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Application of Hybrid SWARA–BIM in Reducing Reworks of Building Construction Projects from the Perspective of Time

Hamidreza Khalesi [1], Amirhossein Balali [1], Alireza Valipour [1,*], Jurgita Antucheviciene [2], Darius Migilinskas [2] and Viaceslav Zigmund [2]

[1] Department of Civil Engineering, Shiraz Branch, Islamic Azad University, Shiraz 5-71993, Iran; khalesi.hr@gmail.com (H.K.); a.shz.balali@gmail.com (A.B.)

[2] Department of Construction Management and Real Estate, Vilnius Gediminas Technical University, 10221 Vilnius, Lithuania; jurgita.antucheviciene@vgtu.lt (J.A.); darius.migilinskas@vgtu.lt (D.M.); viaceslav.zigmund@vgtu.lt (V.Z.)

* Correspondence: vali@iaushiraz.ac.ir; Tel.: +98-9177914214

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Abstract: One of the major issues of the construction industry has been the "reworks" that affect the time, quality, and cost of projects. Therefore, reworks and the ineffective use of site resources and materials will always result in significant losses on projects. The development of information technology has led to the widespread use of Building Information Modelling (BIM) to enhance the delivery of more sustainable building construction projects. The purpose of this study is to combine the Step-wise Weight Assessment Ratio Analysis (SWARA) method and BIM technologies to identify and reduce time delays caused by reworks in construction projects. Firstly, 49 rework causes in residential buildings were identified and ranked. Then, BIM was generated and compared to the initial model. It was observed that working hours were reduced by 4.6%. Moreover, using an Earned Value Management (EVM) system, a 0.06 increase in Schedule Performance Index (SPI) factor was illustrated. Results obtained by this study provide an effective step in reducing a project's time in the construction industry.

Keywords: rework causes; BIM; SWARA method; time; project success

1. Introduction

Rework is regarded as a serious issue for construction industry projects [1]. Cost, schedule, performance, and productivity of construction projects are influenced by reworks [2]. Cost and schedule overruns often occur due to rework in construction projects [2,3]. According to previous studies, rework costs range from 5% to 20% in major civil engineering projects [4,5]. To manage rework, its roots and causes must be identified first [1,6]. Many studies have been conducted to identify such causes [1,6–10]. It is essential to reduce rework due to severe potential consequences. Thus, managers are highly recommended to identify factors which result in rework in the planning phase of projects [1].

There have been various definitions of rework given by different researchers. According to Josephson et al. (2002), rework is defined as dispensable output resulting due to mistakes during the construction project [7]. Love (2002) defines rework as an event or process which is caused due to quality accidents, unqualified quality problems, deviations, or faults [11]. Ye et al. (2015) define rework as redoing a process which has already been done, to satisfy the functional requirements of the project [2]. Forcada et al. (2017) mention that any additional work that has resulted from order changes, design errors and scope changes must also be regarded as rework [12]. Many researchers have attempted to identify factors of rework. It is crucial to analyze all factors and to use appropriate decision-making tools for clients and construction project managers. Research has shown strong attention to these complex management issues to improve the productivity of projects in the construction industry. Most of the researchers are focused on the identification of risk processes and factors to support managers and decision-makers in identifying problems for efficient risk management [13].

According to Hwang et al. (2019), these factors in the construction projects can generally be put into six groups including "Contractor", "Subcontractor", "Supplier", "Manufacturer", "Designer" and "Client" [1]. Fayek et al. (2003) developed a fishbone diagram to illustrate the actual and potential causes of rework. They concluded that "Poor workmanship of prefabricated material", "Lack of inspection", and "Consistency not insured before issued for construction" are the major reasons for rework [6]. Rework can affect a projects' performance [1], thus, it seems necessary to identify and prevent them.

There have been various definitions for Building Information Modelling (BIM). For instance, Penttilä (2006) defines BIM as

> "A set of interrelating policies, processes and technologies that generate a systematic approach to managing the critical information for building design and project data in digital format throughout the life cycle of a building" [14].

The U.S. National BIM Standard also defines BIM as

> "A shared knowledge resource for information about a facility forming a reliable basis for decisions during its life-cycle; defined as existing from earliest conception to demolition" [15].

Most importantly in the use of BIM technologies for construction projects is to have reliable information at any construction project implementation stage and to make correct decisions [16].

There are different dimensions in BIM which are used in construction projects according to the complexity and requirements of such projects. The dimensions in BIM are known as 3D, 4D, 5D, 6D and 7D [17]. The third dimension of BIM (3D) represents the three geographical dimensions of a structure, commonly known as x, y, and z, which stand for length, width, and height of a structure, respectively [13,17–19]. The fourth dimension of BIM (4D) adds time and scheduling to the 3D BIM by simulating the construction process, which enables the project to be visualized at any point in time [19]. The fifth dimension of BIM (5D) integrates the 4D BIM and the project costs. This way, changes of the economic situation of a project can be observed at any phase of the construction project, which is a valuable feature, especially for an estimation of the initial budget forecast [20] and for the management of actual expenses. The sixth dimension of BIM (6D) considers sustainability, and more specifically energy, by estimating energy consumption in all phases of the project. The last dimension (7D) adds a facility management feature for a structure including its status, technical specifications, warranty information, and maintenance/operation manuals for owners and managers [17].

Using BIM technologies in construction has numerous positive effects [21]. For example, probable construction clashes can be identified and prevented using the model [22]. According to other studies, the overall performance of a project and project information management can be improved dramatically by using BIM besides other strategic innovations [23,24]. Non-value adding activities and their resulting wastes can be investigated in BIM-based project delivery [25]. The impact of various factors on delays can also be analyzed using BIM [26]. It is necessary to emphasize, that the use of BIM technologies is not limited with the construction of new buildings but can also be used in the reconstruction of heritage buildings. There are different ways of using BIM, and this effective support is not limited to the 3D modelling, but also uses photogrammetry, 3D scanning and other tools for existing buildings [27].

Lu et al. (2018) illustrated that construction errors on site can be decreased by sharing design information with site workers [28]. Decreasing the causes of rework, including design errors and defects, has been an aim for many researchers. For instance, Kwon et al. (2014) explored a defective management system by integrating BIM, image-machining and augmented reality to automatically identify and omit defects [29]. Moreover, according to different research, defect data were proposed to be shared using a BIM-integrated network [30]. Bryde et al. (2013) investigated the advantages and disadvantages of BIM use in projects and concluded that the advantages of using BIM are much greater in comparison to its drawbacks, challenges, and limitations [16,31]. However, the direct use of BIM technologies in reducing rework needs more investigation.

This paper aimed to reduce rework in the construction projects from the perspective of time using Building Information Modelling (BIM). As mentioned in the previous paragraphs, most of the research focuses on investigating the effect of BIM technologies on reducing rework. Thus, the consequences of using BIM technologies in a projects' schedule is considered as a gap in the body of knowledge. The novelty of this paper is that time effects of reworks are specifically investigated by using BIM technologies. A Step-wise Weight Assessment Ratio Analysis (SWARA) method was employed to weigh and rank the identified rework factors. Autodesk Revit software and Autodesk Navisworks software were used as the BIM tools in order to evaluate the benefits of using BIM in comparison to the traditional method, using the most important identified rework causes that are able to be simulated in BIM. Status-Curves (S-Curves) and an Earned Value Management (EVM) system were also used to calculate factors which illustrated the improvement of using BIM technologies. The findings of this study will illustrate the benefits of combining one of the decision-making tools, the SWARA method, with BIM technologies in order to identify and decrease reworks, and consequently their effects on the construction industry projects, and to ultimately enhance projects' sustainability.

2. Research Methodology

At first, rework causes in building construction projects were identified using literature including books, papers, documents, and online databases, as well as asking expert's opinions and also conducting field investigations. In this process, factors which had the most effect on increasing the projects' time (fourth dimension) were identified and ranked by the SWARA method. These causes were then illustrated on a fishbone diagram.

In the second stage, a building was selected as a case study and analyzed in terms of construction time using two different scenarios. The first scenario analyzed the construction process using the traditional system. On the other hand, the second scenario analyzed the abovementioned process according to BIM, in which clashes and therefore reworks could be diagnosed and managed at the beginning of the project.

In the next stage, the effects of utilizing BIM technologies on reducing reworks were investigated by comparing the two abovementioned scenarios in the previous stage. To do so, construction times of both scenarios were analyzed using S-Curves in Microsoft Project Software, and the effects of using BIM on reducing delays in the construction time were investigated.

Finally, the last stage focused on analyzing the benefits of using BIM technologies on reducing delays in the construction project by using the EVM system. These stages are demonstrated in Figure 1.

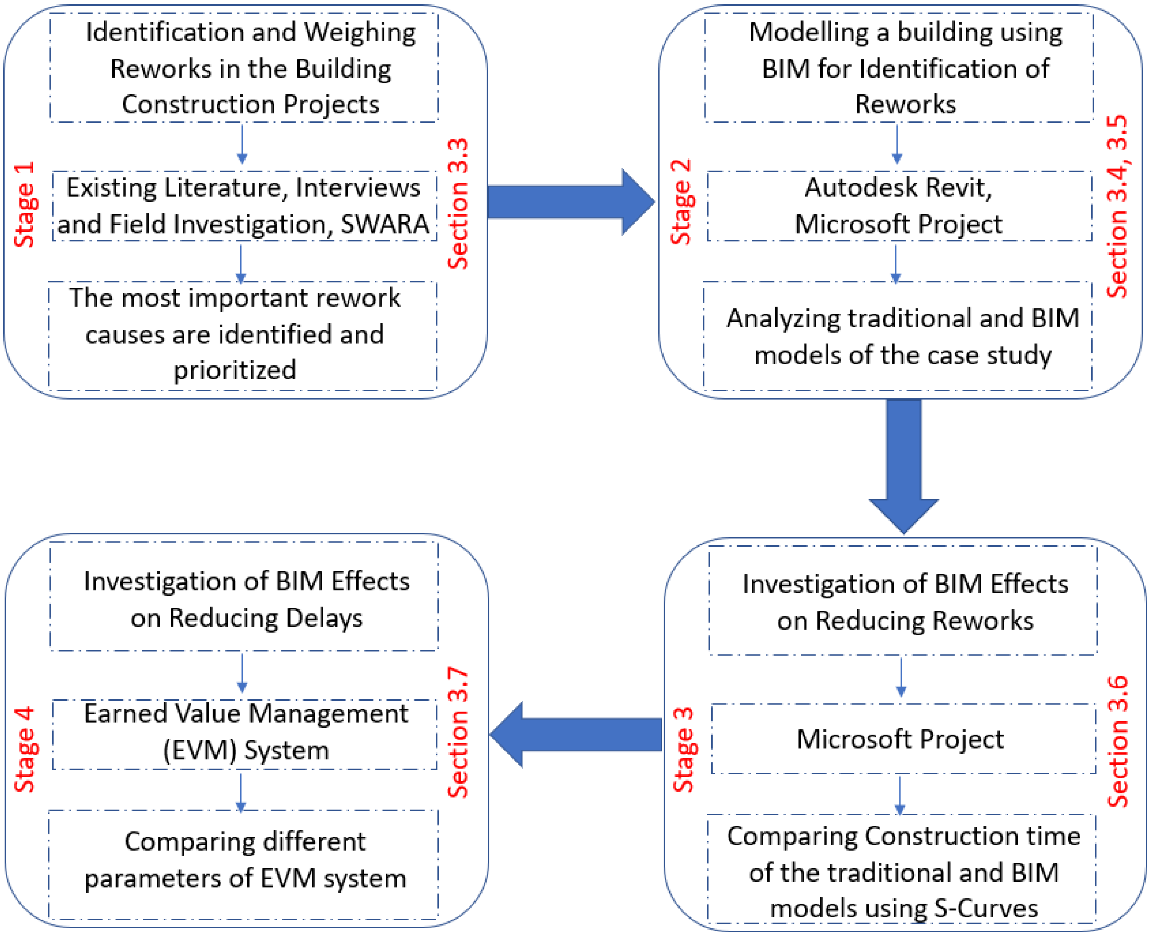

Figure 1. Research methodology.

2.1. Questionnaire

In the current study, a questionnaire was designed to weigh and rank rework causes. Designing the abovementioned questionnaire was conducted carefully, and experts played a significant role in making the final version. The final questionnaire included three sections. In the first section, there were some questions regarding general information such as occupational experience. In the second section, respondents were asked to weigh rework causes by considering the identified selection criteria. To attain this goal, a 5-point Likert scale was used in which 1 was the least importance, while 5 was defined as the most importance. Lastly, in the third part of the questionnaire, respondents were asked to mention any other rework causes or points about the topic. The information gained by this questionnaire was then analyzed by the SWARA method.

Cronbach's alpha is a coefficient calculated to check internal consistency. Therefore, it was a suitable coefficient to illustrate the reliability of the questionnaires. Cronbach's alpha values range from 0 to 1, where 0 means that all items are independent, while 1 means that items are perfectly correlated [32]. In this range, in terms of reliability, values above 0.9, 0.8, 0.7, 0.6, 0.5 are considered excellent, good, acceptable, questionable, and poor, respectively. Therefore, values below 0.5 are regarded as unacceptable [33,34]. There are two ways to calculate Cronbach's alpha. It can be calculated manually, according to the formula below [32]:

$$\alpha = \frac{j}{j-1}\left(1 - \frac{S_j^2}{S^2}\right) \tag{1}$$

where the number of items, variance of the j^{th} criteria and variance of the total score are shown by j, S_j^2 and S^2, respectively. The second way to calculate Cronbach's alpha is by using software programs such as SPSS. Due to the complexity and difficulty of manual calculations, this way is usually preferred. In this study, Cronbach's alpha was computed using SPSS software.

2.2. SWARA (Step-Wise Weight Assessment Ratio Analysis) Method

Various Multi-Criteria Decision Making (MCDM) methods can be used in different cases, for example, they can be used for efficient application based on sustainability assessment tool efficiency, cost analysis and renewable energy evaluation [35,36]. Keršuliene et al. introduced the SWARA method in 2010 [37], and, in comparison to the other MCDM methods, SWARA is easier to employ in decision-making problems due to its understandable concept and analysis procedure [38].

The SWARA method is usually used for weighing decision criteria, which are the basis of assessing and prioritizing various alternatives [36]. To do so, knowledge, experience and opinions of experts are considered [39]. SWARA has been used in different topics by numerous researchers. For instance, the SWARA method was selected in an Iranian study to assess selection criteria for choosing the best passive energy reduction measures in Iran [40]. Balki et al. (2020) determined optimal operating parameters in Turkey and criteria were weighed using the SWARA method [38]. Rani et al. (2020) provided Solar Panel Selection [41], while Jafarzadeh Ghoushchi et al. (2020) ranked failures in Solar Panel Systems using the abovementioned method [42]. Akcan et al. (2019) aimed to reduce ecological risk factors by evaluating green suppliers and employed the SWARA method as a part of this evaluation [43]. Zarbakhshnia et al. (2018) evaluated and selected sustainable reverse logistic providers and used the abovementioned method in their analysis [44]. Chalekaee et al. (2019) applied SWARA when analyzing construction delay change response problems [45]. Morkunaite et al. (2019) evaluated the significance of criteria in contractor selections for the refurbishment of heritage buildings [46]. There is a lot more research which has utilized the SWARA method [47–58].

In this study, SWARA was used to weigh rework causes using the questionnaire. The procedure of using the SWARA method is illustrated below:

A. Selection criteria are identified and considered.
B. The abovementioned criteria are prioritized using experts' attitudes and then they are sorted from the most important to the least important.
C. Each criterion is compared to the upper criteria and the comparative average value of importance, s_j, is calculated.
D. Comparative importance (k_j) is computed as follows:

$$k_j = \begin{cases} 1 & j = 1 \\ s_j + 1 & j > 1 \end{cases} \tag{2}$$

E. Recalculated weights (q_j) are obtained using the formula below:

$$q_j = \begin{cases} 1 & j = 1 \\ \frac{q_{j-1}}{k_j} & j > 1 \end{cases} \tag{3}$$

F. Final weights (w_j) are calculated as follows:

$$w_j = \frac{q_j}{\sum_{m=1}^{n} q_m} \tag{4}$$

2.3. Case Study

Shiraz is one of the cities in Fars province, Iran, which is located in the southwest of the country. It is surrounded by various mountains and has a temperate climate [59]. A building which is located in Shiraz was considered as a case study for this research. The building is a 4-story steel structure in the western section of Shiraz, with an infrastructure area of 1100 square meters.

2.4. Formation of the BIM Output

Three kinds of BIM software were used as the key tools of this study. To model the case study building's elements, Autodesk Revit software and Autodesk Navisworks software were used. Autodesk Navisworks software and Microsoft Project software were also applied in the time management section of the research. Details about the usage of BIM software are shown in Table 1.

Table 1. Building Information Modelling (BIM) software used in the process of modelling.

Stage	BIM Software
Initial idea modelling	Autodesk Revit Architecture
Identifying the ability to build the idea	Autodesk Navisworks Manage
Modelling of the structure	Autodesk Revit Structure
Modelling the electrical and mechanical installation	Autodesk Revit MEP (Mechanical, Electrical, and Plumbing)
Identifying architectural and structural clashes	Autodesk Navisworks Manage
Identifying the change of results	Autodesk Revit Architecture and Structure
Identifying the construction schedule	Autodesk Navisworks Manage and Microsoft Project

2.4.1. Modelling the Architectural and Structural Information of the Building

Architectural and installation information of the building was modelled as follows:

- Step 1: Introducing the number of stories, as well as the height of each story according to the architectural plans.
- Step 2: Introducing and modelling the major elements of the building such as walls, roofs, and stairs.
- Step 3: Introducing and modelling the minor elements of the building such as doors and windows.
- Step 4: Adding supplementary details of the building such as stepped ceilings and parapets.
- Step 5: Modelling the building's risers and ducts, where installation components are located.
- Structural information of the building was modelled as follows:
- Step 1: Introducing the number of stories, as well as the height of each story according to the structural plans.
- Step 2: Introducing and modelling the major elements of the building such as the foundation, columns, and beams.
- Step 3: Modelling lateral bracing system.
- Step 4: Introducing and adding roofs and diaphragms.
- Step 5: Adding supplementary details such as roofs and connections.

2.4.2. Integrating and Simulating the Construction Process

In this study, Autodesk Revit was used in different parts. Autodesk provides the ability to integrate between the three versions of Revit, including Revit Architecture, Revit Structure and Revit MEP (mechanical, electrical, and plumbing) [60].

2.5. Data Extraction of the Traditional and BIM Methods

2.5.1. Traditional Method

In this part of the study, the abovementioned building case study was considered. All the construction documents of the buildings were investigated carefully to obtain reworks and gain the total construction time of the project.

2.5.2. BIM Method

As mentioned in the previous section, all the elements of the building were modelled in the BIM tools. Thus, all the clashes and reworks were identified and prevented at the beginning. This way, a massive amount of time and budget was saved.

2.6. Investigating the Ability of BIM Tools in the Identification of Clashes and Reworks

2.6.1. Automatic Identification of Errors Within the Process of Modelling

Using Autodesk Revit software, all the errors including clashes between architectural, structural and installation elements of the building were identified automatically, and a solution was given by the software. This feature gives engineers the ability to observe and prevent a large number of clashes and reworks at the initial level. Figure 2 illustrates one of the clashes that was identified by the software.

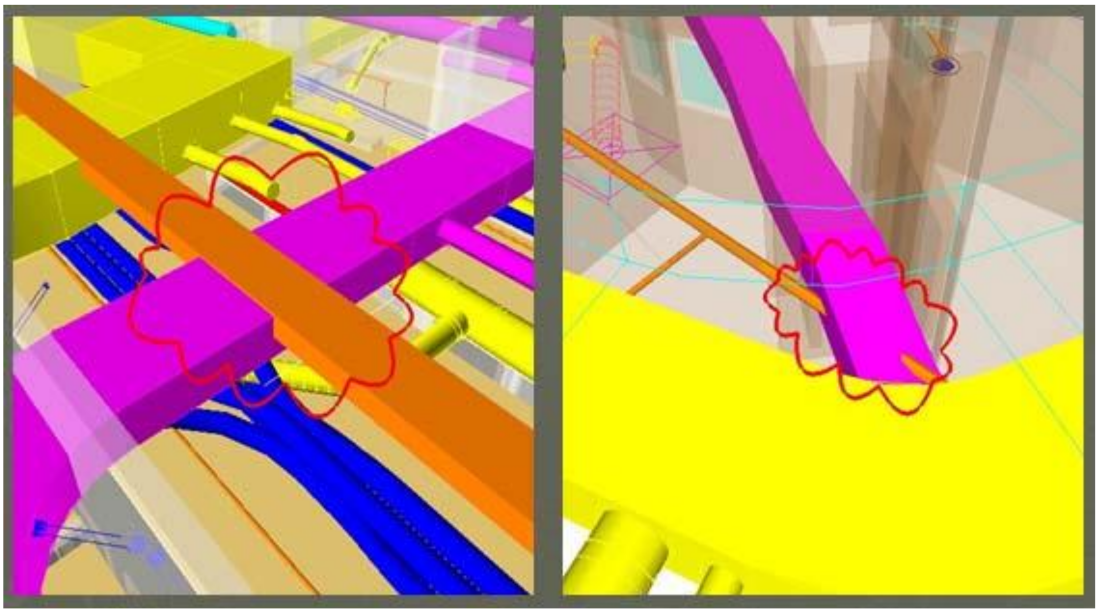

Figure 2. Automatic identification of errors within the modelling process.

2.6.2. Identification of Errors after the Process of Modelling

In this stage, BIM outputs and simulations were integrated, and all the clashes and errors were checked again using Autodesk Navisworks software. Data were imported directly from Autodesk Revit to Autodesk Navisworks. After this step, the probability of any clashes occurring during the construction process becomes almost zero. One of the identified clashes after the process of modelling is shown in Figure 3.

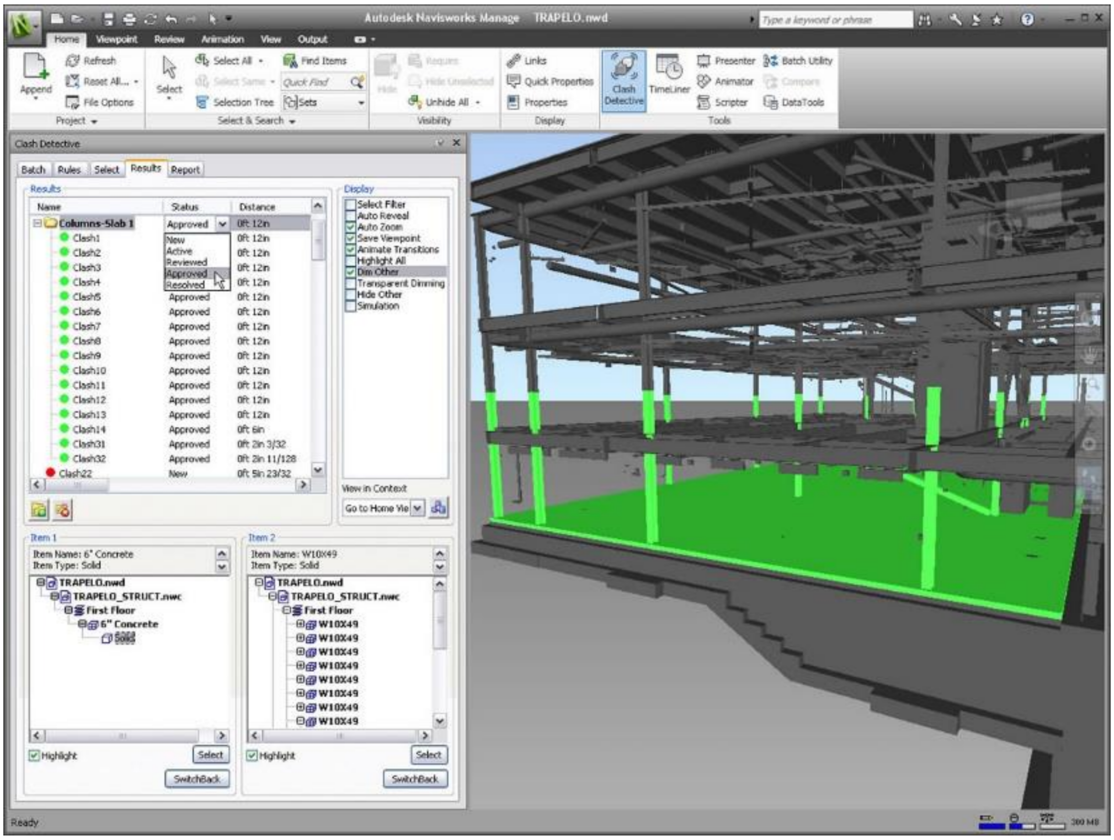

Figure 3. Identification of errors after the modelling process.

2.7. Earned Value Management (EVM)

The Earned Value Management (EVM) method is used to measure time, cost, and scope, for predicting the performance of projects [61,62]. The EVM method can consider the time passed as well as the cost, for calculating the value of work done [63]. In this stage, the aim was to observe the benefits of using BIM technologies in reducing delays in construction of the building. Thus, the procedure of this observation is illustrated as follows:

A. Calculating the Schedule Variance (SV) as follows:

$$SV = EV - PV \tag{5}$$

where EV and PV stand for Earned Value (budgeted cost of work performed) and Actual Cost (actual cost of work performed), respectively.

B. Calculation of Schedule Performance Index (SPI):

$$SPI = EV/PV \tag{6}$$

3. Results and Discussion

3.1. Analyzing the Sample Size

135 experts who have been involved in various sectors of the construction industry, including both private and governmental sectors, were the selected sample size of this study. In order to identify a sufficient number of respondents, Cochran's sample size formula was used. This formula is shown below [64]:

$$n = \frac{Nt^2pq}{Nd^2 + t^2pq} \tag{7}$$

where n, N, t, p, q and d stand for the sample size, population, confidence level value, probability of success, probability of failure and acceptable margin of error, respectively. In order to gain the required number of respondents, N, t, p, q and d were considered to be 135, 1.96, 0.5, 0.5 and 0.05, respectively. Therefore, n was computed as follows:

$$= \frac{135 * 1.96^2 * 0.5 * 0.5}{135 * 0.05^2 + 1.96^2 * 0.5 * 0.5} = 99.89.$$

Therefore, at least 100 respondents were needed to fill the questionnaire out. The abovementioned 135 questionnaires were distributed using the Internet (75 questionnaires) and postal system (60 questionnaires). 115 questionnaires were returned, which meant an 85.1% return rate: that was considered to be acceptable. Among the abovementioned returned questionnaires, six of them were unverified. Therefore, 109 questionnaires were analyzed which was more than required. Information regarding the questionnaires is shown in Table 2. Information about the experts who completed the verified questionnaires is illustrated in Table 3.

Table 2. Questionnaires return rate.

Questionnaire	Number	Percentage
Total distributed	135	100%
Total Returned	115	85.1%
Unreturned	20	14.8%
Unverified returned	6	4.4%
Verified returned	109	80.7%

Table 3. Information about the respondents.

Classification	Classification	Number	Percentage
Working background	Construction Engineer	29	26.6%
	Technical director	43	39.4%
	Project manager	12	11%
	Installation engineer	15	13.8%
	Employer	10	9.2%
Qualification	Bachelor	50	45.9%
	Master	36	33%
	PhD	23	21.1%
Working Experience	Less than 10 years	27	24.8%
	Between 10 and 20 years	32	29.3%
	More than 20 years	50	45.9%

3.2. *Reliability of the Questionnaires*

To assess the reliability of the questionnaires, Cronbach's alpha was calculated. Rework causes were categorized into seven groups according to their properties (Section 3.3). Thus, for each of the questionnaires, Cronbach's alpha value was computed separately. This value was calculated in order to check the reliability of questionnaires, and ranges from 0 to 1, where 0 and 1 stand for complete independency and complete dependency, respectively [32]. These computed values are demonstrated in Table 4.

Table 4. Values of Cronbach's alpha.

Questionnaire	Categorization of Rework Causes	Number of Rework Causes	Cronbach's Alpha
A	Engineering and Reviews	8	0.783
B	Implementation of Project	10	0.803
C	Material and Equipment Supply	6	0.776
D	Human Resource Capability	8	0.803
E	Construction Planning and Scheduling	4	0.735
F	Leadership and Communication	5	0.721
G	Effective External Causes	8	0.758

3.3. Identification and Prioritization of Rework Causes

The first step in this section was identifying rework causes. A comprehensive investigation took place in various literature resources. Then, experts were interviewed to add any other rework causes to the identified ones. Information regarding the experts is shown in Table 5. 42 of the identified causes were extracted from the literature [1,6] and the other factors were introduced by experts. Table 6 illustrates the final categorization of identified rework causes. Figure 4 also shows the abovementioned causes using a fishbone diagram. In the abovementioned figure, rework causes are separated into seven different groups including Engineering and Reviews (A), Implementation of Project (B), Material and Equipment Supply (C), Human Resource Capability (D), Construction Planning and Scheduling (E), Leadership and Communication (F), Effective External Causes (G). Each category also constitutes several subsections, which are illustrated in Figure 4.

Table 5. Information regarding experts.

Category	Classification	Number
Occupation	Academia	8
	Manager	9
	Contractor	8
	Technical expert	12
Sex	Male	20
	Female	17
Experience (years)	<5	7
	5–10	9
	10–15	10
	>15	11

Table 6. Categorization of rework causes.

Categorization of Rework Causes	Rework Causes	Sign
Engineering and Reviews	Design Errors	A1
	Scope Changes	A2
	Late Design Changes	A3
	Poor Document Control	A4
	Design Changes	A5
	Poor Supervision and Control	A6
	Poor Knowledge of Designer	A7
	Lack of Using Modern Design Tools	A8
Implementation of Project	Lack of Using Modern Implementation Systems	B1
	Changes in Work Volume	B2
	Difference among Plans and Operational Specifications	B3
	Incoherence of Structural Implementations	B4
	Unspecified Essential Operations	B5
	Lack of Operational Standards	B6
	Lack of Using Appropriate Appliances	B7
	Lack of Supervision in Controlling Quality	B8
	Poor Experience of Contractors	B9
	Poor Quality of Implementations	B10
Material and Equipment Supply	Non-compliance with Specifications	C1
	Materials not in the Right Place When Needed	C2
	Untimely Deliveries	C3
	Structural Non-compliance	C4
	Poor Quality of Materials	C5
	Lack of Suppliers' Information Regarding the Status of Project	C6
Human Resource Capability	Insufficient Skill Level	D1
	Lack of Knowledge in Occupational Planning	D2
	Unclear Instructions to Workers	D3
	Excessive Overtime	D4
	Lack of Occupational Security	D5
	Inadequate Control of Human Resource	D6
	Lack of Workers' Responsibility	D7
	Inadequate Training of Human Resource	D8
Construction Planning and Scheduling	Unrealistic Schedules	E1
	Insufficient Turnover and Commissioning Resourcing	E2
	Late Designer Input	E3
	Constructability Problems	E4
Leadership and Communication	Ineffective Management of Project Team	F1
	Lack of Operations	F2
	Lack of Safety and QA/QC Commitment	F3
	Poor Communication	F4
	Poor Attendance of Stakeholders	F5
Effective External Causes	Governmental Changes in Law	G1
	Economic Fluctuations	G2
	Social Contradictions	G3
	High Cost of Modern Technologies	G4
	Lack of Stakeholders' Training	G5
	Physical and Infrastructural Circumstances	G6
	Geographical Hazards	G7
	Political Circumstances and Sanctions	G8

After identifying the causes of rework, the next step focused on weighing the abovementioned causes. To do so, experts' opinions were extracted using a questionnaire. In the questionnaire, experts were asked to score the importance of causes from 1 to 5, where 1 and 5 meant the least and most effective, respectively. Mean values of the questionnaires were calculated after the questionnaires were returned. Then, using the SWARA method, rework causes were weighed and ranked in their specific groups. As defined above, rework causes were categorized into seven groups. Tables 7–13 show the results of the SWARA method for each group. The most important rework causes are also demonstrated in Table 14.

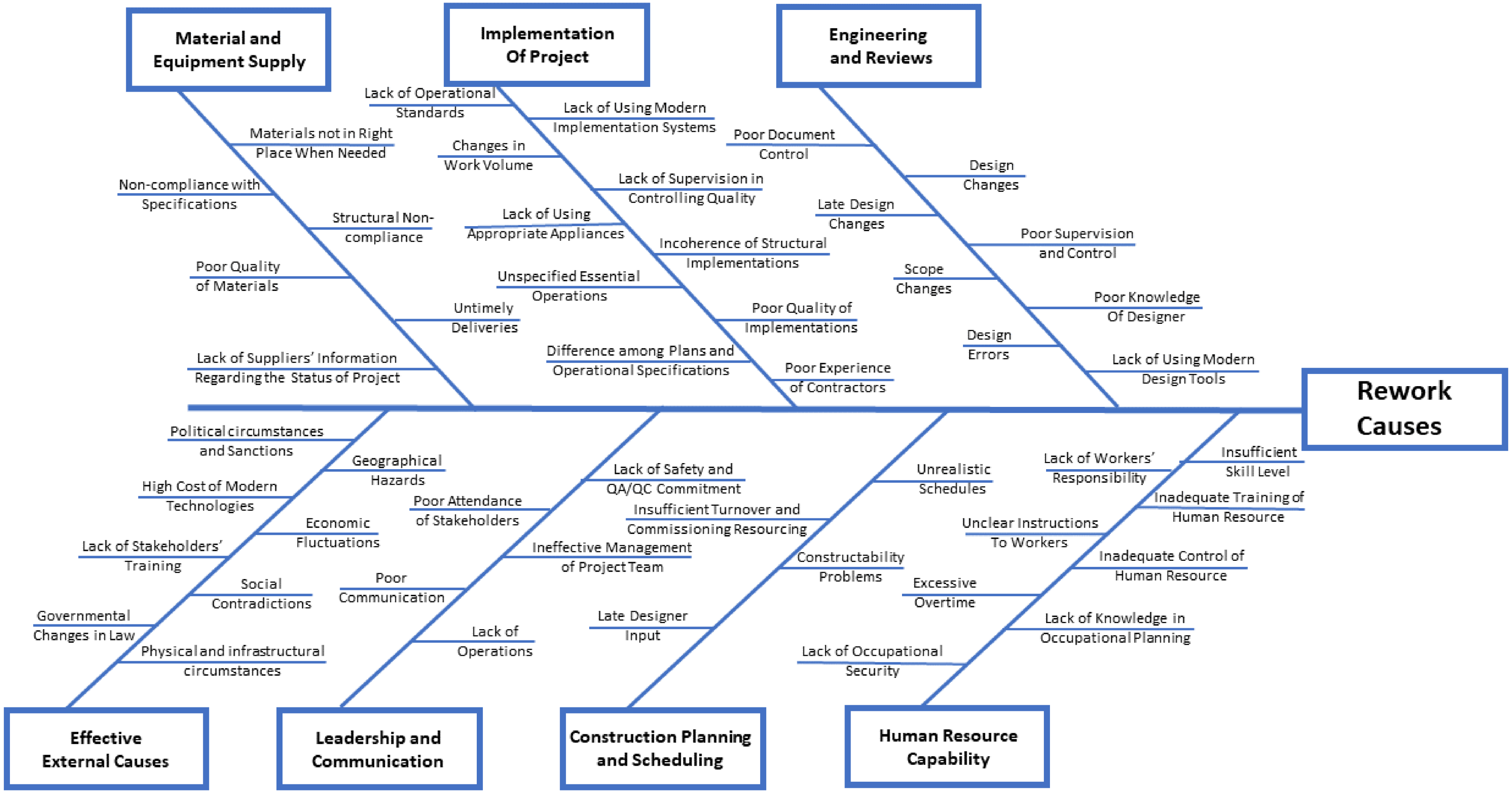

Figure 4. Fishbone diagram of rework causes.

Table 7. Weights of rework causes categorized in the "Engineering and Reviews" group.

Rework Cause	S_j	K_j=s_j+1	q_j	w_j	Rank
A1	—	1	1	0.48925	1
A5	0.902	1.902	0.52576	0.25723	2
A3	0.885	1.885	0.27892	0.13646	3
A8	0.831	1.831	0.15233	0.07453	4
A2	0.752	1.752	0.08695	0.04254	5
A6	0.712	1.712	0.05079	0.02485	6
A7	0.61	1.61	0.03154	0.01543	7
A4	0.585	1.585	0.01990	0.00974	8

Table 8. Weights of rework causes categorized in the "Implementation of Project" group.

Rework Cause	S_j	K_j=s_j+1	q_j	w_j	Rank
B3	—	1	1	0.48250	1
B10	0.896	1.896	0.52743	0.25448	2
B1	0.865	1.865	0.28280	0.13645	3
B5	0.712	1.712	0.16519	0.07970	4
B7	0.701	1.701	0.09711	0.04686	5
B8	0.618	1.618	0.06002	0.02896	6
B2	0.583	1.583	0.03792	0.01829	7
B6	0.524	1.524	0.02488	0.012000	8
B4	0.512	1.512	0.01645	0.00794	9
B9	0.493	1.493	0.01102	0.00532	10

Table 9. Weights of rework causes categorized in the "Material and Equipment Supply" group.

Rework Cause	S_j	K_j=s_j+1	q_j	w_j	Rank
C1	—	1	1	0.48299	1
C5	0.884	1.884	0.53079	0.25636	2
C6	0.842	1.842	0.28816	0.13918	3
C2	0.821	1.821	0.15824	0.07643	4
C4	0.697	1.697	0.09325	0.04504	5
C3	0.658	1.658	0.05624	0.02716	6

Table 10. Weights of rework causes categorized in the "Human Resource Capability" group.

Rework Cause	S_j	K_j=s_j+1	q_j	w_j	Rank
D1	—	1	1	0.48364	1
D3	0.893	1.893	0.52826	0.25549	2
D4	0.823	1.823	0.28978	0.14015	3
D7	0.808	1.808	0.16027	0.07752	4
D5	0.794	1.794	0.08939	0.04321	5
D8	0.769	1.769	0.05050	0.02443	6
D2	0.742	1.742	0.02899	0.01402	7
D6	0.717	1.717	0.01688	0.00817	8

Table 11. Weights of rework causes categorized in the "Construction Planning and Scheduling" group.

Rework Cause	S_j	K_j=s_j+1	q_j	w_j	Rank
E1	—	1	1	0.493960	1
E2	0.946	1.946	0.51387	0.25383	2
E3	0.873	1.873	0.27436	0.13552	3
E4	0.829	1.829	0.15000	0.07410	4

Table 12. Weights of rework causes categorized in the "Leadership and Communication" group.

Rework Cause	S_j	K_j=s_j+1	q_j	w_j	Rank
F4	—	1	1	0.47721	1
F5	0.864	1.864	0.53648	0.25602	2
F1	0.822	1.822	0.29445	0.14051	3
F2	0.754	1.754	0.16787	0.08011	4
F3	0.736	1.736	0.09670	0.4615	5

Table 13. Weights of rework causes categorized in the "Effective External Causes" group.

Rework Cause	S_j	K_j=s_j+1	q_j	w_j	Rank
G2	—	1	1	046900	1
G8	0.832	1.832	0.54585	0.25600	2
G4	0.768	1.768	0.30874	0.14480	3
G6	0.759	1.759	0.17552	0.08232	4
G1	0.719	1.719	0.10211	0.04789	5
G3	0.624	1.624	0.62870	0.02949	6
G5	0.607	1.607	0.03912	0.01835	7
G7	0.573	1.573	0.02484	0.01167	8

Table 14. The most important rework causes.

Sign	Rework Cause
A1	Design Errors
A5	Design Changes
B3	Difference among Plans and Operational Specifications
B10	Poor Quality of Implementations
C1	Non-compliance with Specifications
C5	Poor Quality of Materials
D1	Insufficient Skill Level
D3	Unclear Instructions to Workers
E1	Unrealistic Schedules
E2	Insufficient Turnover and Commissioning Resourcing
F4	Poor Communication
F5	Poor Attendance of Stakeholders
G2	Economic Fluctuations
G8	Political Circumstances and Sanctions

As it is clearly illustrated, the most three crucial rework causes are Design Errors (A1), Design Changes (A5), and Difference among Plans and Operational Specifications (B3). By considering the identified rework causes, and specially the most important causes, they will be reduced effectively or even prevented. Therefore, it can be very useful for different parties of the building industry. Then, through BIM, these effects were analyzed for the case study building.

3.4. Investigating the Traditional Method of the Case Study Building's Construction

As it was mentioned in the previous part of the paper, the case study of this project was a 4-story steel building located in the western section of Shiraz, Iran. Initial documents of the project's schedule were investigated carefully to find the predicted construction time. Using a Work Breakdown Structure (WBS), the project was divided into 25 levels, and the planned construction time was 348 days. However, after investigating the final documents of project, it was shown that the project had experienced a 176 days delay, and the project was finished after 524 days. Table 15 illustrates the project's WBS, anticipated, and implemented construction time.

Table 15. The case study building's Work Breakdown Structure (WBS), anticipated, and implemented construction time.

No.	WBS Level	Anticipated Time (Days)	Implemented Time (Days)
1	Delivery of Site	1	1
2	Site Preparation	12	19
3	Implementation of Foundation	26	42
4	Implementation of Building's Structure	43	99
5	Initial Flooring	46	107
6	Implementation of Stairs' Foundation	5	9
7	Implementation of Roofs and Internal Walls	84	99
8	Implementation of Stories' Foundation	33	38
9	Implementation of External Walls	9	11
10	Moving Frames and Doors to their Places	1	2
11	Implementation of Windows	18	24
12	Implementation of Stairs	2	2
13	Flooring the Stories	33	45
14	Moving Electrical Appliances to their Places	2	3
15	Installation	16	34
16	Installation of Frames	13	32
17	Implementing Toilets	1	5
18	Initial Joinery of the Floors	19	36
19	Final Flooring	24	36
20	Installation of Cornices	6	12
21	Final Joinery of the Floors	30	44
22	Installation of Floors' Appliances	6	12
23	Implementation of Facade	18	43
24	Painting	20	33
25	Delivery of Project	4	7
	Total Time	348	524

3.5. Investigating BIM Output of the Case Study Building's Construction

In this stage, BIM was generated using the initial documents of the project, including the most important identified rework causes. Thus, many of the errors and rework causes could have been found and their effects could have been diminished. Various errors were identified during the modelling and a summary of the errors is illustrated in Table 16.

Table 16. Summary of the identified errors and their effects on schedule.

No.	Error	Delay (Days)	Time Saved Using BIM (Days)
1	Interference among Structural and Architectural Elements	16	10
2	Designing Errors	37	20
3	Interference among Structural Elements, Openings, and Installation	13	9

3.6. Investigation and Comparison of Delays between Traditional and BIM Assessments

In this stage, cumulative working times of the project were calculated and S-Curves (Status-Curves) of the project's anticipated, actual and BIM output were drawn using Microsoft Project software. S-Curves showed that the project's anticipated, actual and BIM cumulative working times were 4336, 6936 and 6617 h, respectively. Results show that the project's cumulative working time would have been reduced by 319 h (4.6%) using BIM technologies, which is regarded as a valuable step in reducing projects' delays. It is necessary to mention that some delay and rework causes were not able to be modelled, such as political sanctions or geographical hazards, as they are not predictable. Figure 5 illustrates the S-Curves of the three abovementioned error circumstances. According to Figure 5, BIM would have reduced the actual time by 319 h, which could be regarded as a great improvement. Therefore, if BIM was used, the project would have been finished in 6617 h as opposed to 6936 h.

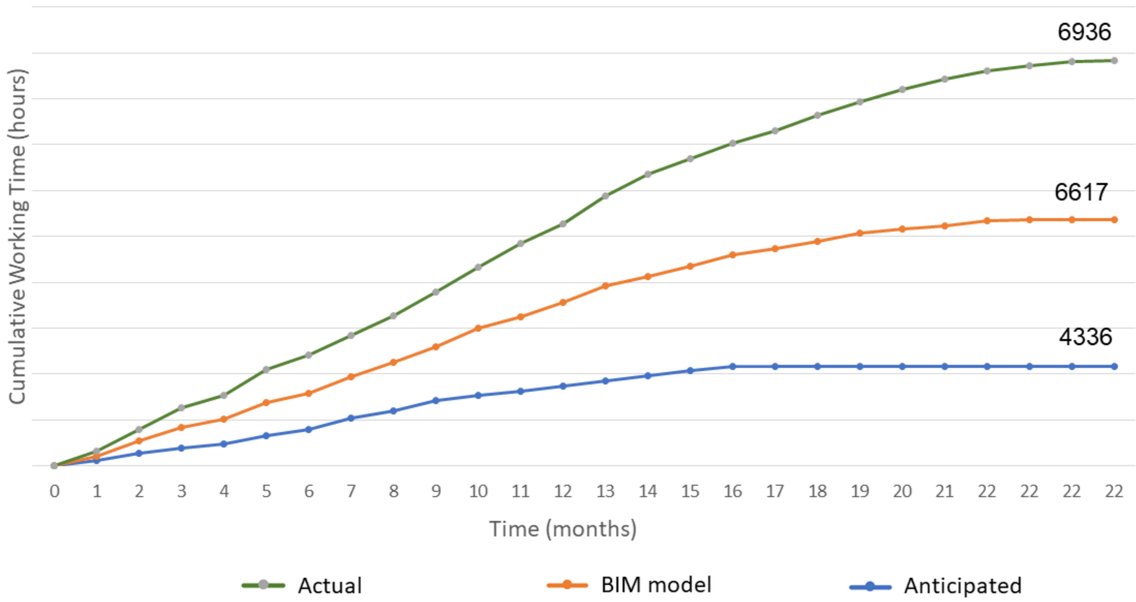

Figure 5. Status-Curves of the anticipated, actual and BIM cumulative working time.

3.7. Analyzing Time Using the Earned Value Management (EVM) System

To analyze the earned values and the status changes of this study, the parameters SPI and SV for the actual implementation and BIM output were calculated and are presented in Table 17. As can be seen, the computed values are still different from the actual values of the case study, although the results show the advantages of using BIM in a case study model. Moreover, a reduction in the SV value proves that using BIM would be successful.

Table 17. Earned values for the case study building's actual implementation and BIM prediction.

No.	Mode	SV	SPI
1	Actual Implementation	−0.18	0.83
2	BIM	−0.11	0.89

4. Conclusions

This study was conducted to identify rework causes in building construction projects and to analyze the benefits of using BIM technologies to process and predict them. Firstly, 49 rework causes were identified and categorized into seven groups including "Engineering and Reviews", "Implementation of Project", "Material and Equipment Supply", "Human Resource Capability", "Construction Planning and Scheduling", "Leadership and Communication" and "Effective External Causes". Then, the SWARA method was employed to weigh and rank the abovementioned rework causes into their own groups. Results showed that the most important causes in the abovementioned groups were "Design Errors (A1)", "Difference among Plans and Operational Specifications (B3)", "Non-compliance with Specifications (C1)", "Insufficient Skill Level (D1)", "Unrealistic Schedules (E1)", "Poor Communication (F4)" and "Economic Fluctuations (G2)". This was followed by Building Information Modelling for the selected case study using BIM software. In the next stage, anticipated, actual and BIM cumulative working times were calculated and illustrated using S-Curves. It was shown that BIM resulted in a 4.6% decrease in the working time. Finally, an EVM system was utilized to compute the positive effect of BIM technologies, and showed a 0.06 increase in the SPI value. The obtained results of this study could be very useful for different parties in the building industry who live in similar climatic and economic conditions. This study's method could be valuable for future studies, and could be very effective in other research as well. One of the limitations of this study was that only residential buildings were investigated. Although these results are highly beneficial for the residential construction sector, it is suggested that other types of buildings should be investigated in further studies. Prospective future researchers are suggested to investigate other dimensions of BIM, such as time. The authors suggest using BIM technologies at any stage of the construction project life cycle, for both new or refurbished buildings, and also recommend its benefits for sustainable construction.

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Abbreviations

Abbreviation	Meaning
BIM	Building Information Modelling
SWARA	Step-wise Weight Assessment Ratio Analysis
EVM	Earned Value Management
SPI	Schedule Performance Index
S-Curve	Status-Curve
MCDM	Multi-Criteria Decision Making
WBS	Work Breakdown Structure
SV	Scheduled Variance

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