APPLICATION OF 4D AND 5D BIM IN COLD-FORMED STEEL RESIDENTIAL BUILDINGS

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ABSTRACT

Traditional residential building systems are not sufficient to produce the required number of housing units needed every year to solve the current housing problem in many countries. To meet such a challenge, it is necessary to explore the latest construction technologies, and to create innovative building systems that have the potential to bring high-performance affordable housing within reach of new markets. Light (cold-formed) steel (CFS) framing systems have proven to be a worthy alternative to traditional systems. Recent advances in the application of Building Information Modeling (BIM) into the Architecture-Engineering-Construction industries present an additional mean to further enhance the efficiency of CFS projects. This paper presents a BIM based integrated approach for project scheduling and cost estimating of cold formed steel residential buildings. The approach integrates the basic 3D BIM model with the construction management tools used for project scheduling and cost estimation to produce a 4D BIM and 5D BIM models that can be used to enhance the project efficiency in both the design and construction phases. The developed models facilitate communication among all project participants and support project management in effectively planning on-site construction activities. A case study is presented to demonstrate the methodology.

Keywords: Building Information Modeling, Construction Scheduling, Cost Estimating, CFS Construction.

1. INTRODUCTION

Traditional residential building systems are not sufficient to produce the required number of housing units needed every year to solve the current housing problem in many countries. To meet such a challenge, it is necessary to explore the latest construction technologies, and to create innovative building systems that have the potential to bring high-performance affordable housing within reach of new markets. Beyond being affordable, these systems have to be flexible enough to suit local climate and site conditions, cultural and living habits, and spatial standards. Construction solutions also should reduce or eliminate the need for skilled personnel on the site, and ideally should be assembled with simple tools and errectable without machinery.

Among the available alternative construction systems that satisfy the previous conditions, light steel framing system using cold formed steel (Figure 1) have proven to be a worthy alternative to traditional systems. Potential advantages of this system include high strength-to-weight ratio, ease of production and handling, faster erection, high recycled contents, and sustainability. The basic building elements of CFS systems are cold-formed C or U sections that are fabricated off-site into panels and then transported to site ready for erection. This construction system already lends itself to the application of industrialization techniques, such as lean and Just In Time (JIT) techniques, to enhance the performance of the construction industry (HUD 2000-2004).
The flooring systems usually used with this type of construction include light timber flooring, cast-in-situ reinforced concrete with or without metal decking or thin ferrocement slabs which are prefabricated off-site from cement mortar reinforced with one or more layers of relatively small wire or expanded metal mesh. These prefabricated slabs can be easily transported to site and erected using self tapping screw (Abu-Hamd 2016). Similarly, walls are usually cladded with gypsum boards or cement boards.

Recent advances in the application of Building Information Modeling (BIM) into the Architecture-Engineer-Construction (AEC) industries present an additional mean to further enhance the efficiency of CFS projects. The BIM Project Execution Planning Guide (Building SMART Alliance 2010) identifies twenty-five BIM uses which are organized by project phases: planning, design, construction and operation. An extensive survey of research work and literature on BIM implementation is presented by Ding 2014 and Liu 2015.

Review of available BIM implementation in CFS residential projects (Barret 2013) concluded that CFS projects have not yet benefitted from the information integration provided by BIM implementation. Abu-Hamd 2015 studied how BIM can be employed to enhance the efficiency of CFS residential projects during the planning phase, the design phase and the construction phase. During the planning phase, programming can be used to create complex floor plans from few simple architectural modules. During the design phase, design authoring can be used to create parametric objects for CFS components such as walls, floors and bracings. During the construction phase, digital fabrication tools can be used to enhance the quality and speed of construction. This way the entire building can be created from wall and floor parametric objects as shown in Fig. 2.

Figure 1: Cold-formed steel residential building

Figure 2: BIM Parametric Objects for CFS Buildings
Once the 3D building model has been created, available BIM tools can then be used efficiently to explore and evaluate the project’s constructability before it is built, visualize construction processes through schedule simulation and monitor the cost at different construction stages.

This paper describes how available BIM tools may be used to develop 4D and 5D models by integrating time and cost dimensions to the 3D-BIM model to produce the time schedule, resource utilization, and cost for any given CFS residential building. The methods presented are applied to a case study of a cold formed steel educational building constructed at Cairo University.

2. PROJECT SCHEDULING IN BIM (4D BIM MODEL)

The project schedule dictates the pace at which construction is performed and sets a timeline for project completion. Project schedules are vital to the construction process, making massive projects manageable by breaking them down into individual parts. It is important to have a well-defined schedule so that all parties understand the activities that need to be completed as well as those that are most critical to the projects on-time completion. Project schedules are often subject to changes due to many reasons including inclement weather, design change, lack of worker production, poor scheduling, and lack of funds among many others. Since some of these reasons are unpredictable, such as poor weather conditions, there is often extra time built into the schedule to account for the potential additional setbacks. Project schedules are comprised of individual activities that are either critical or secondary. Critical activities are those that have no lag time, meaning they must have no extra time built in for them to be completed. These activities need to be completed on time or the entire schedule will be forced back. Non-critical activities do not dictate the schedule as directly as critical activities since they have lag time built in, however if they are not completed on time they can delay the overall schedule. A single project can have tens of thousands of activities that need to be completed before the project is finished, so it is vital to determine the relationship between them and their level of critical completion.

Project scheduling can be implemented in BIM by linking the 3D BIM model to the project schedule so that the construction progress over time can be visualized. The developed model, called 4D BIM Model, integrates the three dimensional building model database information with the fourth dimension; time. In other words, a Visual 4D model combine 3D models with construction sequencing activities to display progression of construction over time, and thus improving the quality of construction documents and schedules. Accordingly, planning of construction projects, and communication and coordination among the different project stakeholders will be enhanced. The 4D model is useful during both the design and construction phases. During the design and planning phase, it allows the owner to leverage the greatest value out of their BIM by visualizing construction sequences in order to develop a phasing sequence to include in the construction documents. Moreover, it can allow the contractor to evaluate the design to ensure that it is feasible and constructible. In the construction phase, a 4D Model can provide both the Contractor and the Owner a better visualization of the planned construction sequence compared to the actual sequence. It allows the real-time project process to be updated more frequently. The process of the project can be updated automatically according to any changes in the building design. The contractors can even arrange the site logistics based on the virtual 4D simulation such as arranging lay-down areas, crew movement, and location of equipment.

Several techniques exist for the development of 4D BIM. These can be classified as (Jiang 2012):

i) Built-in 4D features in a 3D or BIM tool, and
ii) Export 3D/BIM to 4D tool and import schedule.

i) BIM Tools with 4D Capability (Jiang 2012)

In these methods a “phase” of a BIM object is assigned to the object property or parameter by adding the “phase” parameter to the BIM object. For example, in Autodesk Revit Architecture, users can define the project phases such as Existing, New Construction and Demolished or by timeline such as March 1st or by the end of March under the Project Phases Tab. The BIM objects in Revit Architecture could be assigned to these phases, and the phase works as the 4th parameter of the model. When the building model is completed, users can get a straight-forward breakdown of project phases generated by the software. Users can also apply filters to show the objects in a specific period of time or in a specific phase. Under the Phase Filters tab, users can manage how to show the related objects.
For example, “show demo + new” filter will show all objects that are demolished and the objects that are in new construction phase. However, the built-in 4D capability in BIM tools is for basic project phasing since the phases defined are not based on the “date” and “time”. For users who need to track a more accurate project schedule such as the Actual start date, Actual end date, Planned start date, Planned end date, etc., the direct integration with schedules generated by professional scheduling software tools is more applicable.

ii) Export 3D BIM to 4D tool and import schedule (Jiang 2012)

The limitations of previous BIM 4D method encouraged the software developers to find out a way which can fully integrate the scheduling software with the 3D model. Generally, the steps involves importing the existing 3D BIM model into the BIM software tool, importing the schedule created by another scheduling software tool (such as Primavera) and then linking the schedule with its relevant objects in the BIM model.

Accordingly, the work flow to develop the 4D BIM scheduling model shall use the following tools:
1- A BIM 3D modeling tool to develop the 3D BIM Model.
2- A scheduling software to develop the Project Schedule
3- A BIM 3D scheduling tool to link the 3D model to the Project Schedule.

The flow chart for this work flow is shown in Fig. 3. The Figure also contains the process for developing the 5D model as explained in the next section.

![Figure 3: Schematic diagram for developing 4D and 5D BIM Models](image)

The BIM 3D scheduling tool can assign a group of objects in the BIM file to a schedule activity ID and then display the objects in the sequence portrayed in the construction schedule. The output is a 3D video that can be rotated during playback. It can also import schedules from a variety of scheduling software tools and allow the user to connect objects in the model with tasks in the schedule, simulate the schedule showing the effects on the model, including planned against actual schedules, and exports images and animations based on the result of the simulation. Timeliner will automatically update the simulation if the model or schedule changes.

The steps needed to develop the 4D BIM model are:

**Step 1:** Develop a 3D BIM model for the project using a 3D BIM modeling tool; e.g., AutoDesk Revit software, as shown in (Abu-Hamd 2015).

**Step 2:** Develop the project schedule using a scheduling software tool; e.g., Primavera software:
First the project activities are organized in an Excel sheet which when imported to Primavera can be used to create the schedule. Cold formed residential buildings have four distinctive work packages: foundations, cold formed steel, and ferrocement slabs for floors and ferrocement boards for walls. These four work packages make up approximately 50% of the total cost of all work package items for this building type.

This excel file includes a description of the activity, the work package, the planned start and finish date, the activity ID code, as well as the quantity take off. For every activity in the schedule an ID is created in order to easily identify the activity without reading its description. Each ID is made using an activity coding system made up of a sequence of eight digits as follows:

1- The first six digits define the activity trade code as defined by the CSI Master Format (CSI 2014). Out of the sixteen trades listed in the CSI Master Format, we needed only the following four codes:
   - Code 033000 for cast-in-place concrete used in foundation works
   - Code 034100 for pre-cast concrete units used as floor slabs
   - Code 034900 for Ferrocement cladding panels
   - Code 054000 for Cold Formed Steel Framing

2- The last two digits define the level of the building as follows:
   - 00 for ground floor
   - 01 for first floor
   - 02 for second floor
   - 03 for third floor

The quantity take off shall be obtained by linking the developed 3D BIM model to a quantity take off tool; e.g., AutoDesk QTO, which can calculate the quantity of each element.

Step 3: Linking 3D Model Activities to Schedule Activities
Once every activity has been identified the ID is used in the 3D Model in order to link the corresponding objects to the activities found in the Schedule. To identify these objects a Parameter labeled “Activity ID” is created to contain the text data of the code for each activity. Once the Activity ID Parameter has been defined, the different objects in the 3D model corresponding to the same activities in the Schedule are highlighted. With all the objects highlighted, the ID code pertaining to that specific activity is saved. This process is done to each object in the model which pertained to the activities in the Schedule. Once completed, the progress of the construction of the four chosen work packages on a daily, weekly, or monthly basis may be shown. For this type of construction, two different Revit models – Structural and Architectural – are used because all elements are not included in one centralized model. The Structural model contained the concrete, steel, and roof elements, while the Architectural model contained the façade elements.

Step 4: Generation of 4D Model: Exporting to BIM scheduling tool
Successive to the completion of the schedule and the object identification in the 3D BIM model, both items are exported into a 3D BIM scheduling software; e.g., Navisworks, so that all model elements are linked to the schedule. This generates the 4D BIM model with the time of each activity linked to the elements of the 3D BIM model. Once the simulation is created it may be paused on the last day of each month in order to obtain the month-by-month pictures. These pictures may used in the future for the quantity take-off.

3. COST ESTIMATION IN BIM (5D BIM MODEL)
The two main elements of a cost estimate are quantity take-off and pricing. Quantities from a Building Information Model can be extracted to a cost database or an excel file. However, pricing cannot be attained from the model. Cost estimating requires the expertise of the cost estimator to analyze the components of a material and how they get installed. If the pricing for a certain activity is not available in the database, cost estimator may need a further breakdown of the element for more accurate pricing. Cost estimator may need this level of detail from the model to figure out the unit price which consists of the unit material cost, unit labor cost, overhead and profit. The unit labor cost is driven by the mobilization and installation durations, and the labor wage while the unit material cost is the sum of the material costs used for the activity per unit. Once the unit price is attained, the cost of the entire activity can be attained by multiplication of the total quantity extracted from BIM and unit price.
The cost estimating process involves performing quantity takeoff (QTO) and adding cost data to the QTO list. Traditional QTO process with CAD drawings involves selecting individual elements in CAD drawings, using the software to automatically determine the dimensions for the take-off, and inputting the quantities into the QTO list. This process requires estimators to spend substantial amount of time on generating the QTO of the entire drawing. Since BIM models are object-based with built-in parametric information, it will be more accurate with less errors to capture the quantities of the objects directly from the BIM model using quantity take off tools. The QTO process is also expedited— it can require 50% to 80% of a cost estimator’s time on a project. QTO process can be enhanced with higher accuracy and less time using BIM technology. Mapping the QTO list with cost databases, which can be built-in in BIM models or a standalone external cost database, estimators can generate a more accurate and reliable cost estimate of the building with minimal effort.

The resulting BIM model is called 5D BIM model in which project cost is integrated with the 3D model of the building making it possible to forecast and track the project cost throughout all the phases of construction. It is helpful in the early stages of the project to establish budget areas. With the evolvement of the model, cost estimation can be enhanced with the increased level of model detail and the cost implementations of different design alternatives can be estimated at any stage of design phase. The cost data extracted from the 5D model can also be utilized to measure the financial performance of the project during the actual construction phase.

Most BIM software tools offered by software vendors include features for extracting the QTO off the BIM Model. Example of this is: Autodesk QTO which can automatically extract QTO from the building model according to category information leveled on the object model and it also allows manual modification of the takeoffs based on the users’ own preference. After that, the QTO list can be exported to the MS Excel spreadsheet and users can associate the quantities with any suitable cost database. After the automatic takeoff, users can also make some changes on the QTO list manually.

4. CASE STUDY OF BIM IMPLEMENTATION

As a case study of BIM implementation, the procedures described in the previous sections are applied to a three-story digital library building constructed at Cairo University using cold formed steel construction (Fig. 4). The building plan dimensions are 12.27 m width by 16.65 m length giving a floor area of 204 m² per floor. It shall be used by the Faculty of Engineering as a Digital Library to provide access to digital resources from various disciplines which can be used for research and teaching.

The structural systems comprises cold formed steel bearing walls for carrying the vertical loads and shear wall strap bracing in selected bays for carrying the lateral loads. Nominal spacing of wall studs and floor joists is taken equal to 600 mm. Galvanized high strength steel of suitable thickness is used. Walls are sheathed using 10 mm ferrocement boards from interior and exterior sides. Floors consist of 30 mm ferrocement slabs on top of the cold formed steel joists. Floor finish consists of 20 mm mortar screed and ceramic tiles. Revit software was used to construct a 3D model of the building using parametric CFS objects of walls , floors, and bracings (Abu-Hand 2015) as shown in Fig. 5,. This 3D model was used during the design stage for visualization, clash detection and for planning staged construction. The workshop drawings and bills of material quantities needed for fabrication were obtained using the Revit add-in 'StrucSoft' software Furthermore, the 3D model was also used for efficient coordination between design, fabrication and erection.

Figure 4: Digital Library Building at Cairo University
4.1 4D BIM Model

*Step 1: Develop the project schedule using a project scheduling tool*

First a work breakdown structure of the building activities is prepared as shown in Fig. 6. The work is generally divided into off site fabrication and on site erection. We focused on four different major work packages for the construction and tracked their progress: foundations, cold formed steel, and ferrocement slabs and boards. These four work packages make up approximately 50% of the total cost of work package items for this project. We chose these work packages since other items are the same as for traditional reinforced concrete construction.

The project activities are then organized in an Excel sheet which when imported to Primavera can be used to create the schedule. This excel file included a description of the activity, the work package, the planned start and finish date, the activity ID code, as well as other relevant information. For every activity in the schedule an ID was created in order to easily identify the activity without reading its description. Each ID was made using an activity coding system made up of a sequence of eight digits as shown in section 2 of this paper.

*Step 2: Linking 3D Model Activities to Project Schedule Activities*

Once every activity had been identified, the ID was used in the 3D Revit Model in order to link the corresponding objects to the activities found in the Project Schedule Software; e.g., Primavera. To identify these objects we created a Parameter to hold the information for the ID. To do this we went to the Project Parameters
and created a parameter labeled “Activity ID” whose future use was to contain the text data of the code for each activity.

Once the Activity ID Parameter had been defined we went into the 3D Model and highlighted the different objects corresponding to the same activities in the Primavera Schedule. With all the objects highlighted we inputted the ID code pertaining to that specific activity. This was done to each object in the model which pertained to the activities in the Primavera Schedule. Once completed, we were able to show the progress of the construction of our four chosen work packages using the 3D Model on a daily, weekly, or monthly basis. We used two different Revit models – Structural and Architectural – because all elements are not included in one centralized model, however we used the same exact process for each. The Structural model contained the concrete, steel, and roof elements, while the Architectural model contained the façade elements. The next step is to export the excel file into Primavera. Once the dates are in Primavera, the activities and the flow of the project progress can be visualized as shown in Fig. 7.

![Figure 7: List of Activities and Project flow in Project Scheduling Software](image)

**Step 3: Generation of 4D Model: Exporting to Navisworks**

Successive to the completion of the Primavera schedule and the object identification in the Revit Structural and Architectural Models both the Revit models and the Primavera schedule were exported in a manner which would allow them to import into Navisworks. Upon the exportation of the schedule and models, each model was opened in Navisworks. From there we imported the schedule and created a rule which we labeled “Link Element To Schedule”. This rule allowed Navisworks to link that object ID from the Revit model to the matching activity ID in the schedule. Once the rule was created we went to the simulation tab in Navisworks and clicked “construct” on each activity. Lastly we ran the simulation and reviewed it for any potential identification errors. Once the simulation was created we were able to pause the simulation on the last day of each month in order to obtain the month-by-month pictures. These pictures would be used in the future for our quantity takes-off.
4.2 5D BIM Model

**Step 1: Export the 3D Building Model from Revit to Material Take off Tool**
The material take off of the building was obtained using the Autodesk QTO software. First step is to export the building model from Revit into QTO software. Figure 6 shows the interface of QTO and the generated QTO list.

**Step 2: Export the QTO list to Excel and calculate the cost**
The next step is to export the QTO list to a cost calculation software; e.g., MS Excel. The Excel sheet contained the cost of each building component categorized by its activity ID code. This enables the calculation of the cost of each activity and the total cost.

**Step 3: Export cost data to Primavera and Navisworks to generate the 5D BIM Model**
Once the cost data was calculated in the Excel sheet, it is exported to the Project Scheduling software (Primavera) and the linked to the simulation tool (Navisworks) to generate the 5D BIM model as shown in Fig. 8.

![Image](image.png)

**Figure 8:** The 5D model simulation showing the duration for each phase with construction and cost

5. CONCLUSIONS

The paper presents a BIM based integrated approach for project scheduling and cost estimating of cold formed steel residential buildings. The approach integrates the basic 3D BIM model with the construction management tools used for project scheduling and cost estimation to produce a 4D BIM and 5D BIM models that can be used to enhance the project efficiency in both the design and construction phases. The developed models facilitate communication among all project participants and support project management in effectively planning on-site construction activities. A case study is presented to demonstrate the methodology.

ACKNOWLEDGMENT

The research presented in this paper was funded by the Egyptian Science and Technology Development Fund (STDF).
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