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D[3] City project — Economic impact of BIM-assisted design validation

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ABSTRACT

This paper reports a return-on-investment (ROI) case study of the use of building information modeling (BIM) in "design validation" based on the avoidance costs of rework due to design errors. The ROI was analyzed using the 709 individual design errors found during the BIM design validation of the six high- and medium-rise buildings in the D3 City project in Seoul, Korea. Each design error was categorized according to its cause and the likelihood of detecting it before construction. The likelihood of detecting errors in the ROI analysis made a large difference of a factor of four to fifteen. An additional analysis on the potential impact of design errors on the schedule shows that costs associated with schedule delays has a much larger economic impact than rework costs.

1. Introduction

Monetary evidence is a strong driver for any technology adoption. For this reason, a number of case studies have been conducted that analyze the returns on investment (ROIs) from the use of building information modeling (BIM). They report extraordinarily high (sometimes over 1600%) ROI results [1–3,5,6,8,9,13,14,16]. However, the reliability of most of the analysis results is in question because only the ROI values are reported, without providing details about the ROI data collection and analysis methods. These details provide the basis of validating the analysis results.

Another limitation of previous BIM ROI studies is their bases for calculating returns. Previous studies commonly use perceived ROI [2,20], productivity gain in drafting and documentation [1,14,16], shortened project duration [5,8,9], and the reduced number of requests for information (RFIs) [3,13]. Perceived ROI, despite its subjectivity, is used as the basis of the largest BIM ROI study [17,20]. Perceived ROI is an important metric for understanding people's perceptions about the benefits of BIM, but it cannot replace actual ROI. Productivity gains in drafting and documentation can be direct benefits for architectural or engineering firms that adopt BIM, but not for contractors, whose work focuses much less on modeling or drafting, compared to architects and engineers. For this reason, shortened project duration is often used to discuss the benefits of adopting BIM during construction [5,8,9]. However, there are many other factors than BIM, such as types of construction methods and equipment, the number of workers, and management quality, which may affect the project duration more. Hence, shortened project duration may not be an appropriate metric for measuring BIM ROI, unless a careful and detailed analysis of the role of BIM in the shortened project duration is included.

Another common metric that is used to measure the benefit of BIM is the number of RFIs [3,13]. This is based on an assumption that the number of RFIs decreases when adopting BIM, because a building information model provides high-quality information. However, our observations show that the number of RFIs differs greatly, depending on the characteristics of projects and project participants. If a project is a fast-track project, it is unavoidable to have a large number of design changes, and, thus, a larger number of RFIs. The number of RFIS also varies, depending on the characteristics of project participants. Some clients and project participants, especially in Korea, prefer informal and verbal communication to official documents such as RFIs, which may be used as legal documents against them in the future. In such cases, the number of RFIs will decrease, compared to those of similar projects, regardless of BIM. On the other hand, some clients and contractors are very keen on accumulating legal documents; they keep track of even informal communications in the form of the confirmations of verbal instructions (CVIs). It is, therefore, arguable that a project with fewer RFIs is better than one with more RFIs, especially in countries like South Korea. These kinds of arguments can be avoided if the number of errors and amount of missing information in a design can be directly tracked, instead of indirectly tracking the RFIs, which may or may not be generated when there are errors or missing information in the design. Peter Love and his team [12] reported two interesting findings from their longitudinal and extensive "rework in construction" study based on 260 construction projects: 1) rework costs 11.07% of the original contract value; and 2) the errors and omissions in contract documentation were two of the most highly correlated causes of rework. Other studies [7,11,18] also show that design errors are the major causes of schedule delays and quality defects as well as rework, and, thus, it is extremely important to detect and correct them in advance. In fact, detecting building-element clashes and other causes of rework was chosen as the most beneficial way of using BIM by the owners [20] and has become a common BIM practice, called a "BIM-assisted design validation" process, today.

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It is, however, rare to find BIM ROI studies based on design errors. One of the rare reports on the tracking of design errors for a BIM ROI analysis is an interview with Michael LeFevre, of Holder Construction Company [19]. Like most other previous studies, the interview vaguely explains the data collection and analysis process, without giving details. BIM ROI studies based on design errors are rare, even though error detection is noted as one of the most beneficial ways of using BIM [20], probably because such data are not easily accessible to researchers, and even to the people who can access such data, keeping track of design errors identified using BIM is laborious and time-consuming. Another reason might be found in practitioners' criticisms of BIM-assisted design validation. Some practitioners complain that experienced construction engineers can find most design errors before or during construction even without using BIM and the number of errors is meaningless because many design errors found using BIM have very little economic impact on the project.

This practitioners' view implies that it is important in a BIM ROI analysis to distinguish errors that can be easily found even without using BIM from the ones that cannot be easily found without using BIM. This study proposes a BIM ROI analysis method in design error detection that considers the "likelihood of detecting errors without using BIM." The proposed method also categorized errors by cause.

Because some design errors are very obvious and likely will be identified before construction even without using BIM, the economic impact of the errors is analyzed by considering the likelihood of identifying each error without using BIM: if the likelihood of identifying an error is high, the economic impact is low. This study compares and reports on the differences in the ROI analysis results when the likelihood of detecting errors is not considered as in many previous ROI studies and when the likelihood of detecting errors is considered. A large urban rehabilitation project, the D^3 City (pronounced "D Cube City") project composed of six high- and medium-rise buildings, is used as a case study to illustrate the differences.

This paper is organized as follows. The next section reviews previous studies on BIM ROI. The third section briefly describes the D^3 City project. The fourth section discusses the data collection process. The fifth section describes the distribution of errors by their cause, the type of work involved, the likelihood of identifying the errors without using BIM, and so forth. The sixth section analyzes the BIM ROI based on the 709 design errors collected from the D^3 City project, and discusses potential additional savings by considering the impacts of errors on the schedule and quality of the buildings.

2. Previous studies

Many studies have reported that inaccuracy and errors in design were the dominant causes of rework, schedule delays, quality defects, and cost overruns [7,11,12,18]. These researchers envisioned that such economic losses due to design errors could be reduced by adopting BIM. An example is a case study by Sacks et al. [15]. They investigated the economic loss due to design errors from seven precast concrete construction cases and claimed that at least 50% of the design errors could have been eliminated if BIM had been adopted.

Several other studies analyzed the economic impact of BIM adoption. One of the earliest efforts to study the benefits of using BIM is the study on the benefits of three-dimensional and four-dimensional computer-aided design (CAD) collected by CIFE [3]. However, it was a mere collection of benefits described in one or two lines, without any analysis. Another early, but more analytical BIM ROI study was conducted by Autodesk [1]. It measured ROI based on the reduction in labor cost due to the productivity gain from using a BIM software application as "return" and the cost of hardware and software and monthly labor cost as "investment." The productivity data were collected from about 100 users through an on-line survey in 2003. Despite its significance for being one of the earliest analytic BIM ROI studies, it leaves several questions unanswered. First, it is not clear why the investment omitted a training fee. Did all the users who participated in this ROI study assume that the training would be provided by internal staff, without extra cost?

Second, ROI is typically calculated as return minus investment cost, divided by investment cost. The return is also called the gain, savings, earnings, and benefits. In this case, if ROI is over 0%, the investment is judged beneficial. ROI 0% is the break-even point. Sometimes, ROI is calculated as return divided by investment cost. In this case, ROI 100% is the break-even point; the ROI value should exceed 100% to be judged a positive investment. The Autodesk study took the latter approach. The first-year ROI reported in the Autodesk study was about 62%, but since the investment costs were not subtracted from the returns in the given ROI equation, 62% ROI actually meant a 38% loss in the first year. The projection of ROI in the second and third years was not mentioned in the article. However, if we use the same given numbers for the return and investment costs, the ROI can be recovered, with up to a 43% gain in the second year. This assumes that there will not be any additional investment in upgrading or buying software and hardware, or training employees in the second year. If hardware and software are upgraded in the third year, the ROI again drops to about 10%. This type of ROI pattern is not wrong, and is actually common in reality, but it was not clear if this was the interpretation intended by the original study's report.

At any rate, whether the results were valid or not, these questions could have been raised and discussed, because at least the equation and the variables were described. Most other BIM ROI studies, thus far, have provided no details on how the ROI data were collected and analyzed, only final numbers. For example, the *SmartMarket Report* annually conducts the largest BIM ROI survey today. In 2008, the number of respondents was 302 [19] and, in 2009, 2228 [20]. The respondents were asked to provide "measured BIM ROI values" if the respondents were formally measuring ROI, or "perceived BIM ROI values" if the respondents were not measuring BIM ROI. The results are somewhat vague. The study reported that, in 2008, 48% of respondents answered that they saw positive ROI at a moderate level or above. The perceived ROI on average was between 11% and 30%. In 2009, 53% to 72% of respondents answered that they experienced positive ROI on their overall investment in BIM. Less than 19% of respondents answered that they experienced over 50% ROI. The focus of the survey seemed to be more on understanding the general perception or value of using BIM in the industry than on getting reliable ROI data. Each respondent might have had a different basis and method for collecting and calculating BIM ROI. The study cares little about coordinating and understanding how each respondent derived the ROI value.

In contrast to the Autodesk and *SmartMarket Report* studies, some studies show unusually high BIM ROI. Holder Construction reported that its initial ROI was 300% to 500% [19]. Again, the details on how the ROI was calculated are not known. Giel et al. [5] calculated BIM ROIs based on schedule differences between projects of similar characteristics — those that used BIM and those that did not. Two sets of projects were compared. The results showed that the ROI values varied from 16% to 1654%. This discrepancy between the two cases might be natural because even if two projects have a similar size and similar conditions, there are too many factors other than BIM that may affect the schedule. It is difficult to say that the schedule differences of two similar projects were solely attributable to using BIM.

This paper analyzes the benefits of adopting BIM in the design validation process, which is known today to be the area most benefited by adopting BIM [20]. It discusses details about the characteristics of the data and their collection, as well as the calculation method used with ROI data. The next section briefly introduces the target project.

3. Overview of the D^3 City project

The D^3 City project is a USD 583 million urban rehabilitation project composed of several high- and medium-rise buildings, including a hotel, a shopping mall, a musical theater, an office building, residential buildings, and a 15,824 m^2 public park (Fig. 1). The total floor area is 350,247 m^2, and the project duration is 4 years. The final design was handed over to Daesung Engineering and Construction (Daesung in short), the main contractor, in a set of drawings and documents. Since the project is very large and complex, Daesung decided to adopt BIM to effectively manage the project. The first step was to develop a building information model from the drawings from the architectural firm. Daesung, with little experience in BIM, hired a professional BIM team from outside. Each design error identified during the BIM process was recorded using a simple template with screen shots and short descriptions of the problem. The design errors were categorized by cause, likelihood of identifying each error without using BIM, and potential impacts on the project schedule and quality.

The D^3 City project used BIM to identify 709 design errors during the design validation process. The economic impact (or potential savings) from using BIM was estimated based on the direct cost of each error. The indirect costs and the home office costs were calculated proportionally to the direct costs. The data collection process and the ROI calculation method are described in more detail in the following sections.

4. Data collection process

As aforementioned in the Introduction and Previous studies sections, many BIM ROI studies have been conducted. However, no study has provided details about how the data were collected and analyzed. Our approach classified and analyzed design errors according to the "level of impact." The level of impact was subcategorized into five specific indices: the cause, the potential impact on the schedule, the potential impact on the direct cost, the potential impact on the quality of the project, and the likelihood of identifying an error before construction using the traditional drawing-based approach. Table 1 summarizes the indices and the classification. The project team classified the errors following the authors' guidance, as specified in Table 1, and estimated the direct cost of each error for the ROI analysis.

Through an iterative process, the causes of the errors were categorized as one of the following three types: 1) illogical design, 2) discrepancies between drawings, and 3) missing items. Fig. 2 through Fig. 4 illustrate an example of each error type. Fig. 2 is an example of the illogical design that has a column that blocks a door. Common examples of illogical design are clashes between different building elements. Fig. 3 shows an example of discrepancies between two drawings. The exterior wall is represented as a solid wall in the drawing on the left-hand side, while the exterior wall is represented as steel beams without a solid wall on the right-hand side. Fig. 4 shows a structural drawing with missing beam identifier numbers. In such cases, field engineers need to request information to either a structural engineer or an architect, in order to know which size of beam should be ordered and where the beams should go.

The likelihood of identifying an error without using BIM was categorized into three groups (Table 1). Value 1 indicates that the error is unlikely to be identified before construction without using BIM. The 25% or less likelihood was given as the general guideline for defining "unlikely" to the project team. Here the 25% likelihood is a figurative

Fig. 1. D^3 City project: An urban rehabilitation project composed of several large buildings. (Courtesy of Daesung Engineering and Construction).

Table 1
Classification of design errors.

Index	Definition	Classification
Cause	Type of the error by cause	1: Illogical design 2: Discrepancies between drawings 3: Missing items
Likelihood of identifying the error	Likelihood of identifying the error before construction without using BIM (i.e., in the traditional drawing-based process)	1: 25% or below 2: about 50% (25% to 75%) 3: 75% or above
Impact on schedules	Potential impact of the error on the project schedule	0: Practically no impact 1: Mild 2: Serious 3: Severe
Impact on quality	Potential impact of the error on the project quality	0: Practically no impact 1: Mild 2: Serious 3: Severe
Impact on direct cost	Estimation of the direct cost when the problematic part is rebuilt due to an error	Estimated direct cost

value, not a definite value. Value 2 indicates that the likelihood is about 50% (between 25% and 75%). Value 3 indicates that the error is likely (the 75% or above likelihood) to be identified even in the traditional, non-BIM, drawing-based approach. Since even very obvious errors can be missed, 100% or 0% likelihood of detecting errors before construction was not considered.

Both the impact on schedules and the impact on quality were categorized into four groups. Group 0 indicates "no impact," Group 1 "mild impact," Group 2 "serious impact," and Group 3 "severe impact." These values are not in scale, while the likelihood of identifying an error is in scale. That is, if the impact value of an error on schedules is 3, it does not mean that the error has a three-times greater impact on the schedule than on the error, whose impact value is 1. For example, whether one floor collapses or the whole building collapses, both will be categorized as cases with a severe impact on schedules, but the difference in the monetary value will be more than 100 times greater. On the other hand, if the likelihood of identifying an error is 1, it means that the error can be detected three times more easily than an error whose value is 3.

5. Distribution and economic impacts of errors

Before analyzing the BIM ROI based on the avoidance costs of design errors, this section discusses the characteristics, distribution, and potential economic impacts of the errors by error type. Table 2 shows the occurrences of design errors by cause; i.e., illogical design, discrepancies between drawings, and missing items. The discrepancies between drawings accounted for 50.49% of design errors, followed by missing items (27.22%) and illogical design (22.28%). The errors were subcategorized by the type of work involved and causal details. The work-type categories were as follows: structure; architecture; and mechanical, electrical, and plumbing (MEP). Since drawings represent how structural, architectural, and MEP elements should be laid out, the work types here are equivalent to the drawing types. When the design errors were grouped by work type, most design errors (54.42%, 449 cases) occurred in structures, 33.82% (279 cases) in architecture, and 11.76% (97 cases) in MEP. After grouping them, the errors across two work types were counted twice, once for each work type.

When focusing on illogical designs among three types of design errors, MEP accounted for 53.83% of illogical designs, structure for 30.38%, and architecture for 15.82%. The most common type of illogical design error was the clash (83.54%). A clash is a situation where two or more building elements occupy the same space, which is not possible in a physical space [4]. Among these clashes, those between MEP were the most common (53.80%). On the other hand, there was almost no discrepancy among MEP drawings or between MEP and other drawings. The discrepancies between structural and architectural drawings explain 96.65% of the total number of discrepancies between drawings. Among missing items, three items, i.e., missing schedules (34.72%), missing identifier numbers (25.39%), and missing details (26.42%) accounted for 86.53% of missing items. Of missing items, 77.72% were found in structural drawings.

Table 3 shows design errors by the likelihood of identifying errors, the impact on schedules, and the impact on quality. Of the design errors categorized, 52.61% had 75% or above likelihood of being identified, 32.02% had 50% likelihood, and 15.37% had less than 25% likelihood. Regarding the potential impact of errors on schedules, 70.10% of errors were categorized as having a mild or serious impact, 20.17% as having practically no impact, and 9.73% as having a severe impact. The distribution of the potential impact of errors on quality showed a similar pattern. Regarding the impact of design errors on project quality, 68.69% were categorized as having a potentially mild or serious impact, 22.14% as having practically no impact, and 9.17% as having a severe impact.

When the errors were grouped by cause and likelihood of identifying errors (Table 4), missing items (88.60%) were very likely to be

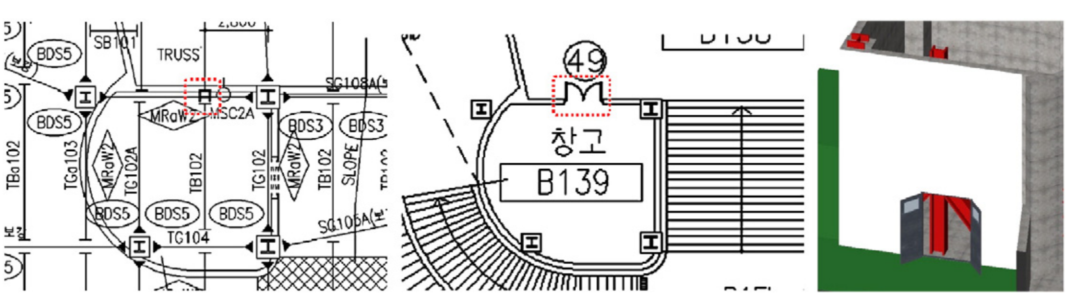

Fig. 2. Example of illogical design: An architectural drawing that shows a column interfering with a door.

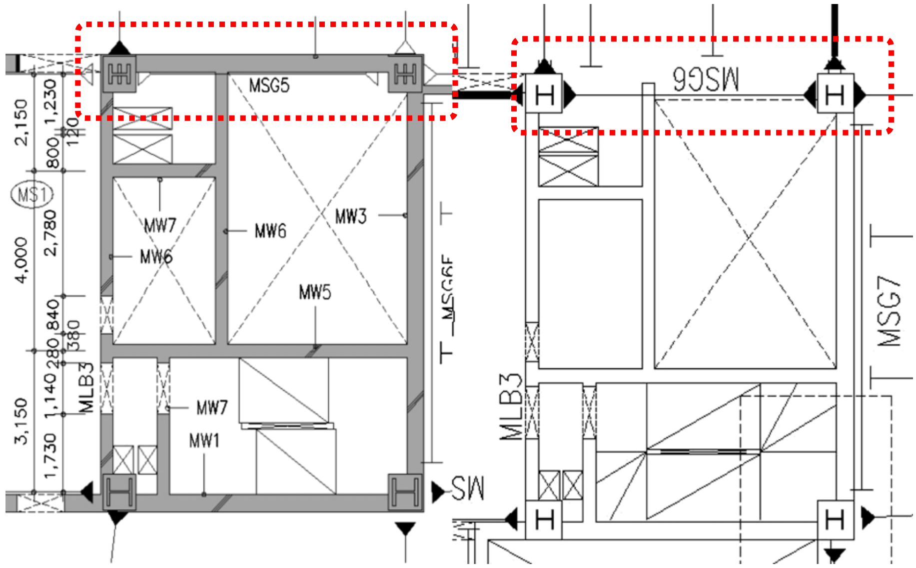

Fig. 3. Example of a discrepancy between drawings: Two drawings of the same location, which do not match.

identified without using BIM, whereas illogical design and discrepancies between drawings were relatively difficult to detect without using BIM. In the case of illogical design, almost 30% (27.85%) of errors were categorized as errors that had less than 25% likelihood of being identified without using BIM.

To analyze the economic impact of each design error, the direct cost potentially caused by each design error was estimated. Table 5 and Table 6 show detailed analyses of the impact on direct cost, categorized by each index. The project team estimated that 401 (57%) out of 709 total errors had a potential impact on direct cost (Table 5); 308 errors (43%) had practically no impact on direct cost (Table 6), although they might slightly delay schedules. When the direct cost estimates were analyzed according to the cause of error, the direct cost potentially caused by discrepancies between drawings accounted for most (87.86%) of the direct cost. The direct cost potentially caused by illogical designs was 12.13%, and that by missing items was 0.01%. When the direct cost per error type was analyzed, the direct cost per error due to discrepancies between drawings ranked the highest (USD 10,397 per error).

We often have a perception that an error that is difficult to detect may have a strong impact on the cost. An interesting finding is that, when the direct cost was grouped by the likelihood of identifying errors, the errors that could be easily detected had potentially higher impacts (USD 13,425 per error) on the cost than did the errors with lower chances of being detected (USD 3,481). However, this also means that missing obvious errors can result in huge economic losses. The number of errors with a potentially severe impact on schedules was much smaller than the number of errors with potentially mild or serious impacts on schedules. However, the errors with a potentially severe impact on schedules had a potentially critical impact on direct cost (USD 26,660 per error), even without considering delayed schedules and added indirect costs. On the other hand, the analysis results showed that the errors with no or mild impact on quality could cause a larger loss of direct cost (USD 11,357 to USD 18,639 per error) than errors

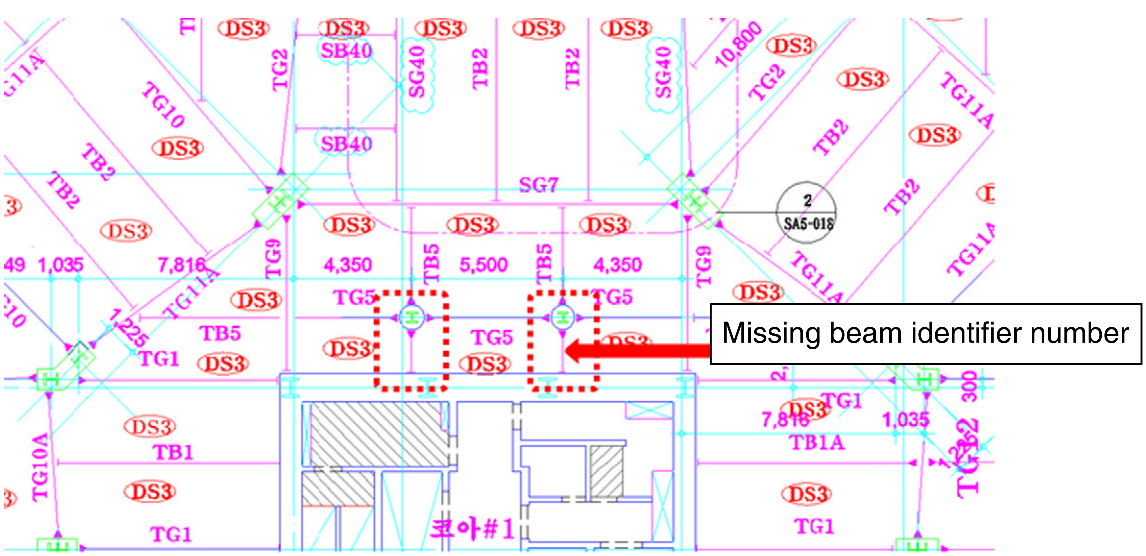

Fig. 4. Example of missing items: Beam identifier numbers are missing.

Table 2
Occurrences of errors by work type and detailed cause.

Cause	Work type	Detailed cause	Number of occurrences	% of total	% of grand total
Illogical Design	Structure	Clashes	28	17.72%	6.77%
		Drafting errors	10	6.33%	
		Unclassifiable items	10	6.33%	
		Subtotal	48	30.38%	
	Architecture	Clashes	19	12.03%	3.53%
		Drafting errors	3	1.90%	
		Unclassifiable items	3	1.90%	
		Subtotal	25	15.82%	
	MEP	Clashes	85	53.80%	11.99%
		Drafting errors	0	0.00%	
		Unclassifiable items	0	0.00%	
		Subtotal	85	53.80%	
	Total		158	100.00%	22.28%
Discrepancies	In structure		140	39.11%	50.49%
	In architecture		99	27.65%	
	In MEP		3	0.84%	
	Between structure and architecture		107	29.89%	
	Between structure and MEP		4	1.12%	
	Between architecture and MEP		5	1.40%	
	Total		358	100.00%	50.49%
Missing Items	Structure	Missing identifier numbers	34	17.62%	21.16%
		Missing lines/symbols for stepped floors	8	4.15%	
		Missing schedules	64	33.16%	
		Missing dimensions	1	0.52%	
		Missing details	34	17.62%	
		Missing finish materials	1	0.52%	
		Unclassifiable items	8	4.15%	
		Subtotal	150	77.72%	
	Architecture	Missing identifier numbers	15	7.77%	6.06%
		Missing lines/symbols for stepped floors	0	0.00%	
		Missing schedules	3	1.55%	
		Missing dimensions	1	0.52%	
		Missing details	17	8.81%	
		Missing finish materials	4	2.07%	
		Unclassifiable items	3	1.55%	
		Subtotal	43	22.28%	
	MEP	Subtotal	0	0.00%	0.00%
	Total		193	100.00%	27.22%
Grand total			709	n/a	100.00%

with serious or severe impacts on quality (USD 5755–6734 per error) when they were not detected before construction.

Table 6 shows a detailed analysis of errors with potentially no impact on direct cost. Of the missing items, 99.48% were categorized as errors that had practically no impact on direct cost, and 60.32% of errors that could be easily detected had no impact on direct cost. Errors that were categorized as having no impact on schedules (94.41%) or quality (98.73%) were also categorized as errors that had practically no impact on direct cost. An ROI analysis based on these direct costs is discussed in the next section.

6. ROI analysis

To analyze ROI, the input (investment) and output (return) variables were defined first. The costs required to develop a building information model were set as input variables. The input variables

Table 3
Design errors categorized by likelihood of identifying errors, impact on schedules, and impact on quality.

Index	Classification	Number of errors	Percentage
Likelihood of identifying errors	1: 25% or below confidence	109	15.37%
	2: 50% confidence	227	32.02%
	3: 75% or above confidence	373	52.61%
	Total	709	100.00%
Impact on schedules	0: Practically no impact	143	20.17%
	1: Mild impact	281	39.63%
	2: Serious impact	216	30.47%
	3: Severe impact	69	9.73%
	Total	709	100.00%
Impact on quality	0: Practically no impact	157	22.14%
	1: Mild impact	245	34.56%
	2: Serious impact	242	34.13%
	3: Severe impact	65	9.17%
	Total	709	100.00%

Table 4
Errors categorized by cause and by likelihood of identifying the errors.

Cause	Likelihood of identifying the errors	Number of errors	% of total
Illogical design	1	44	27.85%
	2	52	32.91%
	3	62	39.24%
	Total	158	100.00%
Discrepancy	1	55	15.36%
	2	163	45.53%
	3	140	39.11%
	Total	358	100.00%
Missing items	1	10	5.18%
	2	12	6.22%
	3	171	88.60%
	Total	193	100.00%
	Grand total	709	n/a

included costs related to purchasing hardware and software, and hiring BIM modelers and coordinators. When Daesung contracted with a professional BIM team, the initial outsourcing fee (i) of USD 577,089 included all software and hardware costs. It also included the costs of training the project team, the 4D simulation, and the eleven BIM modelers for the six high- and medium-rise buildings (five modelers for architectural and structural modeling, four for HVAC, and two for electricity). In addition, two BIM coordinators were hired and paid about USD 8,613 per person per month (l) for 18 months (m). Since this project outsourced BIM to a professional BIM team, productivity loss or gain during or after training was not considered in the ROI calculation.

For the output variables, the direct costs (d) that could be potentially saved by avoiding problems caused by design errors were considered in the ROI calculation. Since some errors can be found without using BIM before or during construction, the direct cost was multiplied by the likelihood of not being able to identify the errors without using BIM (w), to reflect the chances of identifying the errors when the traditional, non-BIM, drawing-based approach was used. The likelihood of not being able to identify an error without using BIM (w) was calculated with one minus the likelihood of identifying the error.

Added indirect costs and home office costs due to the increased direct costs were included in the output variable by multiplying the ratio of the indirect and home office costs to the direct costs of the project by the increased direct costs. Cost estimators in South Korea generally set the indirect costs to 10% to 15% of the total contract costs and the home office costs to 2% to 6% of the total contract costs in rough cost estimation. The percentages vary depending on the size, type, location, and other local conditions of projects, and on the number of projects that a company is operating when performing the calculation. The converted ratio of indirect costs relative to direct costs (idc) is 12% to 22%, and the ratio of the home office costs relative to direct costs (hoc) is 3% to 9%. In the BIM ROI calculation of a specific project, it would be ideal to use the ratios of indirect and home office costs in the contract costs of the target project if the data were accessible.

Additional costs might be saved by avoiding schedule delays, legal disputes, and quality degradation. Those potential savings were not directly included in the ROI equation because it was practically impossible to define how much one or a combination of errors would affect the schedule delay, legal disputes, and quality degradation. For example, if an error does not affect activities on a critical path, it may have little impact on the schedule. One huge error may not cause a schedule delay, but a combination of small errors may cause a schedule delay. For these reasons, the benefits from the additional direct and indirect costs were discussed as additional potential savings separately from the ROI based on the prevented rework costs. This BIM ROI calculation based on prevented rework costs can be formulized as follows:

$$ROI_r = \frac{output - input}{input} = \frac{\left(\sum_{p=0}^{n}\left(d_p \times c_p\right)\right)*(1 + idc + hoc) - \left(i + \sum_{q=1}^{k}\left(l_q * m_q\right)\right)}{i + \sum_{q=1}^{k}\left(l_q * m_q\right)}$$

where the input variables are:

ROI_r	BIM ROI based on prevented rework costs
i	initial outsourcing fee that includes software and hardware costs, training, and architectural-BIM-to-construction-BIM conversion fee,
l	monthly salary of a BIM coordinator (each BIM coordinator may have a different monthly salary),
q	BIM coordinator serial number,
k	total number of BIM coordinators, and
m	total work months of a BIM coordinator;

and where the output variables are:

d	estimate of the direct costs potentially caused by an error,
c	likelihood of not being able to identify the error in the traditional drawing-based approach,

Table 5
Detailed analysis of impact on direct cost by index.

Index	Classification	Number of errors	Estimated direct cost (in USD[a])	% of total cost	Direct cost per error (in USD[a])
Cause	Illogical design	107	420,582	12.13%	3931
	Discrepancy	293	3,046,223	87.86%	10,397
	Missing item	1	215	0.01%	215
Total		401	3,467,020	100.00%	14,542
Likelihood of identifying errors	1	80	278,482	8.03%	3481
	2	173	1,201,600	34.66%	6946
	3	148	1,986,939	57.31%	13,425
Total		401	3,467,020	100.00%	23,852
Impact on schedules	0	8	31,060	0.90%	3883
	1	180	951,180	27.44%	5284
	2	156	965,173	27.84%	6187
	3	57	1,519,607	43.83%	26,660
Total		401	3,467,020	100.00%	42,014
Impact on quality	0	2	37,278	1.08%	18,639
	1	170	1,930,675	55.69%	11,357
	2	185	1,245,835	35.93%	6734
	3	44	253,233	7.30%	5755
Total		401	3,467,020	100.00%	42,485

[a] USD 1 = KRW 1163.

Table 6
Detailed analysis of errors without impact on the direct cost.

Index	Classification	Total number of errors (A)	Number of errors with no impact on direct cost (B)	B/A	B/Σ(B)
Cause	Illogical design	158	51	32.28%	16.56%
	Discrepancy	358	65	18.16%	21.10%
	Missing item	193	192	99.48%	62.34%
Total		709	308	43.44%	100.00%
Likelihood of identifying errors	1	109	29	26.61%	9.42%
	2	227	54	23.79%	17.53%
	3	373	225	60.32%	73.05%
Total		709	308	43.44%	100.00%
Impact on schedules	0	143	135	94.41%	43.83%
	1	281	101	35.94%	32.79%
	2	216	60	27.78%	19.48%
	3	69	12	17.39%	3.90%
Total		709	308	43.44%	100.00%
Impact on quality	0	157	155	98.73%	50.32%
	1	245	75	30.61%	24.35%
	2	242	57	23.55%	18.51%
	3	65	21	32.31%	6.82%
Total		709	308	43.44%	100.00%

p error number,
n total number of design errors
idc ratio of indirect costs relative to direct costs in the contract costs, and
hoc ratio of home office costs relative to direct costs in the contract costs.

The input value (investment) is the sum of the initial outsourcing fee and the cost of hiring two BIM coordinators for 18 months, which is USD 887,166 (USD 577,089 + USD 310,077). In the calculation of the output values, the ratio of indirect costs (*idc*) relative to direct costs of the D^3 City project was 11.4%. Because the D^3 City project was Daesung's own project, home office costs (*hoc*) were not included in the cost breakdown.

The potentially increased direct costs (d) were calculated in three ways for comparison: 1) without considering the identification chance of each error, 2) using the static value for the identification chance of each error, and 3) using a probabilistic approach. When the identification chance was not considered, the total sum of the direct cost of each error was USD 3,467,020, and the indirect cost was USD 395,240. The overall ROI was 335% as shown in Table 5. This approach is based on the assumption that none of the design errors that were detected in the BIM-assisted design validation process would be found in the traditional drawing-based process.

However, since this assumption is unrealistic, the chances of identifying errors in the traditional drawing-based process were multiplied as a fixed number in the second "static value approach." If an error was classified as an error that was likely to be identified with an above 75% chance in the traditional drawing-based process, the error was multiplied by 0.25 (= 1–0.75) as the weighting value to reflect only 25% of the direct cost of an error in the calculation of the return. For the same reason, those with a 50% chance of identification were multiplied by 0.5. Those with a chance of identification of less than 25% were multiplied by 0.75. The total sum of direct costs in the second approach was USD 1,306,396, and the indirect cost was USD 148,929. The overall ROI was 64%.

In the last probabilistic approach, the identification probability was randomly generated in three ranges of values assuming that the probability of identifying errors was the normal distribution. The mean values of the distributions were respectively set to 25%, 50%, and 75%, and the standard deviation of each distribution was set to 8%. The Monte Carlo simulation was used to calculate the ROI. The Monte Carlo simulation was run 5000 times in Crystal Ball. The average total sum of the direct and indirect costs of each error was USD 1,449,934 (63% ROI); this value is similar to that from the second static value approach. The minimum total sum was USD 1,080,694 (22% ROI), and the maximum total sum was USD 1,746,893 (97% ROI) at the 95% confidence interval.

When all these approaches were considered, the BIM ROI was expected to be 22%–335%, including the results from the first approach, by which none of the design errors would be detected before construction in a traditional drawing-based approach. This sounds unrealistic. However, there is a suspicion that some of the projects with high BIM ROI might have measured ROI by taking the first approach, i.e., by assuming that all the design errors would result in rework cost. When such extreme cases are excluded and the ROI is calculated to consider the chances of identifying errors, the ROI is expected to be between 22% and 97%. This is the minimum cost that does not consider potential schedule delays, legal disputes, and quality degradation. Table 7 summarizes the analysis results. The next section illustrates how much additional cost can be saved by preventing schedule delays.

7. Additional potential savings due to schedule delays

Examples of additional potential savings that can be expected by avoiding potential errors using BIM include preventing schedule delays, unnecessary claims and lawsuits, and potential quality degradation. It is difficult to predict how long schedules might be delayed by a certain error or a combination of errors. In addition, construction delay fees vary according to the type of buildings and contractual conditions. Nevertheless, the magnitude of these savings can be easily demonstrated through an example. In the D^3 City project case, if the schedule is delayed by a month, the loss when considering only the job overhead cost, bank interest, and loss by not being able to run a hotel, offices,

Table 7
Results of the BIM ROI analysis.

Output calculation method	Input (in USD)	Output (in USD)			ROI
		Direct costs	Indirect costs (11.4%)	Home office costs (0%)	
Without considering the identification likelihood	887,166	3,467,020	395,240	0	335%
When static values for identification likelihood were applied	887,166	1,306,396	148,929	0	64%
When a probabilistic approach was taken	887,166	970,102 to 1,568,127	130,449 to 166,513	0	22% to 97%

Table 8
Potential additional savings per week and month.

Item	Cost/week (in USD)	Number of weeks	Cost/month (in USD)
Job overhead cost (indirect and home office costs) (joc_w)	150,732	4	602,928
Bank interest (5%) (bin_w)	628,050.5	4	2,512,202
Liquidated damages for delayed delivery (loss by not being able to run a hotel, offices, a shopping mall, and theaters) (liq_w)	556,273.3	4	2,225,093
Total	1,335,056	4	5,340,223

shopping malls, or theaters already exceeds USD 5,300,000, as shown in Table 8.

If we include the additional savings by preventing potential schedule delays in the ROI calculation, the equation is as follows:

$$ROI_s = \frac{output - input}{input} = \frac{\left(\left(\sum_{p=0}^{n}\left(d_p \times c_p\right)\right)*(1 + idc + hoc) + \sum_{j=0}^{w}(joc_w + bin_w + liq_w)\right) - \left(i + \sum_{q=1}^{k}\left(l_q * m_q\right)\right)}{i + \sum_{q=1}^{k}\left(l_q * m_q\right)}$$

where the additional variables are:

- ROI_s BIM ROI based on a potential schedule delay
- joc_w weekly increase in the job overhead costs including indirect costs and home office costs
- bin_w weekly paid additional bank interest
- liq_w weekly paid liquidated damages for delayed delivery
- j week number, and
- w delayed number of weeks.

Table 9 shows the ROI analysis results when a one-week schedule delay and a month delay are assumed. If we can prevent a one-week schedule delay caused by rework and other problems attributed to design errors, the overall ROI is 172% to 247%. If a month schedule delay is prevented, the overall ROI is 624% to 699%. This shows that the BIM ROI grows enormously as the potential impact of design errors on the schedule increases.

8. Conclusions

Currently about 20% of companies are reported to keep track of the BIM ROIs of more than 25% of their projects in the U.S. [20]. Quite a few studies on BIM ROI have reported the BIM ROIs of various projects [1,3,5,8,9,13,14,16]. However, details about BIM ROI analysis methods and data are rarely found, especially those about construction projects. This lack of details weakens the reliability of the reported BIM ROIs.

This study proposes a structured method for analyzing the BIM ROI based on the avoidance costs of rework due to design errors. The proposed method was applied to the D^3 City project, a large urban rehabilitation project composed of six high- and medium-rise buildings. This study has provided an analysis of 709 design errors captured during the design validation process of the D^3 City project. The errors were categorized by cause, work type, likelihood of identifying the errors without using BIM, impact on schedules, impact on quality, and impact on direct cost.

The causes of design errors were illogical designs, discrepancies between drawings, and missing items. Discrepancies between drawings accounted for 50.49% of design errors. Clashes were the most common type (83.54%) of illogical designs. Among clashes, MEP clashes were the most common (53.80%). Of missing items, 99.48% were found to have no impact on direct cost. Counter to our general expectations, the errors that could be easily detected had a potentially higher impact on the direct cost than did those that could not be easily detected when BIM was not used. This means that if obvious errors are missed, the potential impact on the direct cost is very high. As we expected, the errors with a potentially severe impact on schedules also had a critical impact on direct cost (USD 26,660 per error), even without considering the increased costs due to schedule delays. However, the analysis results show that errors with no or mild impact on quality could cause a huge impact on direct cost.

Design errors, which were identified during the design validation process using BIM, might or might not have been detected if the traditional drawing-based approach had been taken. Considering the likelihood of identifying errors even when the traditional drawing-based approach was taken, the ROI was analyzed in three ways: 1) without considering the chance of identifying design errors in the traditional drawing-based method, 2) applying the identification chance of each error as the static numbers (25%, 50%, and 75%) in calculating ROI, and 3) taking a probabilistic approach in predicting the likelihood of identifying errors. These three approaches differ by a magnitude of approximately 15 (e.g., 335% vs. 22%). This stresses the importance of providing details on the data collection and calculation methods used, in order to make the ROI results more reliable. When the ROI was calculated by considering the identification chance of each error, the ROI was between 22% and 97% (63% on average), a conservative calculation that considered only the rework costs due to design errors.

By excluding these design errors in advance, other benefits, such as preventing schedule delays, unnecessary claims and lawsuits, and potential quality degradation, were also expected. It is not easy to come up with a reasonable number that can show the magnitude of these additional potential savings because those problems are attributed to various complex reasons, not only to design errors, and because it is practically impossible to predict how large the impact of one or a combination of errors on these factors will be. However, if we assume that the schedule was delayed by a week to fix design errors, the expected ROI was 172% to 247%. When a month was assumed to be delayed, the expected ROI was 624% to 699%. This shows that costs associated with schedule delays has a much larger economic impact than rework costs.

Table 9
Potential savings from design error avoidance.

Output calculation method	Input (in USD)	Output (in USD)			ROI	
		Prevented rework costs	Delay		Week delay	Month delay
			One week	One month		
Without considering the identification likelihood	887,166	3,862,260	1,335,056	5,340,223	486%	937%
When static values for identification likelihood were applied	887,166	1,455,325	1,335,056	5,340,223	215%	666%
When a probabilistic approach was taken	887,166	1,080,694 to 1,746,893	1,335,056	5,340,223	172% to 247%	624% to 699%

A limitation of this study is that it was based on the prevented errors, which have not occurred, of a small number of cases (six high- and medium-rise buildings). However, we expect that this study can be used as an example of generating accurate and reliable BIM ROI data, which will be essential in continuing the momentum toward reforming the architecture, engineering, and construction industries through the adoption of BIM. In parallel, it will be important to study methods for quantitatively and reliably measuring other benefits of BIM, such as benefits from the IPD (Integrated Project Delivery) method, integration of BIM with FM systems, Green BIM [10], and others.

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