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A BIM-Based Tool for Formwork Planning in Reinforced Concrete Buildings

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Abstract: Reinforced concrete (RC) is the most popular material used in high-rise buildings in developing countries, and formwork activities have major impacts on reinforced concrete construction. Prefabricated modular formwork is the preferred option as it reduces labor work on site. The preferred method for formwork procurement is renting instead of leasing or purchasing, as significant investment risks are transferred to the supplier. Formwork planning is critical for the success of projects in terms of cost, schedule, quality, and safety. Current formwork planning practices rely solely on contractor experience, and there are few tools and methods available for effective formwork planning, particularly when a formwork supplier has not been defined. Building Information Modeling (BIM) has been extensively used in building projects, but very rarely when planning and designing temporary structures. There is a need to determine an adequate Level of Development (LOD) of BIM models for formwork to address challenges such as reducing the time and resources needed for modeling formwork during the planning stage. This paper discusses the design, development, and testing of a planning tool, using BIM methodology for prefabricated modular rented formwork in building projects. For the design of this tool, a survey was conducted to define the LOD of the formwork model, the rental option of formwork in unit cost per month (unit or m^2), the level of automation required for processing formwork quantities, and the Key Performance Indicators (KPIs) using BIM tools. Dynamo for Revit was utilized for automating the computation process. Two building samples of 5 and 20 stories each with a total constructed area of 46,500 m^2 and with similar architectural layout plans, were modeled using Revit. Finally, the tool was tested using formwork KPIs that were created as part of the framework developed for this research.

Keywords: Building Information Modeling (BIM), lean construction, generative design, formwork management.

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1. Introduction

Reinforced Concrete (RC) is the most common material used for high-rise buildings, especially in developing countries where the expertise in using RC is greater than the expertise in using structural steel framing (Wood and Parker, 2013). In RC buildings, formwork is the largest cost component, representing between 35% and 60% of the structural framing cost, and 15% of the total cost of the building (Johnston, 2014). Optimizing formwork planning can lead to a positive impact on project performance. Optimal formwork planning involves: (1) *standardization* of concrete elements dimensions, (2) selecting formwork systems that improve onsite labor *productivity*, (3) consideration of formwork *economy* to ensure that formwork systems that have few pieces and light materials are appropriately used, and (4) selecting the best formwork *reuse* scheme that maximizes the number of uses (rotation) and minimizes the number of formwork sets (Johnston, 2014).

Contractors may have little influence on *standardizing* the dimensions for concrete elements during design phases. However, contractors are responsible for selecting the formwork system (Peurifoy and Oberlender, 2011). Since formwork is labor intensive, the efficiency of formwork installation and *reuse* depends on selecting formwork systems that increase *productivity* and planning the optimum *reuse* schedule for those systems (Huang et al., 2004). Prefabricated modular formwork systems are preferred by contractors to increase *productivity* and *economy* since (1) minimum labor is required on-site, (2) lead times for delivering prefabricated modular formwork are minimum compared with tailor-made on-site formwork, (3) materials used typically have higher durability, and (4) less skilled labor is required for using these systems

(Huang et al., 2004). Contractors also prefer renting formwork equipment to improve formwork *economy* due to minimal initial investment and transfer of investment risk to the formwork supplier. When formwork systems are rented, formwork manufacturers provide engineering and technical support, and suppliers are often flexible in order quantities and delivery lead times (Johnston, 2014). For these reasons, more than 40% of contractors prefer renting rather than purchasing or leasing formwork equipment (Krawczyńska-Piechna, 2016).

Once the formwork provider and formwork system are selected, contractors define the formwork reuse schedule for that system. Typically, formwork reuse scheme relies only on contractor experience. None of the steps of the formwork planning process are automated often leading to risks of human error in estimating quantities and increasing the computation time for identifying optimal formwork reuse schemes (Biruk and Jaskowski, 2017). Relying solely on contractor experience may lead to overestimating or underestimating formwork materials. Key Performance Indicators (KPIs) can help contractors to complement their experience with a data-driven formwork planning methodology. Selection of appropriate formwork systems, estimation of formwork quantities, cost estimation associated with renting formwork, and computation of KPIs can be time-consuming and complex. Building Information Modelling (BIM) can be used to automate the computation of these KPIs. Also "Lean" metrics (takt time, cycle time, lag time, and lead time) can be used to create a framework for formwork planning and defining the optimal formwork reuse scheme.

In this paper, the term "Lean" implies adding value and eliminating or reducing waste in a process, including the reduction of the production unit size (batch) and leveling the workload between workstations of a production line (i.e., reducing variability). BIM uses digital models of a building to coordinate multidisciplinary information during the asset life cycle. Using BIM, formwork engineers can reduce human error and minimize processing time for formwork planning (computing quantities, estimating costs, and calculating KPIs for decision-making). Project stakeholders have typically focused on using BIM for permanent elements in buildings (Hyun et al., 2018), and temporary structures like formworks are typically not included in BIM models (Jin and Gambatese, 2019). There are key challenges to the adoption of formwork BIM models. First, typically formwork BIM models are developed by formwork providers, but these models are needed during planning phases even before the formwork provider has been hired for a project. Second, due to the high frequency of design changes, updating formwork BIM models is time-consuming. Finally, formwork modeling, layout plans, and shop drawings are not completed before concrete activities start (Mansuri et al., 2017).

The current practice for formwork planning is based solely on contractor experience. Since BIM is not typically used for formwork planning), an evaluation is needed for defining the appropriate Level of Development (LOD) required for implementing a BIM-based formwork planning tool. Furthermore, an evaluation of practitioners' preferences is needed to determine if the rental cost rate would be based on surface contact area (SMCA – square meter contact area) or system components (unit). Hence, this paper aims to answer the following research questions: (1) what is the minimum LOD for a BIM model that is required for formwork planning? (2) what is the appropriate preference for formwork rental cost that is suitable for formwork planning during the early stages of the construction phase? (3) how can formwork planning be automated to enable data-driven decision-making during the early stages of the construction phase? The research objective of this paper is to propose a BIM-based tool as a proof of concept that enables contractors to automate the computation of formwork quantities, cost, and Key Performance Indicators (KPIs) that provide sufficient information for formwork planning during the early stages of construction.

2. Literature Review and State of Practice Review

Prior research explored the use of BIM for formwork design, layout, planning, and monitoring. Researchers have used BIM during the design process to automate formwork design and formwork layout for different formwork materials and casting uses such as: (1) timber formwork for columns, walls, and slabs (Jin and Gambatese, 2019, 2023; Romanovskyi et al., 2019), and (2) aluminum formwork for walls and slabs (Lee et al., 2020, 2021; Zhang, 2020a, 2020b). Prior literature has also described the use of BIM for improving the planning process through the automated calculation of the quantity of formwork components required considering their potential reuse to reduce waste during construction (Mei et al., 2021). BIM has been used during the planning process as a tool to automate the computation of formwork quantity takeoffs (Khosakitchalert et al., 2019). BIM has been also used in combination with wireless sensors for real-time monitoring of concrete maturity to provide reduced formwork removal times (Hamooni et al., 2020). Most of the prior cases reported in the literature are based on self-owned formwork or built-on-site formwork. Recent research has analyzed the benefits of using BIM in the case of rented prefabricated modular formwork from formwork suppliers such as Peri and Doka (Mésároš et al., 2021; Schlachter et al., 2022).

Typical services of formwork providers include designing, providing technical support, preparing 2D layout plans, shop drawings, installation manuals, and preparing packing lists. Formwork modeling is not a common service included by formwork providers, but large formwork companies such as Peri and Doka provide 3D CAD modeling or BIM modeling for formwork activities. The main challenges when providing such services are as follows: (1) contractors have to hire the services of the formwork supplier before implementing a BIM model, (2) modeling tools are oriented to the formwork supplier's objective for instance, maximizing the efficiency of equipment and not maximizing labor efficiency, (3) formwork options are limited to supplier stock and inventory, and (4) contractors are not comfortable using different in-house tools from each formwork manufacturer (Biruk and Jaskowski, 2017).

Currently, available formwork CAD tools are mainly "plug-ins" that enhance the design process, layout plans drafting, computing packing lists, and managing inventories. Doka CAD 9 is an AutoCAD "plug-in" for formwork layout plans and populating packing lists usually available only for use by Doka company staff but also available in a few countries like USA, Germany, Austria, and UK for Doka customers. Peri ELPOS is an AutoCAD "plug-in" for formwork and scaffolding systems, that can compare the list of pieces required versus the list of pieces owned by the contractor and generate a new list with the missing pieces required to complete formwork systems. Peri CAD is a tool that can be used for creating layout drawings and packing lists automatically. Peri and Doka are currently migrating from CAD to BIM tools. Peri CAD has a built-in 3D modeling environment that is enabled to work with Industry Foundation Class (IFC) format created using BIM modeling authoring tools (i.e., Revit, Tekla) for creating formwork layout plans. The formwork model can be shared in a Common Data Environment (CDE) such as Autodesk BIM 360 or Navisworks. Similarly, Doka CAD 9 is available as a "plug-in" for Revit and Tekla, that can be used for creating 3D models, 2D formwork layout plans, creating formwork pieces, and 4D simulations. Doka also has a complete library of 3D formwork components for Revit and Tekla.

Based on the literature review and state-of-practice, two gaps were identified: First, current formwork planning frameworks focus only on specific formwork elements/components and there is no rigorous framework for early-stage formwork planning for total formwork assemblies. Second, modeling tools available in the market require that the contractor hires a formwork company that can provide a BIM model for formwork planning, which poses challenges since many formwork companies are unable or reluctant to provide BIM modeling services due to the time-consuming nature of building BIM models for formwork planning.

3. Research Methods

To address the gaps in current practice and research, this paper describes the development of a BIM-based framework for early-state formwork planning. The framework uses Lean principles for defining the optimal formwork reuse scheme. This section includes a brief description of the survey conducted for designing the BIM-based formwork management tool, followed by a short introduction of Lean metrics used to develop the framework for determining the optimal solution of workspace zoning. The section then discusses concepts related to formwork planning utilized to develop a proposed set of KPIs for measuring formwork performance.

3.1. Survey Instrument

A survey was conducted with 136 Latin American practitioners (7% academics, 12% formwork providers, 32% BIM specialists, and 49% general contractors) for defining the requirements that form the basis for designing the new BIM-based tool for formwork planning. The survey focused on Latin America because of the preference in this region for cast-in-place concrete buildings in contrast with the USA where steel framing and precast structures are preferred. The survey instrument included questions regarding three main themes of interest: (1) Level of Development (LOD), (2) formwork rental option preference, and (3) level of automation for formwork planning.

LOD represents the depth of detail embedded in a BIM model. For formwork models, LOD 100 is a generic representation of the formwork system. LOD 200, is also a generic representation but includes approximate quantities, size, shape, location, and orientation. LOD 300 is a specific representation of a formwork system, while LOD 350 interacts with other RC building elements or other temporary structures for clash detection. LOD 400 provides information for fabrication, assembly, and installation. LOD 500 is an as-built representation of the actual formwork on site. Results of the survey showed that even when 64% of the formwork suppliers can provide a LOD 400 or higher to their customers, 62% of contractors typically prefer modeling formwork systems as a LOD 200 or lower.

Formwork providers typically work with two renting options: (1) cost per contact area per time unit ($/SMCA-month), and (2) cost per number of components or pieces per time unit ($/unit-month). The advantage of the first option is that the contact area is a common and homogeneous unit regardless of the structural element formed (i.e., wall, slab), the formwork system (i.e., handset, climbing) or the formwork provider (i.e., Doka, Peri, EFCO). The advantage of using the second option is that it is easier to track formwork pieces when only a few formwork components are required on-site. This option is commonly used when pieces must be replaced because of damage or loss. Survey results show that both formwork suppliers (64%) and general contractors (81%) prefer renting formwork systems based on the contact area (USD$/$m^2$-month) instead of a cost rate based on components (USD$/piece-month).

Two main facets were explored using the survey: (1) the tools used (i.e., CAD, PDF, BIM Spreadsheets), and (2) the level of automation (i.e., none, "plug-ins", Guide User Interface) to gain an understanding of practitioners' familiarity with software tools and their experience in using customized tools for automating formwork management. Survey results showed that more than 60% of practitioners currently use only CAD and spreadsheets and less than 17% use BIM for formwork planning. More than 70% of contractors do not automate any process related to formwork planning.

3.2. Work Zoning in High-Rise Buildings

Work zoning involves dividing the scope of work into smaller parts where the amount of work in each part (batch) is similar. Takt time, cycle time and lead time are Lean metrics that can be used for defining the number of work zones required for a building project. Takt time is the maximum amount of time available for completing a client's objective, see Eq. (1). Cycle time, also known as net production time, is the actual time a product is in process and should be always less than the takt time, as shown in Eq. (2). Finally, lead time Eq. (3) is the total time from the first activity for producing a unit starts until the product is complete, and the difference between the lead time and the cycle time is the total lag time.

$$\text{Takt time} = \frac{\text{Production time available}}{\text{Required units of production}} \tag{1}$$

$$\text{Cycle time} = \frac{\text{Net production}}{\text{Number of units produced}} < \text{Takt time} \tag{2}$$

$$\text{Lead time} = \text{Cycle time} + \text{Total lag time} \tag{3}$$

Since the minimum practical time unit in construction activities is a shift or a working day, a work zone (WZ) will be the portion of a building where each activity produces a daily batch. The lead time or duration of a high-rise building construction will be the "cycle time" or the total number of work zones (since each work zone is produced in one day), plus the "lag time" or number of days to complete one work zone. For example, if we consider a 10-story building with 6 work zones in each story, 5 days of lag time for completing a work zone, and a cycle time of one work zone (WZ) per day, then the duration of the project will be 65 days using Eq. (4) or represented as a lookahead table as shown in Fig. 1.

$$\text{Duration} = \text{Lag time} + \text{Cycle Time} \tag{4}$$

Lookahead story level 10

ACTIVITY	Day 55	Day 56	Day 57	Day 58	Day 59	Day 60	Day 61	Day 62	Day 63	Day 64	Day 65
Verticals rebar installation	WZ-55	WZ-56	WZ-57	WZ-58	WZ-59	WZ-60					
Verticals formwork installation		WZ-55	WZ-56	WZ-57	WZ-58	WZ-59	WZ-60				
Verticals concrete placing		WZ-55	WZ-56	WZ-57	WZ-58	WZ-59	WZ-60				
Beam formwork support			WZ-55	WZ-56	WZ-57	WZ-58	WZ-59	WZ-60			
Beam steel reinforcement				WZ-55	WZ-56	WZ-57	WZ-58	WZ-59	WZ-60		
Beam formwork sides				WZ-55	WZ-56	WZ-57	WZ-58	WZ-59	WZ-60		
Precast slab support				WZ-55	WZ-56	WZ-57	WZ-58	WZ-59	WZ-60		
Precast slab placing					WZ-55	WZ-56	WZ-57	WZ-58	WZ-59	WZ-60	
Slab steel reinforcement					WZ-55	WZ-56	WZ-57	WZ-58	WZ-59	WZ-60	
MEP conduit rough in					WZ-55	WZ-56	WZ-57	WZ-58	WZ-59	WZ-60	
Horizontal concrete placing						WZ-55	WZ-56	WZ-57	WZ-58	WZ-59	WZ-60

Fig. 1. Lookahead for 10-story building

3.3. Work Zones Leveling

According to Lean philosophy, the main purpose for eliminating idle time (waste) is protecting the workflow. Since formwork installation is labor intensive, the work zone leveling objective is minimizing the variability of work between work zones. A new algorithm is proposed for optimizing the work zone leveling as shown in Eq. (5).

$$\min_{i,j}(\delta_C + \delta_F + \delta_I) \tag{5}$$

Where: "δ_C", "δ_F", *and* "δ_I" are the variation of labor hours between 2 consecutive work zones for concrete, formwork, and ironworkers' trades respectively.

3.4. Formwork Planning

This section describes general concepts used for formwork planning including formwork demand curve, formwork cost analysis, and formwork KPIs. The formwork demand curve represents the required amount of formwork across the project duration. The objective of this curve is to estimate the amount of formwork required at any point of time in the project. Formwork cost analysis includes the estimation of all cost components (labor, materials, equipment, and subcontract) and therefore, the overall cost. Finally, formwork KPIs are values that can be used for decision-making, benchmarking, and control regarding formwork.

3.4.1. Formwork demand curve

The formwork demand curve is obtained by plotting on the abscissa the time unit (i.e. days, weeks, months), and on the ordinate the formwork demand in terms of formwork contact area (m^2) or cost (USD$). The area under the curve represents the total area required during a number of days (m^2-days) or the total cost of the formwork required for that period (USD$).

In high-rise building projects, the term "Formwork Used" (FU) refers to the ideal net contact area of the cast-in-place concrete elements necessary for (1) stripping the forms from a previous work zone and re-using them for forming or shoring a new work zone, (2) holding concrete during placing, and (3) holding concrete newly placed until the placed concrete has gained sufficient strength for bearing self-weight and construction loads. "Formwork Demand" (FD) is the minimum formwork area required in the project, FD sets are defined by the number of days necessary for assembling and installing formwork, placing concrete, and holding concrete in place until it gains sufficient strength. Finally, the term "Formwork Requirement" (FR) refers to the area of the formwork elements/systems that will be delivered to the construction site. FR considers not only the FD but also additional formwork to account for contingencies. Formwork curves (FU, FD, FR) show similar patterns during project execution, with the formwork area increasing until the curves reach the maximum point at "Formwork maximum setup" (FMSU), then maintaining a steady amount of formwork until the demobilization stage starts after all concrete placement is complete, after which the curves show decreasing amounts of formwork required and placed (see Fig. 2).

The key to effective formwork planning is assessing formwork contingencies, i.e., ensuring that FR is as close as possible to FD. An overestimation of contingencies can result in excessive idle formwork equipment which can generate additional expenses for formwork components damaged or lost because of poor housekeeping. On the other hand, an underestimation of contingencies can result in project delays due to the lack of material available to sustain the construction speed.

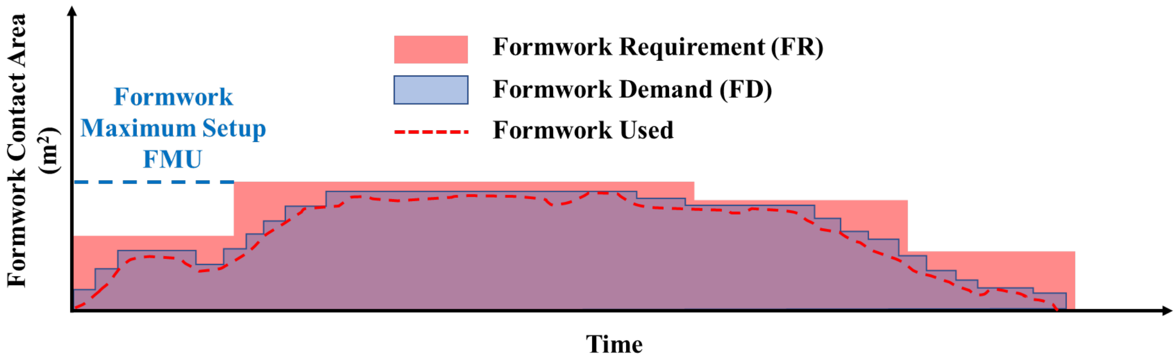


Fig. 2. Formwork curves

3.4.2. Formwork cost analysis

The cost associated with prefabricated modular formwork usually has three components: labor cost, materials cost, and rental cost. Labor (C_0) is usually the largest cost component and is related to labor productivity which is directly affected by the formwork system selection. The use of formwork systems with a smaller number of pieces, lightweight components, and not requiring disassembly for reuse, will increase the productivity of crews. The cost of materials is related to the costs of lumber (C_1), plywood for sheathing (C_2), accessories, and consumables (C_3). Lumber (C_1) includes all extra timber that is not part of the formwork solution system and may be variable depending on the formwork supplier. Examples of C_1 may include bulkheads, chamfers, block outs, reveals, overhang decking, railings, etc. Accessories and consumables (C_3) refer to material that is required for the formwork system but cannot be rented since they will be used up relatively quickly. Examples of C_3 include materials like PVC cones, PVC pipes, tie sleeves, etc. Subcontract costs may include (C_4) rental cost, (C_5) formwork maintenance and cleaning, (C_6) penalties for formwork repairs or components replacement, and (C_7) freights required for delivering and returning equipment. The formwork cost is the addition of all previous cost components and could be represented by Eq. (6).

$$Formwork\ Cost = \sum_{i=0}^{7} C_i \tag{6}$$

3.4.3. Formwork key performance indicators (KPIs)

Three new KPIs, namely, Cost Ratio (CR), Reuse Factor (RF), and Formwork Efficiency (FE) were proposed as part of this study to gauge formwork system efficiency. Cost Ratio (CR) is the ratio of all the formwork cost components (excluding labor) to the total contact area to be formed, and is represented by Eq. (7). Reuse Factor (RF) is the ratio of the number of reuses of the formwork element/system to the number of formwork sets, and is represented by Eq. (8). Formwork Efficiency (FE) is the ratio of the total contact area for formwork in the project to the total contact area of the formwork sets, and is represented by Eq. (9). Although Cost Ratio or unit cost is a common indicator for decision making based solely on the best cost offered by different formwork suppliers, this ratio does not necessarily represent the efficiency of the formwork reuse scheme. For this reason, the KPIs, RF, and FE were included in the study since they gauge the formwork rotation and efficiency of the reuse scheme, without a bias due to rental rates.

$$Cost\ Ratio\ (CR) = \frac{\sum_{i=1}^{7} C_i}{\sum Formwork\ Contact\ Area} \tag{7}$$

$$Reuse\ Factor\ (RF) = \frac{\#\ Formwork\ Reuses}{\#\ Formwork\ Sets} \tag{8}$$

$$Formwork\ Efficiency\ (FE) = \frac{Formwork\ Contact\ Area}{Formwork\ Sets'\ Contact\ Area} \tag{9}$$

3.5. BIM Formwork Planning Automation

BIM automation refers to the use of programming for creating repetitive tasks in a BIM tool in order to reduce time and eliminate human error. Due to its popular use in the construction industry, Revit was the BIM authoring tool used in this study. Similarly, the open source Dynamo was the graphical programming tool used for developing the code for 3D modeling of formwork, computing quantities take-off, estimating the maximum formwork set size, performing cost analysis, developing the formwork demand curve, calculating KPIs, and performing 4D/5D simulations.

The BIM-based tool for formwork planning proposed has two phases that are shown in Fig. 3. Phase 1 creates a formwork BIM model based on a structural BIM model of a Reinforced Concrete (RC) building and Phase 2 utilizes the results from Phase 1 to compute formwork quantity take-off schedules, perform formwork cost analysis, estimate KPIs, simulate 4D/5D schedules, and create color-coded layouts.

Phase 1 has only the structural BIM model of the RC building and has five steps: (1) creating BIM parameters for each of the building components of the BIM model, (2) auditing the BIM model, checking if structural elements are modeled according to construction sequence and phases, (3) dividing the building into work zones for a construction sequence, (4) model formwork LOD 200, considering generic model surfaces to represent formwork contact area, and (5) compute BIM parameters and populate information in BIM model using parameters fields created on step one. Phase 2 has as an input the BIM model enriched with data into its parameters and consists of performing formwork planning tasks like: (1) automating the computing and extraction quantity takeoffs, (2) using cost parameters, estimating formwork cost analysis, (3) computing formwork KPIs using data related to formwork area, formwork sets, and formwork contact area, (4) creating a 4D and 5D simulation based on construction sequence and formwork cost analysis, and (5) extracting color-coded layouts from the model.

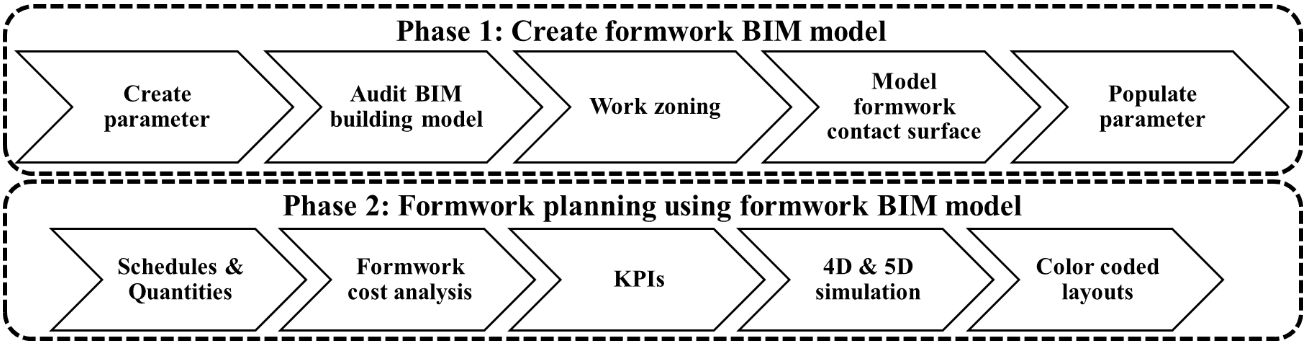


Fig. 3. BIM-based tool for formwork planning

4. BIM-Based Tool for Formwork (Phase 1)

Considering practitioner preferences as reported in the survey (see section 3.1), Phase 1 of the proposed tool is based on 5 steps, which include: (1) creating parameters to store information related to formwork data, (2) auditing the input structures BIM model considering the logical construction sequence, (3) defining the work zones for all the structural elements according to construction planning and workload leveling, (4) generating a generic LOD 200 BIM model for formwork, and (5) populating the data for the parameters created in the first step.

4.1. BIM Parameters for Formwork Planning (Step 1)

Parameters are containers of information that can be assigned to any “category” of element in a BIM model, to enrich the model with information that is not contained in the generic parameters of that category. The information stored in parameters could be of the data type - text or numeric. The categories in Revit are the type of elements that together compound the BIM model i.e., “Structural Foundations, “Structural column”, “Walls”, etc. For formwork planning the parameters required in the BIM model can be grouped into Model (MOD), Formwork (FORM), time (TIME), Productivity (PROD), and Cost (COST).

MOD parameters include information such as the type of element, the height of the element, the story level where the element is located, the work set name or number, the work zone of the element, the pouring phase, construction sequence code, reinforcement ratio (kg/m^3), reinforcement steel of the element (kg), and the depth of the beam if applicable. Table 1 provides a summary of the MOD Parameters including their name, data type, and the associated Revit categories. Fig. 4 shows examples of some elements and the parameter information that could be stored.

Table 1. MOD Parameters - Group: MODEL

Parameter Name	Data Type	Revit Categories
MOD_Element, MOD_Height, MOD_S_Level, MOD_S_WorkSet, MOD_S_WorkZone, MOD_S_F/V/H, MOD_S_Code	Text	Structural Foundations, Structural Columns, Walls, Structural Framing, Floors, Stairs
MOD_Steel_Ratio, MOD_Steel	Number	Structural Foundations, Structural Columns, Walls, Structural Framing, Floors, Stairs
MOD_Beam_Depth	Text	Structural Framing

PROD parameters store information about productivity indexes for concrete placing, forming/stripping, and steel installation. Additionally, a parameter will be reserved for storing the total amount of labor hours required for performing the concrete, formwork, and steel activities involved for each RC element in the BIM model. TIME parameters store information related to dates and timing for formwork planning. FORM Parameters store information related to computed formwork contact area, formwork weight ratio, the total weight of formwork, and the total weight of shoring systems required for each RC element. COST Parameters stores information related to rental rates for formwork systems, shoring systems, PVC consumables, and the total cost for formwork, shoring, and consumables.

A total of 36 parameters distributed into MOD, PROD, TIME, FORM, and COST parameters are required for enriching the BIM model with formwork data. These parameters can be created using a Dynamo Script for automating the process. The automation process includes naming the parameter and assigning discipline, data type, and element category. Parameters can be created as shared parameters or project parameters. Either one of the cases must be assigned to each of the instances (elements) of the BIM model in the project.

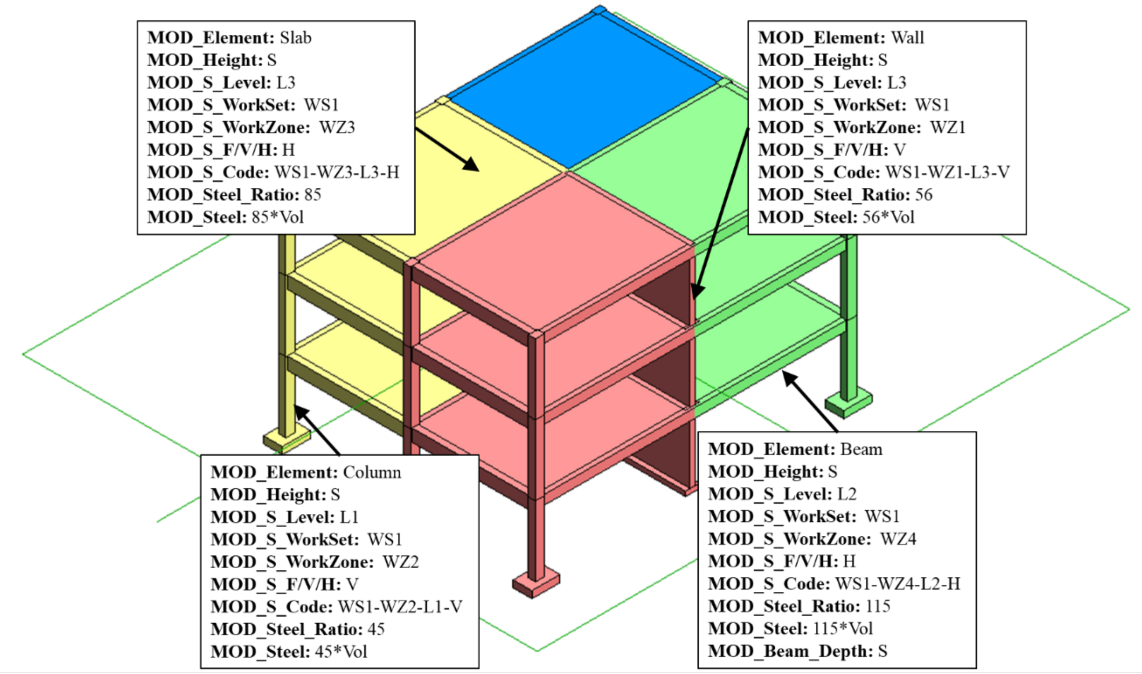


Fig. 4. Examples of MOD parameters data

4.2. Auditing BIM Model (Step 2)

The workflow for auditing a BIM model includes assigning priorities for elements in the hierarchy, and 'splitting' joints in structural frames. A Dynamo script was created for automating the process of switching joint priorities according to the hierarchy of the category of elements. Another Dynamo script was implemented to automate the process of splitting vertical elements into two phases, the first phase considers the concrete pouring to the bottom of horizontal elements, and the second phase models the deck pours. For a detailed review of the Dynamo Scripts for this section see (Rojas, 2021).

4.3. Work Zoning (Step 3)

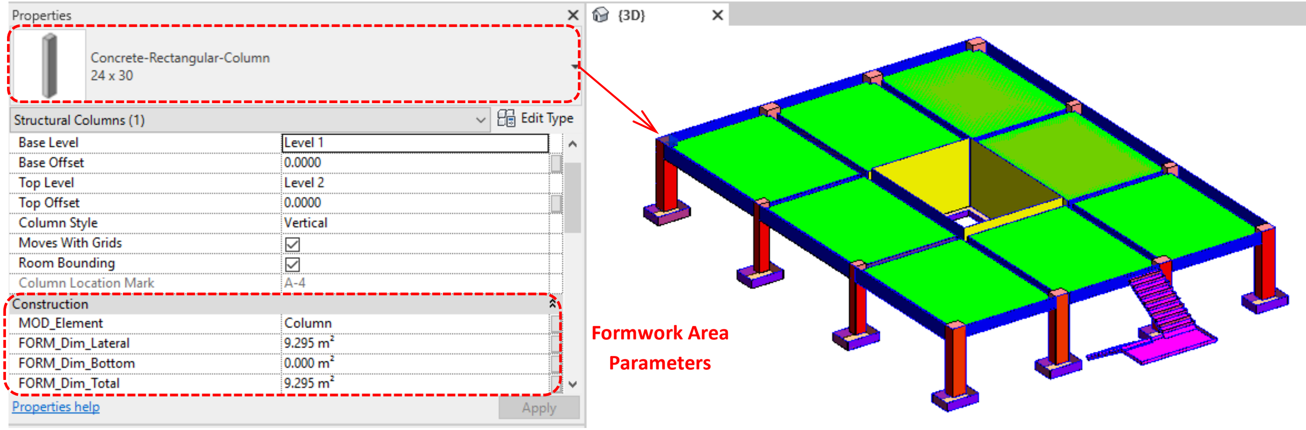
Equation 5 in Section 3.3 can be used to iterate the work zoning process for finding the optimal solution that maximizes productivity and minimizes the number of hours required for building the RC framing. The optimal solution is based on the minimum variation of labor hours (amount of work) between consecutive work zones. This process can be automated using Dynamo since the RC building model is already enriched with parameters related to quantities, and productivity ratios. Concrete volume is a standard parameter for Revit, formwork area is a FORM group parameter, steel reinforcement quantity is a MOD parameter, and productivity ratios and labor hours are PROD parameters.

A Dynamo script was also created for using draft lines in Revit to create work zones in a BIM model. Fig. 4 in Section 4.1 shows 2D lines created in a plan view that can be used as a reference for Revit to group the elements of the building in work zones. Using this data, all the parameters can be presented in a table to verify the variability of labor hours across work zones.

4.4. Formwork Modeling (Step 4)

The "Generic Models" category from Revit can be used for creating a LOD 200 formwork BIM model using an automated process that uses the RC building model as an input. LOD 200 model provides a sufficient representation of the location, shape, and contact area of formwork for each RC element in the model. Since Revit lacks a built-in tool for computing formwork contact area, two Dynamo scripts were created for estimating the area of lateral, bottom, and total formwork surfaces for each RC element in the model.

The first Dynamo script creates materials that represent each formwork system (column, beam sides, beam bottom, slab, shoring, etc.). The second Dynamo script creates a 3D solid with the union of all the RC elements of the building in the model. Then the script computes the area of each formed face (lateral and bottom) and stores these values in the corresponding formwork area parameter for each of the RC elements. Finally, using solids of the "Generic Models" category to represent forming faces and taking the materials created with the first script, all the formwork faces in contact with concrete are modeled automatically as shown in Fig. 5. Revit materials created with the first script will be used for better representation of each formwork solution with a color-based representation of each of the solutions.



(a) (b)

Fig. 5. Formwork Modeling using Dynamo. (a) QTO - parameters populated (b) Formwork 3D modeling

4.5. Setting Parameters (Step 5)

Using the set of Dynamo scripts described in this section, the parameters created in the first step (as described in Section 4.1) are enriched with data required for formwork planning. The parameters are grouped into Model Parameters (MOD), Time Parameters (TIME), Formwork Parameters (FORM), Productivity Parameters (PROD), and Cost Parameters (COST).

"MOD" parameters are computed using four Dynamo Scripts - the first one populates parameters based on built-in parameters of Revit. The second script is used to assign the work zone of each element into a parameter. The third script concatenates the parameters related to the work set, work zone, building level, and construction phase. Finally, a fourth script takes steel reinforcement ratios from a database (previously created by the author that can be customized accordingly by future users of the BIM-based formwork management tool) and computes the steel quantity take-off by multiplying this ratio by the concrete volume.

"TIME" parameters are populated using a Dynamo Script that imports the information from an MS Project schedule that contains the date on which a form needs to be stripped, the number of days a formwork system needs to be holding a concrete element, and the number of days a shoring system needs to support a horizontal structure. Since Revit parameters cannot have a "date" type format, this value is represented as an integer that counts the number of days since 1/1/1990.

"FORM" parameters related to the formwork area are populated using a Dynamo script described in step 4 (as described in Section 4.4). Another Dynamo Script is used to calculate formwork weight parameters that are populated based on a database based on Peri's data sheets but can be customized based on information provided by any formwork manufacturer. The same script is used to compute the total weight of the formwork and shoring systems required in an RC element by multiplying the system weight rate (kg/m^2) by the formwork contact area.

"PROD_PI" parameters store information related to productivity rates for concrete placing (hours/m^3), forming, shoring, striping (hours/m^2), and steel erection (hours/kg). These productivity parameters are populated based on a productivity indicators database that can be updated and imported from a spreadsheet implemented by the author that can be customized according to the script user's preferences. "PROD_Labor" is populated based on Eq. (10).

$$PROD\_Labor = (Volume)x(PROD\_PI\_Conc) + (FORM\_Dim\_Total)x(PROD\_PI\_Form) + (MOD\_Steel)x(PROD\_PI\_Steel) \tag{10}$$

"COST_Rate_Consumable" and "COST_Consumable" parameters are populated with a Dynamo script which imports the consumable cost rate from a database (implemented based on a supplier quote that can be updated based on user preferences) and estimates the total cost of consumables by multiplying the formwork contact area by the consumables cost rate. Likewise, parameters like "COST_Rate" and "COST_Formwork" are estimated using a Dynamo script that imports cost rental rates from a similar database and computes the rental cost by multiplying rental cost rates by formwork contact area. Eq. (11) and Eq. (12) are used to estimate the consumables cost and rental cost respectively.

$$COST\_Consumable = (COST\_Rate\_Consumable)x(FORM\_Dim\_Lateral) \tag{11}$$

$$COST\_Formwork = (COST\_Rate\_Lateral)x(FORM\_Dim\_Lateral) + (COST\_Rate\_Bottom)x(FORM\_Dim\_Bottom) + (COST\_Rate\_Linear)x(FORM\_Dim\_Linear) \tag{12}$$

5. BIM-Based Tool for Formwork (Phase 2)

Phase 2 of the BIM-based tool uses a set of Dynamo scripts that focuses on utilizing the BIM model created in Phase 1 enriched with parameters required for formwork planning. Dynamo scripts from Phase 2 can (1) compute quantities take-off, (2) perform formwork cost analysis, (3) calculate KPIs for formwork efficiency, (4) plot formwork demand curves, (5) create 4D/5D schedules, and (6) represent color-coded formwork layouts.

5.1. Formwork Quantity Takeoff

A Dynamo script was implemented for computing the quantities of RC building elements such as concrete volume (m^3), formwork contact area (m^2), steel reinforcement (kg), and the number of labor hours. Concrete volume is obtained based on a built-in parameter in Revit, but the formwork contact area is estimated based on the script described in Section 4.4. For rebar and labor, estimation is based on rate values of steel reinforcement (kg/m^3) and productivity rates (hours/unit produced).

Another Dynamo script was created to estimate the formwork maximum set size, which is the maximum amount of formwork contact area required for each formwork system to complete the entire building project. The formwork maximum set size is estimated by adding the formwork contact area of the "n" consecutive work zones, where "n" is the number of days a formwork set cannot be reused. Eq. (13) represents the formula for estimating formwork maximum set size and Fig. 6 shows the result of using the Dynamo script with the associated Python code. Where "N" is the number of work zones, and "n" is the number of formwork sets.

$$Max\ Set = \max_{i=1\ to\ N-1}\left(\sum_{j=1}^{n} Area\ WZ_j\right) \tag{13}$$

5.2. Formwork Cost Analysis

Formwork cost analysis consists of estimating all the cost components of formwork. Cost analysis is used during the planning phase for selecting a formwork system, or provider. Cost is estimated based on Eq. (14), and the results of using the associated Dynamo script are presented in Fig. 7. Note: C_1 is formwork rental cost, C_2 is reshoring rental cost, C_3 is labor cost, C_4 is consumables cost, C_5 is freight cost, and C_6 is plywood cost.

$$Formwork\ Cost = C_1 + C_2 + C_3 + C_4 + C_5 + C_6 \tag{14}$$

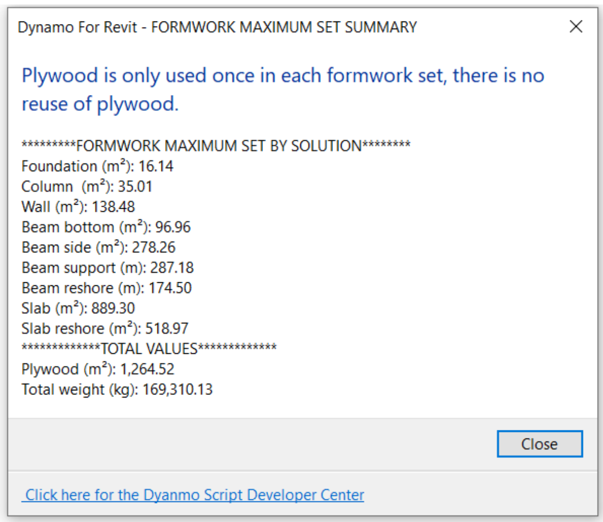


Fig. 6. Formwork maximum set size

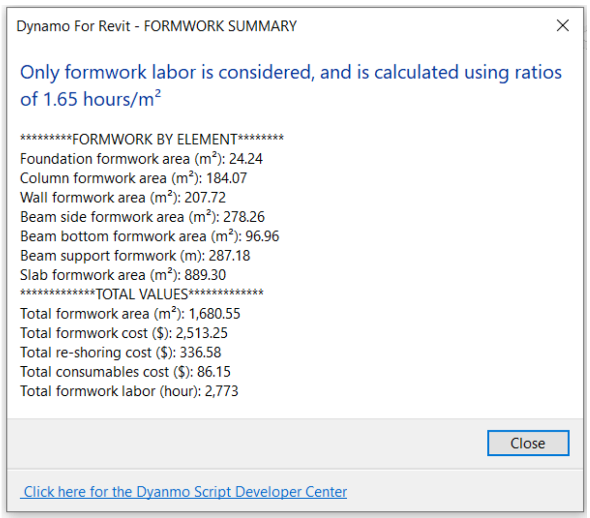


Fig. 7. Formwork systems and cost components

5.3. Formwork KPIs

Formwork KPIs are computed using a Dynamo Script as shown in Fig. 8 and using Eq. (7), (8), and (9) (discussed in Section 3.4.3). Cost ratio (CR) values can be used for decision making, forecasting, and benchmarking with Eq. (7). The Reuse Factor (RF) is computed using Eq. (8) and separately for vertical and horizontal elements since the number of formwork sets are different for each type. A RF value closer to "1" implies that the formwork has a low reuse or rotation cycle. Typically, the RF for vertical formwork is higher than that for horizontal formwork. Formwork Efficiency (FE) combines the rotation efficiency of vertical and horizontal formwork systems, using Eq. (9). FE is expected to be greater than RF and greater than "1". If FE is close to "1" it implies that the rotation of formwork needs to improve.

5.4. Formwork Planning Reports

The BIM model enriched with formwork data can also be used for creating formwork planning reports such as formwork demand curves, 4D/5D schedules and a color-coded map showing formwork stripping dates. Using data from the cashflow tool of MS Project, a Dynamo script exports cost and time parameters into a spreadsheet to generate a formwork demand curve as shown in Fig. 9.

A Dynamo script was used to create an "Extensible Markup Language" (XML) file that can be imported into Navisworks for creating a 4D/5D simulation. Navisworks is a common data environment (CDE) for combining and coordinating 3D and BIM models from different formats. Fig. 10 shows the result of importing to Navisworks the XML file created with the Dynamo Script and the MS project.

Since all RC building elements include parameters such as the date on which an element needs to be stripped, this information can be used to create a filtered color layout plan or color-coded 3D model. More information about the color-coded 3D view and other scripts and tools for formwork planning can be found in (Rojas, 2021).

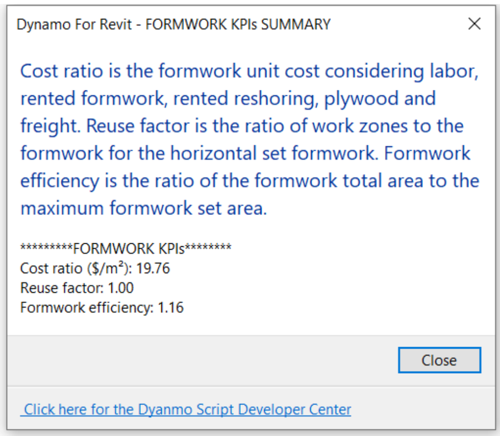


Fig. 8. KPI Results

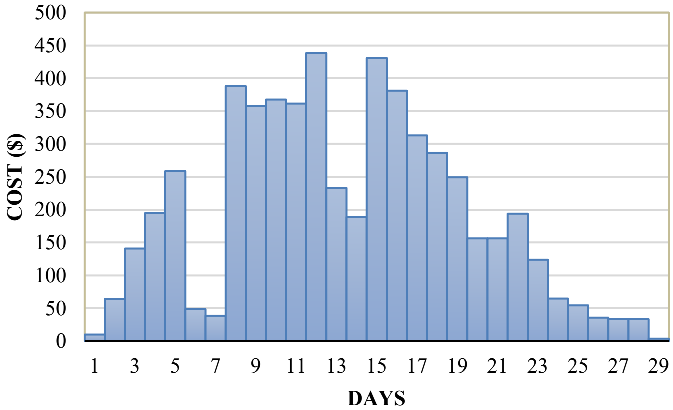


Fig. 9. Formwork demand curve

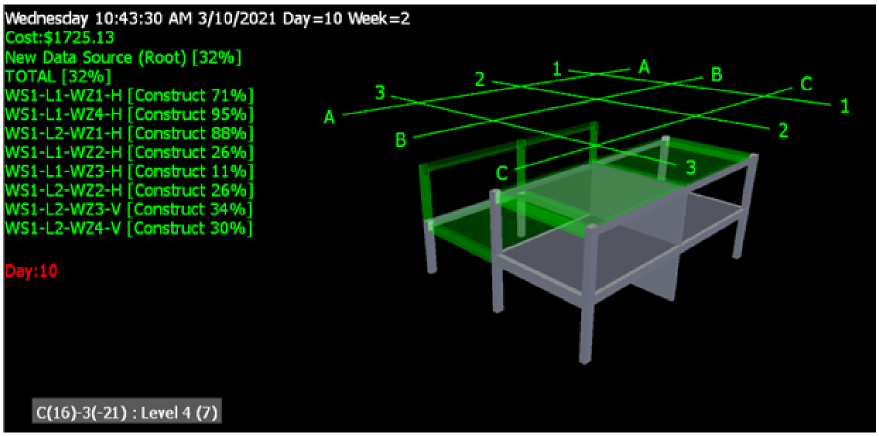


Fig. 10. 4D/5D formwork schedule

6. Testing the BIM-Based Tool

For testing the BIM-based formwork planning tool, two BIM models were created with same built area (46,650 m^2), same headroom (4.5 m), and similar floor plan distribution, but with different number of stories (20 and 5) and different number of work zones per level (4 and 16), to compute the formwork KPIs. The details of these two models are shown in Table 2.

Table 2. BIM model testing samples

Feature	20-Story	5-Story
Number of stories	20	5
Built area	46,650 m^2	46,650 m^2
Work zones/level	4	16
Total № of work zones	80	80
One story cycle time	4 days	16 days
Horizontal strip time	7 days	7 days
№ of sets	12	12
Head room height	4.5 m	4.5 m
Total height	90 m	90 m

Fig. 11 and Fig. 12 show the results of the Dynamo script for computing the following KPIs - "Cost Ratio (CR)", "Reuse Factor (RF)", and "Formwork Efficiency (FE)". The KPIs in both models have very similar values since both only have the same built area, but also work zone floor plans. Both models also have the same value for RF since the number of work zones and formwork sets is the same for both buildings. CR and FE are slightly higher for the 20-story building compared to the 5-story building because a taller building has a greater envelope area (which implies that vertical elements have more formwork area, leading to slight increases in these KPIs). The comparison of the KPIs of the two buildings shows that the BIM-based formwork planning tool developed in this study can accurately determine formwork contact areas, formwork demand curves, and the values of associated Key Performance Indicators using parameters populated with Dynamo Scripts. This procedure minimizes the probability of human error, and enables automatic computation of formwork planning tasks that expedite decision making through quicker iterations using different formwork options, different rental costs, and different options of work zone definition.

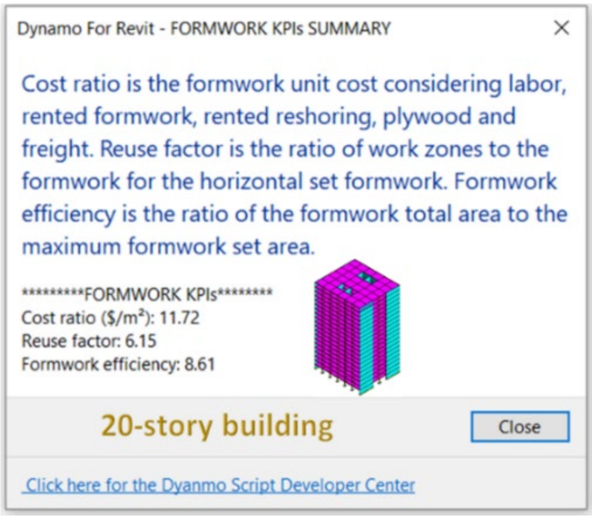


Fig. 11. KPI results for the 20-story building

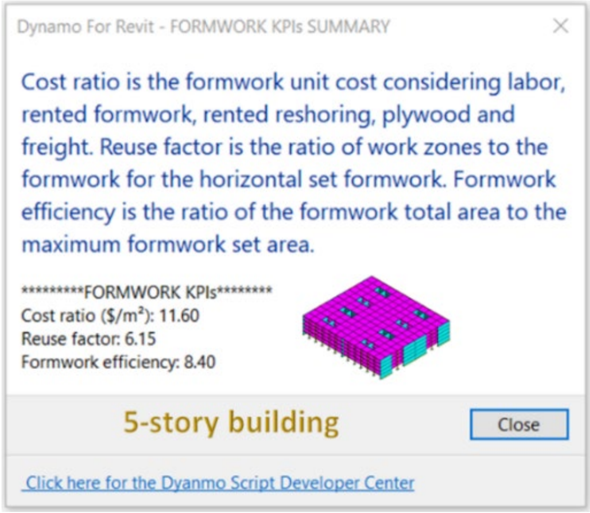


Fig. 12. KPI for the 5-story building

7. Conclusions

Currently, BIM models are rarely employed for formwork management. Practitioners prefer working with prefabricated modular formwork and using a renting option where the price is based on the contact area of the formwork rented. This paper discusses the design, development, and testing of a BIM-based tool for formwork planning for prefabricated modular rented formwork in building projects.

The proposed BIM-based tool works for both vertical (columns and walls) and horizontal (beams and slabs) formwork systems, and the formwork supplier does not have to be pre-selected. The BIM-based tool provides a strong first step towards formwork planning without merely relying on contractor experience. The tool provides a data-driven approach using Lean metrics (lead time, takt time, cycle time) and new formwork planning metrics (Cost Ratio, Reuse Factor, Formwork Efficiency).

In its initial version, the current tool does not include modeling of individual formwork pieces and the model does not generate a packing list for formwork pieces. Future versions of the tools could include customization of the population of the parameters using technologies such as Radio Frequency Identification (RFID) and wireless concrete sensors for real-time temperature/maturity monitoring. RFID could be used to identify the location of formwork components and link them to the work zones in the BIM model. Additionally, concrete sensors could be used to track which work zones should be stripped, and this information can be used to update the BIM model formwork parameters.

Author Contributions

Jorge Rojas conceived the research idea, conducted a comprehensive literature review, designed the survey instrument, collected data from respondents, analyzed the collected data from surveys, prepared BIM models, wrote scripts, designed visual programming networks, prepared simulations, analyzed the results from simulations, wrote paper draft, edited, and prepared revisions. Dulcy M. Abraham reviewed survey instruments, provided comments, reviewed, and edited paper drafts, and supervised the entire research process.

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