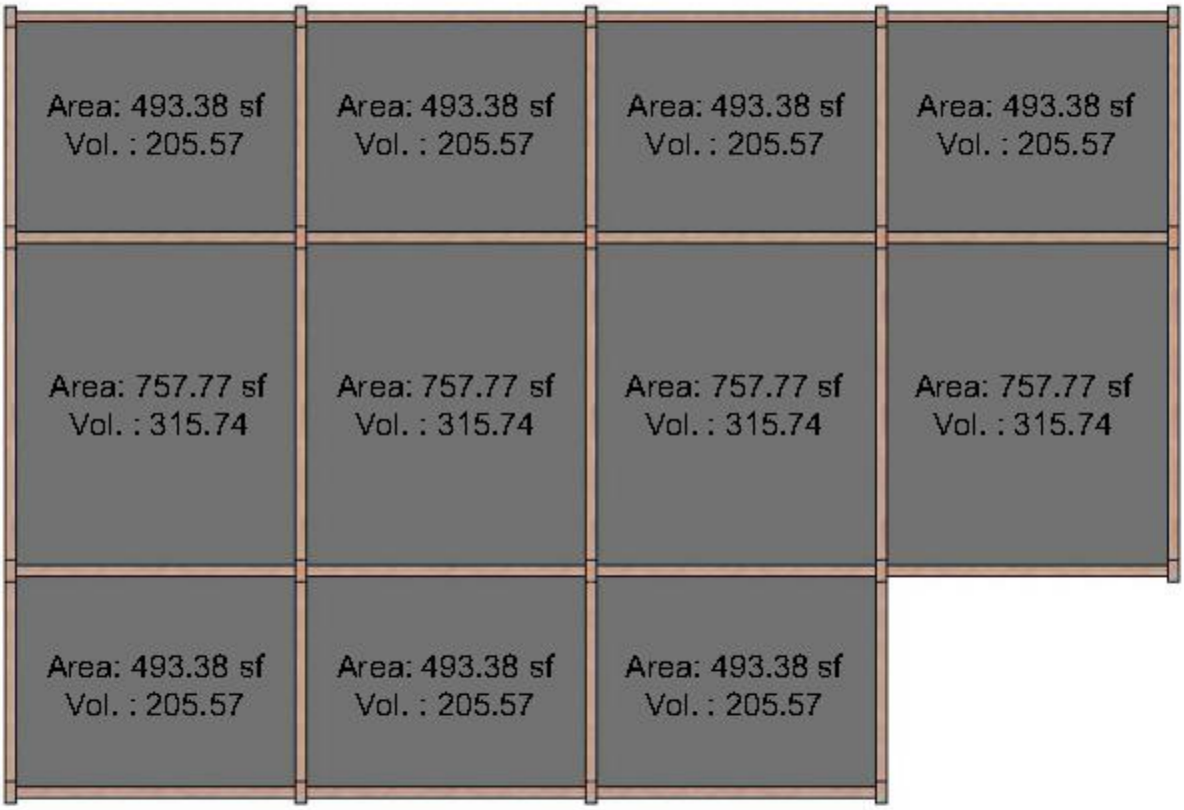


Figure 7. Total areas in the Revit model which need concreting

Figure 8 presents the pour plan that includes 5% of concrete waste and 400 ft^3 daily concrete available on site, assuming that the total available concrete volume can be poured.

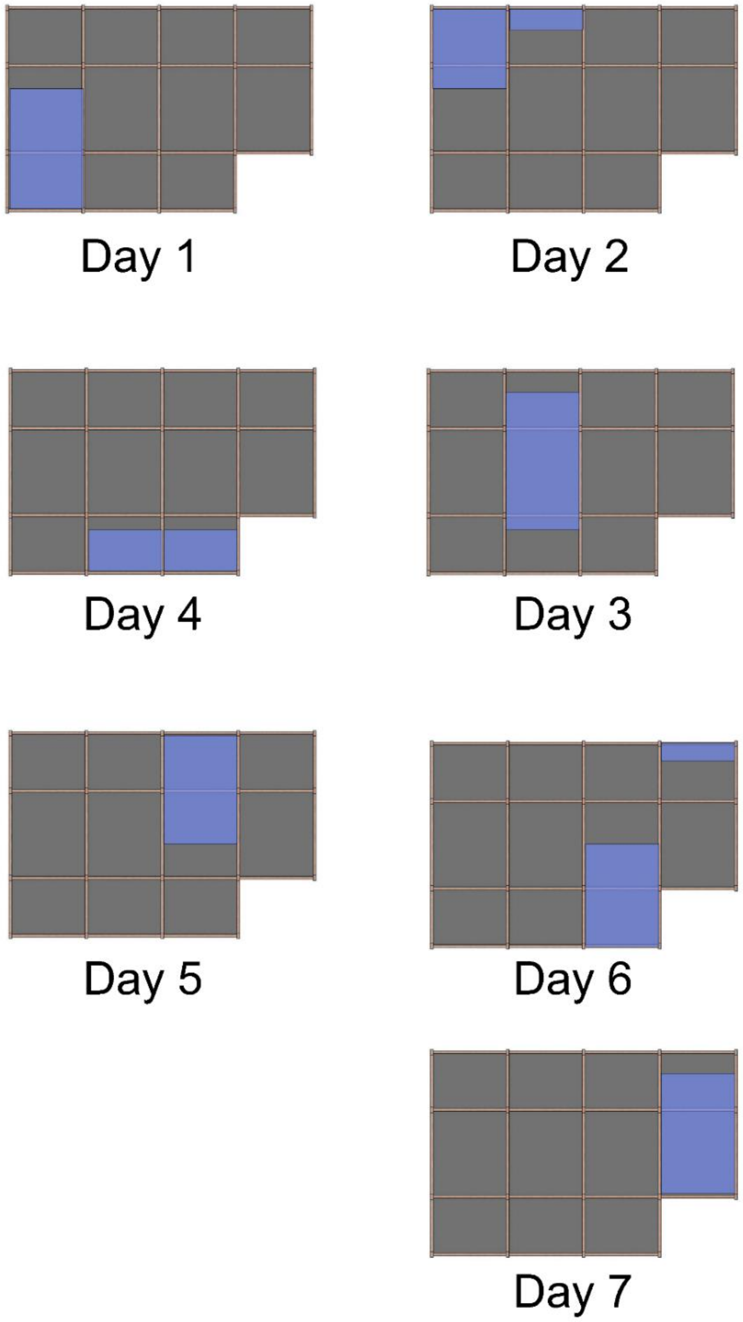


Figure 8. Concrete pouring plan with maximum daily concrete available (without using the automated procedure)

Figure 9 illustrates the pour schedule using the developed plug-in. Comparing the plan in Figure 8 with that of Figure 9 reveals that in Figure 9, the pour is ceased prior to reaching the available amount, based on the criterion: “where is the best position to stop”, with the aim of having the least possible impact on the structural strength. As a result, daily pour activities must cease at 381.612 ft^3 with 5% waste included, where the last day volume is 165.76 ft^3. While using the traditional method of concreting can complete the task in a tighter schedule, from the structural waste generation perspectives, the plan will be clearly different.

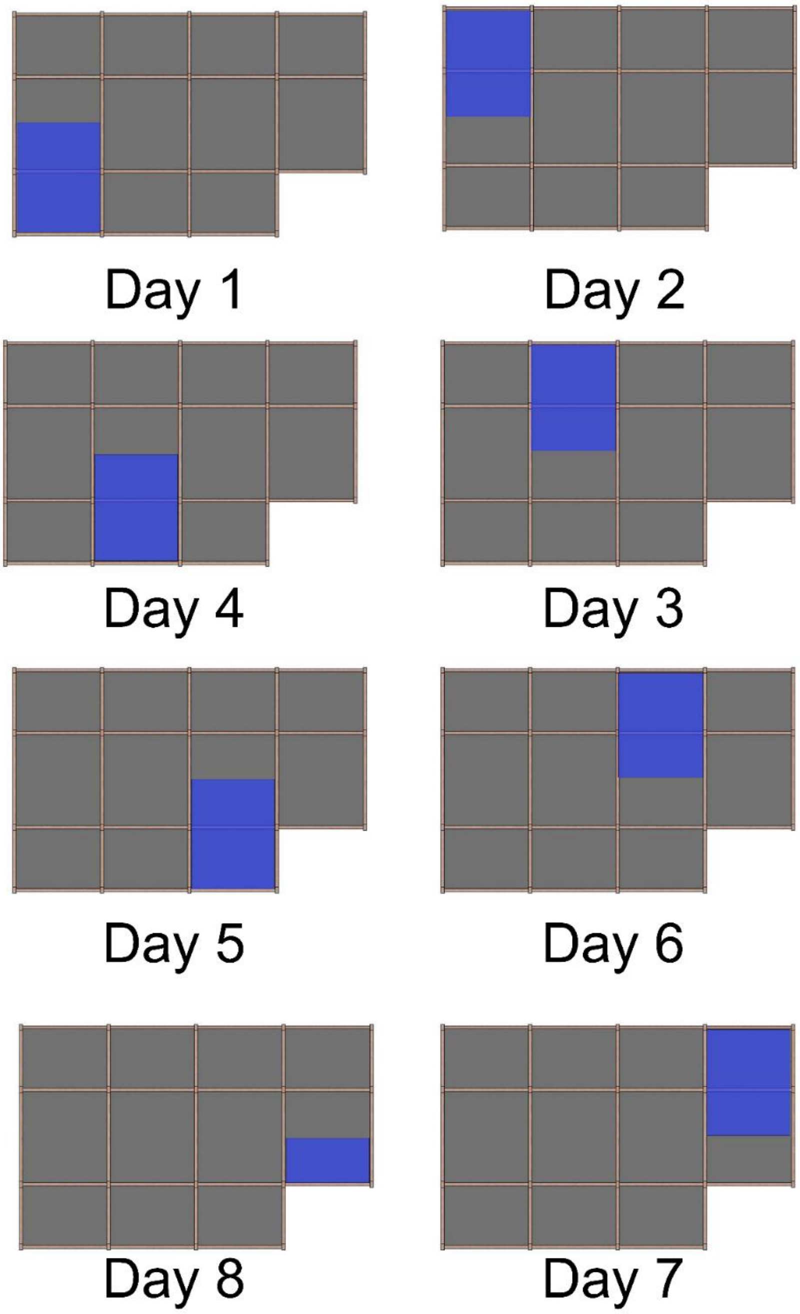
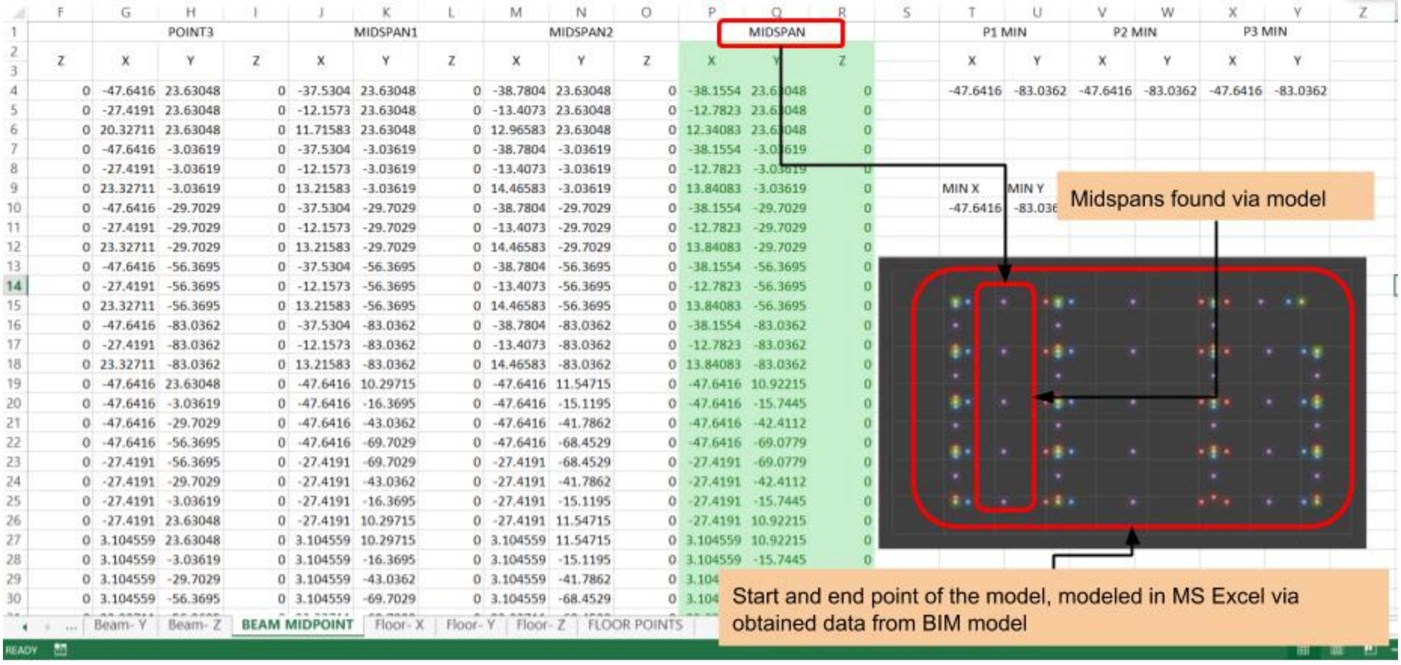


Figure 9. Concrete pouring process developed via the proposed automated methodology

Figure 10 illustrates how the extracted data from the model fulfils the structural consideration for ceasing the pour. That is, the purple dots indicate mid-spans in the model while the other dots show the beams extracted from the model. This illustrates that the mid-spans finding process from Revit to MS Excel works properly.



	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y
1			POINT3			MIDSPAN1			MIDSPAN2			MIDSPAN			P1 MIN		P2 MIN		P3 MIN	
2 3	Z	X	Y	Z	X	Y	Z	X	Y	Z	X	Y	Z		X	Y	X	Y	X	Y
4	0	-47.6416	23.63048	0	-37.5304	23.63048	0	-38.7804	23.63048	0	-38.1554	23.63048	0		-47.6416	-83.0362	-47.6416	-83.0362	-47.6416	-83.0362
5	0	-27.4191	23.63048	0	-12.1573	23.63048	0	-13.4073	23.63048	0	-12.7823	23.63048	0							
6	0	20.32711	23.63048	0	11.71583	23.63048	0	12.96583	23.63048	0	12.34083	23.63048	0							
7	0	-47.6416	-3.03619	0	-37.5304	-3.03619	0	-38.7804	-3.03619	0	-38.1554	-3.03619	0							
8	0	-27.4191	-3.03619	0	-12.1573	-3.03619	0	-13.4073	-3.03619	0	-12.7823	-3.03619	0							
9	0	23.32711	-3.03619	0	13.21583	-3.03619	0	14.46583	-3.03619	0	13.84083	-3.03619	0		MIN X	MIN Y				
10	0	-47.6416	-29.7029	0	-37.5304	-29.7029	0	-38.7804	-29.7029	0	-38.1554	-29.7029	0		-47.6416	-83.036				
11	0	-27.4191	-29.7029	0	-12.1573	-29.7029	0	-13.4073	-29.7029	0	-12.7823	-29.7029	0							
12	0	23.32711	-29.7029	0	13.21583	-29.7029	0	14.46583	-29.7029	0	13.84083	-29.7029	0							
13	0	-47.6416	-56.3695	0	-37.5304	-56.3695	0	-38.7804	-56.3695	0	-38.1554	-56.3695	0							
14	0	-27.4191	-56.3695	0	-12.1573	-56.3695	0	-13.4073	-56.3695	0	-12.7823	-56.3695	0							
15	0	23.32711	-56.3695	0	13.21583	-56.3695	0	14.46583	-56.3695	0	13.84083	-56.3695	0							
16	0	-47.6416	-83.0362	0	-37.5304	-83.0362	0	-38.7804	-83.0362	0	-38.1554	-83.0362	0							
17	0	-27.4191	-83.0362	0	-12.1573	-83.0362	0	-13.4073	-83.0362	0	-12.7823	-83.0362	0							
18	0	23.32711	-83.0362	0	13.21583	-83.0362	0	14.46583	-83.0362	0	13.84083	-83.0362	0							
19	0	-47.6416	23.63048	0	-47.6416	10.29715	0	-47.6416	11.54715	0	-47.6416	10.92215	0							
20	0	-47.6416	-3.03619	0	-47.6416	-16.3695	0	-47.6416	-15.1195	0	-47.6416	-15.7445	0							
21	0	-47.6416	-29.7029	0	-47.6416	-43.0362	0	-47.6416	-41.7862	0	-47.6416	-42.4112	0							
22	0	-47.6416	-56.3695	0	-47.6416	-69.7029	0	-47.6416	-68.4529	0	-47.6416	-69.0779	0							
23	0	-27.4191	-56.3695	0	-27.4191	-69.7029	0	-27.4191	-68.4529	0	-27.4191	-69.0779	0							
24	0	-27.4191	-29.7029	0	-27.4191	-43.0362	0	-27.4191	-41.7862	0	-27.4191	-42.4112	0							
25	0	-27.4191	-3.03619	0	-27.4191	-16.3695	0	-27.4191	-15.1195	0	-27.4191	-15.7445	0							
26	0	-27.4191	23.63048	0	-27.4191	10.29715	0	-27.4191	11.54715	0	-27.4191	10.92215	0							
27	0	3.104559	23.63048	0	3.104559	10.29715	0	3.104559	11.54715	0	3.104559	10.92215	0							
28	0	3.104559	-3.03619	0	3.104559	-16.3695	0	3.104559	-15.1195	0	3.104559	-15.7445	0							
29	0	3.104559	-29.7029	0	3.104559	-43.0362	0	3.104559	-41.7862	0	3.104									
30	0	3.104559	-56.3695	0	3.104559	-69.7029	0	3.104559	-68.4529	0	3.104									

Midspans found via model

Start and end point of the model, modeled in MS Excel via obtained data from BIM model

Figure 10. Midspan and start floor points

6 DISCUSSIONS

Efforts on automation of various construction activities are to be considered early on the front end of projects [72]. Solutions must enable designers and practitioners to analyse available options and choose optimum ones that capture all operational constraints as well as design principles, alike. A large body of the BIM literature suggests drawing upon the potentials provided by 4D BIM, to tackle operational considerations and design principles simultaneously [22,82]. Nevertheless, except for few existing studies like that of Hyun *et al.* [41], practical applications of 4D BIM, for bringing operational aspects back into design procedures within the context of concrete structures, are very limited, where there have been calls for research into the topic [39].

The developed Revit plug-in in this study and the proposed analytical considerations can be seen as a shift towards bringing 4D BIM applications into design procedures of concrete structures, in connections with operational constraints. This makes the present study a deviation from the current trend observed in the literature. The findings here are considered as complementary to the findings of available studies that have focused on the design or post-design stages of 4D BIM use, where both these stages are linked in developing the plug-in. Moreover, focusing on concrete structures makes the study unique and the first in its kind.

The current study still has some limitations, which are under study to be resolved. Some limitations to name are shortcomings of the developed application in dealing with circular building structures (or other different types of building plan layouts). The application is also affected by fluctuating available concrete volume for every day in the workshop.

As for the future works, the team is looking at the possibility of developing calibrated BIM models, by employing on-site sensors and drones to model the concreting constantly in the 4D BIM model and specify it with different colour codes. Here sensors and drones can act as intelligent agents [5] to collect data from the concreting process, whilst these data could be synchronised with the BIM model, using linked-data [67], machine learning and artificial intelligence (AI) algorithms [75]. It has been shown that by accurate tuning the AI algorithms [74], the decision making in tasks related concrete pouring can be facilitated by forecasting the duration [29], estimating the productivity [55] and identifying the real-time hazards [47]. This process helps project managers compare the concreting process with the developed concrete schedules. Another future work to name is the integration of mixer trucks with the concreting process. This integration helps to develop a more accurate concreting schedule based on project distance from batching plant, traffic conditions and on-site truck limitation factors. Sensors could also be employed on trucks, which could be very helpful in integration with on-site drones and sensors to make real-time concrete scheduling programs.

7 CONCLUSION

The study contributes to the field of digital construction and project management in several ways. First, in terms of research, the study displays a real-life application of 4D BIM capabilities to combine operational data with design considerations, to increase the efficiency of on-site activities that are affected by many variables. Second, it proposes a novel method of using BIM in structural engineering activities, an area which lacks prior academic attention. The study, therefore, bridges these theoretical and technical gaps and contributes to knowledge, by providing an integrated platform, bringing together, capabilities of various software applications, as a use case of 4D BIM for structural engineering activities.

From an application development point of view, the study offers a readily available plug-in, and a cost-effective solution that takes into account construction managers' requirements (e.g., the need to order and schedule the correct volumes of concrete), on one hand, and structural engineers' concerns (e.g., structural integrity particularly on joints), on the other hand. This can not only expedite the design and planning stages of concrete pouring, but it also can help improve the delivery of construction projects, by helping projects run on the basis of realistic concrete schedules and work orders. This can tremendously reduce waste of material as well as time, compared to traditional projects, where unplanned joints are imposed, due to dunning out of materials (adding extra layers of complexity to continue work), or excessive amount of concrete is wasted, due to fluctuating patterns of consumption, during different working days, effected by diverse combination of mandatory joints. The practicality of the solution is tested, via a real case study project, to demonstrate the positive differences in solutions, provided by the developed proof of concept prototype application, when compared to the traditional manual methods.

The framework and innovative approaches adopted in developing this software application could be used as a baseline, for developing a robust commercial plug-in, for the industry-standard BIM design tools. Such an integrated design software application will be invaluable for practitioners since it can offer a cost-effective and accurate methodology that will address the limitations and inefficiencies of traditional methods, used for planning pours and designing construction joints. It also takes into consideration structural principles, constructional procedures and operational constraints.

Despite the significant positive progress that this research made, several limitations have also been acknowledged, mainly concerning the limitations of the developed algorithms, in recognising vast range of forms and geometries of plan layouts, various floor levels, multiple beam sections, and fluctuating level of concrete supply, depending upon changing the capacity of vendors. As such, it has been suggested that a new version of the proposed system must be capable of being trained based on the data collected from on-site sensors and information provided from various stakeholders (e.g. temperature, productivity, absenteeism, traffic conditions, availability of equipment), to provide a dynamically evolving solution for pouring activities.

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