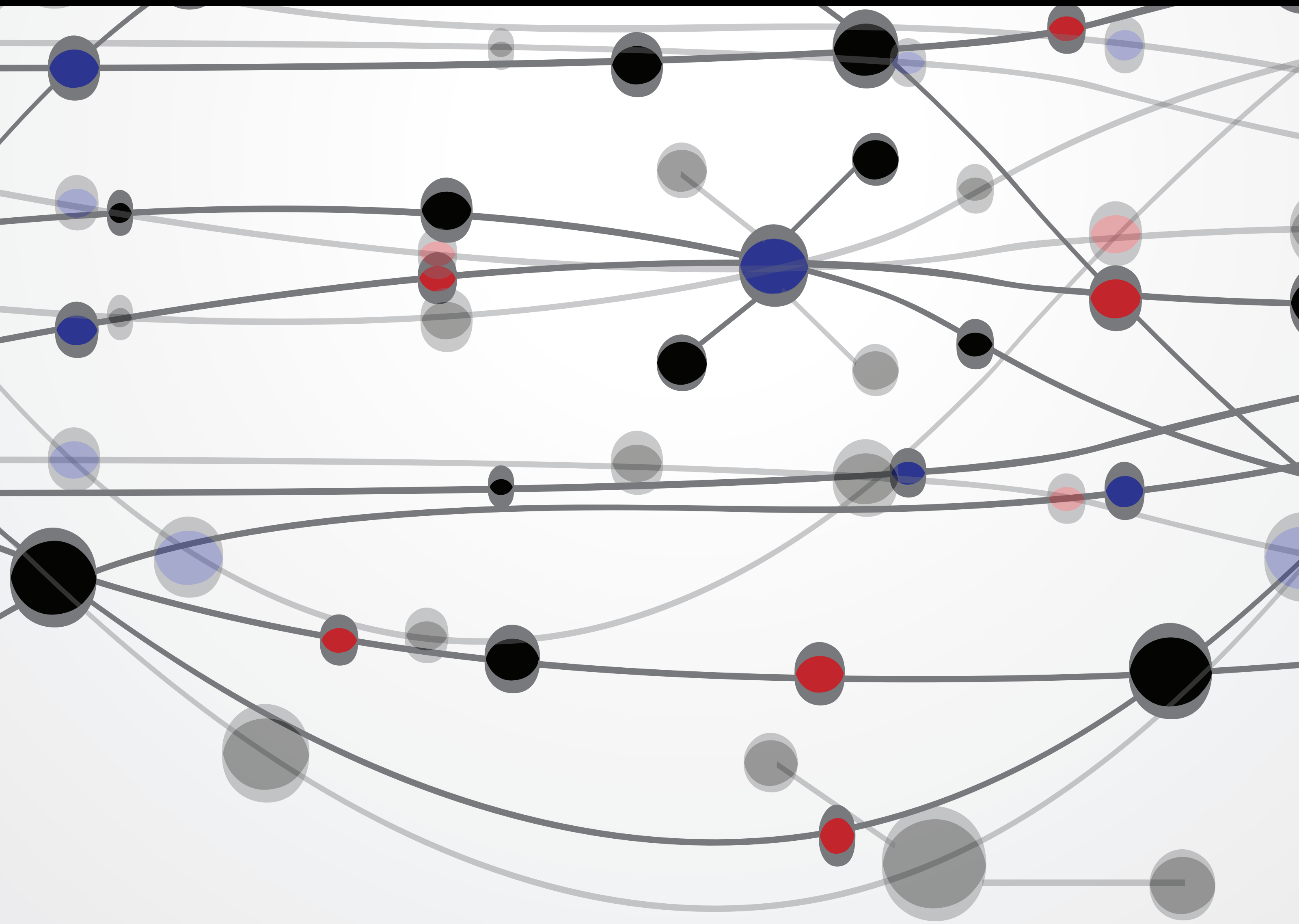
The Scientific World Journal

Knowledge and Asset Management in Sustainable Civil Engineering

Guest Editors: Eddie W. L. Cheng, Neal Ryan, and Yat Hung Chiang



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Editorial

Knowledge and Asset Management in Sustainable Civil Engineering

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This special issue aims at fostering the dissemination of high-quality research in methods, theories, and techniques concerning the application of knowledge and asset management in sustainable civil engineering. Similar to that of other special issues, the selection process was rigorous and only articles with good quality could be accepted. We, as editors, would like to thank all of those who had submitted their articles for possible publication. Some articles with good quality were not chosen because they were not definitely relevant to the issue scopes. Some others that were relevant were excluded because some modification work was required. Unfortunately, the stringent reviewing guideline set for the special issue puts us in a situation that we could not accept articles with major revision. Thus, we had to sacrifice these articles although they had the potential to be published in the special issue. Finally, six articles were published in this special issue, which brings together contributions from authors originating from various geographical locations including Australia, China, Korea, Sweden, and Taiwan.

This special issue has published four research and two review articles. The article by Y. Liu et al. discusses the use of case-based reasoning and variable fuzzy sets to develop appropriate safe early warning systems for highway construction projects in China. They argue that there is a lack of study of production safe early warning, especially early warning in construction projects. They realize that good early warning technologies can help reduce losses by restricting the possible accident sources and can indirectly lower investment costs by maximizing the benefit from the safety inputs. In their article, they introduce the key technology for safe early warning systems and explain the concepts of association rules, support vector machine, and variable fuzzy qualitative and quantitative change criterion mode. They provide solutions for solving three key issues of index selection, accident cause association analysis, and warning degree forecast, through the above concepts, to improve the highway construction early safe warning systems.

The other three articles are related to the application of building information modeling (BIM) for civil engineering projects. Y.-C. Lin and Y.-C. Su studied facility maintenance management (FMM) for the operation phase of the construction life cycle in Taiwan. They envisage the use of BIM to support the maintenance service of facilities depicted in 3D object-oriented CAD. Specifically, the BIM approach is used to store facility information in a digital format, which can facilitate easy updates of FMM information in a 3D CAD environment. They introduce the novel BIM-based FMM (BIMFMM) system for the acquisition and tracking of maintenance information. This system acts as a platform that enables maintenance staff to share information through webcam-enabled notebook or tablet. They demonstrate a case study, which was to apply the system in a commercial building in Taiwan, to evaluate the effectiveness of the system. Their combined results support that the system is a useful BIM-based FMM platform that integrates web and BIM technologies for handling FMM.

S.-P. Ho et al., a research group from National Taiwan University, also propose the application of building information modeling (BIM) technology to share construction knowledge. They introduce a BIM-based knowledge sharing management (BIMKSM) system. In this knowledge-based sharing system, construction knowledge can be communicated and reused among project managers and jobsite engineers. The BIM technology further supports the generation of 3D drawings that are particularly useful for identifying knowledge and experience feedback relevant to construction projects. The authors expect that this system helps alleviate problems on a construction jobsite and reduces the time and cost of solving problems related to constructability. In their article, the system was applied in a case study of a construction project in Taiwan to demonstrate the sharing of knowledge within the BIM environment.

Another article by R. A. Kivits and C. Furneaux focuses on the important concept of building information management (BIM), which as they quote is "the use of virtual building information models to develop building design solutions, to design documentation, and to analyze construction processes." Their paper outlines the current promise and future potential for BIM and makes recommendations in relation to how the problems can be addressed. They also argue that the concept can be applied to other civil infrastructure projects, such as dams, bridges, and tunnels, despite its primary link to building projects. A set of cases are presented to indicate how BIM has been implemented. Their paper further suggests that BIM has the potential for improving all stages of the construction life cycle and has implications for both sustainability and asset management.

The study by S. Lee et al. is intended to develop a financing model to solve financial barriers for implementing green building projects in the Republic of Korea. They highlight the importance of green buildings that reduce greenhouse gas energy but realize the difficulty in attracting private funding. Their financing model takes the governmental support into account by incorporating the government guarantee for the increased costs of a green building project in return for certified emission reduction (CER). One of the main components in the model is to compare between the value of the governmental guarantee and that of CER This can make sure that the government can secure return from its guarantee. An example has been demonstrated to show how the payback period can be calculated using the model. Such an asset management approach can help finance sustainable green building projects. Further, the authors argue that private guarantees may also be feasible given the promising value of the guarantee from CER.

The last, but not least valued, study by A. Warsame et al. draws the attention to the role of knowledge management and incentives that can improve the quality of transport infrastructure projects. They underscore the role played by a client organization on developing a knowledge culture for dealing with procurement and organizational issues. They argue that all procurement methods can give good results if the right conditions are given. They then introduce the knowledge conversion modes and identify the four major conditions from the knowledge management perspective. They also discuss the use of incentives to motivate employees to generate the behavior appropriate for knowledge management. They further propose that the client organization should seek independent second opinions from external actors in a systematic way during all stages of an infrastructure project in order to improve knowledge and create incentives.

Now, when our work, as guest editors, comes to an end, we hand in to our readers this special issue that was bred on several seeds, in which we firmly believe that they bring to the world new insights, ideas, and recommendations. We finally hope that readers will enjoy reading the special issue, dedicated to exploring knowledge and asset management in sustainable civil engineering.

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Research Article

A Financing Model to Solve Financial Barriers for Implementing Green Building Projects

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Along with the growing interest in greenhouse gas reduction, the effect of greenhouse gas energy reduction from implementing green buildings is gaining attention. The government of the Republic of Korea has set green growth as its paradigm for national development, and there is a growing interest in energy saving for green buildings. However, green buildings may have financial barriers that have high initial construction costs and uncertainties about future project value. Under the circumstances, governmental support to attract private funding is necessary to implement green building projects. The objective of this study is to suggest a financing model for facilitating green building projects with a governmental guarantee based on Certified Emission Reduction (CER). In this model, the government provides a guarantee for the increased costs of a green building project in return for CER. And this study presents the validation of the model as well as feasibility for implementing green building project. In addition, the suggested model assumed governmental guarantees for the increased cost, but private guarantees seem to be feasible as well because of the promising value of the guarantee from CER. To do this, certification of Clean Development Mechanisms (CDMs) for green buildings must be obtained.

1. Introduction

An overwhelming body of scientific evidence now clearly indicates that climate change is a serious and urgent issue. The Earth's climate is rapidly changing, mainly as a result of increases in greenhouse gases (GHGs) caused by human activities [1]. Among the GHGs, excessive emissions of carbon dioxide from the use of fossil fuel for energy generation have created unprecedented environmental pollution and health risks [2]. Sustainable and renewable energy technologies are solutions for reducing the use of fossil fuel and for meeting energy demands [3]. In particular, construction products constitute a major problem to solve in terms of their large amount of energy consumption, and thus minimizing their negative impacts on the environment is an important issue [4]. From this perspective, green buildings, to which sustainable and renewable energy technologies are applied, minimize the impacts of buildings on the environment [5].

In tune with the global trend and a growing interest in green buildings for greenhouse gas energy reduction, the government of The Republic of Korea began to emphasize green growth as its national growth paradigm. However, a green building generally has greater initial construction costs than other buildings [6]. With uncertainties in the future value of a project, increased costs may have negative effects on financing. Therefore, the government needs to take the necessary measures for smooth financing to vitalize green building projects. In other words, the government needs to share the risks with the private sector or to provide means to hedge the risks. For example, Public-Private Partnership (PPP) is a way to share risks through governmental guarantees [7]. In this way, using governmental guarantees can support private financing for green building projects.

However, when the government participates in green building projects as a party to risk sharing, returns on risks are necessary. This is because the government is so sensitive to the risk of project failure that it can be passive in providing guarantees.

This study suggests a financing model for green building projects with governmental guarantees based on Certified Emission Reduction (CER), which is an emerging trend in environment finance.

For analysis, this study utilized energy savings (%) and increased costs (US$/3.3 m^2) data of three residential building cases having different equipment for energy saving. Thus, this study assumed three cases of the residential building project having various equipment. Cash flow was estimated with the assumption that variables, except construction costs and financing costs resulting from increased construction cost for the residential building project, are the same.

The financing model suggested in this study can be tested by estimating the time to retrieve the value of governmental guarantee through the CER transaction. Thus, the values of governmental guarantee and CER need to be estimated. First, the value of governmental guarantee was estimated using the concept of a put option. To estimate the value of CER, the carbon emissions of the residential building project were estimated using the equation suggested by the IPCC. The estimated carbon emissions of the residential building project were applied to the three cases of energy savings (%) to obtain the CO_2 emission reduction of each case. For the price of CER, the European Climate Exchange (ECX) data from January 9, 2006, to November 19, 2010, were used. This study set the greatest price of unit CER as the best scenario, the smallest price as the worst, and the average price as a moderate scenario. Thus, by combining the CO_2 emission reduction and CER of each scenario, the value of CER for each scenario was obtained. Using the value of CER estimated for each scenario and the governmental guarantee, the payback period was obtained and the feasibility of the financing model was tested.

2. Background

2.1. Literature Review. There is a growing interest in green buildings as the great effect of building activities on the environment is gaining attention. Thus, the review of the literature on green building revealed that there have been a number of studies on various subjects such as assessment tools [8], occupant satisfaction [9], energy ratings [10], design [11], and barriers to implementing green building [12, 13].

Green building is a new business model resulting from global awareness of the environment, and various ways forward for success need to be reviewed. From this perspective, barriers to implementing green building need to be considered not only from the technical point of view but also from the business point of view.

Zhang et al. [12] investigated the effects of increased costs and various barriers when green elements were applied to a construction project. They demonstrated that construction cost increases for all cases in which green elements were applied. Furthermore, ten barriers were selected and a survey was conducted on them, resulting in the identification of construction costs as the greatest barrier. Intrachooto and Horayangkura [13] suggested that the application of a new technique to a construction project incurs increased costs and results in increased risk and uncertainty from the perspective of business feasibility. This problem constitutes a financial barrier to implementing green building projects. Accordingly, the increased costs can be a barrier to financing. Thus, this study suggested a financial model to overcome the financial barriers resulting from the additional costs.

2.2. Financial Barriers for Implementing Green Building Projects. Investors' primary goal is to make benefits or to get a return on investment. This rate of return can be determined by three different indicators: payback time, the return on investment, and the internal rate of return [6]. These indicators are also considered three downsides of a green building project. Concretely, investment in a green building project can be returned in about 7-8 years because the benefit of energy saving occurs in the operation stage [14]. As investors prefer a short-term payback time [15], they are relatively passive in investing in green building projects with their long-term payback time. Moreover, long-term payback time tends to be accompanied by uncertainties regarding project success, exposing the projects to greater risks. On that account, if the interest rates increased, damage from the rising project costs cannot be avoided in spite of well-disposed investors [6]. In the end, a green building project has barriers in private financing due to the long-term payback time, relatively high interest rates, and increased initial costs. Therefore, to launch green building projects, governmental supports are necessary to remove such financial barriers.

2.3. Green Building in the Republic of Korea. The Republic of Korea was ranked the 10th country in carbon emissions in 2008 according to the announcement by the International Energy Agency (IEA) [16]. After the Kyoto Protocol mandated reduction of greenhouse gas (GHG) emissions, a green growth policy was set by the government of The Republic of Korea in order to meet the requirement.

To reduce CO_2 emissions, building energy consumption needs to be reduced. According to the IEA, buildings account for 40% of the world's final energy consumption and 24% of CO_2 emissions. The IEA referred to commercially available, renewable technologies as a means to improve the efficiency of buildings' energy systems and to reduce a large portion of the energy consumption [6]. Further, as reported by statistics from Korea Energy Economics Institute (KEEI), buildings accounted for about 22% of the total energy consumption and 25% of the total CO_2 emissions as of 2007 in The Republic of Korea [17]. From this perspective, it is expected to the substantial effect on decrease in CO_2 emission, aggressively utilizing green building projects is an urgent matter in the Republic of Korea.

2.4. Environment Finance. Environment finance encompasses all market-based instruments designed to deliver environmental quality and to transfer environmental risks [18].

In this respect, the financing structure model of this study would fall under environment finance.

Due to the recent growing global interest in the environment, various environmental issues are changing and shaping investment markets and capital flows [19]. Thus, researches on environment finance have been performed actively. Peszko and Zylicz [20] stated that the demand for environment finance is influenced by environmental policy or a company's financing capability, and thus governmental support needs to be thoroughly reviewed. They specifically referred to measures that effectively attract private investment in environment finance [20]. Actually, Branker and Pearce [21] mentioned the important role of government support in large-scale, thin film solar photovoltaic manufacturing and the feasible financial return on it. Green building projects may have difficulties in obtaining private funding because they have large initial investments to improve energy efficiency, compared to other building projects. Therefore, governmental guarantees, to share the risk of project default with the private sector, can be effective for the efficient funding of green building projects [21].

In addition to the government role in environment financing, carbon has attracted attention as an asset in this field. Chaurey and Kandpal [22] measured the carbon mitigation potential through Solar Home Systems (SHS) and, based on this, studied the effect of carbon finance. In other words, they regarded carbon, a representative GHG, as a kind of asset and, using this, tested the effectiveness of their finance model [22]. Lewis [23] analyzed how carbon finance currently plays a role and how it can be reformed afterward in the developing world [23]. An emerging trend in environment financing is a trading market for CER given that carbon, generated from the use of fossil fuel, has a great effect on the natural environment.

The financing model of this study would facilitate the sharing of risks by using governmental guarantees. The government could continue to provide guarantees whether there were returns on the risks. Namely, CER is an asset from the perspective of environment finance because of the existence of a trading market. Consequently, the government could see CER, predicted carbon emission reduction through the green building project, as a return for the guarantee.

2.5. Real Options Theory. This study suggests a financing structure model for green building projects having a governmental guarantee agreement based on carbon emissions reduction by diminishing energy consumption. The government may face financial difficulties if it shares risk for green building projects with no strings attached. Governmental guarantees and expected profits from CER need to be compared to test the feasibility of the financing structure model. Thus, this study evaluated the value of governmental guarantees using real options, which can consider uncertainties involved in the success of the project.

An option is a security given the right to buy or sell an asset, subject to certain conditions, within a specified period of time [24]. In financial market, the most common types of options are a call option and a put option. A call option gives the owner the right to buy a stock at a predetermined exercise price on a specified maturity date. Conversely, a put option gives its owner the right to sell the stock at a fixed exercise price [25]. The option pricing theory has been applied in the evaluation of nonfinancial assets or real investments; researchers also called it real options. This dynamic pricing process overcomes difficulties in the discounting approach, such as the Net Present Value (NPV) method, and computes the value of a strategic investment more realistically [26].

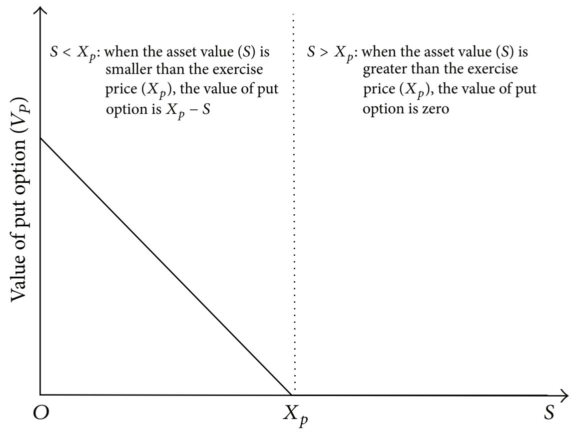

Figure 1: The value of put option depending on the change of the asset value.

To measure the value of governmental guarantee, the value of a put option used is described as in Figure 1. In other words, when the asset value is greater than the exercise price ($S > X_p$), a put option does not have any value because selling the asset for its value is better. However, when the asset value is smaller than the exercise price ($S < X_p$), selling the asset for the exercise price is much better. Here, the value of a put option is $X - S$.

Previous studies on real options show that real options are used not only for assessing the value of various tangible assets, such as a technology investment [27], infrastructure investment [28], and mine production [29], but also for assessing the value of contracts to parties such as material procurement contracts [30] and guaranteed contracts [31].

This study suggests a financing structure model for green building projects having a governmental guarantee agreement based on carbon emissions reduction by diminishing energy consumption. The government may face financial difficulties if it shares risk for green building projects with no strings attached. Governmental guarantees and expected profits from CER need to be compared to test the feasibility of the financing structure model. Thus, this study evaluated the value of governmental guarantees using real options, which can consider uncertainties involved in the success of the project.

3. Suggestion about Financing Model for Green Building Projects

3.1. Proposed Framework. As mentioned above, a green building project has increased initial construction costs. In the end, it negatively works as a barrier to attracting private funding due to uncertainties about future project

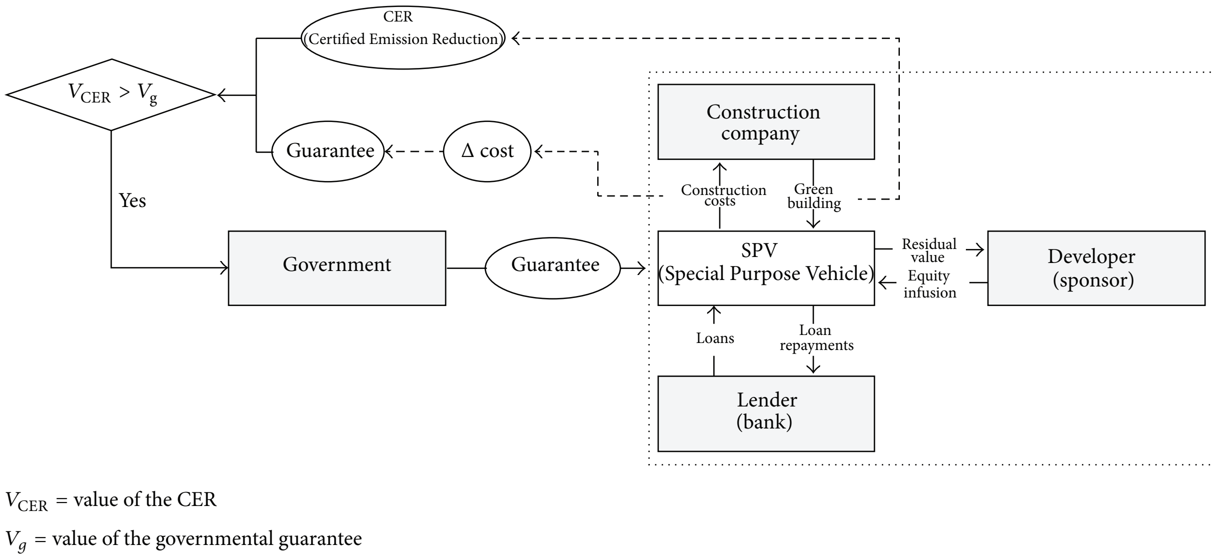

Figure 2: Proposed financing model for facilitating Green Building.

value. Thus, governmental support for gathering private funding for green building projects is necessary and this study suggests a financing model with governmental guarantees for the increased initial construction costs. Figure 2 shows the conceptual diagram for the financing model in this study.

Existing building projects are funded by project financing. Special Purpose Vehicle (SPC), invested by a developer (sponsor), raises funds from lenders using future cash flow of the project and makes construction contracts with a construction company. A green building project generally has greater construction costs than other building projects. If the government provided guarantees for the increased construction costs, lenders could remove additional uncertainties caused by them. However, the governmental guarantees entail governmental participation in the project, and thus, the government is also directly affected by the risk of project failure. Further, if the government has to provide guarantees only because a project is a green building project, the government may have to bear a considerable burden. As a result, the government needs to secure return for its guarantee. This return must be defined in terms of assets for which a trading market exists. From this perspective, this study defined CER, benefits from energy saving in the operational stage, as a return on a green building project. Actually, CER is being traded as an asset through the Clean Development Mechanism (CDM). As a result, after assessing the value of governmental guarantees for green building projects and comparing it to the value of CER, governments could determine whether to provide guarantees.

3.2. Concept of Valuing Governmental Guarantee Using Real Options. Guarantee contract is one of the safety provision to retrieve the investment. Accordingly, the value of guarantee increases when the project fails. This is very similar to the concept of a put option. There are a number of studies, which have applied the concept of put options to the evaluation of various payment guarantees such as valuation of deposit insurance by Federal Deposit Insurance Corporation (FDIC) [32] or Federal Loan Guarantees to Corporations [33]. The process of this study, to value the governmental guarantee using the option theory, is as follows: total costs (C_t) for a green building project can be defined as the sum of costs (C_s) for a building of the same size and additional costs(ΔC_a) for the green building. Therefore, one has

$$C_t = C_s + \Delta C_a. \quad (1)$$

Here, liabilities (L) can be defined as total costs (C_t) less equity (E) invested by a developer (sponsor) as follows:

$$L = C_t - E. \quad (2)$$

For project financing in The Republic of Korea, equity (E) is generally used to purchase land for the project and liabilities are generally used for actual construction. In other words, additional costs (ΔC_a), for the green building project, are lowly relevant to equity (E). Thus, (2) can be simplified as follows:

$$L = (C_s - E) + \Delta C_a. \quad (3)$$

Let us assume that the value of the green building project is S and the guarantee for liabilities (L) was provided. This means even if S is less than L, lenders can get L through the guarantee. In other words, the value of the guarantee changes, like the value of the put option mentioned above. Figure 3 shows that when S is greater than L ($S > L$), L can be retrieved by S and the value of the guarantee is zero. However, when S is smaller than L ($S < L$), L cannot be retrieved. However, through the guarantee, even if S is smaller than L, L can be retrieved, and thus the value of the guarantee increases as S decreases, being $L-S$. Thus, L is the same as the striking price of the put option (X_p). The value of the put option (V_p) is the value of the guarantee (V_d).

Table 1: Overview of three residential building projects applying different energy reduction items.

Category		Items	Equipment Case 1	Equipment Case 2	Equipment Case 3	Energy saving (%) Case 1	Energy saving (%) Case 2	Energy saving (%) Case 3	Additional costs (US$/3.3 m^2) Case 1	Additional costs (US$/3.3 m^2) Case 2	Additional costs (US$/3.3 m^2) Case 3
IR	Application of the insulating materials	Change of the insulating materials	Neopor thermal insulation (0.032 W/m^2K)			4.00			1.45		
		Change of the insulation thickness of the bedroom and balcony	0.156 W/m^2K/170 mm			7.80			5.70		
		Change of the insulation thickness of the balcony	0.432 W/m^2K/55 mm								
		Change of the insulation thickness of the ground and top floor	—	0.195 W/m^2K/0.175 W/m^2K 150 mm/150 mm (65 + 85)		—	1.50		—	0.32	
		Reinforcement of the pipe insulation	—	Elastomeric flexible cellular insulation		—	0.50		—	2.12	
	Application of hi-per windows	Change of windows of the bedroom	0.97 W/m^2K/22 mm + 16 mm (double glazing) (PVC290)			3.40			2.62		
		Change of windows of the balcony	Dry: PVC170 (L/S), wet: PVC130 (S/D)			2.20			1.52		
		Change of windows of the living room	1.51 W/m^2K/52 mm (triple glass (R183))	1.18 W/m^2K/52 mm (triple glass (PVC220))		4.30	8.30		2.66	4.02	
		Reinforcement of thermal performance of the windows	—		1.51 W/m^2K (double window) (PVC16 mm + PVC16 mm)	—		1.40	—		4.23
		Reinforcement of thermal performance of the front door	—		0.99 W/m^2K (insulation door)	—		0.50	—		1.09
		Reinforcement of thermal performance of the door to balcony	—		2.16 W/m^2K (wood door)	—		1.30	—		1.36

Table 1: Continued.

Category	Items		Equipment Case 1	Equipment Case 2	Equipment Case 3	Energy saving (%) Case 1	Energy saving (%) Case 2	Energy saving (%) Case 3	Additional costs (US$/3.3 m^2) Case 1	Additional costs (US$/3.3 m^2) Case 2	Additional costs (US$/3.3 m^2) Case 3
HE	Boiler	Boiler		Condensing boiler			8.94			0.36	
	Application of the private high efficiency equipment	High efficiency lamps (bedroom)		FPL32W			1.05			0.03	
		High efficiency lamps (bathroom)		FL28W			0.14			0.03	
		High efficiency lamps (front door, balcony)		LED21W/EL15W			1.04			0.58	
	Application of the public high efficiency equipment	Ventilation system	—	Heat recovery ventilator + heat exchanger		—	7.00		—	5.30	
		High efficiency lamps (basement garage)		FL29W			1.23			0.03	
		Electric transformer		High efficiency electric transformer			1.53			0.84	
RE	Photovoltaic system			0.06 kw/housing unit			3.2			2.78	
O	Water treatment system			Water transportation pump			0.12			0.02	
	LED (light-emitting diode) signs			LED			0.46			0.11	
			Total			33.96	46.96	50.16	18.71	27.53	34.50

IR: insulation reinforcement.
HE: high efficiency equipment.
RE: renewable energy.
O: other.

Table 2: Cash flow for each case.

Project	NPV	Costs				Income
		Loans	Direct costs	Financial costs	Sum of other costs	
Base project	6.76	205.89	55.70	24.32	145.03	249.59
Project applied case 1	5.48	206.98	57.03	24.42		
Project applied case 2	4.87	207.49	57.65	24.47		
Project applied case 3	4.39	207.90	58.14	25.51		

Unit: million US$.

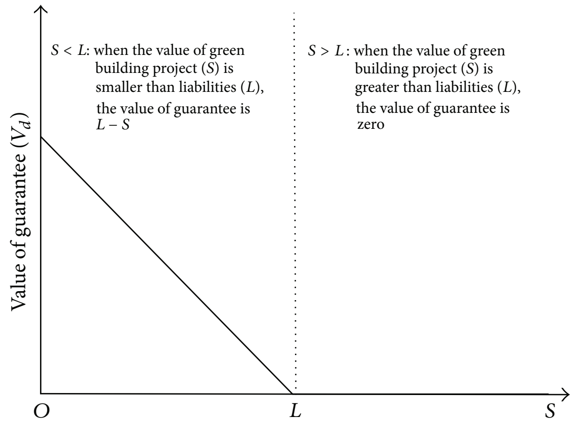

Figure 3: The value of guarantee depending on the change of a project value.

Table 3: Parameters to estimate the value of governmental guarantee.

Parameters	Value
Underlying asset value (S_0, million US$)	US$221.76
Time step (dt)	1/2 year
Volatility (σ)	25.6%
Risk-free rate (rf)	5.36%
Up-step size (u)	1.198
Down-step size (d)	0.834
Risk-neutral probability (P)	0.529
Striking price (X_c, million US$)	
Application of case 1	US$206.98
Application of case 2	US$207.49
Application of case 3	US$207.90

Accordingly, the value of the governmental guarantee (V_g) for the additional costs (ΔC_a) is as follows:

$$V_g = V_d \times \left(\frac{\Delta C_a}{L} \right). \quad (4)$$

4. Applications

4.1. Data Set. The aim of this section is to test the financing model for a green building project having a governmental guarantee agreement based on CER, which is obtainable from energy saving. Three cases for a residential building project having different equipment for energy saving were analyzed. Table 1 shows each case's equipment for energy saving, energy savings (%), and increased costs (US$/3.3 m^2). The residential building project of this study was assumed to have three kinds of equipment.

Variables, except construction costs and financial costs increasing construction costs for the residential building project, were assumed to be the same for cash flow as presented in Table 2. Using the cash flow, the value of the governmental guarantee was assessed.

Cash flow for each case and the details for variables estimating the value of governmental guarantee are as follows.

In Table 3, the underlying asset value (S_0) is the present value of income and, in this study, was estimated as US$221.76 million. As described above, the striking price (X_p) is the same as the loan, and thus, for each case, it was estimated at US$206.98 million, US$207.49 million, or US$207.90 million. Sales income was determined by sales price and sales rate. In this study, house price index data from March 2004 to October 2010 and sales rates of 50%~100% were used and combined to measure volatility (σ). Volatility (σ) was about 25.6% interest for a three-year maturity government loan and public bonds were used as a risk-free rate (rf), which was 5.36%. The time step of a half-year unit was used.

Thus, up-step size (u) of 1.198, down-step size (d) of 0.834, and risk-neutral probability (p) of 0.529 were obtained. Using these, the put option value for liabilities was estimated and using (4) the value of the governmental guarantee for the increased construction costs for the green building project was obtained.

CER is currently traded on the EU Emission Trading Scheme (EU-ETS) in the EU and on Chicago Climate Exchange (CCX) in the USA. CER prices from January 9, 2006, to November 19, 2010, at the European Climate Exchange (ECX) were used in this study.

4.2. Valuing the Governmental Guarantee. To test the financing model for a green building project supported by a governmental guarantee agreement based on CER, the value of the governmental guarantee was obtained using the option theory. As described above, the put option value was obtained to calculate the guarantee value. Building project data are discrete as monthly data, unlike continuous data for other financial assets. Thus, a binomial lattice model was used to estimate the option value, and not the Black-Scholes model,

Table 4: Value of guarantee for each case.

Classification	Option value (V_d)	Loan (base)	Loan (L)	Additional costs (ΔC_a)	Guarantee value (V_g)
Project applied case 1	20.33	205.89	206.98	1.09	0.11
Project applied case 2	20.70	205.89	207.49	1.60	0.16
Project applied case 3	20.98	205.89	207.90	2.01	0.20

Unit: million US$.

Table 5: Annual CO_2 emissions for the residential building project.

Parameters	Value
Energy consumption ($TOE/m^2 \cdot year$)	0.018
Carbon emission factor (ton C/TOE)	0.812
Burning rate (%)	99
Subject project G.F.A (m^2)	70,825
CO_2 emission (ton CO_2/year)	3,736.820

assuming continuous time flow. Table 4 shows the values of the governmental guarantee for each case, obtained using (4).

As Table 4 shows, additional equipment for energy saving leads to increased construction cost and increased value of the governmental guarantee. By comparing the obtained value of the governmental guarantee to the value of CER, the feasibility of the financing model for a green building project was tested.

4.3. Comparison of the Values of the Governmental Guarantee and CER. First, CO_2 emissions were estimated for the project to compare the values of the governmental guarantee and the CER. The CO_2 emissions were estimated using (5) suggested by the IPCC, and Table 5 shows the results. One has

$$\begin{aligned} CO_2 \text{ emission } (\text{ton } CO_2) &= \text{Energy consumption (TOE)} \\ &\quad \times \text{Carbon emission factor } (\text{ton C/TOE}) \\ &\quad \times \text{Burning rate } (\%) \times \left(\frac{44}{12}\right). \end{aligned} \tag{5}$$

The result of energy saving (%) of each case applying into the residential building project and value of governmental guarantee in Table 4 is following Table 6.

CER prices at European Climate Exchange (ECX) from January 9, 2006, to November 19, 2010, were used in this study. This study used the highest price of unit CER as the best scenario, the lowest price of unit CER as the worst scenario, and the average of both as the moderate scenario. As a result, Table 7 shows payback periods for the value of governmental guarantee using CO_2 emission reduction, guarantee value, and CER price for each case and each scenario.

As in Table 7, as the CER unit price goes down, the total CER goes down and the payback period becomes longer. Further, as energy saving (%) increases, total CER increases as well. However, as construction costs increase, the value of the governmental guarantee increases as well. However, the increase in the value of the governmental guarantee is greater than that in the total CER by increased energy savings (%), and thus, as energy savings (%) increase, the payback period becomes longer. If the efficiency in energy saving for equipment is improved, the payback period would become shortened. Given the forty-year limitation for legal reconstruction in The Republic of Korea, the longest payback period of 7.55 years for the worst scenario shows that the financing model of this study is feasible for implementing actual green building projects.

4.4. Discussion. The financing model of this study assumed governmental guarantees for the increased cost, but private guarantees seem to be feasible as well because, in return for the guarantee, the value of the guarantee can be obtained through CER. To vitalize this financing model, private investments have to become active in the market system. Nevertheless, this study assumed the governmental participation to test the feasibility of the financing model. Showing the market the feasibility of the financing model, involving governmental participation in a green building projects, may induce private investments. In addition, given the national priority to meet CO_2 emission reduction targets imposed by the climate accord, the government needs to take the initiative and to play an important role in implementing the financing model. To vitalize the financing model in the market, CDM certificates need to become vitalized as well. Current CDM certified projects are mostly plant projects. However, given that buildings account for 40% of the total final energy consumption and 24% of CO_2 emissions in the world according to IEA, active implementation of green building projects will be very effective in CO_2 emission reduction. From this perspective, the CDM certificate system for green building projects needs to become active. If it would be active, various financing methods can be developed based on the financing model of this study and CER.

5. Conclusions

The Kyoto Protocol, which went into effect in February 2005, has led to global efforts to reduce CO_2 emissions. Especially in The Republic of Korea, the government has set green growth as its paradigm for national development and there is a growing interest in greenhouse gas energy reduction for green buildings. However, green buildings have increased initial construction costs and there may be difficulties in financing for green building projects. To deal with this problem, this study suggests a financing model for a green building project having a governmental guarantee based on CER obtainable from energy saving. In other words, by providing

Table 6: The estimated values of guarantee value and CO_2 emission reduction for each case.

Classification	Guarantee value (million US$)	Energy saving (%)	CO_2 emission reduction (ton CO_2/year)
Project applied case 1	0.11	33.96%	1269.02
Project applied case 2	0.16	46.96%	1754.81
Project applied case 3	0.20	50.16%	1874.39

Table 7: Total annual CER and payback period for guarantee value for each scenario of CER unit price.

	Case 1		Case 2		Case 3	
	Total CER (million US$)	Payback period (year)	Total CER (million US$)	Payback period (year)	Total CER (million US$)	Payback period (year)
Best scenario	0.065	1.64	0.090	1.78	0.096	2.11
Moderate scenario	0.037	2.86	0.052	3.09	0.055	3.67
Worst scenario	0.018	5.89	0.025	6.36	0.027	7.55

a governmental guarantee for green building projects, the government can be directly affected by the risk of project failure. If the government provides a number of guarantees for green building projects, the government's financial status could be affected. Accordingly, this study used CER in actual trading markets as a return for the guarantee.

By testing the suggested financing model using the combination of degree of energy saving and CER price scenarios, the payback period for the worst scenario was about 7.55 years. Comparing this to forty years of remodeling limitation, the financing model of this study turned out to be feasible for actual green building projects.

The financing model of this study used the governmental guarantee for the increased cost. However, there is a return for the guarantee through CER, and thus, private guarantees are feasible as well. Therefore, the financing model of this study can be used in the private sector as well.

However, for the application of the financing model suggested in this study, the CDM certificate system needs to be implemented first. To trade CER, the corresponding project must be CDM certified. Actually, most CDM certified projects are plant projects. However, given that buildings account for 40% of the final energy consumption and for 24% of CO_2 emissions, the CDM certificate system needs to be applied to buildings as well.

Most financing models have a risk as a result of uncertainties in future asset values. The financing model of this study also has such risk even if the value of the guarantee was estimated in consideration of such uncertainties using the real options theory. If a project fails, additional costs greater than the estimated value of the guarantee need to be paid, and, in this case, the payback time can be greatly lengthened. From this perspective, even if the value of the guarantee can be retrieved through the CER transaction, ways for reducing the risk need to be prepared.

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Review Article

BIM: Enabling Sustainability and Asset Management through Knowledge Management

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Building Information Modeling (BIM) is the use of virtual building information models to develop building design solutions and design documentation and to analyse construction processes. Recent advances in IT have enabled advanced knowledge management, which in turn facilitates sustainability and improves asset management in the civil construction industry. There are several important qualifiers and some disadvantages of the current suite of technologies. This paper outlines the benefits, enablers, and barriers associated with BIM and makes suggestions about how these issues may be addressed. The paper highlights the advantages of BIM, particularly the increased utility and speed, enhanced fault finding in all construction phases, and enhanced collaborations and visualisation of data. The paper additionally identifies a range of issues concerning the implementation of BIM as follows: IP, liability, risks, and contracts and the authenticity of users. Implementing BIM requires investment in new technology, skills training, and development of new ways of collaboration and Trade Practices concerns. However, when these challenges are overcome, BIM as a new information technology promises a new level of collaborative engineering knowledge management, designed to facilitate sustainability and asset management issues in design, construction, asset management practices, and eventually decommissioning for the civil engineering industry.

1. Introduction

Building information management (BIM) is "the use of virtual building information models to develop building design solutions, to design documentation, and to analyse construction processes" [1]. We would suggest that such a definition, while useful, should be extended to include the operational phases of built assets (such as maintenance and decommissioning) and also be applied to the whole area of civil construction. BIM has considerable potential for enhancing the efficiency, sustainability, and effectiveness of civil engineering in all stages of the construction process: planning (or design), construction, facilities management, and decommissioning as it extends the functionality and application of existing computer-aided design (CAD) technologies. The main extension is by linking the 3D built asset model to a relational database that can carry all information related to the built asset [2]. This added functionality provides a mechanism for extended collaborations between designers, engineers, constructors, and facility managers across the life cycle of built assets. Another aspect of BIM is that information, which is created once, can be reused many times, resulting in less errors, greater consistency, clarity, accuracy, and clear responsibility of authorship. This paper argues that BIM holds considerable promise for enhancing a range of activities for civil engineering, with leading authors suggesting 20–30% increase in productivity when using the technology [3]. Despite the prediction that the uptake of BIM in civil construction and facilities management will be slow but inevitable [4], there are some real barriers which need to be addressed in order for this adoption to occur.

This paper outlines the current promise and future potential for BIM and makes recommendations in relation to how the problems can be addressed. Additionally, while BIM has been primarily explored in relation to buildings, there is little reason why the technologies could not also

Table 1: The application of BIM to the asset life cycle (adapted and expanded from Hartman and Fischer [3]*).

Design	Construction	Operations/facilities management	Decommissioning
Ensure the right facility is designed. Evaluate the design from many perspectives. Evaluate the design against building codes and sustainability before construction.	More productive crews, as there are fewer changes to the design once the construction has started, the ability to track work in real time, faster flow of resources, and site management. Enables demonstration of the construction process, including access and egress, traffic flows, site materials, machinery, and so forth. Better tracking of cost control and cash flow, particularly for large projects.	Keep track of built asset. Manage the facility proactively. Such a model can be handed from one contractor to another, thus enhancing facilities management. Capability to schedule maintenance and review maintenance history.	Identify elements which can be recycled or those which require particular care (e.g., hazardous materials). Know the composition of structures prior to demolition.

*Hartman and Fischer [3] also argue that BIM can enhance procurement processes. However, procurement could apply to any or all of the construction phases discussed here. Likewise Building Smart (2007) argued that BIM had application for increasing the speed of Development Assessment approvals through local councils.

be applied to other civil infrastructure projects for example, dams, bridges, and tunnels. A set of cases are provided which provide exemplars of how BIM has been implemented.

From the outset, this paper argues that BIM has the potential for improving all stages of the construction life cycle and has implications for both sustainability and asset management. Accordingly, it is appropriate to firstly provide an overview of the various phases of construction and subsequently how BIM might be implemented in these phases.

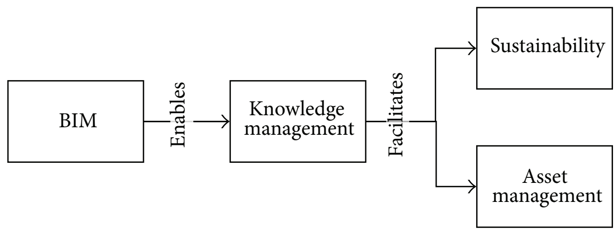

Figure 1: BIM as the foundation to civil engineering sustainability and asset management improvement.

1.1. Overview of BIM. BIM holds the promise of being an important factor in the built asset industry in the future. It can facilitate the users of all stages of the built asset life-cycle, integrating design, engineering, construction maintenance, and decommissioning information about a built asset project into a single “rich” model. As such, BIM technology enables the use of 3D built asset models to move beyond the design phase and into the construction and maintenance phase of the built asset as well as move the 3D model into a 4D simulation. Table 1 summarises these implications.

BIM offers the opportunity to develop better cost estimates based on actual elements of the built asset, better design and construction processes and methods, and a means to engage the client in the design phase of the built asset [3]. Figure 1 gives a succinct summary of how BIM can improve sustainability and asset management as it enables collaborative knowledge management across all stages of the asset lifecycle. The enablers such as IT allow for engineering knowledge management by easily sharing information not only within a single organization but also across organizations. This improved and simplified knowledge management in turn facilitates the potential to increase sustainability and asset management for all stages of development.

Much of the potential for BIM has yet to be realised due to the current level of development. As Ashcraft comments, “in current practice, BIM is a hybrid, with several differing approaches being used. Each approach seeks to tighten integration, but the single universal model and perfect interoperability are still aspirations, not achievements” [5]. Ways in which these aspirations can be achieved will be outlined at the end of the paper as future research trajectories.

2. Methods and Methodology

The methods deployed in this paper are an extensive review of the extant academic, policy, and elements of the practitioner literature. A set of extant cases are used as exemplars for showing how BIM has been used in civil engineering projects, with each case purposively chosen to studies discussing the role of BIM in different phases of the construction life cycle. This review goes beyond much of the rhetoric espousing the potential of BIM and carefully considers the barriers as well as benefits of BIM to the civil engineering industry. The cases were deliberately selected in order to learn about the case [6], particularly the application of BIM in various stages of the life cycle, in different sorts of assets, and because the cases generated considerable insight about the phenomenon [7]. Thus, cases were selected in order to provide information on the phenomena of interest [8].

Table 2: Overview of applications of BIM in the current and past projects.

Project or organisation	Role of BIM within the project
The Sydney Opera House [9]	BIM as a support for integrated facility management
The Construction Operations Building Information Exchange (COBIE) project [10]	COBIE is creating a standardized content and format for information handover to operations and maintenance, as a part of the U.S. National BIM standard (NBIMS)
Public schools in Bourgogne (France) [12]	All the public schools of the region will progressively become available in IFC format (CADOLE project, funded by the region as facility manager)
US General Services Administration (GSA) [11]	The GSA has created its own 3D-4D BIM Program. Starting from 2007, the GSA has mandated the use of interoperability and IFC for all major projects. This followed a pilot study which tested BIM on 9 separate projects
The US Pentagon Renovation and Construction Program (PENREN) [56]	The US PENREN Program uses the diagnostic Postoccupancy Evaluation (POE) process which systematically evaluates the performance of built assets after they have been built and occupied for a length of time
The Airbus restaurant in France (IAI 2006)	Main purpose: to populate the FM system with IFC files provided by the designers
The Freedom Tower in New York City [30].	When completed, the Freedom Tower will be 1,776 feet tall, the world's tallest built asset, and contain approximately 2.6 million square feet. Given the high visibility and aggressive schedule associated with such a large, complex project, SOM's commitment to a full BIM approach to the project is both a bold bet and the only realistic way to deliver on the unique demands of this project
The UK Process Protocol model [57]	Based on a 2D model, the process protocol adopts a normative approach to inspire companies to use a more disciplined strategy to project management
The model from the Finnish Construction Process [58]	The Technical Research Centre of Finland created a model that followed existing practice quite close, since the input consisted of checklists of tasks produced by the Built asset Information Institute, which are the "de facto" standard in Finland
The IBPM of Pennsylvania State University [59]	The work carried out by the Pennsylvania State University has a large influence on the later work in formalised modelling technology. It was carried out with close collaboration with industry and real projects
The Dutch "Bouw informatie model" [60]	They used BIM in essence as a design process model, intended to serve as a framework for describing information in the creation and modelling of the model
Queensland State Archives, Runcorn	This is pilot project conducted by the Department of Public Works where a 3D model was developed from 2D drawings and used for the design and construct phase. The project is currently being evaluated. A 4D construction scheduling was also a key element of this project
US Army Corps of Engineers	The US Army Corps of Engineers and a global engineering, procurement, and construction management (EPCM) firm,as a partnership, work together to develop new US Army Corps of Engineers (USACE) project deliverable standards for BIM applications

3. Application of BIM Case Studies

3.1. Applications of BIM in the Past and Present. In the literature, several applications of BIM in the industry can be identified. Table 2 gives an overview of all the identified projects that have implemented BIM, either as a subject of study or as a tool. The most important ones will be discussed in the following section.

Of this set of cases, four have been chosen as exemplar projects to explore the role of BIM in knowledge management: the Sydney Opera House [9], which is an exemplar of an iconic public asset, and three cases from the United States of America: The Construction Operations Building Information Exchange (COBIE) project [10], US General Services Administration (GSA) [11], and the US Army Corp of Engineers [12].

3.1.1. Sydney Opera House. The Sydney Opera House is recognised throughout the world as an iconic symbol of Australia. As FM is considered an ideal tool for the "integration of disparate information management systems, firstly in order to better align FM performance objectives with the organisational objectives, and secondly to further FM objectives in terms of better and more effective FM practices and service delivery" [9]. In a response to this idea, the Sydney Opera House was used to conduct research on FM in practice with the objective of using the research to demonstrate FM as a business enabler and to provide insight into the need to develop a more generic integrated FM solution for the FM industry as a whole. The FM Exemplar Project combines three research streams dealing with Digital Modeling, Services Procurement, and Benchmarking as a whole and then develops collaboration between them. It aims to achieve innovative FM strategies and models that will showcase improved FM performance and promote best practices [9, 13].

The results of the project as a whole and the benefits for using BIM in the FM in general encompass the following benefits as put forward by the project. The key benefit of digital modeling is its accurate geometrical representation of the parts of a built asset in an integrated data environment as follows:

(i) faster and more effective processes: information is more easily shared and reused;

(ii) controlled whole-of-life costs and environmental data: environmental performance is more predictable and lifecycle costs are understood;

(iii) integration of planning and implementation processes: government, industry, and manufacturers have a common data protocol [9].

3.1.2. COBIE. "The Construction Operations Built asset Information Exchange (COBIE) is built upon earlier work. COBIE is a built assetSMART initiative of the National Institute of Built Asset Science's Facility Maintenance and Operations Committee, the Facility Information Council and International Alliance for Interoperability, and the National Built asset Information Model Standard. It is a federal government (UA) sponsored effort to support the development of Built asset Information Model(s) (BIM) via information exchange between construction and operations phases" [14]. "The Construction Operations Built asset Information Exchange (COBIE) project, with funding from the U.S. National Aeronautics and Space Administration (NASA), is creating standardized content and format for information handover to operations and maintenance as part of the U.S. National BIM standard (NBIMS). The COBIE approach envisions capturing this information incrementally throughout the facility planning, design, and construction processes" [10].

3.1.3. GSA BIM. In 2003, the U.S. General Services Administration, which is responsible for the management of all civilian federal public built assets in the United States, created its own 3D-4D BIM program, the National BIM Standard. Starting from 2007, the GSA has mandated the use of interoperability and IFC for all major projects [11]. This followed nine pilot projects where BIM was trialed. According to Matta and Kam [15], the direct benefits from these pilot studies include optimizing construction schedule (e.g., reducing the duration by 19%), improving the as-built documentation, uncovering design errors and omissions, and improving the means for communications through 3D-4D BIMs. Furthermore, GSA's initiative has led other federal agencies in the adoption of BIM and has made a major impact on the industry (people, culture, and process), on peer owners, on the attitude towards open standard, and on the importance of establishing an owner's BIM and its requirements.

3.1.4. US Army Corps of Engineers. The US Army has recognised the importance of BIM, and through the US Army Corps of Engineers (US ACE) it is implementing BIM [12]. By 2010, US ACE wants to have 90% compliance with the National BIM Standard (NBIMS) [12]. US ACE actively participates in the development of open standards (NBIMS) for a number of reasons [12] as follows:

(i) greater competition,

(ii) nonrestrictive contracts,

(iii) government owns the data in long-term format.

What the American Department of Defence (DoD) wants to achieve is the implementation of BIM in a Common Output Level Standard (COLS) that has to provide a common language that is critical for the creation of Joint Base installations. The DoD expects to "significantly . . . reduce duplication of effort with resulting reduction of overall manpower and facilities requirements capable of generating savings" [16]. The US ACE recognizes that BIM supports their Military Construction (MILCON) program, which covers the construction of facilities and structures as it benefits the design and construction. At the moment, under the Military Transformation program, BIM is a primary deliverable in the US ACE's "FY08 RFP," the request for a project preproposal. The US ACE expects its design and construction contractors to develop BIM capabilities and their software vendors to use Industry Standards (e.g., NBIMS) and achieve interoperability [12].

At the moment, the four other US federal organisations are effectively implementing BIM; in addition to DoD, these are the U.S. Coast Guard, General Services Administration, NASA, and the Smithsonian Institute.

4. Analysis of the Case Studies

By examining those case studies, a set of advantages and disadvantages of BIM in facilitating knowledge management will be explored, followed by the barriers and enablers to full implementation of BIM in civil engineering. The mechanisms of overcoming the barriers and disadvantages will then be discussed.

BIM is held to offer a range of advantages over hand-drawn or 2D models of built assets. As suggested in the introduction, BIM has emerged alongside a number of other technological and social accomplishments which have enabled BIM as a technology to be developed. Table 3 provides an overview of how BIM has benefitted the four

Table 3: Overview of benefits of BIM to the asset life cycle stages.

	Planning	Construction	Facilities management	Decommissioning
Sydney Opera House			Faster and more effective processes. Information is more easily shared and reused/controlled whole-of-life costs and environmental data Environmental performance is more predictable and life cycle costs are understood	Identify elements which can be recycled or those which require particular care (e.g., hazardous materials)
COBIE	Creating standardized content and format for information handover to construction	Better tracking of cost control and cash flow, particularly for large projects	Creating standardized content and format for information handover to operations and maintenance	Identify elements which can be recycled or those which require particular care (e.g., hazardous materials)
GSA BIM	Evaluate the design from many perspectives and through time	Enables demonstration of the construction process, including access and egress, traffic flows, site materials, machinery, and so forth	Capability to schedule maintenance and review maintenance history	Know the composition of structures prior to demolition
US Army Corps	Evaluate the design against building codes and sustainability before construction	More productive crews, as there are fewer changes to design once the construction has started, the ability to track work in real time, faster flow of resources, and site management	Manage the facility proactively	Identify elements which can be recycled or those which require particular care (e.g., hazardous materials)

case studies in the different stages of the asset life cycle. These benefits will be further explored in this section.

4.1. Enablers of BIM. For the implementation of BIM, there have been three major enablers. The first is the advent of enhanced IT infrastructure and capability of computers to develop and display 3D models with underlying large databases. The second enabler is the creation of the Industry Foundation Classes (IFC) by the International Alliance for Interoperability (IAI). The third is the increasing worldwide support for BIM. These enablers will be explained in detail below.

The implementation of ICT technology in an organisation poses challenges that need to be overcome. In general, these barriers can be technological in nature, but they can also be related to the need for organisational changes or changes to business processes or even just the speed of implementation [17]. While BIM may contribute a lot of benefits to the construction process, the implementation of this technology presents numerous challengers which need to be overcome.

4.1.1. Major Advances in Computer Technology and IT Infrastructure. The internet, as a global self-regulated and interconnected network of institutions driven by educational and subsequently commercial priorities, has evolved into an element within a broader "global information society" [18]. The internet is one of the driving forces of globalization, and there is a strong correlation between exporting products and services and internet access at the enterprise level [19]. At a practical level, the internet and roll-out of high speed broadband across OECD countries have facilitated the exchange and sharing of large files across time and space. This has meant that firms can be separated geographically and can operate in separate time zones, and yet the internet enables these firms to collaborate on major projects. Continuous innovations in internet technology and IT infrastructure have in turn increased the performance of BIM.

Additionally, enhanced computer capacity in processing power and graphics, storage, and memory [20], not to mention better compression algorithms, has meant that larger, more resource intensive files can be created and shared. This enhanced capacity of computers is one of the enablers for BIM technology. The current trend in IT infrastructure, with the latest innovation of fibe optic cables, gives rise to the possibility of sharing even larger data files among users all over the world. BIM is heavily reliant on this infrastructure, since BIM files are large and need to be accessible at all times. Thus, the internet, IT infrastructure, and enhanced capacity of computers have all served as enablers of the creation of large graphical models with huge databases embedded in the models.

The current development of IT systems can lead to a new organisational architecture and new ways of doing business and delivering services. In the built asset management sector, BIM can enhance the facility management for civil construction. Harris described that, with the need to deliver services differently, the civil construction sector needs to restructure the organisation and engage in dialogue within the organisation and between organisations [21]. This contact and "opening up" of communication channels and developing cooperative arrangements in itself can lead to further synergies in terms of more information sharing, collaboration, and examining new ways to effectively deliver services [21].

The widespread adoption of BIM for civil engineering could possibly be the catalyst to speed up this process, as BIM requires the development of new communication channels and cooperative agreements. The OECD sets out its case for IT in terms of efficiency gains (savings in data collection, information provision, communications with clients and transaction costs) and service improvements (improved customer focus for service delivery and increased accessibility to services) [22].

Enhanced capability is not enough however. There need to be specific protocols which enable the sharing of information between firms and software packages. This is discussed next.

4.1.2. BuildingSMART (International Alliance for Interoperability). Interoperability can be described as "the sharing and exchanging of information via integrated technological solutions, no matter what project phase, discipline or participant role in the built asset life cycle" [23]. Although BIM may be considered as an independent concept, in practice, the business benefits of BIM are dependent on the shared utilisation and value-added creation of integrated model data across multiple firms. To access model data therefore requires an information protocol, and although several vendors have their own proprietary database formats, the only open global standard is that published by buildingSMART called the Industry Foundation Classes (IFC).

There are several reasons for the buildingSMART to create a global standard for the built asset sector. One of those is the huge added cost of coordination errors. "Effectively, the historic inefficiencies of the built asset process have driven the industry to look at a new approach to the built asset process. According to the Construction Users Roundtable member companies in the US, it is generally accepted that as much as 30% of the cost of construction is wasted in the field due to coordination errors, wasted materials, labour inefficiencies, and other problems" [24, 25].

In addition to that, in 2004, the National Institute of Standards and Technology (NIST) conducted a study on the cost of inadequate interoperability in the United States' Capital Facilities Industry. The NIST study involved "design, engineering, facilities management, business processes software systems, and redundant paper records management across all facility life cycle phases. It estimated the cost of inadequate interoperability to be roughly $15.8 billion per year, and of these costs, two-thirds are borne by owners and operators" [26].

In order to address this waste of resources, money and time, the IAI is most responsible for promoting interoperability to civil engineering. BuildingSMART is a global, industry-based consortium for civil engineering. It was formed in 1994 and their mission is "to enable interoperability among industry processes of all different professional domains in civil engineering projects by allowing the computer applications used by all project participants to share and exchange project information" [27]. Originally, buildingSMART's main objective was to "define, publish and promote specifications for IFC as a basis for project information sharing in the built asset industry" [28]. BuildingSMART currently has more than 400 members in 24 countries and is the leading interoperability organization [5].

The integration and interoperability of the hundreds of software applications supporting the design and construction of the built environment have been providing one of the most challenging environments for the application of information and communication technologies [29]. BuildingSMART's stimulus in developing the IFC protocol was the recognition that the greatest problem in the construction industry today is the management of information about the built environment. Although every other business sector has embraced IT and adopted industry-specific standards, the construction industry worldwide has stuck to its trade-based roots and dependence on drawings, with a continuing record of poor quality, low investment value, and poor financial rewards [9].

The Industry Foundation Classes (IFC) are a set of rules and protocols that describe and store built asset information. According to Batcheler and Howell [30], the "effort to define a single built asset model as one authoritative semantic definition of built asset elements, their properties and interrelationships" has been largely successful. Bazjanac [31] describes IFC as "the first open object oriented comprehensive data model of built asset that provides rules and protocols for definitions that span the entire life of a built asset." IFC are also the only such model that is an international standard (ISO/PAS 16739). Presently, IFC are the only nonproprietary intelligent, comprehensive, and universal data model of built assets [31].

The creation and existence of these Industry Foundation Classes and the increasingly widespread use of them throughout the industry enable the implementation of BIM in the built asset sector. When all the sectors of the built asset industry are using IFCs as the standard protocol, the sharing of data, as required by BIM, is increasingly easier and barriers due to incompatibility of standards and protocols are reduced.

Capability of software and hardware to undertake a specific task, to a certain level of performance, is important. The demand for hardware and software that can perform these tasks is what will ensure that there is continued investment in the hardware and software which make this possible. Some government organisations have mandated the use of IFCs, such as Finland and the United States of America.

4.1.3. Increasing Worldwide Support for BIM. There is an increasing worldwide support for BIM. According to a 2006 survey conducted by the American Institute of Architects (AIA), 16% of AIA member-owned architecture firms have acquired BIM software, and 64% of these firms are using BIM for billable work [1]. The same survey found that "35% of the AIA member-owned firms with an international scope of practice have acquired BIM software, which may be at least partially due to the fact that firms with an international scope tend to be large in terms of staff and billings and may also be working on large projects. But BIM may also simplify overseas projects, as it allows for easy transmission of detailed information quickly over long distances" [1]. As more and more companies start using BIM as the built asset designing and modeling standard, other companies will be forced to follow, to keep a competitive advantage, and to remain interesting as partners for larger firms that require their subcontractors to use BIM as well.

Pragmatically, the number of firms using BIM is quite low, and this may have to do with the adoption cycle of any new technology. Moore [32] provides a useful insight into this by arguing that there is a gap between the early adopters of a new technology and the adoption by the majority of the field. It is in this gap that many innovations fail or falter. Another way of viewing this adoption gap is what Kiviniemi et al. [33, page 56] call the basic dilemma of BIM, which can be described as a paradoxical loop. There is not enough market demand for integrated BIM, because there is not enough measured evidence of benefits of the integrated BIM, because there are no adequate software tools to use integrated BIM in real projects [33].

Some pressure is needed to pull a technology from the promising early start to wide spread adoption by the majority of professionals. Enhancing client demand for the benefits provided by BIM is one catalyst for the adoption of the technology by most of the civil engineering industry. For this to occur, major clients of the civil construction industry would need to be convinced of the benefits of BIM and ensured that all risks had been satisfactorily addressed.

4.1.4. Summary of Enablers of BIM. In summary, BIM as a suite of technologies has been enabled by the significant improvements in IT infrastructure, the capabilities of computer hardware and software, the increasing adoption of BIM, and the development of IFC which facilitate the sharing of information between firms.

In current practice, BIM is a hybrid, with several differing approaches being used. Each approach seeks to tighten integration, but the single universal model and perfect interoperability are still aspirations, not achievements [5]. It is likely that the full capability of BIM will not be able to be demonstrated until these barriers and implementations are clearly understood and addressed.

The civil construction industry, for its part, can enable the adoption of BIM through the use of BIM in various demonstrator projects and supporting the development and adoption of interoperability standards which are necessary precursors to the wider spread utilisation of the technology.

4.2. Promise of BIM. Using a BIM model has a number of advantages over traditional 2D approaches to design and construction. BIM models can enable collaboration between different professionals involved in the design and construction phase of the built asset and can manage changes to the built asset design so that a change to any part of the built asset model is coordinated in all other parts of the model and underlying database, together with the capability of capturing and preserving information for reuse by additional industry-specific applications [5, 34–36]. BIM models can also offer a wealth of information that is generated automatically as the model is created. In turn, this information can be used for cost estimating, project planning and control, and eventually for management of the operation and maintenance of the built asset [37]. The following benefits of BIM have been identified from the literature, which are explored in detail below:

(i) increased utility and speed,

(ii) enhanced collaborations,

(iii) better data quality,

(iv) visualisation of data,

(v) enhanced fault finding.

If properly implemented, BIM has clearly some advantages and benefits for civil engineering. However, these advantages are not without some challenges. The technology and business process, upon which BIM is based, does have some disadvantages. Additionally, there are some barriers to be overcome before the full potential of BIM is realised for civil engineering. Just as with benefits and enablers, government policy has a role in the mitigation of the barriers and disadvantages of BIM implementation.

It is important to note that while BIM is applicable to all stages of construction, Hartman and Fischer [3] note that no single project to date has used BIM in every single phase of construction. Consequently, one of the main hurdles which needs to be overcome is the integration of BIM across all construction phases and by the different participants in a construction project [3, page 3].

Not all benefits are achieved in all phases of the built asset life cycle. Although all benefits are applicable for the design and construction phase, the maintenance and decommissioning phase benefit most from the increased speed and utility, better data quality and the visualisation of the data. In Table 4, these benefits have been summarized.

Having reviewed the benefits of BIM across the project life cycle, it is appropriate to note some of the factors which are enabling the growth and uptake of the technology.

While some governments have mandated the adoption of BIM, this has been following extensive use of pilot studies which have trialled a number of BIM applications in a number of settings (e.g., GSA in the USA [38]). Demonstration projects are likely to be necessary prior to the use of other policy instruments such as education, regulation, and policy.

4.3. Problems with BIM. Just as there are a number of advantages to the use of BIM in civil engineering, there are a number of challenges. Those discussed here are the single model, interoperability, added work for the designer, and the sheer size and complexity of BIM:

(i) a single detailed model,

(ii) interoperability,

Table 4: The benefits of using business information modelling.

Benefit	Result
Increased utility and speed (in all phases)	Information is more easily shared, can be value-added, and reused
Enhanced collaborations (mainly in the design and construction phase)	Across discipline and organisation, built asset proposals can be rigorously analysed, simulations can be performed quickly, and performance benchmarked, enabling improved and innovative solutions
Better data quality (in all phases)	Documentation output is flexible and exploits automation. Requirements, design, construction, and operational information can be used in FM resulting in better management of assets
Visualisation of data (mainly in the design and construction phase)	The added value of 3D visualization leaves little room for misinterpretation by all parties involved, and it helps to realign their expectations
Enhanced fault finding (in all phases)	BIM greatly reduces conflict issues by integrating all the key systems into the model. Designing BIM systems can detect internal conflicts, and model viewing systems can detect and highlight conflicts between the models and other information imported into the viewer

The key advantage of BIM is its accurate geometrical representation of all the parts of a built asset capturing all necessary and relevant data of every part in an integrated environment.

(iii) added work for the designer,

(iv) the size and complexity of BIM,

(v) Trade Practices implications.

These disadvantages are mostly identified in the design and construction phase of the built asset life cycle. These disadvantages mainly have to do with the differences in which architects and engineers work. Although all benefits are applicable for the design and construction phase, the maintenance and decommissioning phase benefits most from the increased speed and utility, better data quality, and the visualisation of the data. In Table 5, these benefits have been summarized.

In the very traditional profession of civil engineering, new technologies are not easily introduced. In general, when a new technology is introduced, there is a certain period of time in which the claims about the potential of the technology need to be examined, tested, and verified. Particularly, the AEC/FM industry is known for the very long adoption periods of promising technologies, despite the highly mobile workforce that must collaborate with a range of on- and off-site personnel and make use of the large volumes of information [37]. Even while new standards are being, and have been, developed (IFCs), the adoption of these standards has been slow. Due to this slow speed of adoption, it is very difficult to demonstrate the benefits of these standards [25].

The first barrier is addressing the legal issues involved with BIM and the interorganisational way of operating, using one single complex project file. In relation to BIM, the legal concerns identified to date include risk allocation, standard of care, privacy and third party reliance, economic loss doctrine, who is the designer, and intellectual property [5].

These concerns are grouped together and in this section the IP, liability and risk, and contractual issues are treated.

The foregoing section has dealt with several barriers of implementation for BIM. To give a short overview of all the barriers, Table 6 gives a summary of these barriers.

Not only the technical limitations of BIM have been identified but also have the legal, social, and financial barriers that can prevent a successful implementation of BIM. For the further development of BIM, new business models will have to be designed that assist the integration of BIM as a project delivery method, rather than the old methods where it is attempted to integrate these new technologies into conventional practices [5]. "This rethinking must necessarily include a disavowal of the build it and they will use it' mentality that infiltrates much of web-enabled thinking" [39]. Given the potential of BIM as a set of technologies, it is certainly time to address the numerous financial, intellectual, legal, and organisational issues which currently inhibit the widespread adoption of BIM. As has been outlined above, it is likely that a range of policy instruments would be required to address all of these concerns policy and regulation, financial support allowances and incentives, education, and the trialing of the technology in numerous settings.

4.4. Longer Term Potential of BIM

4.4.1. The Utility of BIM in the Design Phase. Historically, designing a built asset involved drawing a two-dimensional (2D) image of the built asset on paper and making hard copies for other participants to use in the next phase construction. In the early 1980s, architects started using CAD, or computer-aided design, which allowed designs to be created on a computer in a 2D format and copied more easily. In the evolution from paper-based drafting to 2D CAD, the relationship between designers and contractors remained stable, with little change noted in procedures [34–36]. The reason for this is that while CAD improved processes for architects as they designed built assets, the end product—a 2D drawing—was effectively the same. CAD systems produced marginal benefits for many organisations over conventional drawing methods. This was because the electronic design invariably became committed to a hard-copy version at numerous stages. The electronic version was dispensed with and at each stage the drawing had to be recreated from scratch [40].

While CAD enabled drawings to be created on a computer, in the end, the drawings were converted to 2D hard

Table 5: The disadvantages of built asset information modelling.

Disadvantages of BIM	Description
A single detailed model	BIM does not allow alternative design options or the managing of "what if" scenarios.
Interoperability	One software standard needed. Often firms have their own software; for BIM, every firm needs to change to the same software standard throughout the entire built asset process.
Added work for the designer	For BIM to work "optima forma", the designer needs to create the "rich" model. They will be drawing something that will form the foundations of a complete system analysis. This means a lot more work for the designer.
The size and complexity of BIM	The large size of BIM will require different means of data sharing, and real time access into the database will require broadband internet access, together with security of data being worked on.
Trade Practices implications	While some countries have mandated BIM, this is unlikely to occur in Australia, if this restricted trade.

Table 6: The barriers to the implementation of built asset information modelling.

Barriers of implementation	Description
Issues concerning IP, liability, risks, and contracts	As the designer is responsible for the creation of the "rich" model that will be used throughout the process, this raises issues of who owns the IP, who is liable, what are the risks involved, and how will new contracts be structured?
Issues concerning the authenticity of users	Using electronic environments for tendering raises authenticity questions because manipulation of data may be possible, and the authenticity of users needs to be secured.
Costs	For designers, the economic advantages of BIM are less tangible. Yet, it is the designer, not the owner, that must adopt and invest in the new technology, So unless the designer shares in the economic benefits, the owner, not the designer, reaps the immediate benefits and the designer pays the price. Builders and owners benefit significantly from BIM.
Sociotechnical issues	Attention needs to be given to the socio-technical issues which arise from implementation of new technology, which results in new ways of doing business.
Skill issues	Access to BIM may be limited or inhibited by users either not having the capability or the "know how" in terms of connecting to the system. Obtaining sufficient level of knowledge and expertise that is required for BIM may be difficult and prohibitively expensive.

copy and handed over to the contractor. So up until the early 1990s, innovations driven by ICT only affected the design stage of the construction process. The remainder of the construction process remained relatively unchanged.

The introduction of Object Oriented CAD (OOCAD) systems in the early 1990s involved the replacement of 2D symbols in CAD drawings with built asset elements (objects) which were capable of representing the behavior of common built asset elements. The key improvement of this technology was that these built asset elements could have nongraphic attributes assigned to them and associations between the various elements of a built asset to be made [30]. Additionally, this new 3D computer technology enabled designers to better visualise a built asset, by being able to rotate the built asset and view it from multiple angles. The third parallel development in the 1990s was the increasing use of internet for digital data sharing [41, 42]. This increased use of object oriented modeling in the design phase and the capability of the Internet to enable information sharing between geographically and temporally distant firms resulted in the emergence of BIM as a set of technologies. In line with the increasing computer hardware and software capability, most CAD vendors have launched more powerful object-based CAD software in recent years. These software programs are now commonly known as Building Information Modeling, (BIM), Virtual Building, Parametric Modeling or Model-Based Design [43].

The latest developments in BIM technology mean that all of the 3D building objects created in the design phase can coexist in a single "project database," or "virtual building", that captures everything known about the building. A building information model (in theory) provides a single, logical, consistent source for all information associated with the building. Instead of representing a wall two-dimensionally with two parallel lines, the wall object has properties that describe geometrical dimensions such as length, width and height as well as materials, finishes, specifications, manufacturer, and price which are also included. Doors, windows, slabs, structural members, and stairs can be objectified in the same way [44].

Additionally, the location of an object within a built asset can be pinpointed using unique geospatial referencing [45] which can be incorporated into the model. An example of these relations is the following strain of links from an object: "A duct, having an asset code of BSE-DU694 is installed on building storey Level 3 of the building named Block B situated on a land parcel with Lot No 1222546" [45].

In BIM, the model comprises individual built assets, sites or geographic information system (i.e., precise geometric coordinates coupled with accurate geometry and represented visually), with attributes that define their detailed description and relationships, that specify the nature of the context with other objects. Because all components within a BIM are objectified and have properties and relationships attached to them, BIM is called a "rich" model. In this way, BIM offers a variety of information that is generated automatically as the design model is created. In turn, this information can be used for cost estimating, project planning and control, and sustainability (such as Life Cycle Analysis and Life Cycle Costing) and eventually for management of the operation and maintenance of the built asset [37].

For government, BIM offers a digital modeling technology that offers the potential to integrate design, engineering, and construction maintenance and decommissioning information about a built asset project into a single "rich" model. Further, BIM technology enables the use of 3D drawings to be moved beyond the design phase and into the construction, maintenance, and decommissioning phases of the built asset although few projects have been able to demonstrate this level of functionality to date.

4.4.2. The Utility of BIM in the Construction Phase. The application of BIM to the construction phase is possible because the underlying data of the BIM contains rich data concerning not just individual elements of the model but also the relationships between these elements. Cyon Research [46] provides an example: "although a door has an independent existence, it will move with a wall in which it has been inserted." (Design professionals will recognise that the concept of "parametric integrity" is being discussed here.) For designers and builders, this means that amendments to building designs can be made rapidly, easily, and accurately as all of the related elements of a particular drawing are adjusted at the same time.

While the models created in BIM software are detailed 3D representations of built assets, they are more than that. Although BIM can create 3D visualization, the model is not constructed from simple graphical elements. Instead, it is generated from a relational database containing information regarding the elements of a structure and their relationships [5]. Built asset elements can contain many nongeometric attributes, fire resistance, for example, or manufacturer's name and model number. This makes for a realistic model: one whose every aspect is linked to every other aspect to reflect reality. A change made to any "view" of the model, whether graphical or textual, is immediately reflected in every other view [46].

The elements of a built asset in a BIM model can include data concerning their composition, cost, manufacturer, relationship to other elements, and related properties such as dimensions, weight, fire resistance, or combustibility. Such information becomes very useful for estimating costs and bills of quantity and so forth.

An extra addition to this 3D parametric modeling is that it is also the basis for the possibility to apply 4D simulations. 4D is industry code for the addition of the element of time to a built asset model. A 4D simulation program is a software tool that automatically prepares construction schedules together to show a 3D simulation of the construction progress over time—which is where the idea of 4D originates. The process of assigning time to each of the elements of a 3D built asset model greatly reduces the chance of human errors in the construction process. Also the visualisation of the construction process enhances the understanding of the process involved, so that any issues can be identified by nontechnical people, and the visualisation may highlight constraints that had not been previously identified or made explicit [47]. A 4D BIM can greatly enhance traditional project management software as the specific visual representation of construction elements is linked to specific points in time. A client and builder can see a visual representation of the state of the finalised building at any given point of time.

An example of this was given in the construction of a hospital, where the 4D model was shown to the clients (who worked for a large hospital) prior to construction [48]. The 4D model showed all the stages of the construction process, including the equipment needed to construct the built asset. When viewing the construction process, the gantries and large cranes planned to erect the building were also displayed. The hospital staff quickly pointed out that this equipment blocked the primary flight path of emergency helicopters to the helipad essential to the rest of the hospital; therefore, such equipment could not be used. This had obvious implications for the construction planning process, and considerable effort was required in order to resolve this issue. However, it was resolved prior to commencement of construction, thereby demonstrating the utility of BIM for not just the planning phase but also the construction phase.

Williams [49] provides a useful overview of how BIM has been used in the construction of a variety of transport infrastructure including bridges, viaducts, and railway tunnels. 4D BIM is used in these applications to not only demonstrate the construction of the infrastructure itself but also to show how traffic could keep flowing, although rerouted, at different stages of a subway construction, how a section of a viaduct could be demolished and rebuilt in only 3 days, and what various construction options would look like if implemented. Examples of this are above ground versus underground highways, the impact this would have on a city's foreshore, and what the construction of a high rise building would look like at different times of the year.

There are also advantages for subcontractors involved in the construction phase as the detailed designs facilitate computer-controlled manufacturing, automated estimated/quoting, and accurate off-site manufacture resulting in improved coordination, reduced time, and less waste.

For government, BIM provides a way to better engage with clients in the design phase but can also result in significant productivity improvements in the delivery of the built asset. The ability to provide detailed model, which contains detailed specification of a built asset in one place, enables the rapid identification of errors and collaboration between various design professionals. The functionality goes beyond the specifics of the built asset itself and has also been applied to the access, egress, traffic, equipment, and other elements essential to the effective running of the project.

Just as the introduction of BIM in the design phase has indirect advantages for the government, so does the introduction of BIM in the construction phase. BIM allows for better cost estimates of the project. As every phase of the construction is modeled, unforeseen costs can be eliminated in the planning phase, instead of "fire fighting" behavior during the project, which in general costs more time and money than estimated. In addition, it also leads to a better service quality delivery, increased consultation, reduced disputes, and reduced lead time. These advantages of BIM to the government will be discussed in detail later.

4.4.3. The Utility of BIM in the Operations/Maintenance Phase. BIM also has applicability to the maintenance phase of built assets. Since all the specifications for a built asset, down to an individual component level, are recorded, BIM provides a repository of detailed information about the built asset and its components that can be used after the completion of the built asset for Facility Management (FM). The FM has easy and quick access to important information during the maintenance phase and moreover can update this information over time, which can result in better management of the asset. This framework also means that the owner of the built asset can easily change from one facility manager to another, as only one single BIM file needs to be exchanged [50, 51].

Facilities Management is "a business practice that optimises people, process, assets, and the work environment to support delivery of the organisation's business objectives" [52]. If maintained properly during construction, BIM can become a tool that can be used by the owner to manage and operate the structure or facility [5]. According to the CRC Construction Innovation [9], facilities management is one of Australia's fastest growing industries which contributes significantly to the economy and employs a great number of people. Recent statistics on the FM industry support this contention. The combined direct and indirect contribution of the FM industry in 2002/2003 was AUS $12.2 billion of value added, AUS $12.4 billion in GDP terms, and (full time equivalent) employment of 172,000 persons. The combined contributions represented 1.8%, 1.65%, and 2.1% share of the corresponding Australian GDP and employment totals [13].

The addition of BIM in the maintenance phase has particular utility for governments in the maintenance of a built asset. As BIM can contain all of the data concerning the components of a built asset, the condition of these components can also be entered and audited. Given the typical longevity of government built assets and the current regime of contracting-out asset management to private firms, any given asset may have multiple firms contracted to maintain them. This presents a challenge for effective asset management, as the change of firms often results in loss of local knowledge about the built asset itself. BIM provides a tool which can retain records of all the updated data of the built asset. Additionally, if a particular building element was to fail, then the constructor or supplier of that particular asset could be readily identified and contacted to provide a replacement element.

As there is one knowledge base for a built asset, multiple firms can be used to manage the built asset, as every facility manager would update the BIM with additional information. Such a database would also provide a basis for auditing the performance of the facilities manager as well as the performance of the built asset itself. Additionally, switching from one facility manager to another is simplified, as the BIM contains all the needed information for a new facility manager. Thus, BIM has the potential to reduce opportunistic behaviour from the facility manager and creates incentives for the facility manager to perform as best as possible.

For government, there would appear to be great benefit in using BIM models for FM applications, as BIM can be used to integrate "a digital description of a built asset with all the elements that contribute to its ongoing function such as air conditioning, maintenance, cleaning, or refurbishment and describe the relationship between each element" [47]. The Sydney Opera House FM Exemplar Project is an example of BIM used as a facilities maintenance tool [13, 47, 53]. There are advantages to a computer model which can be handed on from one contractor to another in contracting-out regimes, the primary advantage being continuity of available information from one FM contractor to the next, thus enhancing the stewardship of such assets in contracting-out regimes.

4.4.4. The Utility of BIM in the Decommissioning Phase. At the end of the built asset life, when it is decommissioned, BIM is useful in supplying the information of the built asset construction, materials, and the whole life history. From the BIM, information about hazardous materials or elements used in the built asset or in repair work can be identified, and these can be extracted and stored as deemed appropriate. This readily available data will increase the speed at which the built asset can be decommissioned and will also increase the safety of the decommissioning. As some built asset products are only deemed hazardous many years after construction (e.g., Asbestos), having a detailed database available of the built asset and the composition of its components greatly assists in the management of risk. Also, BIM increases the overall sustainability of the built asset as it allows the identification of dangerous materials that require special handling and valuable materials that can be reused. It also can assist possible future needs for dismantling built assets and reusing the entire built asset or components of a built asset, instead of simply demolishing the built asset.

For government, having a detailed model of a building ready that contains the composition of all elements of the structure, enables the identification of (potentially) hazardous materials like lead and asbestos. Some construction materials are recognised as being hazardous long after their incorporation into the built asset. Just like the evolution of asbestos from a renowned built asset material to a dangerous substance, currently used materials can in the future be classified as dangerous. The availability of a BIM can help in identifying where and how often these materials were used. Additionally, some components of a built asset could still hold considerable value, such as copper, and could be reused in an economically viable manner.

5. Addressing the Challenges

The challenges as set out in the previous section need to be addressed when BIM is desired to be implemented. Addressing these points will increase its strength and output. In this section some suggestions to mitigate the disadvantages are discussed.

5.1. A Single Detailed Model. Even though BIM is a single detailed model, this should not limit the possibilities of experimenting with different versions in the design phase. In this phase, if desired, two or more initial models could be initiated, giving the designer room to experiment with alternative design schemes. This is assumed to take up a lot of storage space, but as the design progresses, in time only one design will remain. Together with the latest advances in IT technology, which allows for increasing storage capacity this disadvantage could become less challenging.

5.2. Interoperability. As it is vital for the success of BIM that all participating parties of the project use the same programs, the same versions of programs, and IFC standards, this will have to be accomplished before starting the project. In the initiation stage, all participants will have to agree on switching to the new standard if they are not using these yet. Another option would be only entering arrangements with partners that comply with the requirements beforehand. In this way interoperability challenges are addressed, as incompatibilities leading to delays can be avoided. For example, the UK government will require fully collaborative 3D BIM as a minimum, by 2016 [2].

5.3. Added Work for the Designer. Certain incentives for the designers and architects of the model will have to be integrated in the contracting process, as the initial creators of the model, the designers, and architects have a big influence on the future development of the model. The initial design stage therefore carries extra responsibilities, liabilities, and work. Straightforward rewards of money can be offered to the designer to compensate them for the work, or certain arrangements like royalties for artists could be incorporated when the underlying data of the model is used again. However, these are just suggestions and have as such not yet been researched whether this is possible or legally achievable. It is however clear that the job description of the architect changes in BIM processes. Some of the issues which need to be resolved for this to happen, particularly IP, are to be discussed in more detail.

5.4. The Size and Complexity of BIM. As addressed earlier, developments in internet and computer technology have greatly enabled the possibilities of larger and more complex technological projects. In general, just the storage of the model should not create the largest of problems as storage space becomes increasingly cheaper. The larger difficulties will arise in creating real-time access and sharing of the database; ubiquitous high speed broadband internet is essential, together with ways of ensuring the data is secure, stable, and accessible. The key here is generating and/or accessing the right data for the right purpose, rather than accessing all the data.

6. Conclusions and Recommendations

This paper outlines the current potential of BIM to enhance the productivity of civil engineering. The promise and advantages of an integrated information and database sharing model across the entire life span of a built asset have been identified, together with the current barriers to implementing such models on a large scale. Of special interest to the industry are the potential cost savings BIM promises to deliver—particularly through improved efficiencies and effectiveness through enhanced collaboration at all stages of the construction cycle. Recent advances in IT (both hardware and software) have enabled advanced knowledge management, which in turn facilitates sustainability and improved asset management in the civil construction industry.

Many of the tools and technology that have been discussed in this paper are embedded in daily work practices of civil engineers already. The main challenges are not the interconnection of software tools anymore, but rather establishing processes and best practices, overcoming the barriers, and managing the social element of sociotechnical systems. [54] said that research indicates that one of the last available "mechanisms" left for organisations to improve their competitive position is by considering its people (culture) along with its technology [54]. In other words it is not the technology itself that we should be focusing on anymore, but the process of interaction between architects, engineers, constructors, and government.

Such interactions have implications for the types of procurement arrangements which would facilitate such interactions, together with the contractual, legal, financial, and technological frameworks needed to support the implementation of BIM and the amelioration of some of the difficulties associated with implementing BIM. However, it was already noted by Williams and Dobson [55] that changing the culture of an organisation and its members takes time. That is because it is a slow process for people in existing or newly established "social systems" to develop a new set of common held beliefs, attitudes, and values [55]. What this means for BIM is that changing current ways of working will not make BIM an instant success but is a pathway to future success. Many firms adopt ICT tools and systems for profit-motivated reasons and often fail due to underestimating the social implications of the change brought by the innovation. Successful ICT adoption depends on the "politics of technology" in its management in the organisation [54].

BIM does have significant potential for civil engineering. The government, as a significant client of construction, has been called upon to be an early adopter of the technology [33] and in cases like the UK [2] and the USA [38], they have taken that role. Pilots in various countries have demonstrated significant time, costs savings, and quality enhancements. There are however significant barriers and costs which need to be addressed in order for these benefits to be realised on a broad scale, as discussed here. It is therefore recommended that several civil engineering industries maintain undertaking small and some larger projects, in order to assess the benefits of the technology and to work through the numerous issues raised in this paper. Additionally, these projects could be conducted in different jurisdictions and for different clients, as such variables are likely to provide valuable lessons which have purchase in wider contexts.

Given the barriers identified above, a further review of the interorganisational, legal, public policy, and financial issues inhibiting the implementation of BIM is advised.

Digital construction is coming, and the implementation of BIM is very likely to become reality, maybe very quickly or maybe at a more leisurely pace. What the civil engineering industry should do is to make sure that it is leading the world, and continue to invest in digital capabilities to continuously improve efficiencies and effectiveness through enhanced collaboration at all stages of the construction cycle.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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Research Article

Enhancing Knowledge Sharing Management Using BIM Technology in Construction

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Construction knowledge can be communicated and reused among project managers and jobsite engineers to alleviate problems on a construction jobsite and reduce the time and cost of solving problems related to constructability. This paper proposes a new methodology for the sharing of construction knowledge by using Building Information Modeling (BIM) technology. The main characteristics of BIM include illustrating 3D CAD-based presentations and keeping information in a digital format and facilitation of easy updating and transfer of information in the BIM environment. Using the BIM technology, project managers and engineers can gain knowledge related to BIM and obtain feedback provided by jobsite engineers for future reference. This study addresses the application of knowledge sharing management using BIM technology and proposes a BIM-based Knowledge Sharing Management (BIMKSM) system for project managers and engineers. The BIMKSM system is then applied in a selected case study of a construction project in Taiwan to demonstrate the effectiveness of sharing knowledge in the BIM environment. The results demonstrate that the BIMKSM system can be used as a visual BIM-based knowledge sharing management platform by utilizing the BIM technology.

1. Introduction

It is vitally important for project managers and jobsite engineers to obtain knowledge about construction and to solve any problems that may arise. To achieve this knowledge, jobsite engineers can learn from the experience of other jobsite engineers. Construction experience transfer involves using knowledge gained during the completion of previous projects to maximize the achievement of current project objectives [1]. In order to share knowledge between similar projects, construction professionals have traditionally used techniques ranging from annual meetings to face-to-face interviews [1]. In addition to experts' memory, construction experience can be recorded in various media, such as documents, databases, and intranets. Knowledge management (KM) is the collection of processes controlling the creation, storage, reuse, evaluation, and use of experience-based knowledge in a particular situation or problem-solving context. In construction, KM focuses on the acquisition and management of important experience-based knowledge provided by job engineers.

Regardless of whether a project executed by an architectural firm is successful, valuable knowledge can be gained and should be documented so that jobsite engineers can identify what worked and what did not. From the perspective of KM in construction, these experiences and the knowledge gained from them are valuable, as they are accumulated through large investments in manpower, time, and money. Most jobsite engineers agree that KM in construction projects is a vital tool construction management. The sharing of knowledge and feedback provided by jobsite engineers help to prevent mistakes that have been made in previous projects. Drawing on knowledge and experience thus eliminates the need to solve many problems from scratch.

Most recent construction projects in Taiwan have applied KM systems to improve construction management during the construction phase. However, most of the shared information during the construction phase is in the form of text-based information, with less focus on virtual illustration and sharing. In construction projects, KM may involve many important relationships between the presentation and retrieval

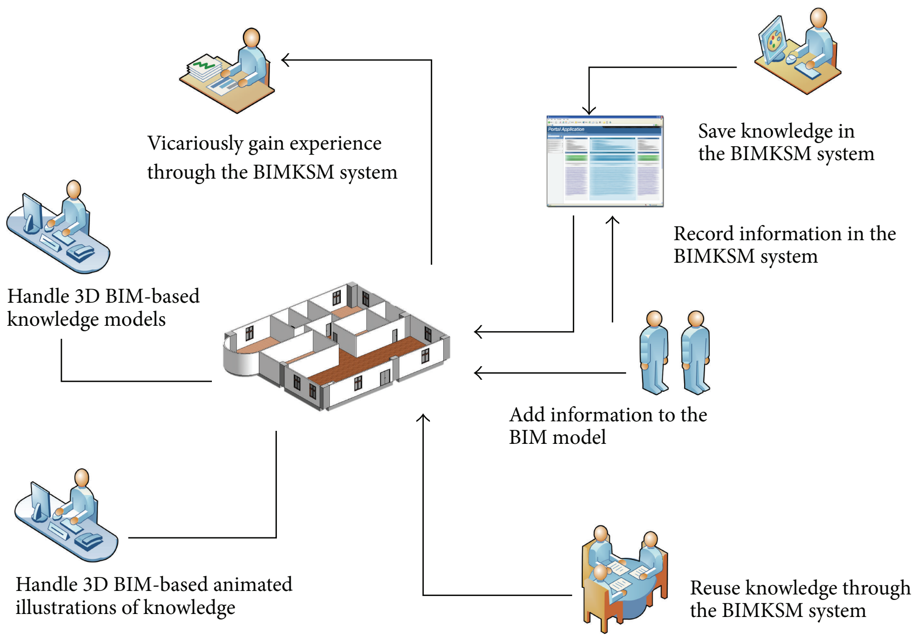


FIGURE 1: The application of the visual knowledge management in construction.

of knowledge and CAD. Furthermore, when knowledge is available for sharing, it is not easy for engineers to understand it directly without 2D or 3D CAD illustrations. Building Information Modeling (BIM) is the process of generating and managing data during the building life cycle [2]. BIM technology has the potential to enable fundamental changes in project delivery that will support a more integrated, efficient process [3]. BIM digitally contains precise geometry and relevant data needed to support the design, procurement, fabrication, and construction activities used to build 3D object-oriented CAD [4]. The main characteristics of BIM include illustrating 3D CAD-based presentations, keeping information in digital format, and facilitating the easy updating and transfer of information in a BIM environment.

The primary purpose of the study is to develop a way for jobsite engineers to effectively acquire, manage, and reuse knowledge gained from other jobsite engineers and integrated using the BIM technology within the 3D CAD environment. The study proposes a novel approach using BIM-based knowledge models integrated with the BIM technology to track and manage valuable experience-based knowledge. The main function of the BIM technology in this study is the 3D BIM-based illustration of experience-based knowledge. The proposed BIM-based animated illustration of knowledge is applied to keep and explain information in a digital format and to facilitate the updating and transfer of knowledge in the BIM environment. Using BIM-based animated illustrations of information, engineers can get an overview of previous scenarios in selected projects and use the knowledge gained for future construction work and understand the setup/process from their own professional perspective. Project managers and jobsite engineers can track and access the most recently shared information on relevant issues during the construction phase. Knowledge of various issues can be updated quickly and made available to each participant in the visual environment. This study addresses the application of knowledge sharing management and proposes a BIM-based Knowledge Sharing Management (BIMKSM) system for project managers and engineers. The research is a pilot study that involves applying the BIMKSM system for knowledge management to a building project in Taiwan (see Figure 1), in order to analyze and discuss the whole process of construction knowledge sharing management and to implement the KM sharing during the construction phase. The processing and content of construction sharing experience-based knowledge can be modified according to a project's particular characteristics. Finally, the BIMKSM system is then applied in a selected case study to verify the effectiveness of sharing knowledge in the BIM environment.

In sum, the purpose of this study is to (1) help jobsite engineers collect and share knowledge effectively through the BIMKSM system during the construction phase; (2) help engineers to refer to and exchange knowledge from the jobsite engineers using the BIMKSM system during the construction phase; (3) develop a web-based KM system to improve the exchange and tracking of knowledge for project managers and jobsite engineers.

2. Background Research

2.1. Knowledge Management in Construction. Knowledge management deals with collecting, modeling, storing, reusing, evaluating, and maintaining knowledge [5–7]. Numerous research efforts have focused on applications of knowledge management in construction. El-Diraby and Kashif [8] presented a distributed ontology architectural design developed by rigorous knowledge acquisition and ontology development techniques for KM in the highway construction industry. Hartmann and Fischer [9] described how project teams can use 3D/4D models efficiently to support the communication of knowledge during the constructability review on construction projects. Ribeiro [10] analyzed KM effort based on case studies and provided recommendations and insights for enhancing KM in construction firms. Chen and Mohamed [11] provided empirical evidence for the stronger strategic role of tacit KM in comparison to explicit KM. Kivrak et al. [12] used a survey to find out how tacit and explicit knowledge are captured, stored, shared, and used in forthcoming projects and to identify major drivers and barriers in knowledge management. Chen et al. [13] presented a knowledge-sharing model to determine whether risk mitigation based on the use of derivatives would be beneficial to the companies. Forcada et al. [14] presented a survey of perceptions of KM implementation in the Spanish construction sector and compares the results obtained from design and construction firms.

2.2. BIM Application in Construction. A great deal of previous research pertains to BIM issues in construction. Tse et al. [15] discussed the core barriers and recommended using BIM technology for construction industries. Mah et al. [16] proposed rapid computations of CO_2 emissions from various house sizes, designs, and materials integrated with BIM technology. Goedert and Meadati [17] extended BIM technology into the construction process to create a single repository of facility data for the owner. Succar [18] explored publicly available international guidelines and introduced the BIM framework as a research and delivery foundation for industry stakeholders. Dossick and Neff [19] examined the use of BIM technologies for mechanical, electrical, plumbing, and life safety systems. Ren et al. [20] proposed a framework for integrating BIM for quantity takeoff and cost-estimating applications with e-commerce solutions for material procurement and supplier performance evaluation. Davies and Harty [21] developed BIM-enabled tools to allow site workers using mobile tablet personal computers to access design information and to capture work quality and progress data on-site. Martins and Monteiro [22] developed BIM-based automated code-checking procedures and system for water distribution systems. Zhang et al. [23] developed automated safety checking platform integrated BIM that informs construction engineers and managers for preventing fall-related accidents before construction starts. Wong et al. [24] highlighted critical initiatives derived from the review of BIM implementations in both the public and private sectors in six selected countries. Bryde et al. [25] explored the extent to which the use of BIM has resulted in reported benefits on a cross-section of construction projects. Succar et al. [26] proposed the five BIM framework components for the design, construction, and operation (DCO) stakeholders to measure and improve their BIM performance. Sebastian and Van Berlo [27] generated an instrument for benchmarking BIM performance to provide insight into the current BIM performance level of design, engineering, and construction firms. Bynum et al. [28] investigated the perceptions of the use of BIM for sustainable design and construction among designers and constructors. Wang et al. [29] explored how BIM will beneficially support facility management in the design phase, such as space planning and energy analysis. Zhang et al. [30] proposed and verified Industrial Foundation Classes-based graphic information model as the foundation of data sharing in virtual construction systems and in other AEC/FM applications.

Although numerous knowledge management systems have been developed for the application of construction knowledge management, such systems typically exist for knowledge sharing using only text-based illustrations. To enhance construction-related knowledge sharing using a BIM-based environment, this study proposes a novel management system for project managers and jobsite engineers.

3. Methodology

3.1. BIM-Based Knowledge Management Approach. In this study, the proposed BIMKSM system facilitates visual knowledge sharing and management using the BIM technology during the construction phase. The BIM technology stores any problems, solutions, and comments, allowing project managers and jobsite engineers to access the most up-to-date knowledge. The primary advantages of the proposed BIMKSM system are (1) to effectively link knowledge using BIM-based graphic representations; (2) to promote relationships between areas of expertise via both vertical and horizontal graphic representations; and (3) to provide statuses of acquired knowledge of different situations using different colors.

Most knowledge can be classified as either tacit or explicit knowledge. Tacit knowledge is personal, context-specific knowledge that is difficult to formalize, record, or articulate. This type of knowledge is stored in the heads of people [31]. Tacit knowledge or experience is primarily developed through a process of trial and error in practice. Tacit knowledge that can be communicated directly and effectively is personal knowledge embedded in individual experience and shared and exchanged through direct, face-to-face contact [32]. In contrast, the acquisition of explicit knowledge is indirect; it must be decoded and recoded into one's mental models and is then internalized as tacit knowledge. Explicit knowledge can be codified and transmitted in a systematic and formal language. Explicit knowledge can be found in the documents of organizations, including reports, articles, manuals, patents, pictures, images, video, audio, software, and other forms. In this study, "tacit knowledge" refers to "hard" information that is visibly or invisibly related to part of an area of knowledge, including experience and know-how. Explicit knowledge is "soft" information that enables or facilitates the execution of specific information, including contracting, drawing, solving problems, or approving proposals. All jobsite engineers are responsible for sharing knowledge pertaining to their own domain. Any BIM model whose integrated information/knowledge sharing requirements have been noted will be classified as explicit in order

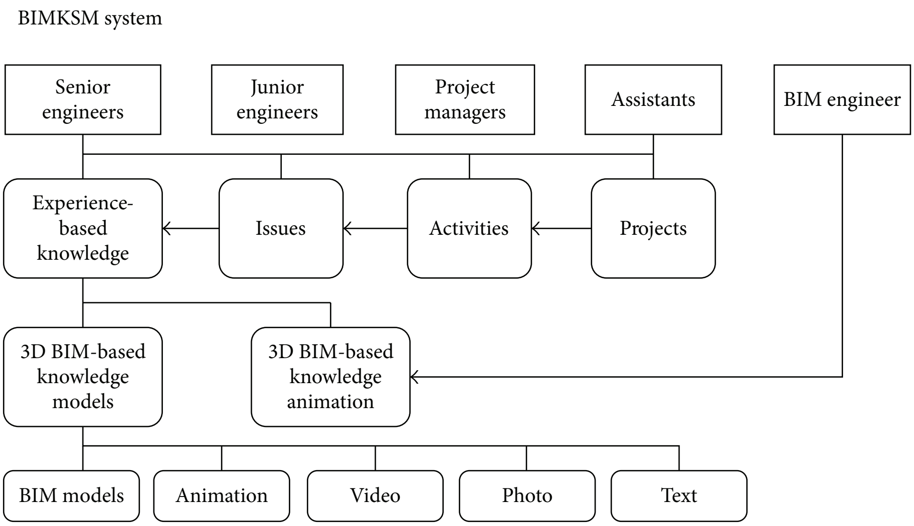


Figure 2: The concept and framework of the BIM-based knowledge models.

to allow relevant experiences and processes to be recorded. Therefore, the shared information associated with objects of BIM model can be referred to and reused in other projects.

Shared information from all jobsite engineers is divided and saved as "activity," "object," or "issue" for collection and management. The main advantage of BIM-based knowledge management is the ease with which information and knowledge can be understood and reapplied. Knowledge saved in the "issue" category includes both tacit and explicit knowledge. With respect to explicit knowledge, BIM-related information normally includes original comments, reports, drawings, documents, and comments submitted by jobsite engineers. In contrast, tacit knowledge may include process records, problems faced, problems solved, expert suggestions, know-how, innovations, and notes on experience. Such information is better saved in issue-based components to facilitate classification and searching by users. Information that relates to the whole project that cannot be easily classified into issue components is saved under the "project" category.

A BIM-based knowledge model can be defined as a graphic representation of experiences linking relationships between objects of the BIM model and aspects of experience-based knowledge. The BIM technology retains knowledge in a digital format, facilitating easy updating and transfer of knowledge into the BIM environment. A BIM-based knowledge model is designed to be easily integrated with experience-based information and objects of the model (see Figure 2). Information in the BIM-based knowledge models can be identified, tracked, and managed, and problems encountered during construction projects can be solved. The most up-to-date knowledge and solutions can be acquired from participating engineers and then shared and saved as objects of the BIM model for future reference. The model is constructed from variables that can be decomposed into objects of a BIM model and can then store the identified knowledge. Information stored in the objects of BIM models includes both facing problems and solutions. Facing problems may be knowledge issues, knowledge attributes, descriptions of problems, or knowledge attachments (e.g., documents, reports, drawings, and photographs).

3.2. Procedures of BIM-Based Knowledge Models Usage. The procedures for using BIM-based knowledge models are based on a knowledge management framework. The procedure consists of three phases: creating an issue, sharing knowledge, and updating said knowledge. Figure 3 presents the flowchart of the procedure of the knowledge models usage for knowledge sharing.

3.2.1. Issue Creation Phase. The initial engineer may determine which projects, activities, and issues are suitable for knowledge sharing. Furthermore, the issue must be set up by the initial participant (engineer) at the beginning of the phase. Such information under knowledge issues includes determining the type of knowledge, objects of BIM model, activities, and projects that should be assigned in association with the issue.

3.2.2. Knowledge Sharing Phase. After studying the published materials, all qualified and interested engineers are invited to edit and submit any knowledgeable comments they may have on the issue. All explicit knowledge prepared by engineers needs to be digitized by them or by assistants before it can be submitted to the BIMKSM system. All knowledge must also be examined and confirmed before publishing. All interested engineers can discuss problems related to selected issues and objects of the BIM model and seek responses from other engineers and managers through the BIMKSM system. Meanwhile, the engineers can direct responses either to individuals or a group. After tacit and explicit knowledge is saved in the system, all knowledge can be referenced and reused. Engineers can gain knowledge from the issues

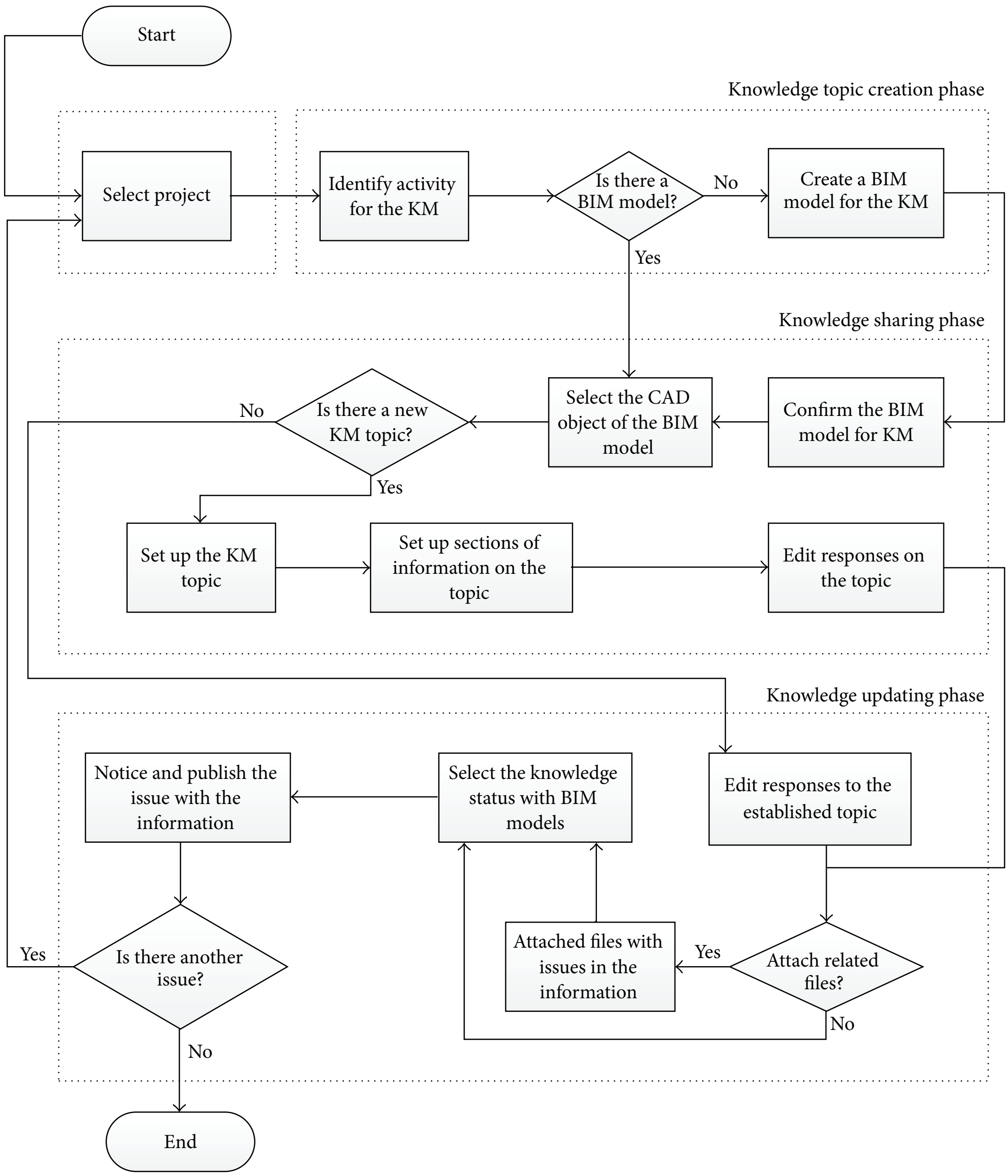


Figure 3: A flowchart of the procedure of the knowledge models usage.

catalogue of the objects and can access this catalogue for use in other similar projects.

3.2.3. Knowledge Updating Phase. After applying tacit and explicit knowledge to similar projects, the engineers can resolve their problems related to those issues. Finally, the engineers can note and submit the new tacit knowledge and record the experiences through which it was gained, and they can associate this information with the original knowledge. Furthermore, the information is updated again because further feedback and updated knowledge are provided regarding the issues. After the approval process has been completed, the updated knowledge set is republished to authorized members.

4. System Implementation

4.1. System Architecture. The BIMKSM system provides a user friendly portal for all project participants. It also serves as a real-time online communication channel for knowledge management. All data are stored and classified using BIM-based knowledge models. The BIMKSM system is a solution that uses a single unified database linked to BIM files with different levels of access granted to users based on their roles. Authorized participants can access the BIM-based knowledge models to update information on content relevant to the user's responsibilities in the project. When information is updated in the BIMKSM system, the server automatically sends e-mails to the project managers and jobsite engineers involved in the project.

The developed BIMKSM system runs on Microsoft Windows 2008 software with an Internet Information Server (IIS) as the web server. The BIMKSM system was developed using Java Server Pages (JSPs), which are easily incorporated with HTML and JavaScript technologies. The BIMKSM system server supports four distinct layers: interface, access, application, and database layers. Each layer has its own responsibilities. The interface layer defines administrative and end-user interfaces. Users can access information via web browsers such as Microsoft Internet Explorer or Google Chrome. Administrators control and manage information via the web browser or a separate server interface. The access layer provides system security, restricted access, firewall services, and system administration functions. The application layer defines various applications for analyzing and managing information. The database layer consists of a primary Microsoft SQL Server 2003 database. A firewall and virus scan can be used to protect the system database against intrusion. Users can utilize the BIM models in the BIMKSM system to request assistance or send word of a problem directly to the BIMKSM system to ask for further support.

In this study, the BIM model is interpreted as an information model in the BIMKSM system. The application of BIM models to acquire and store information about an object involve a description of the problem being faced, knowledge, comments, and attaching documents in the BIMKSM system. Autodesk Revit Architecture and Revit MEP were used to create the BIM model and files. Autodesk Design Review was used to read the files for BIM-based knowledge models. Also, Autodesk Inventor was used to create BIM-based animations to illustrate the knowledge. The integration of the information with the BIM models was achieved using the Autodesk Revit application programming interface (API) and the Microsoft Visual Basic. Net (VB.Net) programming language. The BIM-based knowledge models were developed in Autodesk Revit Architecture and Revit MEP by programming in VB.Net and using Revit API. All information in the BIM files could be exported to an ODBC database for connection with the BIMKSM system. Figure 4 shows the BIM-based knowledge sharing and management process flowchart in the BIMKSM system.

4.2. System Modules. All modules in the system are briefly described below.

4.2.1. Authority Setup Module. The authority setup module is an access control mechanism preventing unauthorized users from entering the system or retrieving sensitive information. The BIMKSM system requires all project participants (managers and jobsite engineers) to register by providing a unique user ID and password for authentication.

4.2.2. Knowledge Edition Module. Through this module, project participants can edit their relevant contributions to the objects in the BIM model. Generally, participants may create a new issue or contribute to those started by others in order to share their knowledge on various aspects of the project. The edited information will be saved in issues by categories associated with the relevant objects of the BIM model. Also, attached documents and report files must be uploaded in PDF format, the standard file format. The knowledge edition module allows experts and engineers to share issue-based tacit knowledge via a discussion forum.

4.2.3. Alert Setup Module. This module helps project participants set up an alert service for monitoring knowledge via e-mail. Dates related to any notification of new information are submitted or updated systematically and project participants can determine who is invited to submit knowledge.

4.2.4. Report Module. The report module allows users to easily access the summarized information to identify needs and analyze what has been recorded. The knowledge report can be illustrated with a BIM model, a description, and a summary of the information. Furthermore, all reports can be presented on the web or extracted to PDF format. This process allows users to make and organize knowledge-related reports from a central location.

5. Case Study

5.1. Case Study Introduction. In the following case, the architecture firm has had sixteen years of experience specifically in construction building projects. The architecture firm hoped to take full advantage of the BIM-based knowledge management system to facilitate knowledge exchange and management during the construction phase and reuse it in other similar projects. Therefore, the architecture firm announced that all jobsite and project managers would be encouraged to use the BIMKSM system to apply knowledge management in order to effectively manage acquired information during the construction phase in the BIM environment. The BIMKSM system was utilized in the construction project to verify the proposed methodology and demonstrate the effectiveness of sharing previous experience in the construction phase. The project used as a case study lasted 4 months. During the study, all jobsite and project managers were encouraged to explore and edit their own recorded experiences in the BIMKSM system. Figure 5 shows the BIM-based knowledge animation usage process. Figure 6 illustrates application of BIM-based knowledge models for knowledge sharing in the case study.

As previously mentioned, the case study was implemented in the middle of the construction phase. All BIM models used in the study were created and developed for the purpose of construction management. Finally, the BIM models were reused and applied for knowledge management.

First, the engineers were invited to explain their experiences and provide comments based on the issue and include relevant information and documents. The initial engineer created issues regarding the selected activity and objects of the BIM model in the initial phase. All related documents for this issue were collected and digitized by the senior engineers and knowledge assistants. After the issue was created, the senior engineers were invited to share their knowledge and comments related to the issue using the system. The posted files included digital documents, photos, and films.

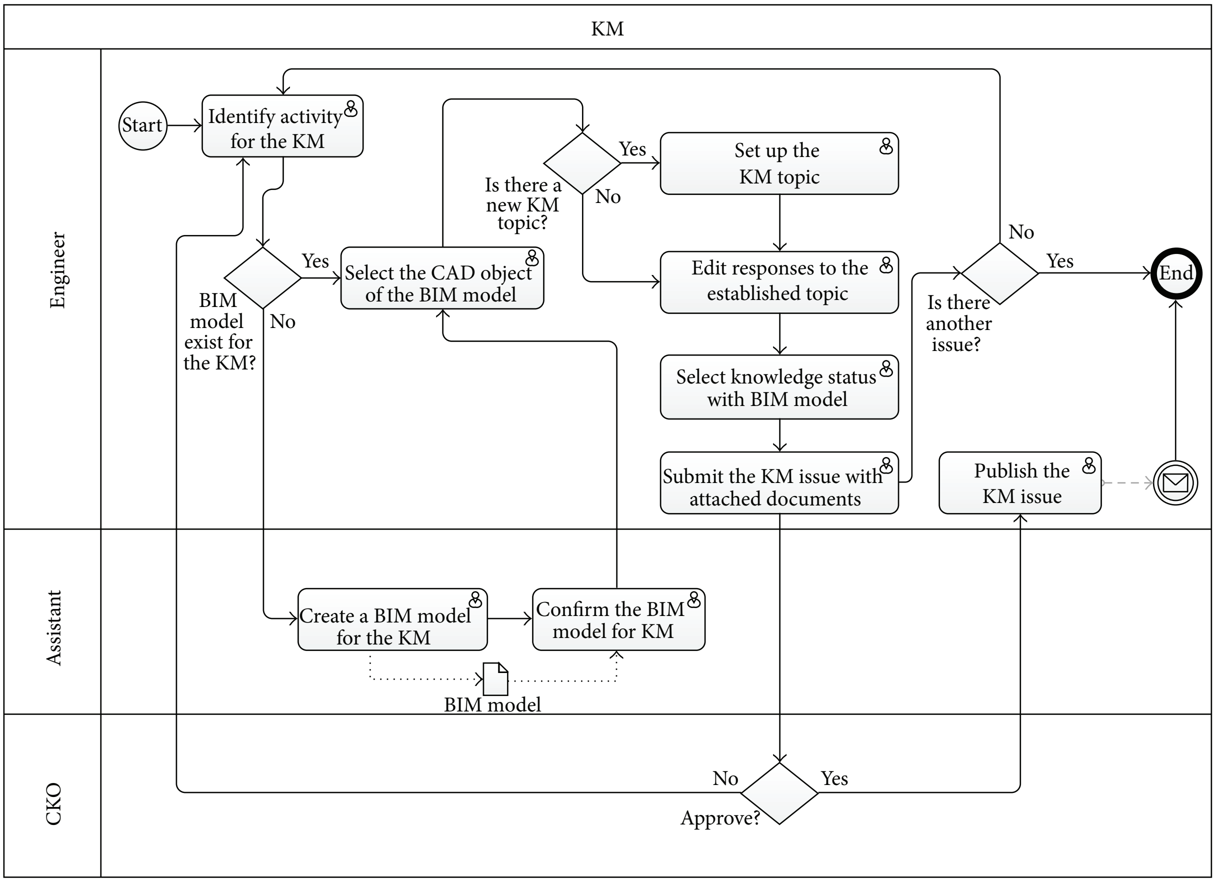


Figure 4: The BIM-based knowledge sharing and management process flowchart.

The knowledge assistants helped the senior engineers to digitize the content, and they then created the BIM objects related to the issue. The other issues were communicated in the same manner. All engineers were required to submit experience-based information and discussions regarding the issue via the BIMKSM system. The engineers read previous comments provided by others, learned from these records, and submitted their own comments via the BIMKSM system, which then allowed other engineers to discuss their work. The comments provided by the senior engineers included notes, actual problems/solutions, and suggestions. The engineers communicated problems and solutions to the senior engineers, posted their comments in the system, and shared their case discussions with others. The engineers were required to submit their knowledge pertaining to the BIM objects of the BIM model via the BIMKSM system. The senior engineers reviewed all questions and solutions and posted comments for all interested individuals. Furthermore, all information was stored in the central database to prevent the collection of redundant data. Finally, the information was automatically backed up from the system database to another database. Moreover, the knowledge was updated later because further feedback and another solution to the same problem were provided. The updated knowledge set was republished in the object of BIM model of the BIMKSM system after the approval process was completed. A notice message was then transmitted to authorized members.

5.2. Case Study Evaluation. Questionnaire results from the case study evaluation reveal that the BIMKSM system effectively shares knowledge. A verification test was performed by checking whether the BIMKSM system could perform tasks as specified in the system analysis and design. A validation test was undertaken by requesting selected case project participants to use the system and then providing feedback by answering a questionnaire. There were 18 respondents: two project managers with ten years of experience; six jobsite engineers with ten years of experience; seven jobsite engineers with five years of experience; two assistants with three years of experience; and one CKO with ten years of experience. The BIMKSM system was demonstrated to the respondents, who were requested to give their opinions on it by completing the questionnaire. Table 1 shows the results of the system evaluation.

Overall, the jobsite engineers' feedback for the case study was positive. Most engineers and project managers agreed that the BIMKSM system helps them to view all collected knowledge and experience in the BIM environment. Questionnaire results indicate that the primary advantages of using the BIMKSM system are as follows: (1) it provides 3D visual illustration of knowledge regarding project-based knowledge (86% agreed); (2) it provides BIM-assisted animation easily and effectively (89% agreed); and (3) it clearly identifies available knowledge and different status of different knowledge in the BIM environment (90% agreed).

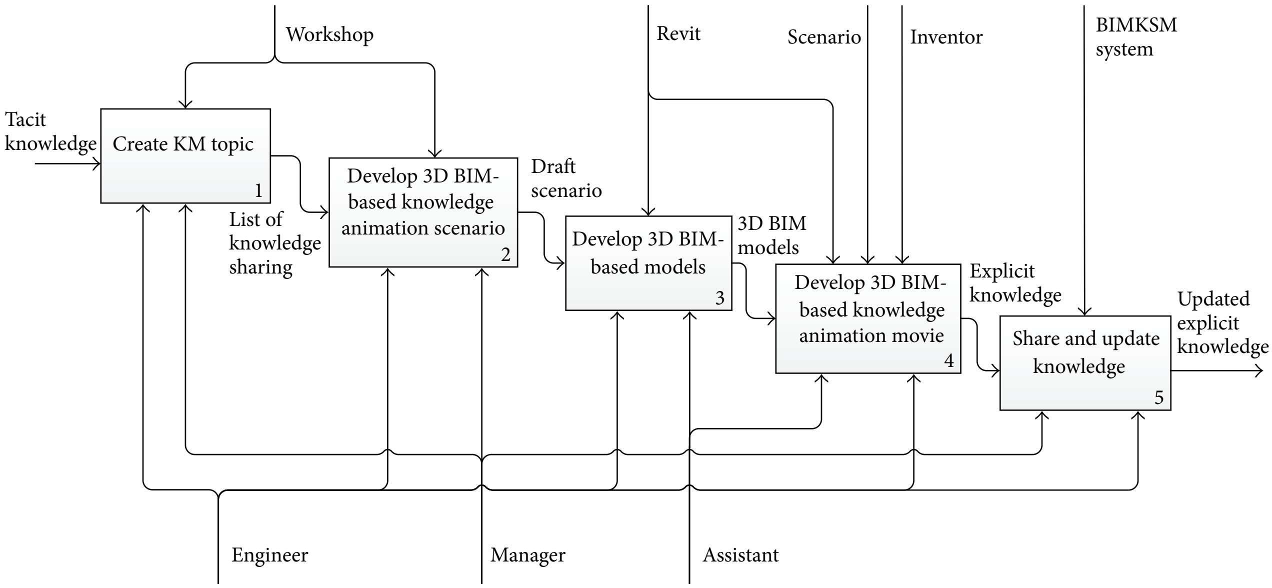
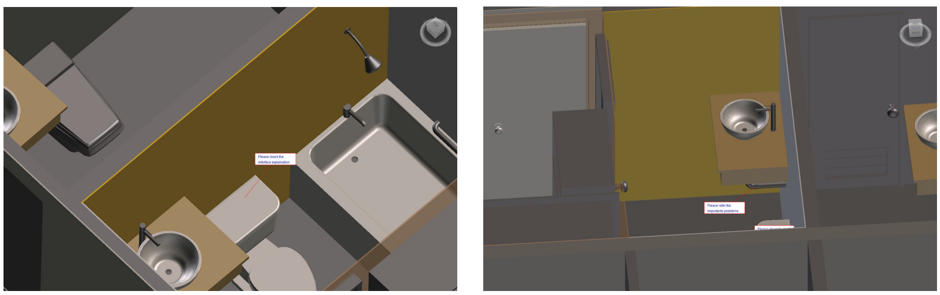


FIGURE 5: The BIM-based knowledge animation usage process.



(a) (b)

FIGURE 6: Application of BIM-based knowledge models for knowledge sharing in the case study.

TABLE 1: System evaluation results.

System evaluation item	Mean score
Enhances visual knowledge illustration	4.5
Applicability to construction knowledge management	4.8
Reduces rework percentage	4.2
Reduces percentage of mistakes occurring	4.3
Improves the knowledge collection	4.2
Enhances knowledge communication	4.4
Improves knowledge sharing	4.7
Enhances learning performance	4.3

The mean score is calculated from respondents' feedback on a five-scale questionnaire: 1 (strongly disagree), 2, 3, 4, and 5 (strongly agree).

Questionnaire results indicate that the primary advantages of the application of BIM in BIM-based knowledge models are as follows: (1) it provides clear 3D representations, thus identifying knowledge and experience feedback relevant to an object or activity (92% agreed); (2) one can generate a visual object of BIM model illustrations of knowledge, thus identifying acquired knowledge and experience feedback relevant to tasks and projects (90% agreed); (3) it allows one to view knowledge and information provided by jobsite engineers easily and effectively (90% agreed); and (4) it enables engineers to trace and manage any acquired BIM-based knowledge feedback (88% agreed).

User feedback indicated that the primary barriers to using the BIMKSM system were as follows: (1) insufficient updated information is related to different types of knowledge; (2) substantial amounts of time and assistance are needed for engineers and managers to use BIM software to edit and update knowledge feedback; (3) further effort is required to update information related to various objects of a BIM model or the activities in a project; (4) the senior and jobsite engineers require substantial time and assistance to edit knowledge feedback in BIM environment; and (5) few engineers do not accept BIM applications in the construction sites.

6. Conclusion

To improve construction knowledge sharing in building projects, this work presented and developed the BIMKSM system as a visual platform. The BIMKSM system illustrates knowledge with problem descriptions and solutions in the BIM environment. BIM is a highly promising means of enhancing knowledge management during the construction phase of a project. Collecting problem descriptions and solutions using the BIM technology allows project managers and jobsite engineers to contribute and share the most up-to-date knowledge and experience regarding problems and solutions in construction. The BIM technology generates 3D drawings, thus identifying valued experience-based knowledge relevant to issues and activities. Additionally, BIM provides objects and illustrations when knowledge is available. The BIMKSM system collects specific problem solutions and supports all information across projects. Overall, field test results indicate that the BIMKSM system is an effective and simple platform for knowledge management in construction projects. The case study results demonstrate the effectiveness of a BIMKSM-like system for KM due to its incorporation of BIM and web technologies during the construction phase.

The concept of a BIM-based knowledge management system was presented, as was a system for use as a knowledge-sharing platform in construction design-build projects. The application of BIM-based knowledge management system mainly allows project participants to access the knowledge easily and effectively. Although effort is required to update information on various problems and solutions, the proposed system benefits KM by (1) developing web-based BIM-assisted knowledge management system for construction knowledge sharing, (2) providing an effective and efficient method to assist and manage visual KM work, (3) enabling users to learn knowledge through BIM-based knowledge animation.

In sum, the engineers were able to increase their understanding of previous captured knowledge and experience from all participants working on different projects. Notably, BIM integrates the objects comprising knowledge management work by incorporating external factors, such as problem and solution descriptions, comments, and suggestions, into a single source for all construction BIM-based KM information. Effectively utilizing web technologies and BIM during the construction phase allows project participants to enhance knowledge sharing for domain knowledge management. The case studies also show that a BIMKSM system can provide a web-based visual BIM-assisted knowledge sharing management platform.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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Review Article

How Can Clients Improve the Quality of Transport Infrastructure Projects? The Role of Knowledge Management and Incentives

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The aim of this paper is to argue for a number of statements about what is important for a client to do in order to improve quality in new infrastructure projects, with a focus on procurement and organizational issues. The paper synthesizes theoretical and empirical results concerning organizational performance, especially the role of the client for the quality of a project. The theoretical framework used is contract theory and transaction cost theory, where assumptions about rationality and self-interest are made and where incentive problems, asymmetric information, and moral hazard are central concepts. It is argued that choice of procurement type will not be a crucial factor. There is no procurement method that guarantees a better quality than another. We argue that given the right conditions all procurement methods can give good results, and given the wrong conditions, all of them can lead to low quality. What is crucial is how the client organization manages knowledge and the incentives for the members of the organization. This can be summarized as "organizational culture." One way to improve knowledge and create incentives is to use independent second opinions in a systematic way.

1. Introduction

Cost, time, and quality are the three main dimensions when project results are evaluated. In this paper, the focus is only on the last of these three: how can quality be improved and what can be done to avoid quality problems? As discussed in Warsame [1] quality in relation to construction projects can be given different meanings. A first distinction is between quality of product and quality of process. In this paper, the focus is on the quality of the product. Another important distinction is between quality as an absolute concept in relation to certain standards and quality as a relative concept where quality is related to what the client had ordered and/or what the client reasonably could expect, given the price they are willing to pay. In this paper quality is used in this relative sense, which more generally can be described as how to get "value for money."

The debate about quality improvement is going on at different levels: from the more practical to the more general. Choice of procurement method is one question on the more practical level [2], while knowledge management and creation of incentives in the organization are questions of the more general level [3]. A main notion in this policy paper is that the more general level is the most important.

The focus of this paper is on infrastructure projects where there is a large public client like the Swedish Traffic Administration which is responsible for both roads and railways and has an operating budget of 50 billion SEK for 2010 (around 5 billion €).

We will argue for three statements: the first one is that "quality is up to the client," and this is developed further in Section 3 below. The second statement is a negative one and says that there is no clear relation between *procurement* *type* and quality (see Section 4). The third and more positive statement concerns two crucial interdependent dimensions for getting high quality: *knowledge* and *incentives* (see Section 5). The famous Swedish builder Olle Engkvist wrote the following in a book from 1949 (translated by authors):

> *That a low-quality building ever is constructed depends on that the builder either lacks one or several of the necessary qualifications for the trade, or that the profit motive is so dominating that it overshadows all other interests. [5, page 9]*

In a governmental organization, it does not have to be the profit motive that creates problems, and the term can be exchanged for "ulterior motives" in general, for example, political ones. This is developed further in Section 5. Concluding comments can be found in Section 6.

2. Method and Conceptual Framework

The paper tries to synthesize both theoretical and empirical results. There is very large literature in this area, but we hope that the selection made covers the most important arguments and results. Our aim is to try to present theoretical and empirical arguments that make the statements presented above convincing. Future debates will determine to what extent we have succeeded. From a broader methodological perspective the approach is closest to the ideas of Karl Popper as the propositions presented can be seen as "conjectures" that, according to our view, have so far not been refuted [6].

The theoretical framework used is general contract theory and transaction cost theory, where assumptions about rationality and self-interest are made and where incentive problems, asymmetric information, principal agent problems, and moral hazard are central concepts. The concepts and ideas from these theories will be presented a little more in detail in Sections 4 and 5 below when procurement is discussed.

3. Why Quality Is up to the Client?

It is possible for a nonexpert to know the quality of a new car reasonably well, but it will be argued here that a traffic authority cannot rely on "the market" if they want to build a road with a certain quality.

The car is typically produced in a large volume in a plant with strict control of the production process. The company has produced cars over a number of years. As the life of a car is rather short, it is possible to collect information quickly about the quality of a certain brand and a certain model. In a country like Sweden where cars have to be inspected every year, a lot of third party data are published on faults in all car models. The result of this is that the household does not have to be an expert or even consult an expert when they buy a new car (with old used car the situation is different, e.g., [7]). Tests of new cars are also regularly published in both general and specialized newspapers.

A section of, for example, a road is instead typically

(i) produced "in the field" where surveillance can differ considerably and where external factors can affect the quality of a specific construction;

(ii) produced by a group of people that change more or less from project to project. If company A does a good job in project 1 in region 1, it does not mean that company A will do a good job in project 2 in region 2 since different group of persons will produce the road. Big construction companies are typically rather decentralized (see e.g., [8]);

(iii) a product where it takes a rather long time to find out if there are quality problems, and it might not be the case that company A today is as bad as it was maybe 10 years ago when the road was constructed.

All this means that the mechanism used by the buyer of a car is difficult to use for a client responsible for an infrastructural project. In the rest of the paper, it is therefore assumed that the market feedback mechanisms in infrastructure construction projects are too weak to be relied upon only. The client must then use more direct methods to assure that a certain quality will be delivered.

This view of the role of public client has been underlined by several authors, even if the theoretical background to their statements is not so clear. The procurement of these assets, and proper operation and maintenance require a client workforce with strong competence, skills, and experience. Ward et al. [9] stress that client's stock of experience and advice received are crucial. Public clients need to maintain enough skilled and competent workers and management in order to manage risks and safeguard public interest of construction projects [10, 11].

4. Procurement Types Have No Determinate Consequences

4.1. Design Responsibility and Quality. The tendency in many countries seems to be moving away from making the design in-house to using external consultants. There can be several explanations for this; for example, fluctuations in the number of projects make it difficult to employ an in-house workforce, and this problem is increased when the workforce becomes more specialized. It might also be more difficult to create strong incentives in an in-house organization. In Warsame [12], there is a more general discussion of the trend away from both in-house technical specialists and in-house construction workforce among developers and public authorities.

Independent of the reason for this development, the discussion here will focus on a comparison between the case where the *client* hires a technical consultant to doing the detailed design and the case where the *contractor* works together with a technical consultant and do the detailed design. Notice that the arguments against the client/developer having their own staff also are relevant for the question whether the *contractor* has an in-house staff or not. This means that it might be the same companies and individuals that make the detailed design independent of whether the client or the contractor is responsible for the design. The question of the skills of the technical consultants doing the work should then not be an argument that points in a specific direction when it comes to who should be responsible for the detailed design.

A classical work on economic organization, Milgrom and Roberts [13], describes the general problems in an economy in terms of achieving *coordination* and creating *incentives*. These aspects seem highly relevant for the choice of who should do the design.

(i) From a *coordination* perspective, the rational choice would be to let the contractor be responsible for the detailed design as the design then can be adjusted to the technical competence of the contractor and the design can be carried out with more knowledge about the construction process.

(ii) From an *incentive* perspective, the rational choice would be to let the client be responsible for the design. If the technical consultant works for the contractor, there should be pressure on the consultant to choose cheaper solutions within the limits set by the standards laid down by the client. It might be difficult to know and observe the exact quality of all technical alternatives, and some incompleteness or vagueness can be expected in the client's standards, and this opens the door for the contractor to influence the design in the direction of cheaper solutions with somewhat lower quality.

A counterargument against this is that stronger incentives for the contractor to choose the "right" solution might be created if the contractor also is responsible for operation and maintenance. This will be discussed more in detail below, and for now it is, assumed that the contract only concerns the construction phase.

The implication of the arguments above is, of course, that things might go wrong in both alternatives. If the client is responsible for the detailed design and does not have enough knowledge of the production phase, there will arise a need for redesign and costly adjustments. CIOB [14] underlines the importance of completeness and clarity of client's needs and objectives when they are responsible for the design phase. The overall quality might also suffer if the design is not adjusted to the skills of the contractor. On the other hand, if the contractor is responsible for the design, there might be a risk that alternatives with lower cost and quality are chosen if the specifications and the monitoring by the client are imperfect.

A client who is aware of these potential problems can however mitigate them, at least partly. If the client is responsible for the detailed design they—and/or the technical consultant—may build up knowledge of the construction phase in order to reduce the risk for coordination failures. If the detailed design is made by the contractor, the client may be more careful with the specifications, or for some components where quality is difficult to evaluate expost, the client might simply say that this is the component that should be used. If the reputation of the contractor is important for the choice of contractor in forthcoming projects, it might also be risky for the contractor to choose a cheaper alternative with lower quality as this might reduce the probability of future work for the client.

We also see here that the line between the alternative procurement types becomes vaguer. A knowledgeable client may, even if they are responsible for the detailed design, leave some room for adjustments of the design after the contractor is chosen in order to take advantage of the comparative skills of the chosen contractor. On the other hand, if the client's specifications become more and more detailed in the case where the contractor is responsible, then the room for the contractor in the design stage might be rather small, even if they formally are responsible for the design.

4.2. Quality and the Integrating of Construction and Operation/Maintenance. In recent years, a number of theoretical studies have pointed out that bundling construction and operation/maintenance can lead to higher efficiency, as is done in, for example, different forms of public private partnering projects (PPP). No distinction will here be made between different forms of contracts where construction and operation/maintenance are bundled, for example, differences in how the project is financed and how the contractor is paid.

Bennett and Iossa [15] and Martimort and Pouyet [16] pointed out that this type of bundling leads to higher efficiency because coordination between construction and maintenance can be improved. The design can in a better way take into account consequences during the operation/maintenance stage, and this reduces life-cycle cost. Better knowledge of how the construction works have been carried out can also lead to operation/maintenance measures that are better adjusted to how the facility was built.

Another important feature of these long-term bundled contracts is that they, at least partly, are formulated in performance terms. The client sets up a number of performance criteria that the facility should fulfill over time, and the payment to the contractor is dependent on that these conditions are fulfilled.

The potential from a quality perspective of contracts that bundle construction and maintenance is clear: the responsibility for supplying the quality that is stipulated in the contact is completely in the hands of the contractor, and their payment is dependent on that they produce a service with this quality.

As argued in, for example, Lind and Borg [17], there are a number of general problems with realizing this potential in bundled contracts, for example, how contractors can collect and transfer knowledge within their organization about how operation and maintenance costs are related to how the facility was constructed. Here the focus will, however, be on issues more directly related to the quality of the object.

The *first* main problem is the possibility of describing the quality that the client wants in a way that is possible to measure in a rather objective way. Robinson and Scott [18] point out that the description of services in PFI/PPP projects typically lists a large number of characteristics and that this has still not been enough to get the contractor to produce what the client really wanted. The quality of the facility, in some dimensions, was not the expected one because it was difficult to write a contract that was complete enough. Their general message is that describing service quality is very difficult and that a lot of resources must be put into specifying service quality. Guo et al. [19] also points out measurement problems in a contract with functional demands.

A *second* contractual aspect that can be problematic in performance based contracts is the verifiability of the specified characteristics. Lind and Mattsson [20], evaluating an experiment with performance based bridge maintenance, show that there were often disagreements between client and contractor about whether the characteristics specified in the contract were fulfilled or not.

In general, one can say that writing complete long-term contracts is a very challenging task and that there are bound to be mistakes or lapses that can lead to lower quality than expected in the objects; see, for example, Milgrom and Roberts [13] for a discussion on conditions for complete contracts and why they are difficult to fulfill.

A *third* general problem with long-term bundled contracts is what happens over time. The theoretical studies typically assume that there is a completely binding contract and that the contractor has a real long-term responsibility for the object. There are several problematic assumptions behind statements like these.

The first assumption is that there will be no renegotiations of the contract. Renegotiations have been common in Latin American PPP projects [21]. Even if they focus on payments and cost-overruns, the same problem might occur concerning certain quality aspects. A contractor with good political connections may be able to renegotiate and get the client to accept a lower quality than the one originally stipulated.

A second assumption is that the contractor will not sell the project. In recent years, a number of infrastructure funds have been started that are buying PPP projects (see, e.g., [22]). Initially the project is owned by a construction company, but when the project is completed, it is sold to an investor. This might seem logical from a comparative advantage perspective as the construction company has their advantages in the initial stages of the project. If the contractor plans to sell the project, the incentives for the contractor to choose techniques that minimize life-cycle costs are reduced as there will be asymmetric information between the contractor and the new investor. The contractor might build with lower quality in dimensions that are difficult to evaluate for a buyer, and this creates higher operating and maintenance costs later on. Entering PPP projects is also risky, and the private party might have underestimated the costs and/or overestimated the incomes. Studies have shown that when an actor gets under financial pressure they tend to reduce quality (see [23] for an example from the retail sector).

4.3. Concluding Discussion of Procurement Types. The proposition in this part of the paper—that quality is independent of choice of procurement type—has, as far as we know, not been formulated as clear and straightforward as here, but there are statements that are very much in line with our views. Many authors discuss in what situations a certain procurement type is best, but typically the statements are vague and very guarded, which is what we should expect given the views formulated above.

Ashworth [24] writes

> *Individual experiences, prejudices, vested interests, familiarity, the need and desire for improvement are all factors that have helped reshape procurement in the construction industry. (page 298)*

> *The arguments for engaging either a consultant or a constructor as the client's main advisor or representative are to a large extent linked with tradition, fashion, loyalty and the satisfaction or disappointment with a previous project. (page 295)*

This means that one client might go from procurement type A to procurement type B in order to increase quality, while another for the same reason moves in the opposite direction. And this should not be surprising if the direct relation between procurement type and quality is weak.

In a similar way, Lædre et al. [25], for example, writes "A client's choice of procurement method, among other factors, could be influenced by the client's familiarity and prior experience with that method as well as the level of client involvement required by the selected method." The same point is made in HM Treasury [26]. Molenaar and Songer [27] underline the role of public agency's staff and experience to the success of projects procured in DB delivery method, which implies that during some circumstances this method might work well but not in other circumstances.

In the literature, one can find statements that each procurement method has advantages and disadvantages and that they are suitable for different situations. Accordingly, the proposition can be formulated in other ways. The most general one is to say that there is no quick fix when it comes to improving quality in infrastructural projects. In other words, there are no simple deterministic relations between underlying factors and the quality that will result in a project. Kwame et al. [2] found that rework causes do not differ relative to various procurement methods. Thus, there is no procurement method that guarantees a better quality than another.

It has been argued that if a client has low technical competence, then choosing design build (DB) procurement would be better as the client then only has to specify the characteristics of the final product. The first counterargument is that if you do not have technical competence, it will be very difficult to specify all relevant characteristics of the object. The second counterargument would be that the client could just as well contact a technical consultant and make the detail design together with them, and then use a DBB procurement. A client that has good relation with a technical consultant would probably choose the second alternative while a client with good experience from working with a specific contractor would choose the first option.

5. The Importance of Knowledge Management and Incentives

In the last section, it was argued that choice of procurement type will not determine quality. In the following sections, the focus is on what we think is important: knowledge management and creating the right incentives.

5.1. General Definition and General Types of Knowledge. According to Nonaka and Takeuchi [4], knowledge can be classified as explicit and tacit. Explicit knowledge is described as knowledge that can be precisely and formally articulated. It is easily codified in different formats that would allow for documentation, transfer, sharing, and communication. Tacit knowledge is a knowledge that comprises experience, and work knowledge that resides only with the individual and is difficult to formally articulate. Pathirage et al. [28] claim that tacit knowledge based on skills, experience and talent of people is considered to be relatively unexplored and underutilized when compared to the work on explicit knowledge. Information technology tools often address the explicit knowledge while non-IT tools address the tacit knowledge.

This distinction between knowledge of different types has shaped the strategies of *knowledge management* followed by different organizations [29]. There are numerous definitions of knowledge management, but here the definition of Scarbrough et al. [30] cited in Al-Ghassani et al. [31] will be used. It combines both the process and outcome perspectives of knowledge management. It states that *knowledge management is any process or practice of creating, acquiring, capturing, sharing, and using knowledge, wherever it resides, to enhance learning and performance in organizations*.

C. Gore and E. Gore [32] suggest a strategy of organization's knowledge management that combines the use of current explicit knowledge, capturing new explicit knowledge, and externalization of tacit knowledge. Egbu and Robinson [33], based on Nonaka and Takeuchi's theory of knowledge creation, also describe four distinct modes of interaction between tacit and explicit knowledge: socialization, externalization, internalization, and combination (see Figure 1).

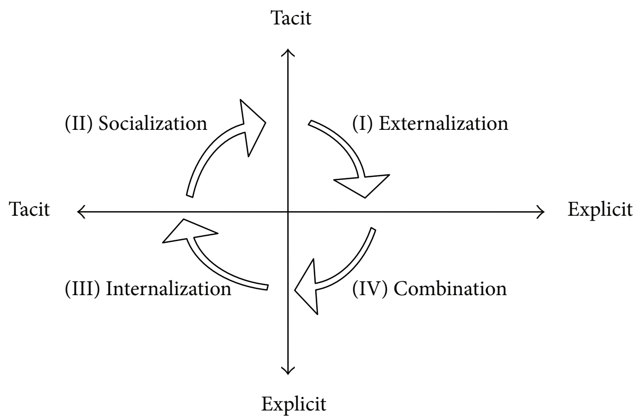

Figure 1: Knowledge conversion modes [4].

A designer's explanation of design concepts to client is tacit to tacit interaction, and it takes place through the process of *socialization* (2nd quadrant). Apprenticeship and mentoring schemes between senior engineers mentoring junior engineer is another example of tacit to tacit interaction. Such experiential knowledge is nurtured through shared experience and continuous interaction [33]. Next the designer uses manuals on design standards and interprets these explicit documents to a unique design that could satisfy the needs and the requirements of clients. This knowledge transformation from explicit to tacit is termed *internalization* (3rd quadrant). When the architect/designer translates a design concept into sketches in order to explain to the client, the architect transforms tacit knowledge to explicit and is called *externalization* (1st quadrant). Another example of externalization process is when a junior engineer transforms the tacit knowledge that he or she gained from senior engineer through the socialization interaction to explicit knowledge. The 4th quadrant represents the *combination* process where explicit to explicit interaction takes place. Knowledge is created through integrating and processing of different documents such as design briefing and sketches, performance and standard specifications, and estimates and contract requirements.

Both socialization and externalization are required to create an ever-growing body of organizational routines [34]. Quality circles and task forces that are widely used to enhance total quality and continuous improvement are examples of externalization processes creating firm specific routines [34].

5.2. Knowledge Management in Practice. From a knowledge management perspective, the following components can be identified and are, as we see it, all necessary conditions for an authority to be able to reach high quality.

(1) *The building up of long-term explicit knowledge through research.* The authority needs research in order to improve their knowledge. It has to be active in procuring and/or doing their research on issues of long-term importance. The Swedish Traffic Board, for example, procures result from a large number of researchers every year.

(2) *The building up of knowledge through tests*. in order to become more sure about how a certain system would work, various solutions have to be tested in practice, and systematically documented.

(3) The *building up of knowledge through cooperation with foreign experts and consultants.* Scanningwhat others do and pooling knowledge with other organizations and firms are examples of this. There is for example, long-term cooperation between Nordic traffic authorities and broader cooperation within various EU-projects.

(4) *The building up of a systematic management of the organization's own experience.* As the typical transport authority handles a large number of procurements

and projects, it is important to underline the need for continuous monitoring of how different projects worked out.

5.3. The Importance of Incentives. Many organizations have recognized that the success of knowledge management depends on people and their behavior [35]. Employees must be sufficiently motivated to share knowledge [36]. Teerajetgul and Charoenngram [37] emphasize how incentives or reward could significantly affect internalization of the knowledge creation process. They state that the vision and aspiration of construction managers in applying creativity in on-site knowledge practices play crucial role on the strength of knowledge management. The question is how to create incentives for individuals to build up, share, and reveal relevant knowledge and information that could be useful in improving the performance of projects. Osterloh and Frey [34] suggest that organizational forms that emphasize participation and personal relationship are needed. However, the answer for the above question also requires a deeper discussion about incentives, and here the economic approach is the starting point.

Milgrom and Roberts [13] attempted to synthesize management theory and economic theory, but the base is clearly in economic theory (microeconomic theory, contract theory, and transaction cost theory). One central starting point in Milgrom and Roberts' economic approach is that the basic unit for understanding how organizations work is the individual. One has to understand the incentives of individuals in different parts of the organization in order to understand how the organization works.

Incentives can be of many different kinds. There might be internal incentives where people do certain things just because they want to do a good job and sustain a certain image of themselves. Ellingsen and Johannesson [38] discuss this from this perspective of why people, for example, give tips to taxi-drivers when travelling in a foreign country, where they never will meet that driver again. Incentives can also concern career opportunities: if I do certain things today, it increases the probability to come to a higher position and get more money, a more interesting job, and/or more power in the future. Of course, incentives can also concern short-run gains including both economic bonuses and positive feedback from colleagues and superiors.

5.3.1. Precondition 1: Knowing Who Did What. An important precondition for creating stronger incentives is that it is possible to know who did what. Carrillo [39] argues that peer recognition of employee's contribution and acknowledgement of individual's achievement such as manager of the year award has a more sustainable impact than financial reward. It is in this respect interesting to compare, for example, what information is presented when a movie is ready and what information is presented when a construction project is ready. At the end of the movie, hundreds of names are presented giving information about who did everything from directing, producing, and acting, to being the driver and the assistant to the actors. This information is available "forever."

But assume that after a few years someone wants to know who did what in a construction project? Finding out who was the architect and what companies were responsible for what might not be so difficult, but that does not apply, for example, for the site manager and also for who was responsible for installing the electric system and who painted the walls inside the building? An important precondition for creating stronger incentives during all the different stages from planning to construction would then be a systematic recording of who did what in a project.

5.3.2. Precondition 2: Repeated Games. One of the strongest ways to create incentives is through "repeated games" (see e.g., [40]). If you do a good job, the probability of getting hired again and getting a better and better paid assignment increases, and the opposite happens if you do a bad job. In a number of sectors in the economy, this type of incentive mechanism is the dominating one. The movie industry is an obvious example mentioned above. Lindahl and Leiringer [41] analyze project management in the event industry where teams are put together for each specific event. One central criterion is that if a person did a good job at an earlier event, then that person is trusted to be responsible for setting up the event.

Looking at infrastructure construction from the perspective of repeated games, it is possible to see several problems. The first concerns the relation between the client and the contractor in the public sector. In a comparison between procurement by private and public clients in the housing sector, one result was that the private clients preselected 2-3 companies according to their earlier experience and knowledge of the companies (see, e.g., [42]). If the client was dissatisfied with a company, then this company was deleted from the list. The public client worked under the Law of Public Procurement and had open tenders, and they had to follow strict criteria both in the prequalification stage and when choosing contractor.

The second problem from the perspective of repeated games is that on the client side the staff on all levels is hired by standard employment contracts with fixed wage. The level of employment protection is high in countries like Sweden which means that the direct difference for the employee between making a good job or not from the perspective of long-term quality can be small. The question is then how incentives can be strengthened *within* a public authority.

5.3.3. Incentives in a Public Administration. The purpose of this section is primarily to give examples of how things should not work and how they might work. The following is a stylized example of a structure where incentives for quality are not so strong (the example is partly inspired by the discussion in [43, Appendix 1].

> *Election time is closing in and it is very important for the government to show both that they are starting up projects and finalizing projects that are important for winning the elections. Projects then have to start up quickly without enough preparations. The civil servants working with the*

> *cases, somewhat disillusioned from earlier cases, also knows that there will be a number of changes and adjustments later in the project, so there is no point in putting in maximum effort concerning the design in an early stage. Civil servants that might have protested against certain "bad" decisions earlier are seen as troublesome and causing delays and have more problems to get promotions. Most employees remain quiet and shrug their shoulders knowing that problems will come later.*

The importance of things working smoothly and of avoiding conflicts can also affect the work during the construction stage, for example, saying yes to proposals from the contractor even if there is a risk of lower quality [44]. Warsame [1] describes different "decision styles," and several of these underline the importance of consensus and avoiding conflicts, and this can lead to client representatives accepting lower quality than actually contracted and/or higher risks for quality problems.

All these things can be described as part of a "company culture," and *creating the right culture is important for the long-term quality of the projects*. The culture in the authority, together with their competence, will affect the incentives for consultants, contractors, and contractors, that—to simplify somewhat—do what it is necessary to survive in the market rather than what is essential to the long-term quality of the project.

In a public authority, the politically chosen board, and leading politicians on all levels, is of course in the end responsible for how the authorities work. These "final" decision makers send out signals about what they approve of and do not approve of, and these signals behavior will affect the company culture in the authority. But, of course, also public employees on all levels have a responsibility towards the taxpayer and citizens to contribute to an efficient use of resources in the public sector.

5.4. "Second Opinions" as a Crucial Instrument. One way to both improve knowledge and creative incentives is to use "second opinions" from external actors in a systematic way during all stages of an infrastructural project. This is already done in some countries to avoid cost-overruns in large infrastructure projects (see [45, 46]), but broadening this to include other aspects including possible quality problems seems to be one promising way to both improve knowledge on possible consequences of various changes and create incentives. Knowing that your proposal will be evaluated by an external reviewer and that this will be documented and be available for others should increase effort and make it easier to evaluate the quality of both departments and individuals.

This will increase cost and could cause some delay in the processes, but the assumption here is that the gains will be bigger than the costs. Choosing the external reviewers is also a problematic issue, and it is rather obvious that if the top management does not take the external review seriously, it will always be possible to find "yes-men."

6. Conclusions

Public client organizations typically act as the owner and the party who instigated a project for the benefit of society. In order to ensure that a desired project performance is achieved and provide better infrastructure projects, it has been argued that the public client's "organizational culture" is the most important, and the core of this culture should be a focus on knowledge management and creating incentives, for the desired behavior in the organization. A central instrument for top management to signal this is to systematically work with "second opinions" from independent actors in a form adjusted to the size and specific stage of the process.

This also implies that, for example, the choice of procurement types cannot by itself improve project performance. Without knowledge and the right incentives it is unlikely that any procurement type will lead to high quality results and an organization with the right knowledge and incentives can adjust any procurement type to the situation and make it work.

Finally, let us repeat that these statements are not "proven facts" but conjectures that we have argued are consistent with both theoretical and empirical studies concerning quality in infrastructure projects.

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Research Article

Developing Mobile- and BIM-Based Integrated Visual Facility Maintenance Management System

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Facility maintenance management (FMM) has become an important topic for research on the operation phase of the construction life cycle. Managing FMM effectively is extremely difficult owing to various factors and environments. One of the difficulties is the performance of 2D graphics when depicting maintenance service. Building information modeling (BIM) uses precise geometry and relevant data to support the maintenance service of facilities depicted in 3D object-oriented CAD. This paper proposes a new and practical methodology with application to FMM using BIM technology. Using BIM technology, this study proposes a BIM-based facility maintenance management (BIMFMM) system for maintenance staff in the operation and maintenance phase. The BIMFMM system is then applied in selected case study of a commercial building project in Taiwan to verify the proposed methodology and demonstrate its effectiveness in FMM practice. Using the BIMFMM system, maintenance staff can access and review 3D BIM models for updating related maintenance records in a digital format. Moreover, this study presents a generic system architecture and its implementation. The combined results demonstrate that a BIMFMM-like system can be an effective visual FMM tool.

1. Introduction

Facility maintenance management (FMM) in the operation phase of facility's life cycle has become an important topic for research and academic study. Managing maintenance information about facilities contributes to successful facility management (FM). Managing FMM work effectively can be extremely difficult on the operation phase owing to various types of equipment and facilities. Furthermore, it is inconvenient for maintenance staff to maintain those facilities by relying on paper-based documents. The latest information technology solutions provide improved FMM. Unlike the manufacturing industry, information technology is limited in its use and application in construction [1], and most of the management work is done by human labor, which is inefficient and sometimes error-prone.

Regarding FMM, maintenance staff usually refers to information such as specifications, checklists, maintenance reports, and maintenance records. Maintenance staff must record maintenance results on hard copies. Consequently, there can be significant gaps in data capture and entry. Such means of communicating information between the facility location and the management office are ineffective and inconvenient. According to the survey findings regarding maintenance work on a commercial building in Taiwan, the primary problems regarding data capture and sharing during the FMM process are as follows: (1) the efficiency and quality are low, especially through document-based media, (2) it is not easy to reference relevant detailed information on facilities, (3) there are data reentry problems, and (4) the use of desktops for operating BIM models cannot be extended to maintenance management service at facility location effectively. However, few suitable platforms exist to assist maintenance staff in using integrated FMM information system from BIM models and sharing maintenance information directly at the facility's location.

The performance of FMM can be enhanced by using web technology for information sharing and communication. In this study, the FMM work includes inspection and maintenance works. Building Information Modeling (BIM) uses precise geometry and relevant data to support the maintenance service of facilities depicted in 3D object-oriented

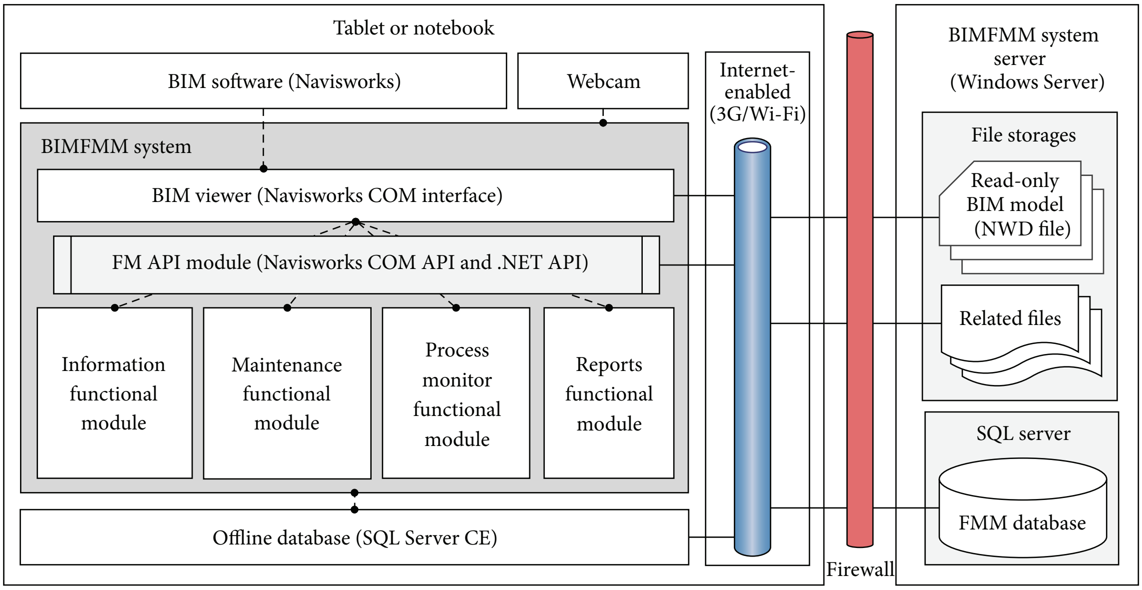


Figure 1: Overview of the BIMFMM system framework.

CAD. By integrating web and BIM technologies, the effectiveness of FMM work is enhanced and improved (see Figure 1). In order to enhance the effectiveness of FMM work on commercial buildings, this study presents a novel system called BIM-based Facility Maintenance Management (BIMFMM) system for the acquisition and tracking of maintenance information and provides an information sharing platform for maintenance staff using a webcam-enabled notebook or tablet. Integrating the web and BIM technologies, information and data entry mechanisms can help to improve the effectiveness and convenience of information flow in the FMM process. The primary objectives of this study include (1) applying BIM and web technologies to increase the efficiency of collecting maintenance data and information, (2) accessing web technologies directly to link detailed information with BIM models of facilities, and (3) exploring the limitations of the system, addressing problems, and providing suggestions based on the implementation of the pilot case study. The BIMFMM system is applied to a commercial building in Taiwan to verify our proposed methodology and demonstrate the effectiveness of the FMM process. The combined results demonstrate that the BIMMM system can be a useful BIM-based FMM platform by utilizing web and BIM technologies.

2. Related Research Studies

BIM digitally contains precise geometry and relevant data needed to support the design, procurement, fabrication, and construction activities to describe 3D object-oriented CAD [2]. BIM is a digital tool that supports continual updating and sharing of project design information [3]. BIM is the process of generating and managing building data during a building life cycle [4]. BIM technology has the potential to enable fundamental changes in project delivery to support a more integrated, efficient process [5]. Much previous research has examined BIM issues in construction. There are many core benefits, barriers, frameworks, and recommendations on BIM usage cited in previous work on supporting decisions and improving processes throughout the lifecycle of a project [2, 6–14]. Related to the design phase of a project, these topics include parametric modeling, BIM at different levels of development (LOD), identification of design conflicts and analysis, green design, design simulation, cost estimation, and accurate geometric representation of all facilities [2, 7, 8, 15–27]. During the construction phase, these benefits using BIM in construction include less rework, reduction in requests for information and change orders, customer satisfaction through visualization, improved productivity in phasing and scheduling, faster and more effective construction management with easier information exchange, accurate cost estimation, effective supply chain, and visualizing safety analysis [2, 28–35]. During the operation phase, these benefits include control of maintenance management process, integrated life cycle data, rapid and accurate information about update and change activities, and more effective FM with easier information exchange [2, 5, 8, 17, 18, 29, 36–42].

The BIM approach, which is used to retain facility information in a digital format, facilitates easy updates of FMM information in a 3D CAD environment. Although there were many practical applications for using BIM in the maintenance management stage, one of the challenges in broader application of BIM models to FMM is that currently the use of PC desktops limits on-site use of BIM models during the maintenance and inspection process. Another problem for most facilities is that vertical position can be difficult to illustrate clearly based on traditional 2D drawings. With the use of mobile devices executing the BIM models, these BIM models need to be processed in advance and reduced to a smaller file size to be used in mobile devices. This study will explore and make recommendations to solve these problems. In order to assist maintenance staff in obtaining the corresponding BIM model automatically for FMM, this study develops a proposed system to integrate web technology to automatically connect the BIM models. This study enhances FMM service using web technology integrated with the BIM approach. By using the web technology, users can quickly click the corresponding BIM model of a facility and access basic information and maintenance problems while managing FMM information during the operation phase.

3. System Schematic Design

The application of BIM technology in the FMM both inside and outside of the buildings supports maintenance staff in handling FMM via the 3D BIM models. By accessing the mobile device, maintenance staff can obtain the corresponding BIM model of the facility and directly access FMM information about the facility such as instruction manuals, photos, video of operations, maintenance history, and manufacturer information. Furthermore, a 3D BIM model improves upon traditional 2D drawings that can make it difficult to illustrate the vertical location or position of facilities.

The BIMFMM system consists of subsystems for BIM, mobile devices, and a hub center. The mobile devices subsystem is located on the client side, while the BIM models and hub center subsystem are on the server side. Each subsystem is briefly described below.

3.1. BIM Modules Subsystem of the BIMFMM System. In this study, BIM is used as an information model in the BIMFMM system. The BIM is applied to capture and store information about the facility, including basic descriptions, parameter-related information, maintenance records, and FMM reports. Autodesk Revit Architecture and Revit MEP were used to create and maintain the BIM model files. Autodesk Navisworks was used to integrate and read the BIM models of facilities. Information integration with the 3D BIM models was achieved using the Autodesk Navisworks API and Microsoft Visual Basic.NET (VB.NET) programming language. The BIMFMM system was developed by integrating the 3D BIM models of facilities and maintenance-related information using Navisworks API programming. Open Database Connectivity (ODBC) was utilized to integrate acquired data from different software programs and all maintenance information, such that BIM files can be exported to an ODBC database for connection with the BIMFMM system.

3.2. Mobile Devices Subsystem of the BIMFMM System. There are two mobile devices used in the BIMFMM system. An Acer Iconia W700P tablet is used as the webcam-enabled tablet hardware. The Acer Iconia W700P tablet runs on Windows 8. An HP Pavilion notebook is used as the webcam-enabled notebook hardware. The HP Pavilion notebook runs the Windows 7 operating system. All data in the tablet and notebook are transmitted between the client and the server sides directly through the web via Wi-Fi or 3G.

3.3. Hub Center Subsystem of the BIMFMM System. The hub center is an information center in the BIMFMM system that enables all participants to log onto a hub center and immediately obtain information required for FMM. Users can access different information and services via a single front-end access point on the Internet. For example, maintenance staff can log onto the hub center and securely access the latest FMM schedule information. FM managers can check maintenance status, results, and various other inspection-related data. All facilities-related pieces of information acquired within the hub center subsystem are recorded in a centralized system database. Maintenance staff can access required information via the hub center subsystem based on their access privileges.

The amount of maintenance information stored will increase over time if all FMM pieces of information are recorded in the BIM model. Because BIM models cover a wealth of building information, central BIM models storage space should be reserved for crucial information, such as spatial information, facility ID and name of facility, facility location, and other critical information. In order to keep the system performance at an acceptable level, the information derived by other applications should be stored in an external location. Therefore, there is one database designed in the BIMFMM system, called the FMM database. The central BIM models stores only basic information (such as position, ID and name of facility, and key parameter information of components). Related maintenance data and information are stored in the FMM database.

The accuracy of the central BIM models will directly affect FMM operations in the BIMFMM system. In order to prevent too many users from simultaneously using central BIM models and in turn affecting the accuracy of the BIM models, the BIM engineer can update central BIM models and export into read-only BIM models (NWD file) directly in the server side. The latest read-only BIM models on the client side automatically re-syncs when read-only BIM models change on the server side. In this framework, all building facility pieces of information from BIM can be saved and updated in the read-only BIM models without accessing the central BIM models directly. Furthermore, central BIM models and read-only BIM model are saved on the server side. Figure 1 shows overview of the BIMFMM system framework.

In the BIMFMM system, major three roles are involved in FMM including BIM engineer, FM manager, and maintenance staff. To ensure that the FMM operation does not affect the maintenance operation of the central BIM models, this study utilizes client-server system architecture. In the BIMFMM system, the read-only BIM model stores all facility basic information and location in the server side. Also, only BIM engineers are allowed to access and edit central BIM models by using BIM software and export into the read-only BIM models directly on the server side. On the client side, the FM manager and maintenance staff reference facility information through the read-only BIM models and edit FMM information through the FMM database in the BIMFMM system.

The BIMFMM system server supports four distinct layers, each with its own responsibilities: management, data access, application, and presentation (see Figure 2). This following section describes the distinct layers in the BIMFMM system.

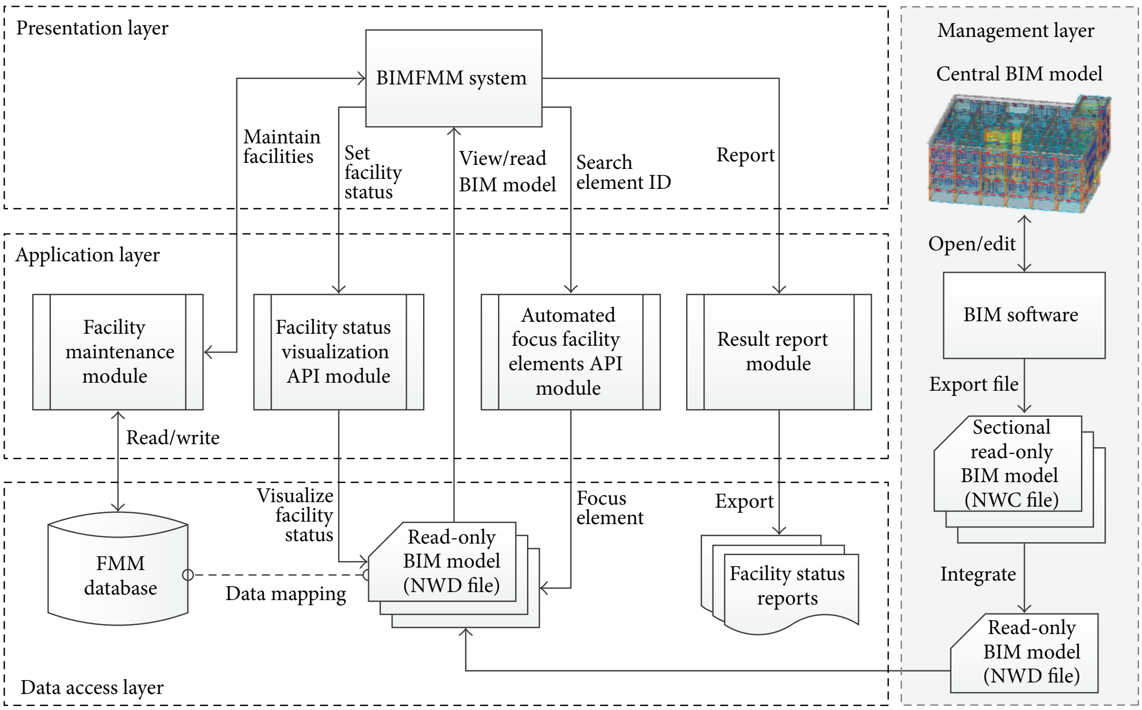


Figure 2: System and module framework of the BIMFMM system.

The management layer provides BIM engineers with tools to edit and manage central BIM models by using BIM software. BIM engineers can create and integrate the read-only BIM models saved in the server through the Internet.

Regarding the data access layer of the BIMFMM system, the FMM database stores all facilities maintenance records, while the read-only BIM models store complete facility information including facility number, name, and type in the BIM models. The FMM database records detailed maintenance information in accordance with the facility ID. The primary key establishes a relationship between facility ID and the main index. Therefore, information can be used for data association for data mapping to retrieve complete facilities maintenance information based on facility ID between read-only BIM models and FMM database.

The application layer defines various applications for major system and API modules. These applications offer indexing, BIM model data updates and transfers, facility status visualization, and report generation functions. The application layer integrates and uses BIM software to open the BIM models by using developed API modules. Finally, the application layer can automatically acquire data and analyze BIM models based on a request and then send the results back to the client side.

The presentation layer is the main implementation platform of the BIMFMM system. During the FMM process, the FM manager and maintenance staff can use a tablet (client side) and utilities in the BIMFMM system for the FMM operation. The presentation layer displays the location information of BIM model automatically, records maintenance information, illustrates different conditions and status of FMM, queries the history, and exports reports on FMM results.

4. System Development

The BIMFMM system server is based on the Microsoft Windows Server 2008 operating system with an SQL Server 2008 R2 as the database. The BIMFMM system is developed using VB.NET programming, which is easily incorporated with ADO.NET to transact FMM and BIM information with an SQL Server database. The BIMFMM system consists of three different user areas, maintenance staff, FM manager, and BIM engineer areas. Access to the BIMFMM system is password-controlled.

4.1. System Functionality Description. This section describes the implementation of each major functionality module in the BIMFMM system.

4.1.1. FMM Information Functional Module. The functional module provides maintenance staff with detailed FMM information on facilities by reviewing 3D BIM models. This module enables all maintenance staff to refer to related FMM information and historical maintenance records for the selected facility quickly and easily in the BIM-based environment. This module allows maintenance staff to refer to basic information and specifications associated with BIM models during the FMM process. This module also has a search function that enables the information to be found and retrieved easily.

4.1.2. Maintenance Functional Module. Maintenance staff can download up-to-date maintenance records through the BIM models and enter facility maintenance results directly into the BIM models. Additionally, the module can automatically produce the corresponding maintenance forms through the BIM models. Tablets display the checklist for every facility maintenance task. Maintenance staff can record maintenance information such dates, conditions, inspection results, descriptions of problems that have arisen during maintenance, and recommendations. Furthermore, maintenance staff can also check tasks that do not pass the inspection and select relevant tasks from lists in the BIM models. One of the benefits of the module is that maintenance results and records can be transferred between a tablet and the BIMFMM system by real-time synchronization, eliminating the need to enter the same data more than once.

4.1.3. Process Monitor Functional Module. This functional module is designed to enable FM managers to monitor the FMM process. The process monitor module provides an easily accessed and portable environment where maintenance staff can trace and record all maintenance information and statuses through the visualized and colorized BIM model.

4.1.4. Reports Functional Module. Users can easily access the FMM reports functional module to identify needs and analyze FMM results information. Authorized records for interfaces can be extracted and summarized for the final FMM result-related reports. Furthermore, all FMM reports can be extracted using commercially available software such as Microsoft Excel.

4.2. System API Modules Description. In order to integrate the system with the BIM models, the following API modules are developed in the BIMFMM system.

4.2.1. Automated Focus Facility Elements API Module. This module allows users easily and quickly to access the related BIM models by entering ID code attached in surface of the facility. When the user enters ID code, this module will automatically identify the facility angle and facility location in the corresponding BIM models automatically for FMM.

4.2.2. Facility Status Visualization API Module. The module provides the visualization functionality for FMM status through a visualized BIM model. Through a systematic FMM analysis of test results, the module displays different colors to illustrate various conditions and FMM status (such as qualified inspection, required repair status, and obsolete facility). Users can access the overall different maintenance conditions and FMM statuses quickly through the visualized BIM model.

There are two subsystems in the BIMFMM system. The first subsystem is the API monitoring subsystem for BIM engineers located on the server side. This subsystem deals with integration services of BIM models in the BIMFMM system. These services include updating facility maintenance information. Another subsystem is the maintenance subsystem located on the client side. This maintenance subsystem is developed for maintenance staff and FM managers to deal with FMM operations in the facility's location, such as clicking the BIM model of the facility, recording FMM, and reporting FMM results.

4.3. System Process Description. There are three processes used in the BIMFMM system including the system initialization process, FMM information monitoring process, and maintenance implementation process.

4.3.1. System Initialization Process. The purpose of the system initialization process is to provide adequate information on FMM operations. The system initialization process includes BIM models initialization and facility information initialization.

BIM Models Initialization. The BIM model must provide all pieces of information and related models on a facility as an information requirement for facility maintenance operations. When the BIM models save complete facility information, the BIM engineer needs only to use BIM software (such as Revit) to create BIM models first. After the BIM models creation by Revit can export into many read-only BIM models (NWC file). All exported NWC files will be integrated a single read-only BIM model (NWD file) using Navisworks. Finally, the read-only BIM models (NWD files) can be downloaded on the client side of the BIMFMM system for FMM usage. When central BIM models change, BIM engineers only need to update central BIM models and export to read-only BIM models (NWD files); the BIMFMM system will automatically update read-only BIM model on the client side of the BIMFMM system.

Facility Information Initialization. Facility information initialization is an important task in the FMM. After BIM models initialization, FMM staff adds new facility information and electronic documents directly in the system. The information will be saved in the FMM database. Furthermore, the facility information must be linked and associated with BIM models to create the relationship of facility information and BIM models in the MM database.

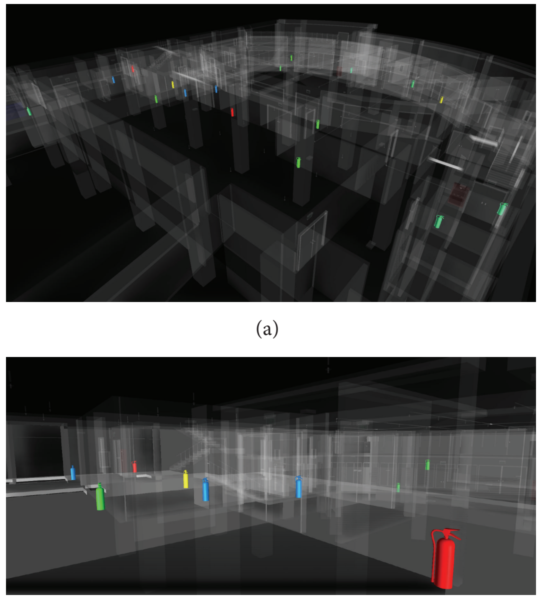
After the facility information initialization process is completed, FM manager and maintenance staff may utilize BIMFMM system to handle the following FMM information monitoring and maintenance implementation tasks.

4.3.2. FMM Information Monitoring Process. When the system initialization process is completed, FM manager can view and access BIM models (NWD file) in the BIMFMM system and then open the BIMFMM system monitoring API module. When maintenance staff handles the FMM process, FM managers can monitor and refer the newest state of FMM with different color visualization of BIM models through the BIMFMM system.

4.3.3. Maintenance Implementation Process. During the maintenance implementation process, the maintenance list varies according to the maintenance task categories. The design lets maintenance staff work on maintenance operations effectively according to the task categories and maintenance list. Maintenance staff can utilize the Web-enabled Tablet PC to access the BIMFMM system and show all the task categories and maintenance list based on different levels of access. After maintenance staff selects a particular task category, the system shows the history task form for that category. Maintenance staff can view the other task form, edit the unfinished task form, or add a new task form. When maintenance staff selects or adds a task form, the system retrieves facility information from the read-only BIM model based on the task types. Furthermore, a list of all related maintenance and results will be illustrated with the BIM model for FMM work preparation. Maintenance staff can access inspection information and the maintenance status effectively. During the maintenance implementation process, maintenance staff can use the system directly and select the corresponding BIM model of the facility. When the system receives the facility ID, the system automatically displays the facility's basic information and historical maintenance data in the BIM model. Furthermore, the facility's BIM model will be selected, focused, and highlighted using different color. User can obtain basic information on the facility by clicking the BIM model, or selecting from a maintenance list. After selecting the facility through one of the three methods, the maintenance staff can handle maintenance work and record the status and result of maintenance. Finally, all maintenance records and pieces of information are stored in the FMM database.

During the process of maintenance operations, the maintenance status also can be enhanced by color visualization in the BIM model through the facility status visualization API module. Through the functionality that visually depicts the status of maintenance list items, the BIMFMM system will get related maintenance status from the maintenance list in the FMM database. Furthermore, the BIM model will visualize different colors based on the each maintenance status in the facilities, and other elements in BIM model will be displayed in translucent white to enhance the visualization effect (see Figure 3).

Integrated with the above design concept, more complex operating procedures of FMM are simplified and developed in the BIMFMM system. One of the major characteristics of the BIMFMM system is to provide users an easy-to-use visualization for handling FMM work. By clicking the list, each task form will show the list of facilities requiring maintenance, historical maintenance information, and the status and condition of facilities maintenance. By clicking the corresponding BIM model of the facility, the BIM model are linked and illustrated quickly and effectively in facility location. All maintenance results are sent back and saved in the main BIM model. The proposed approach provides a means to update the facility information of the BIM model and FMM information synchronization. Finally, in order to let FMM engineers apply the system easily and effectively, the layout of the system is designed based on FMM engineers' suggestions. Figure 4 illustrates the system process flowchart used in the BIMFMM system. Figure 5 shows the graphical user interface (GUI) of the BIMFMM system.



(a)

(b)

Figure 3: The different maintenance statuses of FMM through visualized and colorized BIM model.

5. System Validation

5.1. Pilot Case Study. This study is applied to a building in Taiwan for the case study. This study utilizes a BIMFMM system in the FMM for the building. Existing approaches for tracking and managing FMM work rely on paper-based records. The bulk of FMM work was paper-based and documented by repeated manual entry, although an FMM system was developed for a standalone software application. Therefore, maintenance staff in the FM division utilized the BIMFMM system to enhance FMM work in the pilot case study.

After the critical facilities were selected for FMM work, the unique ID for each facility was entered into the BIMFMM system database for quick search. Before the FMM work began, the maintenance staff could check the facility list from webcam-enabled tablets, refer to the relevant information, and begin preparation work without printing any paper documents. During the FMM process, the maintenance staff selected the relevant BIM model. The BIMFMM system showed the basic information and BIM model of the facility. Maintenance staff could then check further detailed information like maintenance instructions, notifications, and accessories list, all of which are supported by BIMFMM. After the FMM work, maintenance staff entered the results of maintenance, edited the description in the tablet, and provided the updated information to the system. When a facility required repairs, the system also provided the manufacturer's problem information for immediate reference. Finally, the facilities manager and the authorized maintenance staff accessed the updated information simultaneously from their offices. Figure 6 illustrates maintenance staff using webcam-enabled tablet for FMM work in the pilot case study.

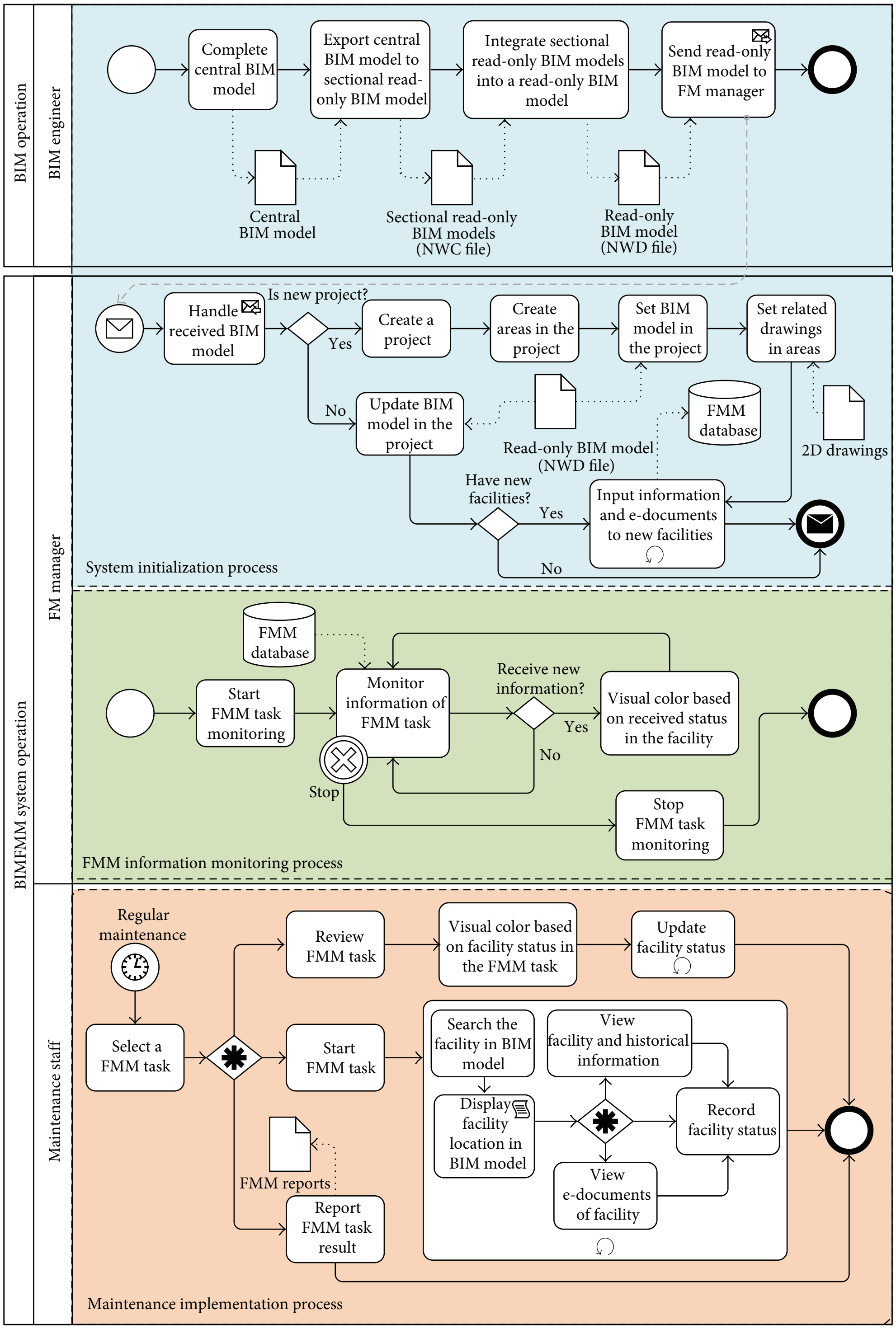


Figure 4: The process diagram used in the BIMFMM system.

5.2. Evaluation and Results. Overall, the field test results indicate that the application of BIM is an effective tool for FMM in a building. All BIM models survived use in the pilot test over the two-month testing period. Approximately 18 users participated in field trials of the FMM process. The BIMFMM system was installed on the main server in the FM division of the building.

During the field trials, verification and validation tests were performed to evaluate the system. Verification aims to evaluate whether the system operates correctly according to the design and specification; validation assesses the usefulness of the system. The verification test was carried out by checking whether the BIMFMM system could perform tasks as specified in the system analysis and design. The validation

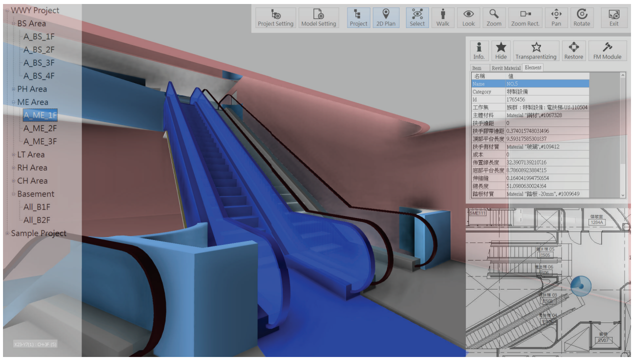


Figure 5: GUI of the BIMFMM system.

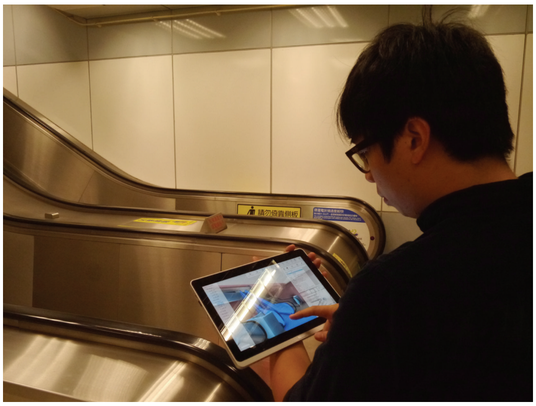


Figure 6: Staff using webcam-enabled tablet for FMM work in the pilot case.

test was undertaken by asking selected case participants to use the system and provide feedback by answering a questionnaire. There were 25 participants involved in the evaluation test. To evaluate system function and the level of satisfaction with the system's capabilities, the users of the system were asked to grade the conditions of system testing, system function, and system capability separately, compared with the typical paper-based FMM approach. Some comments for future improvements to the BIMFMM system were also obtained from the case participants through the user satisfaction survey. Finally, Table 1 shows system evaluation result.

The 92% of users obtained from user satisfaction survey indicates that the BIMFMM system is quite adaptable to current FMM practices in a building and is attractive to users. The overall result implies that the BIMFMM system is considered to be well designed and could enhance current time-consuming FMM processes. The over 98% satisfaction rate also indicates that the visual BIM model providing FMM support is very helpful. The 98% satisfaction rate for the BIMFMM system directly accessing the BIM model at facility location is also effective and necessary. Also, no additional work was required to complete documentation beyond the data collection process. The advantages and disadvantages of the BIMFMM system identified from the pilot study are identified.

Table 1: System evaluation result.

System functionality	Mean score
Ease of FMM information sharing	4.4
Reliability	3.9
Applicability to FMM	4.7
Use of system	Mean score
Ease of use	4.4
User interface	4.4
Overall system usefulness	4.4
System capability	Mean score
Reduces unnecessary time	4.3
Ease of finding maintenance information	4.4
Improves maintenance problem tracking	4.0
Enhances visual maintenance management	4.4
Enhances maintenance problems illustration	3.9

Note: the mean score is calculated from respondents' feedback on five scale questionnaire: 1 (strongly disagree), 2, 3, 4, and 5 (strongly agree).

5.3. Limitations and Barriers. The findings of this case study revealed several limitations of the BIMFMM system. The following are inherent problems recognized during the case study.

(i) It was difficult for new users to operate BIM model in the BIMFMM system. Some maintenance staff was initially unfamiliar with BIM models. It usually takes time to learn how to use BIM models. In the case study, the use of the BIM system initially lengthened the FMM operation over the traditional approach, since users required time to find the corresponding BIM model and fill out the FMM information in the BIMFMM system. After the user is skilled and familiar with BIM model, the time required by the current approach and the proposed system is almost exactly the same in FMM operations.

(ii) Based on the case study, BIM engineers needed to keep and update BIM models during the operation phase. When new equipment or facilities are purchased, BIM engineers must build a new BIM model for future maintenance use. Furthermore, the communications between maintenance staff and BIM engineers are necessary and important during the process. Maintenance staff should tell BIM engineers about any problem regarding the BIM models. The BIM engineers also must notify and discuss with maintenance staff after BIM engineer corrects the BIM models. BIM models require constant maintenance and updates. Another important issue is quality management of BIM models. Although the study proposed that the BIMFMM system help maintenance staff to handle visual facilities maintenance and management work, the advanced management procedures and mechanisms for quality management of BIM models for FMM must be identified and developed in the future. Particularly, the management mechanisms for updating the BIM models should be developed as the next step of BIMFMM system development.

(iii) Although Navisworks provide user with the ability to access a huge integrated amount of BIM models, the integrated BIM models (NWD file) will become larger than original BIM models. Usually, it will take 2 to 5 minutes to download whole BIM models from the server side when applying BIM models in the tablet for FMM work. Therefore, it is necessary to develop appropriate mechanisms to improve the above problem. For example, the BIM models in the client side will be updated and downloaded only from the server side when BIM models changes in the server.

6. Conclusions

The BIM approach, which is applied to retain facility information in a digital format, facilitates easy updating of FMM information in a BIM environment. Although there were many practical cases for using BIM during the maintenance management stage, the one of facing problem is that typically BIM models could only be used with PC desktops in an office, which limited their use onsite during facility maintenance. However, use of high-end desktops for operating BIM models could not be used effectively by maintenance staff onsite during the maintenance and inspection process. BIM models need to be processed and transferred via smaller files for use with mobile devices, which are more commonly used onsite. In order to assist maintenance staff with obtaining the corresponding BIM model automatically for FMM, this study develops the BIMFMM system to integrate web technology to automatically connect the BIM models. The BIMFMM system not only improves FMM efficiency but also provides a real-time service platform during the FMM process. In the case study, MM staff used webcam-enabled tablets to seamlessly enhance FMM work at facility locations, owing to the system's searching speed and ability to support related information collection and access during the FMM process. Meanwhile, on the server side, the BIMFMM system offers a hub center to provide the FM division with real time monitoring capacity during the FMM process. Integrated with characteristics of 3D BIM model illustration and BIM parametric design, the BIMFMM system quickly shows the necessary maintenance information using a facility's BIM model based on the selected task type and clearly presents the position and height of the selected facility.

In a case study, the application of the BIMFMM system helped to improve the FMM work of a commercial building in Taiwan. Based on experimental results, this study demonstrated that BIM technology has significant potential to enhance FMM work. The integration of BIM technology with web technology helps FM managers and maintenance staff to effectively track and control the whole FMM process. Compared with current approaches, the combined results demonstrate that a BIMFMM system can be a useful mobile BIM-based FMM platform. Based on the case study finding, BIM models must be updated and corrected constantly. Another important issue is quality management of BIM models. The advanced management procedures and mechanisms for quality management of BIM models for FMM needs to be identified and developed in the future. Doing so will be the next step of BIMFMM system development. Finally, the limitations, facing problems, and suggestions are discussed based on the implementation of case studies in this study. Although there are some challenges indicated above, the proposed system has shown a great potential to be used for FMM in building with the promising results shown in this study.

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Research Article

Safety Early Warning Research for Highway Construction Based on Case-Based Reasoning and Variable Fuzzy Sets

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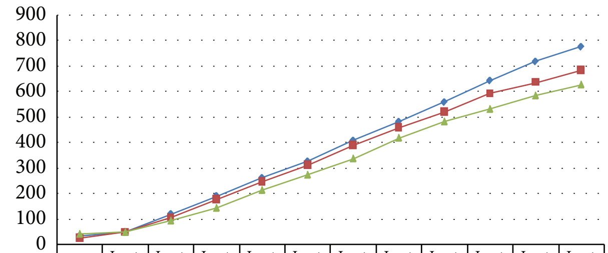
As a high-risk subindustry involved in construction projects, highway construction safety has experienced major developments in the past 20 years, mainly due to the lack of safe early warnings in Chinese construction projects. By combining the current state of early warning technology with the requirements of the State Administration of Work Safety and using case-based reasoning (CBR), this paper expounds on the concept and flow of highway construction safety early warnings based on CBR. The present study provides solutions to three key issues, index selection, accident cause association analysis, and warning degree forecasting implementation, through the use of association rule mining, support vector machine classifiers, and variable fuzzy qualitative and quantitative change criterion modes, which fully cover the needs of safe early warning systems. Using a detailed description of the principles and advantages of each method and by proving the methods' effectiveness and ability to act together in safe early warning applications, effective means and intelligent technology for a safe highway construction early warning system are established.

1. Introduction

China is currently one of the top infrastructure investors in the world. From zero highway breakthroughs in 1988 to the 74,100 kilometers of highway traffic mileage implemented by the end of 2010, comprising the second greatest highway network in the world; China has achieved a level of development that took western countries over 40 years to accomplish in only 22 years, realizing a historic breakthrough in highway construction. In keeping with an overall construction plan for an 850,000-kilometer highway road network [1], an increasing number of highway construction projects will come into operation over the next 10 years, the growth of which is unprecedented. While highways have generated significant economic benefits in the rapid development of the last 20 years, they have also resulted in billions of RMB of economic losses due to safety issues, highlighting the severe safety concerns in this industry.

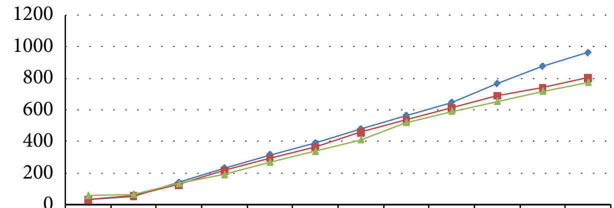
According to the accident statistics for construction project safety issued by the Ministry of Construction shown in Figures 1 and 2, because China's related department strengthened management and improved managerial stuff educational level, the numbers of accidents and fatalities have been decreasing annually over the past three years. The total number of accidents and deaths is relatively large, and the number of people who have died of safety accidents in construction projects in China is 1.5 times that of the total death tolls in 50 other developed countries, including the United Sates, the United Kingdom, Germany, and Japan. The accident occurrences in road construction projects, which are a high-risk subindustry in construction, account for 34% of total construction project accidents, while the fatalities in this subindustry account for approximately 31% of all construction project fatalities and are caused by five types of accidents: height crashes, construction collapses, object attacks, electric shocks, and machinery injuries. The safety conditions in this subindustry are not satisfactory.

According to computations of static investments, it is estimated that the future capital required for national highway network construction is approximately 200 billion RMB. National highway construction will be occurring fairly rapidly until 2020. The annual investment was approximately 140 billion RMB until 2010 and will be approximately 100 billion RMB from 2010–2020. However, the direct and indirect losses caused by safety issues account for 2% of the annual total



	Jan.	Jan.to Feb.	Jan.to Mar.	Jan.to Apr.	Jan.to May	Jan.to Jun.	Jan.to Jul.	Jan.to Aug.	Jan.to Sept.	Jan.to Oct.	Jan.to Nov.	Jan.to Dec.
2008	34	50	120	191	262	327	409	483	560	645	720	778
2009	25	48	105	178	246	311	389	458	519	592	636	684
2010	41	48	93	143	213	273	337	418	482	531	584	627

FIGURE 1: Number of safety accidents in the construction industry (2008–2010).



	Jan.	Jan.to Feb.	Jan.to Mar.	Jan.to Apr.	Jan.to May	Jan.to Jun.	Jan.to Jul.	Jan.to Aug.	Jan.to Sept.	Jan.to Oct.	Jan.to Nov.	Jan.to Dec.
2008	35	51	141	232	318	391	480	566	649	768	878	964
2009	29	56	123	215	294	364	456	535	608	690	739	802
2010	60	68	135	191	270	338	412	521	592	654	718	774

FIGURE 2: Death tolls from safety accidents in the construction industry (2008–2010).

investment, which is a large figure that greatly hinders the development of road construction.

At first, the industry thought that the safety issues had purely incidental or unexplainable reasons, and concern for safety was limited to fatalities and property loss. With improved knowledge and concern for safety issues, the industry began to see that the occurrences were more or less related to incidents but also had their own laws and features. Because it has gotten a late start, the study of safety management in China is only an initial attempt in terms of both theory and practice, with imperfect on-site safety management materials, an indirect and hysteretic quality to safety effectiveness, and widespread uncertainties in construction projects. Thus, the importance of the construction safety work in China has been ignored for decades. So, there is an urgent need for current construction safety work to switch from accident handling after accidents to forecast at the initial stage, switch from handling the accident to predicting and preventing the accident, and switch from traditional management to modern scientific management. The key link to realizing this transition is construction safety early warning technology. The essence of safe early warning technology in construction projects lies in precontrol, prophase management, transitioning from accident handling to accident prevention, discovering and addressing potential risks at any time, and eliminating accidents in the early stages of a project. Therefore, early warning is one of the most effective methods of curbing accidents and reducing safety losses. In April 2011, Wang [2] noted at the 14th session of national construction safety officer working meetings that construction enterprises should establish and perfect safe production dynamic monitoring and early warning systems in addition to analyzing and auditing the hidden dangers and risks of their construction projects at regular intervals.

Further studies on early warning management models exist abroad and are focused mainly on macroeconomic premonitoring and microenterprise crises, such as an early warning study on financial crises [3, 4], computer network crises [5], and natural disasters, such as tsunamis and earthquakes [6, 7]. However, the study of industry production safe early warning, particularly early warning in construction projects [8], is relatively rare. A theoretical study of early warning in China must commence with the circular fluctuation of the economy in the middle of the 1980s [9] and then transition to the noneconomic early warning that has occurred in recent years, beginning with early warning management studies in the field of construction projects, such as coal mining [10, 11], bridge construction monitoring [12, 13], and deep excavation [14, 15]. Although the phrase "early warning" has been mentioned very frequently in other countries, systematic and in-depth studies are still rare and mostly focus on the computer technology involved in early warning management information systems.

The accident losses during highway construction in China over the past 20 years have been caused mostly by the lagging study and practice of safe early warning; thus, improving early warning abilities and preventing safety issues are now the industry's most challenging tasks.

2. Key Technology for Safe Early Warning Systems

Safety and risk are mutually contradictory and dependent in major construction projects. Safety risks do not exist alone on a microscale, and safety issues cannot be induced by a single risk element. In essence, safety is a systematic project containing subunits, such as safety risk forecasting, distinguishing safety risks, risk associations, risk element importance ranking, safety investment and effectiveness, safe early warning, safety evaluation, and an emergency response plan. On a macroscale, safety is related to construction progress, project quality, investment cost, and effectiveness, and these factors are interrelated and interact with one another, leading to an external action mechanism for safety issues.

Based on the current knowledge of safety, the selection of monitoring indices for corresponding early warnings should have a hierarchy. This paper divides early warning monitoring indices into a compulsory index hierarchy and dynamic index hierarchy. The compulsory index includes an average safety training time, safety education coverage rate, licensed personnel rate, site safety member rate, safety symbol installation rate, temporary electricity usage management standard rate, reasonableness of machinery material management, fire protection management standard rate, safety danger patrol, safe production meeting frequency, employment injury insurance coverage rate, height workload, and ecological conditions. The dynamic index includes deviations in the project progress and investment costs, soil stress changes and deformations,

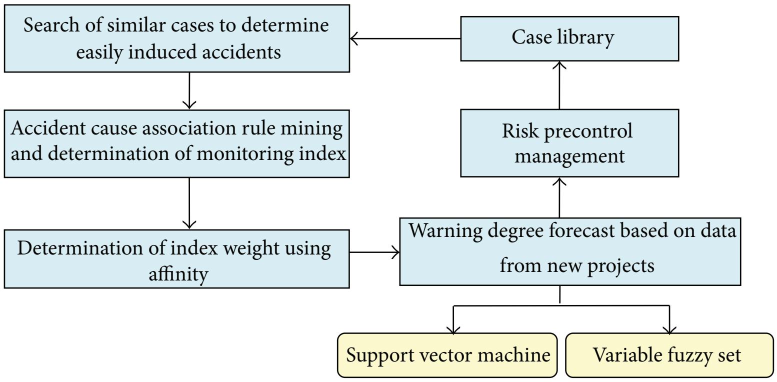


Figure 3: CBR-based highway construction safe early warning system.

and variations in water level and environment. The improvement of safety awareness and safety standards is adopted for the compulsory indices in the early warning process, while such methods as reinforcing the monitoring of dangerous areas and time zones, qualitative and quantitative change monitoring of the index values, and the division of different warning districts are included in the dynamic indices. Once the analyzed data enter the warning districts, we can effectively curb safety issues with the different control measures that are taken according to the warnings made based on the level of severity.

A complete and scientific safe early warning process includes the selection of monitoring indices and association analysis of the causes of the accident and warning degrees. Because a highway has such features as a one-off quality, uniqueness and a high level of uncertainty, the indices for early warning, accident association, and warning degree forecast should be uniquely based on the project features. Therefore, this paper introduces case-based reasoning (CBR) technology to the field of highway construction safe early warning systems to increase the accuracy and effectiveness of the technology. CBR is an important branch of artificial intelligence and originated in 1982 as part of Yale University Professor R. Schank's "Dynamic Memory," a book that created the basic theory of case-based reasoning. CBR is a similar or analogical type of reasoning that is designed to use existing experience and cases to solve new problems while also explaining the new situations. By accessing a knowledge base used to solve similar problems in the past, the current problem solutions are given an inference model or the use of old cases or experiences to solve new problems, evaluate new issues, explain atypical circumstances, or understand a new situation. CBR technology is used to solve a problem directly using previous examples of knowledge and can effectively solve difficult or problem areas that cannot be expressed otherwise. The self-learning function of CBR ensures the continuous enhancement of its reasoning, and it efficiently handles important items that are close or similar to the means [16]. However, papers involving both construction project safety and CBR are very rare—there are dozens abroad and less than 10 from China. However, these papers focus mainly on safety diagnosis, quality control, and slope stabilization and accident emergency response, and none are deep or thorough enough. Based on the advantages of CBR in project applications and its high accountability and communicability, a 2010 key scientific project regarding major accident prevention and solution technologies for safe production, issued by China's national safety supervision bureau, discusses CBR and shows us that CBR technology is increasingly used in construction safety studies.

Timely and accurate early warning systems can effectively reduce the occurrence of accidents and eliminate safety losses while maximizing the effectiveness of safety investments. This study is based on case-based reasoning technology and researches three key links of early warning systems, as shown in Figure 3, which is a virtuous cycle process of self-learning. Using the analogical reasoning-based features of CBR, the key to the application is in searching former cases that are similar to new projects because experiences from previous similar cases are more thorough and accountable and more severe or potential risks can be mined and identified. Therefore, we should search existing cases with similar control properties to the new projects, in which control properties can be set as indices, such as project type, construction technology, geological conditions, and methods of precipitation and water drainage. Next, we can calculate the similarity of comparative properties, such as construction costs and project kilometers, based on the search, filtering finished projects for which the similarities surpass a minimum threshold. The risks and accidents experienced by the similar projects can be summarized and used as keywords to search a case library, mining risk associations that lead to accidents, and then strongly correlated associations exceeding the minimum threshold of association rules' support and confidence as an accident-prone frequent item can be set to reinforce monitoring. This study uses the association degree to determine index weight. The greater the relationship to risk accidents is the heavier the index weight becomes. Because the indices have different types and associations, this paper uses a support vector machine with a strong generalization capacity and variable fuzzy set approach to perform the warning degree forecast and assure the accuracy of the warnings. These two methods have excellent theoretical superiority and comparatively lagging applications, so this paper combines cases to analyze and verify application effectiveness based on the two methods' principles and advantages.

3. Association Rules

Association rule mining is one of the most active directions of study in data mining, which is an important Knowledge Discovery in Database (KDD) research subject initially proposed by Ramakrishnan et al. [17]. Data mining reflects interesting or relevant associations among projects from a large database. With the increasing scale of data collected and stored in data libraries, people are becoming more interested in the mining of relevant association knowledge from these data.

There are two important concepts in the algorithm of association rule, support and confidence. If the proportion of objects A and B in data library D is s, then we can say that the support of the association rule for A and B in D is s, support$(A \rightarrow B)$ = support$(A \cup B)$ = $P(A, B)$. If the proportion of data library D containing objects A and B at the same time is c, then we can say that the confidence of the association rule for A and B is c, confidence$(A \rightarrow B)$ = support$(A \cup B)$/support$(A) \times 100\%$, or $P(B|A)$. The support reflects the importance of association rules in the data library, and the confidence measures the accountability of the association rule.

Using association analyses from previous construction projects, Chen [18] applied the grey association analysis approach to distinguish between the association elements affecting safety preevaluation systems and sequence the primary and secondary associated danger levels of dangerous substances, thus solving the uncertainty and accountability issues in safety accidents. Sawacha et al. [19] analyzed numerous accident samples and summarized the top 5 important elements associated with on-site safe production. Siu and his colleagues [20] made a comparative analysis of their associations from personal elements and accident rates, while Halperin and McCann [21] determined relevant elements from the study of frequent accident locations. Case-based reasoning association rules are different from the association analysis performed in the literature because references provided by similar cases can more accurately reflect the dependence and association between a monitoring index and risk events. In the mining process for early warning rules, we first set the minimum threshold for the support and confidence of the association rules. Then, we search all of the high-frequency risk sets related to safety issues in the case library and generate strongly correlated rules from these cases.

This study uses relational algebra theory-based association rules to perform risk association mining, and the algorithm only needs to scan the data library once (overcoming the classic Apriori algorithm's weakness of needing to scan a data library multiple times) and has good concurrency and scalability. Assuming that D is the case library and $T = \{t_1, t_2, t_3, \dots, t_m\}$ and $I = \{i_1, i_2, i_3, \dots, i_n\}$ are the case set and risk itemset, respectively, the matrix is as follows:

$$R = \begin{bmatrix} r_{11}, r_{12}, \dots, r_{1n} \\ r_{21}, r_{22}, \dots, r_{2n} \\ \vdots \\ r_{m1}, r_{m2}, \dots, r_{mn} \end{bmatrix}, \tag{1}$$

which stands for the binary relation from T to I.

Table 1: Risk associations for height crash accidents.

TID	Items	A	B	C	D	E
T1	$\{A, B, C, D, E\}$	1	1	1	1	1
T2	$\{A, B, C, D\}$	1	1	1	1	0
T3	$\{A, B, C, E\}$	1	1	1	0	1
T4	$\{A, B, D\}$	1	1	0	1	0
T5	$\{A, B, C, D, E\}$	1	1	1	1	1
T6	$\{A, B, C, E\}$	1	1	1	0	1
T7	$\{A, D, E\}$	1	0	0	1	1
T8	$\{B, D\}$	0	1	0	1	0
T9	$\{A, B, C, E\}$	1	1	1	0	1
T10	$\{B, C, D, E\}$	0	1	1	1	1
T11	$\{A, C, D, E\}$	1	0	1	1	1
T12	$\{B, C, D\}$	0	1	1	1	0

In the formula, the value of r_{ij} $(i = 1, 2, \dots, m;\ j = 1, 2, \dots, n)$ is 1 or 0, representing whether case i includes risk element j. $\sum_{i=1}^{m} r_{ij}/m$ is the support of property j for the 1st set. If the support is bigger than the minimum threshold, then the risk item element is 1 large itemset. If an itemset is not large, then any sets including this itemset can never be large. Therefore, 2 large itemsets must search based on 1 large itemset. Assume that A is a 1 large itemset, a_i stores 1 large relevant itemset, and $i = 1, 2, \dots, s$, so A has s elements. $\sum_{p=1}^{m}(r_{pa_i}$ and $r_{pa_j})/m$ is the support of 2 itemsets $\{a_i, a_j\}$, so the support must be larger than the minimum threshold to be 2 large itemsets. These conditions apply to all itemsets. If there exists an item V to make $\sum_{p=1}^{m}(r_{pi_{k-1}}$ and $r_{pv})/m$ larger than the minimum support threshold, then $\{i_1, i_2, \dots, i_{k-1}, v\}$ is a k large itemset.

This paper considers height crash accidents, which have the highest occurrence and number of fatalities, as an example. Table 1 represents cases similar to the 12 height crash accidents obtained from the case library and their risk associations. A–E represent separate risk elements, such as safety belt failure or lack of safety belt use, strut damage, loss of body control, safety facility failure, and safety net damage.

The algorithm is described in MATLAB R2007a as in Algorithm 1.

Set the minimum support threshold t of this early warning association rule to 40%. Then, the 1 large itemset from this algorithm is $\{A\}$, $\{B\}$, $\{C\}$, $\{D\}$, and $\{E\}$; the 2 large itemset is $\{A, B\}$, $\{A, C\}$, $\{A, D\}$, $\{A, E\}$, $\{B, C\}$, $\{B, D\}$, $\{B, E\}$, $\{C, D\}$, $\{C, E\}$, and $\{D, E\}$; and the k large itemset is $\{A, B, C\}$, $\{A, B, E\}$, $\{A, C, E\}$, $\{B, C, D\}$, $\{B, C, E\}$, and $\{A, B, C, E\}$, which is the same as the results gained from the classic Apriori algorithm. A k large itemset can typically represent the mechanism of action, so curbing the occurrence of a k large itemset is key to safe early warnings. The rules set by this association algorithm are fixed, so if we can use it as a base and combine quantitative data, such as the probability of basic events and accidents, sensibility of basic events, safety thresholds, or safety investment effectiveness, the risk element association rules can be further deduced.

```
for j = 1 : n
   f(j) = 0;
      for i = 1 : m
            f(j) = f(j) + r(i, j);
          f(j) = f(j)/m;
   for i = a(1) : a(n − 1)
      for j = a(i + 1) : a(n)
          for p = 1 : m
             d(p) = r(p, i) and r(p, j);
             f = f + d(p);
      f = f/m;
for each (k − 1) large itemset
    for h = 1 : n
       for j = 1 : m
Calculate r(j, c) and r(j, h), and if its support is larger than the minimum threshold, then output a k large itemset.
```

Algorithm 1

4. Support Vector Machine

The accuracy of a warning degree forecast decides the pertinence of safety precontrol measures and the effectiveness of safety investments. Different warning degrees indicate different measures and investment costs. Therefore, safe early warning systems have strict classification method requirements to make full use of investment costs, effectively control risks, and avoid accidents. The interpretation of a neural network does not give it the ability to learn and can easily cause weak generalization characteristics. To combat this tendency, this study introduces the most successful statistical learning theory, support vector machine technology. The support vector machine (SVM) solves small samples with nonlinear and high-dimensional pattern recognition performance, giving it many unique advantages. Cortes and Vapnik [22] first proposed the SVM in 1995 and based it on statistical learning theory, and the theory of VC dimension is based on the structural risk minimization principle according to the limited sample information in the model complexity (the learning accuracy of a particular training sample, or accuracy) and the learning ability (error-free samples that identify any capacity) to establish the best compromise between the two and obtain the best generalization capability (or generalization) [23]. The main advantages of SVM technology are that its small samples can solve machine learning problems, improve generalization performance, solve high-dimensional problems and nonlinear problems, and avoid neural network structure selection and local minimum problems.

Experiments have shown that the results of fitting a low-order function are better than the results of fitting a higher-order function in noisy conditions, even if the true model occurs several times [24]. Thus, attempting to use a very complicated model to fit a limited sample, even with the "optimal" function, results in the loss of generalization ability in low-dimensional space.

Unlike traditional statistical methods, the SVM defines structural risk minimization as its goal and makes a good pre-selection using a nonlinear transformation, nuclear function, and low-dimensional input vectors mapped into a high-dimensional feature space. An optimal separating hyper plane can be constructed in this feature space. In other words, the promotion of a high-dimensional space constructed with a low-dimensional space produces more powerful functions, as shown in Figure 4.

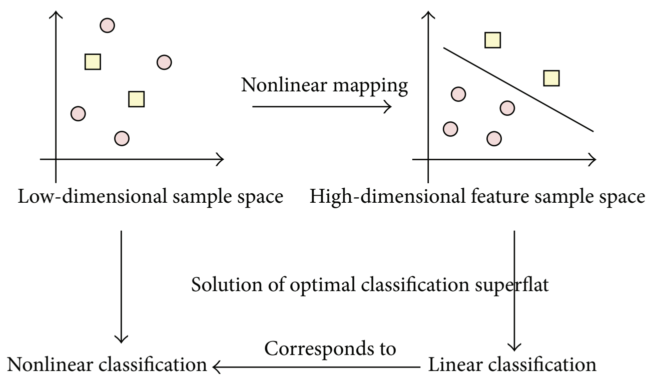


Figure 4: Principles of support vector machine thinking.

The SVM two-dimensional realization of the situation in Figure 5 can be used to explain its use. The solid and hollow points represent two samples H for the classification line, H_1 and H_2, respectively, from the classification of various line types in a sample of recent data. In the classification of lines parallel to the straight line, the distance between the lines is called the classification interval (margin). The so-called optimal separating line requires that the correct classification of a line not only be capable of separating the two line types (a training error rate of 0) but also be capable of classifying the largest interval, or the promotion of capacity control, which is one of the core concepts of the SVM.

The classification line for the equation of H is $x\cdot\ \omega + \ b = 0$, where H_1 and H_2 are classes 1 and −1, respectively, and the equations of H_1 and H_2 are $x\cdot\ \omega + \ b = y$, $y = 1$ and $x\cdot\ \omega + \ b = y$, respectively, with $y = -1$. The determination of whether the sample belongs to class 1 or class −1 can be summarized as

$$y_i\left[(\omega\cdot x_i)+b\right]-1\geq 0,\quad i=1,2,\ldots,n. \tag{2}$$

Table 2: Historical data sheet.

Project number	Warning degree	Workload when working at height	Safety protection level	Engineering geological conditions	Installation and usage of machinery	Workers without safety training	Organizational ability	Safety material status
1	2	0.3	82	2	82	0.14	68	1
2	2	0.38	64	0	72	0.15	84	1
3	1	0.2	73	2	93	0.11	84	1
4	1	0.34	83	2	91	0.12	82	2
5	2	0.22	74	0	94	0.1	88	2
6	1	0.32	94	2	95	0.2	80	2
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
30	1	0.34	85	2	83	0.12	79	0
31	2	0.35	65	2	81	0.08	70	2
32	1	0.3	90	1	85	0.15	88	2
33	2	0.35	72	1	72	0.14	65	1
34	1	0.22	68	1	85	0.04	88	1
35	1	0.25	85	2	80	0.12	85	1
36	2	0.35	70	1	68	0.14	70	1

The interval classification is equal to $2/\|\omega\|$, so the maximum interval is equivalent to the minimum $\|\omega\|^2$. Therefore, (2) the constraints to meet the minimum are $\|\omega\|^2/2$, the classification of surface is called the optimal separating surface, and H_1 and H_2 point to the training samples, called support vectors.

Because the presence of noise will not distinguish between some samples, even if the low-dimensional vector is mapped to a high-dimensional feature space, the introduction of slack variables ζ_i and a penalty factor C represent that the data noise in the fault tolerance of the SVM achieves better classification results. The purpose of the representation is to allow part of the introduction of the point that does not meet the requirement that the outliers give up. The resulting generalized optimal separating line model is

$$\begin{aligned} \min \quad & \frac{\|\omega\|^2}{2} + C\sum_{i=1}^{l}\zeta_i \\ \text{subject to} \quad & y_i\left[\left(\omega \cdot x_i\right) + b\right] 1 - \zeta_i \quad (i = 1, 2, \ldots, l) \\ & (\text{where } l \text{ is the number of samples}) \quad \zeta_i \geq 0. \end{aligned} \tag{3}$$

This equation can be transformed into a dual problem for its resolution, and because it is a convex quadratic programming problem, there exists a global optimal solution.

In summary, the SVM training error and generalization, according to the limited sample information in the model complexity, find the best compromise to solve for small samples in nonlinear, high-dimensional problems, such as pattern recognition. Although the SVM is widely used and the method has many unique advantages, research into its use is still relatively lagging. This paper introduces the use of the SVM method into case-based reasoning for construction safety warning degree forecasts, preserving the objectivity of actual risk elements while maintaining the forecast accuracy

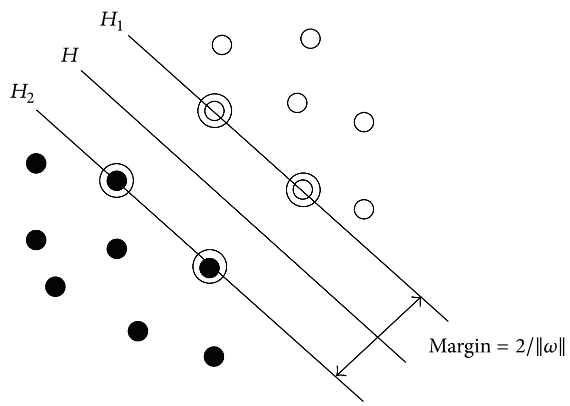


Figure 5: Linearly separable cases with optimal classification lines.

of warning degrees, achieving target precontrol measures, and avoiding accidents.

This paper takes the historical data from [25] (Table 2) as an example and considers a case study of vector machine applications in safe early warning systems.

The process can be described in MATLAB R2007a as follows:

%% Support Vector Machines

[bestacc, bestc, bestg] = SVMcgForClass (train_lable, train, cmin, cmax, gmin, gmax,. . ., v, cstep, gstep, accsetp)

% cross-validation to determine the optimal penalty factor c and nuclear function parameter g model = svmtrain (train_label, train, ["libsvm_options"])

% determine the training set classification

[predict, acc] = svmpredict (test_label, test, model)

% by category model to classify new samples

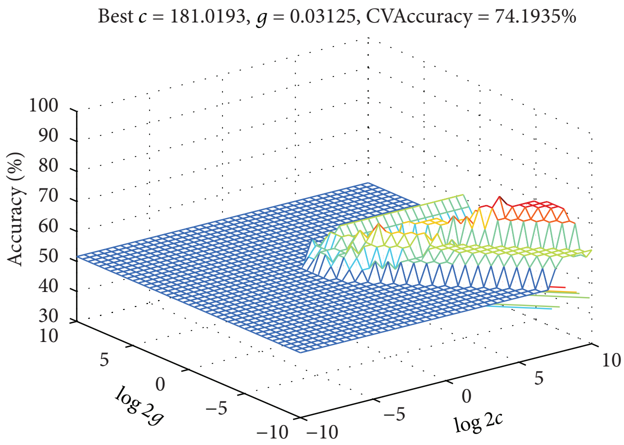


FIGURE 6: Cross-validation optimized three-dimensional display.

This case makes the warning degree its object. Levels 1–3 represent slight, moderate, and severe warnings, respectively, and the other 7 elements represent the risk properties, forecasting the warning degree of this case through the support vector machine classifier. The first 31 cases are set as training samples, and the final 5 are set as testing samples. In the classification setting, the kernel function selects a radial basis function while optimizing the parameters of the cross-validation process. The training samples are randomly divided into 5 groups, and for the maximum number that appears, the cross-validation accuracy of the smallest group of c is selected because the high penalty parameter causes the algorithm to learn and is not conducive to the generalization of the results. Based on this result, the best penalty parameter $c = 181.0193$ and the best RBF kernel parameter $g = 0.03125$, for which the highest cross-validation accuracy rate is 74.1935%, are shown in Figure 6.

In the final training set, the forecast results show that the classification accuracy of the classifiers trained by this set is 90.3226%, and the testing set samples have an accuracy of 100%, with the entire classification process lasting only 3.96 seconds. At the same time, the accuracy of the BP neutral network approach for this testing set is only 60%, and it takes 22.48 seconds to finish the classification, which indicates the generalization capacity strength of the SVM. The SVM has major advantages over neutral networks in terms of its forecast accuracy and efficiency and can efficiently improve the pertinence of precontrol measures and the effectiveness of safety investments.

5. Variable Fuzzy Qualitative Change Criterion Mode

With the existence of a dynamic index, safe early warnings must be a process of dynamic monitoring. As the project progresses, the index values will change dynamically among warning districts, with some changing across warning districts and some changing only within warning districts. Therefore, the index values are a critical test for illustrating warning accuracy and disguising whether the index change is

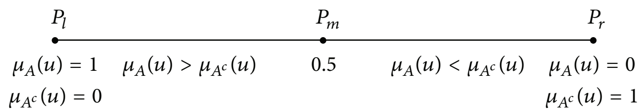


FIGURE 7: Opposite fuzzy set schematic.

a quantitative or qualitative change. Professor Chen proposed relative difference function-based variable fuzzy sets [26–28] with quantitative and qualitative change (i.e., gradual and abrupt) criterion modes [29].

Assume that for any element u ($u \in U$), there is a vague concept A in the universe of discourse U at any point on the reference continuum axis of the relative membership function. The relative membership of U to A is $\mu_A(u)$ and $\mu_{A^c}(u)$ to A^c, the opposite concept of A, and $\mu_A(u)+\mu_{A^c}(u) = 1$. Among these variables, $0 \le \mu_A(u) \le 1$ and $0 \le \mu_{A^c}(u) \le 1$. As shown in Figure 7, the left pole P_l has $\mu_A(u) = 1$ and $\mu_{A^c}(u) = 0$, the right pole P_r has $\mu_A(u) = 0$ and $\mu_{A^c}(u) = 1$, and P_m is the gradual qualitative change in the point of reference continuum interval $[1, 0]$ (for A) and $[0, 1]$ (for A^c), meaning that $\mu_A(u) = \mu_{A^c}(u) = 0.5$.

Assume that $D_A(u) = \mu_A(u) - \mu_{A^c}(u)$ is called the relative difference of U to A. As shown in Figure 8:

If $\mu_A(u) > \mu_{A^c}(u)$, then $1 > D_A(u) > 0$;
If $\mu_A(u) = \mu_{A^c}(u)$, then $D_A(u) = 0$;
If $\mu_A(u) < \mu_{A^c}(u)$, then $-1 < D_A(u) < 0$.

Assume that $\underline{V} = \{(u, D) \mid u \in U, D_A(u) = \mu_A(u) - \mu_{A^c}(u), D \in [-1, 1]\}$.

$\underline{V}$ is called the fuzzy variable set and A_+, A_-, and A_0 are called the attraction basin (main), rejection basin (main), and gradual qualitative change boundary, respectively.

Assume that C is the variable element set of $\underline{V}$ and $C = \{C_A, C_B, C_C\}$, where C_A is a variable model set, C_B is a variable model parameter set, and C_C is the other variable element set excluding the model and its parameters.

When summarizing the above statement, we can conclude that the criterion modes of the variable fuzzy qualitative and quantitative changes are as follows.

(1) If $D_A(u) > 0$ and $D_A(C(u)) > 0$, then $D_A(u) \cdot D_A(C(u)) > 0$ is a quantitative change.

(2) If $D_A(u) > 0$ and $D_A(C(u)) < 0$, then $D_A(u) \cdot D_A(C(u)) < 0$ is a gradual qualitative change (through $D_A(u) = 0$).

(3) If $D_A(u) < 0$ and $D_A(C(u)) < 0$, then $D_A(u) \cdot D_A(C(u)) > 0$ is a qualitative change.

(4) If $D_A(u) < 0$ and $D_A(C(u)) > 0$, then $D_A(u) \cdot D_A(C(u)) < 0$ is a gradual qualitative change (through $D_A(u) = 0$).

Therefore, we can conclude that if $D_A(u) > 0$ or $D_A(u) < 0$, the criterion modes of the quantitative and gradual qualitative changes of the variable fuzzy set are $D_A(u) \cdot D_A(C(u)) > 0$ and $D_A(u) \cdot D_A(C(u)) < 0$, respectively.

As shown in Figure 8, the left and right poles P_l and P_r, where $D_A(u) = 1$ and $D_A(u) = -1$, are both abrupt qualitative

Table 3: Basic information on Contract F (2003.02–2003.09) 10,000 Yuan.

Time	Month	Plan for this month	Actual progress during this month	Total Progress since commencement	Percentage of actual progress to planned progress	Change in contract price
2003.2	14	880.1126	597.9812	5991.5486	0.68	8695.2054
2003.3	15	938.522	717.9559	6709.5045	0.765	8555.2054
2003.4	16	918.4406	530.2455	7239.75	0.58	8555.2054
2003.5	17	959.0213	630.8527	7820.6027	0.6578	8655.2054
2003.6	18	766.6541	218.3175	8029.8021	0.2848	9021.8495
2003.7	19	766.6541	259.7389	8219	0.3388	9221.8495
2003.8	20	68.6561	391.8619	8611.4029	0.586	9221.8495
2003.9	21	593.301	182.7692	8774.9369	0.308	9141.8495

Table 4: Investment cost risk calculations for Contract F 10,000 Yuan.

Time	Number of project changes this month	Investment cost deviation value (accumulated Change)	Earned value	Investment cost deviation rate	Progress deviation rate
2003.2		−1,614.1201	7,605.669	−0.2122	−0.1856
2003.3	−140	−1,754.1201	8,463.625	−0.2073	−0.2050
2003.4	0	−1,754.1201	8,993.87	−0.1950	−0.2050
2003.5	100	−1,654.1201	9,474.723	−0.1746	−0.1911
2003.6	366.6441	−1,287.476	9,317.278	−0.1382	−0.1427
2003.7	200	−1,087.476	9,306.476	−0.1169	−0.1179
2003.8	0	−1,087.476	9,698.879	−0.1121	−0.1179
2003.9	−80	−1,167.476	9,942.413	−0.1174	−0.1277

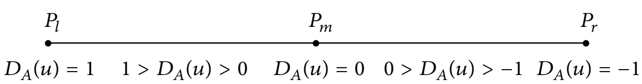


Figure 8: Relative difference function schematic.

Table 5: $[a, b]$ and $[b, d]$ interval eigenvalues for the deviation index.

x_1		x_2	
$[a_1, b_1]$	$[b_1, d_1]$	$[a_2, b_2]$	$[b_2, d_2]$
$[-0.1, -0.18]$	$[-0.18, -0.25]$	$[-0.1, -0.18]$	$[-0.18, -0.25]$

change boundaries. If $D_A(u) > 0$, $D_A(u)$ changes from a certain positive value to "1" (abrupt change), then $D_A(u) \cdot D_A(C(u)) = |D_A(u)|$ is an abrupt qualitative change (without $D_A(u) = 0$). If $D_A(u) < 0$, $D_A(u)$ changes from a certain negative value to "−1" (abrupt change), then $-|D_A(u)| \cdot D_A(C(u)) = |D_A(u)|$ is also an abrupt qualitative change (without $D_A(u) = 0$).

Therefore, we can see that the criterion mode for abrupt qualitative change without $D_A(u) = 0$ can be summarized as $D_A(u) \cdot D_A(C(u)) = |D_A(u)|$.

As this process continues, the criterion mode for abrupt qualitative change with $D_A(u) = 0$ can be summarized as $D_A(u) \cdot D_A(C(u)) = -|D_A(u)|$.

Because current construction projects tend to excessively favor internal indices in dynamic index monitoring for safe early warning systems, the abnormal state of external indices, such as cost and progress, can also have a negative effect on safety situations. This study uses the changes in construction progress and investment for the 210 road section of a national highway as an example to verify the effectiveness of this qualitative and quantitative change model [30]. This road starts at the Qiujiahe River on the cross-boundary between Sichuan and Chongqing and ends at Heishizi in the Jiangbei District of Chongqing, connecting with the Yuchang highway. The highway has a total length of 53.108 kilometer. Tables 3 and 4 summarize the progress and investment costs, respectively, for Contract F of this project.

The linear formula for the relative difference in this application document [31] is

$$D_A(u) = \left(\frac{x_i - b_i}{a_i - b_i}\right) \quad x_i \in [a_i, b_i],$$
$$D_A(u) = \left(\frac{x_i - b_i}{d_i - b_i}\right) \quad x_i \in [b_i, d_i], \tag{4}$$

where x_1 is the investment cost deviation rate, x_2 is the progress deviation rate, the comprehensive evaluation of risk is based on the two deviation rates, and the relative differences between the investment cost and progress from February 2003 to September 2003 are calculated separately according to the $[a, b]$ and $[b, d]$ interval eigenvalues in Table 5.

Assume that the weight vector of the two indices is $\omega = (0.5, 0.5)$. Then, the relative difference in monthly risk is $D_A(u) = \sum_{i=1}^{2} \omega_i \cdot D_A(u)_i$. Table 6 shows the monthly comprehensive relative difference.

Table 6: Relative differences for Contract F (2003.2–2003.9).

Time	2003.2	2003.3	2003.4	2003.5	2003.6	2003.7	2003.8	2003.9
$D_A(u)$	−0.27	−0.37	−0.27	0.26	0.26	0.78	0.80	0.76

The closer the value of $D_A(u)$ is to −1, the greater the risk and the greater the pressure for safety are. The closer the value is to 1, the safer the project is. Based on the results in Table 6, we can see the change in tendency to risk. The safety level experiences a gradual qualitative change from April to May, while the changes from February to April and from May to September are both quantitative. The change is negative from February to April, indicating that the deviation in progress and investment costs during this period have a negative effect on safety production, and the change from May to September is positive, indicating that the deviation in progress and investment costs during this period does not have a negative external effect on safety situations. The results are simple and intuitive, and the existence of association rules means that the occurrence of safety issues is a combined action of multiple risk elements. Therefore, it is far from sufficient to set a warning degree threshold for individual risk elements to ensure safety when monitoring dynamic indices. This method can also be applied to the dynamic monitoring of multiple indices and intervals. We can create corresponding control measures based on the results, thereby curbing safety issues.

6. Conclusions

Early warning technologies are used to determine both safety situations and safety losses. Good early warning technologies can not only reduce losses by limiting the available accident sources but can also indirectly lower investment costs by guiding safety input benefit maximization. Different from other existing research, the following conclusions and recommendations are made based on this research.

(1) By using analogical reasoning-based CBR, this paper gives a basi schematic for solutions to safe early warning technologies by practically solving the three-key issues of index selection, accident cause association analysis, and warning degree forecast, which also penetrate the whole process of safe management.

(2) Combined with the characteristics of highway projects, as well as the possible problems in the process of data processing, this paper introduces association rule mining, support vector machine classifiers and variable fuzzy qualitative and quantitative change criterion modes in order to keep the data of high fidelity. Together with experiments proving the effectiveness of the methods, the proposed method is a completely feasible and effective means of improving our country's early warning technologies.

(3) With the gradual application of artificial intelligence to the security of construction projects, the CBR technology can be applied to safe early warning systems for construction projects in our country. However, research shows that a lack of existing cases and the complexity of the data are the biggest bottlenecks in the application of CBR. Therefore, further study of CBR technology and the settlement of data processing, case statistics, and searches of highway construction safe early warning systems are key to improving the practicability of safe early warning systems and safety management.

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