BIM-assisted labor productivity measurement method for structural formwork

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\textbf{ABSTRACT}

Knowledge of labor productivity is essential for cost estimation and progress control. Due to the limited availability of automatic generation technology for integrated information including both physical component attributes (such as spatial information) and managerial attributes (such as allocated resources), research efforts focusing on cost-time integrated progress control theory have been sparse. However, current advances in 3D building information modeling (BIM) applications have allowed for the practical development of BIM-based visual progress control systems. The goal of this research is to explore the importance of labor productivity data for measuring compound progress. Therefore, this paper develops a field labor productivity data acquisition method by integrating a 3D model with associated information. To evaluate the proposed method, a case project and field data were used to assess productivity. The results of this research are discussed in terms of significant findings and potential further developments.

1. Introduction

Progress control is crucial for successful management of construction projects. Construction progress can be characterized by the percent completed, which involves a complex measure of time and cost. In order to investigate the status of the work performed, data including quantities, time spent, and committed costs of resources for each activity or work package should be considered. In progress control, it is time-consuming to both extract the quantities from construction drawings, schedules, and budget information and collect the required data\cite{1}. Since progress is generally tracked via monetary value, project managers tend to overlook the actual work accomplished. The quality of progress control depends on the quality of the general contractor's paper-based daily progress report, which summarizes the subcontractors' daily reports. Advances in 3D-based integrated information modeling and visualization technologies have allowed managers to visually demonstrate construction progress\cite{2}.

Performance involves all aspects of the construction process and encompasses four main elements: productivity, timeliness, quality, and safety\cite{29}. Productivity can also be referred to as cost effectiveness because productivity is primarily measured based on cost. Productivity is given as a constant in-place value divided by some input, such as worker hours. In all industries, labor productivity is considered to be one of the best indicators of production efficiency. However, due to the unique characteristics of construction projects, heuristic cost projection and scheduling are preferred over productivity-based measurements.

Although important, it can be difficult to measure labor productivity on a job site due to the complexity of job descriptions and the time-consuming process of tracking the productivity of workers. Moreover, it is challenging to identify the measured productivity for a designated activity at a particular quantity in order to produce the unit cost of the task.

The objective of this research is to establish an advanced measurement method for productivity using building information modeling (BIM) and information integrated technology for the purposes of progress analysis and control. This research mainly focuses on a productivity tracking process based on visualized work progress and associated data for developing a productivity measurement system. This paper contains a review of related work, a detailed discussion of the proposed productivity measurement method using BIM, and application to assessment of a case project. A new approach, integrating the information of work progress based quantity with required manpower data using a 3D BIM model, will provide an efficient framework to measure and analyze the productivity over the conventional method. Future research directions are also discussed.

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2. Related research review

Current literature related to the 3D BIM model, progress measures and labor productivity, and visualization and n-dimensional (nD) exploration of computer-aided design (CAD) systems is reviewed in this section.

2.1. Building information modeling (BIM)

Eastman defined BIM as a digital representation of the building process to facilitate the exchange and interoperability of information in a digital format [3]. Eastman also describes six important applications of BIM that apply to contractors as follows.

- Clash detection
- Quantity takeoff and cost estimation
- Construction analysis and planning
- Integration with cost and schedule control and other management functions
- Offsite fabrication
- Verification, guidance, and tracking of construction activities

BIM has many strengths, but its key role is to facilitate mutual understanding and communication. It is essential to identify the well-defined properties of a 3D model and to establish a database structure pertaining to a specific object for the successful application of BIM. BIM facilitates communication with 3D visual drawings and progress representation with associated data among the owner, architects, engineers, and contractors. A 3D digital model differs from a geometric model in that it provides data on inherent properties, as shown in Fig. 1. A geometric model is a solid model having only geometric dimensions. Therefore, a model containing only properties is a 3D object. For example, a ‘wall’ object, as shown in Fig. 1(b), involves properties such as volume, location, and material characteristics as well as geometric dimensions. Further properties can be added based on user requirements.

Advances in BIM technologies have facilitated improvements in integrating diverse information during the planning phase [2]. The main benefit of applying BIM-based tools to estimate the project is its use in material takeoff [3]. Estimators can extract material quantities automatically from the BIM and use this information in downstream cost estimation applications [4]. Hartmann et al. (2012) indicated that BIM-based tools need to satisfy various requirements including: 1) the required level of detail to generate an estimate, 2) quantity takeoff according to the company’s work breakdown structure (WBS), and 3) accurate quantity takeoff for each of the cost items defined in the WBS. Hartmann et al. (2012) conducted a case analysis for the practical implementation of BIM-based cost estimation. The implications of implementation are: 1) the use of BIM-based tools, which saves estimators time during quantity takeoff, and 2) the automatic incorporation of design changes into the estimate, which allows for a reduction in estimated hours [4].

While much of the published research related to BIM has sought to incorporate information and visualize construction processes and components, the outcomes of R&D are still at the theoretical investigation stage, rather than the practical application stage.

Recent research efforts have focused on how to integrate time and cost data into 3D BIM models [5]. Some BIM modeling software programs provide an interface that links 3D models to an external schedule and/or cost control application programs. There are many commercial software products that virtually simulate the construction process using time/cost integration with 3D models.

One of the most commonly used software programs for BIM is Revit by Autodesk. Parametric 3D objects called ‘families’ in Revit are created to represent intelligent 3D model-based designs, coordinated models and documentation, point cloud viewing and editing, energy-efficient building simulation, and construction modeling. ArchiCAD produced by Graphisoft is a competitor of AutoCAD Revit in the field of BIM. Graphisoft continues to expand its functions to allow interdisciplinary collaboration solutions by implementing industry foundation class (IFC) systems [6].

Innovaya Visual Quantity Takeoff and Innovaya Visual Estimating, developed by Innovaya, are among the first BIM-based estimating solutions. These are extended to Innovaya Visual 5D Estimating, which allows a BIM model created in Autodesk Revit to be integrated with MC2 ICE, Sage Timberline Estimating, and MS Excel [7].

2.2. Construction progress measure and labor productivity

Project control analyzes the variance between the actual status and the planned target. The status is normally expressed in terms of progress, which is used to describe the work performed in terms of the percentage of work completed in a designated time period. Thus, the progress measure is composed of cost and time factors. It is crucial to integrate time with cost in order to accurately calculate progress. The project cost projection and completion date can be anticipated with integrated information.

The integration of schedule and cost control has been a natural objective of project control systems since the late 1970s [8]. Carr (1993) summarized related research from the 1980s to the early 1990s. The earned value concept considering the time/cost relationship of the U.S. Department of Defense became widely accepted in 1980. The general implementation issues of schedule/cost integration were
introduced in the 1980s [9]. Automated project control was explored via integrated databases in the early 1990s [30,31]. The integration issue at that time was how to integrate individual breakdowns such as the WBS and cost breakdown structure (CBS). Efforts have sought to link WBS activity with a cost account of the CBS. In this case, a cost account includes several activities, and thus costs should be distributed across activities. It is necessary to extract the exact quantity of the component for an activity in order to allocate the cost. If this work is not automated, it involves manual tasks, which are time-consuming and complicated. Among the many research efforts regarding schedule/cost integration, the object-oriented model proposed by Ibbs et al. (1989) focused on the premise of 3D modeling design [10]. With the advancement of BIM, the approach of linking 3D modeling of design objects with schedule/cost information was reevaluated. Shan et al. (2014) conducted a study to link the 3D modeling of design objects with schedule/cost information [11].

2.3. Productivity assessment

The fierce competition in the construction industry compels all stakeholders to improve their productivity, which explains why productivity estimation has attracted so much attention throughout both industry and academia. Today, productivity management is recognized as a major project management concern in the construction industry [12]. The rate of construction productivity varies from one project to another due to the environmental and managerial conditions. The considerable impact of these project-specific factors on productivity reinforces their importance in productivity estimation simulations [13]. These project-specific factors affect productivity both positively and negatively.

The scheduled overtime, change orders, materials management, weather and human factors were identified by Park [14] as the main factors that influence the productivity rate. The identification of these factors is a preliminary step in creating a model for productivity estimation. The most common approach for productivity estimation is to use the historical data from previous similar projects as a baseline for new projects.

For example, Moselhi et al. [14] developed a decision support system called WEATHER to examine the impact of weather conditions on the productivity of construction operations. The developed model estimates the construction productivity, activity durations, and weather patterns in different modes to improve the accuracy of the planning and scheduling [15]. Given that only weather factors are taken into account in this framework, other complementary models are needed for the consideration of other external factors.

Moselhi et al. [15] investigated 57 different construction projects in order to study the impacts of change orders on the productivity of construction projects. They discovered a direct correlation between the labor component of change orders and the productivity loss in all types of projects [16].

Regression model is the most common statistical model for productivity estimation when considering specific factors [16,17]. Hanna et al. [18] developed a regression model to investigate the effect of change orders on construction productivity. Koehn and Brown [19] employed some non-linear equations to examine the effect of weather changes on the productivity rate. The learning curve theory is another important theory in productivity estimation. According to the learning curve theory, the productivity of a repetitive process gradually increases thanks to the increasing familiarity with the process, improved management, and more efficient application of tools and equipment [20]. In most cases, there is no pre-identified functional relation between variables affecting the level of productivity and their outputs. In addition, there is no guarantee that simple models such as linear regression can satisfy the expected accuracy of a forecasting model. In the wake of these limitations, researchers have considered the application of Artificial Intelligence (AI) systems to model complex relationships between a set of dependent and independent variables.

2.4. Visualization and nD exploration

Many research efforts that have sought to visualize construction processes and operations are rooted in scheduling [21,22,23,24]. They typically involve a link between the construction schedule and 3D CAD models in order to represent a visual sequence of tasks in terms of spatial and temporal aspects. These efforts have achieved the extension of 3D CAD to 4D, which enables graphical animation of construction schedules. The advancement of BIM technology has accelerated research on interactive information flow and communication during the project life cycle. An emerging paradigm for construction visualization is augmented reality (AR) [23]. AR is a multisensory technology that blends virtual content with the real environment [23]. Another aspect of upcoming research interests is to extend 4D to 5D, which includes cost information. Ongoing research continues to explore the integration of 3D BIM objects with their attributes, specifically time and cost information for construction progress control.

Advances in the visualization of the construction process would enable digital representation of physical progress and visual recognition of deviations between actual and planned results in place of limited paper-based representations.

Research has explored advanced progress monitoring techniques using 3D visualization and sensor-based automatic 3D modeling. Kamat et al. (2011) demonstrated 4D CAD and simulation-driven dynamic 3D operations visualization, enabling interactions of various resources and depicting a continuously evolving facility for automated progress monitoring [24]. Son et al. (2010) proposed an automated 3D structural component recognition and modeling method for construction progress monitoring [25]. Shahi et al. (2012) developed an activity-based data fusion model, which incorporates an ultra-wide band (UWB) positioning system for progress tracking of activities [26]. Turkcan et al. (2012) combined 3D object recognition technology (laser scanning) with schedule information in a combined 4D object-oriented progress tracking system [27].

3. BIM-assisted daily productivity measuring system prototype

3.1. Concept and approach

Scheduling control in Korean construction projects is limited to a pure time schedule based on master planning, which is primarily dependent upon the experience and intuition of the subcontractor’s manager. Scheduling based on labor productivity is not practiced in Korean building construction projects due to insufficient productivity data and a lack of appropriate data collection methods. For example, the amount of manpower for formwork is decided based on its influence on the following task (concrete pouring) and/or the allocated budget. Intuitive and empirical decisions can have adverse effects on time management. Therefore, manpower planning should be based on estimated quantities and labor productivity for each work item on the bill of quantity (BOQ). The Korean government publishes the “Standard Estimate for Building Construction (Poom Sem),” which provides the quantity of materials and manpower per unit for every single trade. The standard estimate becomes a baseline for public project estimation. The standard estimate is not directly linked to the BOQ structure. For example, the standard estimate classifies the formwork into wood, ply-wood, and Euroform in order to calculate the quantities and costs of materials and labor. However, in addition to different material types, labor costs for formwork, in practice, are calculated separately considering the location, including the substructure, superstructure, and ancillary facilities. As discussed, the applicability of the standard estimate is limited to normal situations due to the difference in the level of detail. Therefore, a new approach to cost estimation and control of daily in-house productivity information using the standard estimate as a
reference is needed. Thus, the structure of the BOQ is different from that of the prime contractor because it depends upon his/her relationship with subcontractors. Baseline productivity data and quantity surveying per unit are required to obtain accurate productivity data.

The primary concept of the BIM-based daily productivity, progress monitoring, and control systems is to acquire daily information using 3D objects and to enter it into related databases. The process is carried out as follows: 1) extract quantities using 3D models and an integrated breakdown structure, 2) establish a database for standard productivity of each activity based on the standard of measure or historical cost data, 3) measure and report daily input laborers and work volume, 4) compare actual and planned productivity and progress, and 5) record the productivity and progress in the database (see Fig. 2). This research focuses on the acquisition and analysis of productivity information.

3.2. Prototype components and implementation

3.2.1. Spatial information identifiers

Measuring daily work volume on a construction site requires spatial information and quantities. It is relatively easy to identify the spatial characteristics of a superstructure compared with a large open space such as a basement parking lot. A floor plan for apartment projects with three units per floor, for example, is divided into three zones: unit (blue), core (yellow), and unit partition wall (red) (see Fig. 3). A unit partition wall is regarded as a zone that should not be duplicated or omitted while extracting quantity data.

In order to set up zoning in a substructure such as a basement parking lot, the concept of an xy-plane grid and grid-based vertical spatial zoning is applied to identify a unique area and extract the related quantities. A BIM-based database is established for property data of elements such as the slabs, girders, and columns that are involved in spatial zoning (see Fig. 4).

The managerial data of the selected area such as the horizontal/vertical location, x- and y-coordinate values, an object, and description are automatically extracted and displayed in a spreadsheet. Dimensional attribute data, including width, length, and height, are also automatically recognized. Additionally, the area and volume will be calculated using the attribute data, as shown in Fig. 5.

The prototype requires the input of basic information such as the date, component, building number, and floor in the top menu, as shown in Fig. 5. Additional data such as the zone, layer, and percent completed are also required. A working spot within the zoning area needs to be selected, and the percentage of progress is selected on the menu bar. The system is designed to be flexible in terms of the engineer’s judgment. The percentage of progress is assigned by the supposition that a project is 10% complete when the batter board is set out, 30% complete when the walls are finished, 50% complete when the girder/beam is completed, 80% complete when the slab floor is done, and 100% complete when form removal is finished. For example, if the formwork is in progress at the same time as the walls, 20% can be entered instead of 30%. A daily progress input module for the superstructure of an apartment building was developed applying the same concepts discussed above.

3.2.2. 3D BIM-based quantity takeoff

Quantity takeoff is typically conducted manually with the assistance of a computer program using 2D CAD drawings. The first task in daily progress measurement is to break down the work into a micro-manageable level. Quantity takeoff is then conducted using the algorithm established in the 3D BIM model. 3D BIM-based quantity takeoff has the advantage of automatic calculations based on a hierarchical breakdown and the flexible application of design changes. For example, the girder, as shown in Fig. 6, has dimensional attributes such as the section outer length and contacted area.

On the other hand, the amount of concrete for a girder is calculated based on measurements of the length and the section outer length. There is one significant calculation difference in that the BIM-based quantity takeoff includes the girder with the contacted slab floor. It is
necessary to prioritize inclusions in the extraction of quantities for overlaid parts. For example, there is a partially overlapping area between the girder and slab, as shown in Fig. 6. The quantity takeoff formula was developed to extract quantities by considering the overlap based on the order of priority. The overlap belongs to the girder and the formula for the girder formwork is $L_G \times h_G$. The overlap is then automatically deducted when calculating the slab formwork quantity. In this research, the main objects are a column, girder, wall, and slab according to priority (see Table 1).

Whereas the quantity of concrete can be controlled by the grid, the quantity of formwork is extracted based on attributes from grid-based zoning, as discussed in Section 3.2.1. The tasks for extracting the element information identified by the grid and spatial zoning classification are as follows.

- Divide the BIM model using the ArchiCAD separator function
- Insert the element information for the selected grid spot using the zoning function
- Extract the required information using the property extraction function
- Export the extracted information to Excel to sort, calculate, and report

Fig. 7 shows an example of the quantity takeoff process for formwork.

3.2.3. Cost-schedule integration with object-oriented information

A 3D model provides spatial location and quantity information. This information will be integrated with the work activity and cost account. This paper proposes physical integration from three different
perspectives, as shown in Fig. 8. In other words, well-defined 3D objects will be used for cost estimation and scheduling using a hierarchical breakdown structure and coding system.

3.3. Baseline for productivity

Productivity standards and a standardized method of quantity

Table 1
Calculation formula for objects.

|          | 2D-based calculation formula | BIM-based calculation formula |
|----------|-----------------------------|-------------------------------|
| Slab     | $W_{S1} \times W_{S2}$     | $(W_{C1} + W_{C2}) \times 2 \times (H - t_s)$ |
| Column   | $(W_{C1} + W_{C2}) \times 2 \times (H - t_s)$ | $(W_{C1} + W_{C2}) \times 2 \times H$ |
| Wall     | $L_W \times (H - t_s) \times 2$ | $L_W \times H \times 2$ |
| Girder   | $L_G \times (h_G - t_s) \times 2$ | $L_G \times h_G \times 2$ |

Fig. 5. Zoning information.

Fig. 6. Attributes of objects.
measurement need to be established for the measurement of daily progress. This study analyzed the labor input per unit from not only the standard estimate, which is a guideline for public projects but also from three actual bidding documents from 2011. The productivity rates for plywood formwork for carpenters and laborers based on the Korean standard estimate are 9.62 m²/md (man-day) and 17.54 m²/md, respectively.

Productivity is calculated using basic labor data. A crew team for Fig. 7. Database for grid-based 3D.

| Floor | Item   | Formula               | Unit  | Quantity |
|-------|--------|-----------------------|-------|----------|
| 4     | Concrete 25-240-15 | $1.555 \times 0.4 \times 2.85 \times 1$ | M³    | 1.773    |
| 4     | Plywood | $1.555 \times 2.85 \times 2 \times 1$ | M²    | 8.864    |

Fig. 8. Schedule/cost integration using an object-oriented approach.
formwork is composed of carpenters and laborers. A carpenter’s daily productivity is 27.78 m²/ md for a superstructure and 14.29 m²/ md for a substructure. However, there is no significant impact from an individual’s performance, whereas the crew team’s performance is crucial for analyzing the productivity. Therefore, this research considers the productivity of a crew team based on the proportion of labor costs. The proportion of labor costs for a carpenter to laborer is 73:27. Using this proportion, the combined productivity is 26.71 m²/md for a superstructure and 16.06 m²/md for a substructure, as shown in Table 2. Therefore, the combined productivity rate becomes a baseline for planning the schedule and cost. Progress monitoring and control are also based on this baseline.

This research introduced quantity distribution using a grid in CAD drawings for effective quantity takeoff and estimation.

### 4. Application of the system prototype

#### 4.1. Case project overview

The developed system prototype was applied to an apartment project, and productivity data were computed using data collected based on 3D model objects. The project information is shown in Table 3.

#### 4.2. Practical implementation

##### 4.2.1. Input data

4.2.1. Input data

A field engineer was trained to record the daily work volume, including the required manpower planned and the daily work performed, as well as to analyze the variance. Zoning for the superstructure and substructure was conducted considering spatial factors, as explained in Section 3.2.1, and the zoning results are depicted in Fig. 9.

![Fig. 9. Space zoning results.](a) superstructure (b) substructure
4.2.2. Quantity extraction and productivity calculation

One floor plan was divided into five zones based on spatial identifiers, as explained in Section 3.2.1. Each form is denoted using a different color in Fig. 10. The complete work is depicted in plaid.

The results of the quantity takeoff based on zoning are shown in Fig. 11. The quantity for an individual object is explained with attributes. The daily expected work volume is calculated using the amount of manpower and the standard productivity rate, whereas the actual volume of work performed is measured using the BIM takeoff. The daily productivity rate is then calculated by dividing the work volume by the amount of manpower. The achievement rate is simply calculated as the work performed divided by the work planned. The total work volume of an aluminum form for the fifth floor of building #101 is 1012.04 m².

The highlighted numbers in Fig. 11 represent the work volume for the aluminum form performed per day, where the sum is 718.02 m². Productivity and progress were analyzed on a daily basis and cause analysis was performed if there was a significant deviation, as shown in Fig. 12.

For example, the projected work volume for an aluminum form with six crew members on November 21st was 160.26 m² (6 × 26.71), as shown in Fig. 12. However, in order to compensate for construction delays caused by preceding work, additional rush-work (4 h) beyond regular work hours was performed by the working crew (18 members) and, as a result, the actual work performed and productivity were 718.02 m² and 119.67 m²/md (718.02/26.71), respectively. The aluminum formwork progress for the fifth floor was 70.9%, complete as of November 21st.

Daily productivity data can be analyzed for each building, substructure/superstructure, and crew team. The monthly productivity on the superstructure is significantly higher than the baseline; on the other hand, the substructure monthly productivity is lower than the baseline. An analysis of productivity for the superstructure shows an increasing learning effect curve due to repetitive work. Progress can be analyzed, and accurate planning of the remaining work is possible using productivity analysis results.

However, in order to establish a practical baseline, it is necessary to generate the combined productivity considering various working environments.

4.3. Normalized productivity formula

Productivity data from Aug. to Dec. 2011 (Table 4 and Fig. 13) were measured and data for 2012 were projected at the end of Dec. with the following assumptions. To satisfy the time duration considering the remaining quantities, the maximum potential productivity rate needs to be 61.25 m²/md, which corresponds to a 16% increase in the average
for Dec. 2011. In addition, according to YS Jin et al. (1998), it is only possible to work approximately 50% of the time due to adverse weather conditions during the winter [28] and thus the productivity rate in Jan. was assumed to represent an 8% increase rather than a 16% increase, considering the adverse winter weather. Due to the complexity of the work on the penthouse, combined productivity (26.71 m²/man·day) was applied for May (104–104) and June (105–107), and averages of 61.25 and 26.71 (43.98 m²/man·day) were used for Apr. and May, respectively. Table 5 and Fig. 14 show the actual productivity data and projected data measured at the end of Dec., as previously explained. A t-test was
used to verify the validity of the projected data compared to the actual data. The null hypothesis supposes that the projected value is equal to the actual value, while the alternative hypothesis supposes that a projected value is not equal to an actual value. The significance level used in this study was 5%. The null hypothesis was accepted because the p-values were > 0.05 (p > 0.05) during the period from Jan.–Jun. 2012.

A best-fit line and an approximate formula for actual structural work data (11 months) were derived in order to generalize the data, as shown in Fig. 15. Due to the characteristics of the work, each interval showed a different trend for productivity. Formwork for only the substructure was conducted from Aug.–Sept., formwork for the substructure and superstructure was conducted from Oct.–Nov., and formwork for the superstructure was conducted from Dec.–June.

The aforementioned best-fit line was computed using trend line analysis. The trend line was analyzed based on the collected data using five different equations: exponential, linear, logarithmic, polynomial, and involution, as shown in Table 6. The calculated analysis results included R² values of 0.3795, 0.285, 0.4757, 0.9627, and 0.6149 for the exponential, linear, logarithmic, polynomial, and involution equations, respectively.

Therefore, the polynomial formula was selected as the best fit to the

### Table 5

Combined productivity as of June 2012.

( unit: m²/man·day)

| Date   | Apt. # | Average | Projected | p-Value |
|--------|--------|---------|-----------|---------|
| Jan. 2012 | 56.83 | 57.03 | 57.03 | 0.07 |
| Feb. 2012 | 58.17 | 60.00 | 61.25 | 0.06 |
| Mar. 2012 | 64.15 | 59.11 | 61.78 | 0.61 |
| Apr. 2012 | 50.43 | 47.68 | 52.55 | 0.06 |
| May 2012 | 32.07 | 27.13 | 27.83 | 0.61 |
| June 2012 | 27.83 | 20.99 | 25.31 | 0.73 |

### Table 6

Analysis of the trend line for projected productivity.

| Option      | Result                                                                 |
|-------------|------------------------------------------------------------------------|
| Exponential | \( y = 3.0338x + 21.064 \) \( R^2 = 0.285 \)                          |
| Linear      | \( y = 17.492e^{0.1114x} \) \( R^2 = 0.3795 \)                        |
| Logarithmic | \( y = 17.446\ln(x) + 11.508 \) \( R^2 = 0.4757 \)                    |
| Polynomial  | \( y = -0.2252x^3 + 2.491x^2 + 1.4692x + 5.0361 \) \( R^2 = 0.9627 \) |
| Involution  | \( y = 12.502x^{0.6312} \) \( R^2 = 0.6149 \)                        |

Fig. 14. Results of the comparison between projected and actual data.

Fig. 15. Best-fit line and the approximation formula for actual data.
actual line with \( R^2 = 0.9627 \).

\[
y = -0.2252x^2 + 2.491x^2 + 1.4692x + 5.0361
\]

The \( R^2 \) value is a coefficient of determination that indicates how well an approximate (actual) curve fits a best-fit line. The \( R^2 \) value of 0.9627 indicates that the best-fit formula covers 96.27% of the actual data.

5. Conclusions

The objective of this research was to acquire and analyze daily construction labor productivity using a BIM 3D model and associated properties. This research found that productivity information is an essential ingredient of construction progress monitoring and control. This paper discussed the process of 3D BIM modeling, quantity takeoff, and productivity baseline initialization, acquisition, and analysis. The significant findings from this research are as follows: (a) It is possible to represent productivity using visual progress via a 3D BIM model. Productivity has a cost-time compound measure that considers the manpower required and the quantities being produced. This paper explains how to integrate BIM model information with daily productivity-related information obtained from the job site. (b) A productivity best-fit line can be generated based on application of the prototype to a case project. This line be used as a baseline for time and cost projection of similar projects. A standard productivity baseline will be established using accumulated productivity information. (c) This research is limited to BIM-based productivity analysis regarding formwork construction, and further studies based on this information are needed. A study on BIM-based productivity analysis regarding reinforcement work and concrete work will be conducted in the near future so that BIM-based productivity analysis can be applied to the entire RC construction. This will be further expanded into a general methodology that can be applied in other construction systems. Additional research will also be conducted to manage and control the field utilizing deduced productivity data.

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