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Integration of Safety Knowledge into Three-Dimensional Model Design and Construction Plan from the Perspective of Project Executors in Petrochemical Industry

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ABSTRACT

In petrochemical industry, the execution of construction involves three main issues, namely, design planning, construction, and job safety. Three-dimensional (3D) models are increasingly applied to design and construction. However, the improper concept of 3D design has bred potential unsatisfactory behaviors and the lack of vigilance among workers. Besides, many employees are not fully aware of the safety in 3D design and construction planning. Therefore, our goal is to improve the safety and health of construction workers through design practices in the upstream of the construction phase, and verify the applicability of the combination of 3D models and safety knowledge. Specifically, a questionnaire survey was carried out among 124 employees in the construction-related fields of the petrochemical industry. The collected data were processed, and statically analyzed on SPSS. The results show that safety knowledge was acceptable in 3D model design from the perspective of project executors, and the integration of safety knowledge into the design helps to improve the safety environment of the construction site.

1. INTRODUCTION

Petrochemical industry is one of the most dangerous industries, due to the harsh working environment and highly risk operations. Many past studies on job safety focus on the control of on-site risks during construction. However, preventive measures are not necessarily the most effective means of risk control [1].

The occupational health and job safety at construction site are closely related to the specific department activities, which often involve hazardous conditions (e.g., working at height, lifting, welding, and painting) and high-risk conditions like the use of dangerous equipment, materials, and substances [2].

The various projects facing designers are implemented based on design drawings, instructions, and relevant regulations. But these basic data are prone to having contradictions, conflicts, and errors. If the projects are constructed rashly, the tasks often need to be interrupted for review or modification, bringing extra cost and possible delay to the construction.

Construction safety usually conflict with site work, as the safety constraints are often ignored during construction [3]. More than often, the safety information on site is inconsistent with the factors of the actual construction environment. Therefore, it is very difficult to identify safety hazards and notify the staff of them at the correct time during construction [4].

The traditional two-dimensional (2D) engineering drawings and paper drawings are easily lost, and dependent on coordination by engineers. In addition, the drawings modified on site will inevitably drag down the efficiency of hazard identification prior to construction [5].

Previous studies have shown that computer-aided design (CAD) is not an effective platform to obtain spatial information, and 2D design reduces the efficiency of information retrieval. To retrieve information, users are required to manipulate multiple drawings, and understand the space of the construction site [6].

In the design phase, technicians may face difficulty in coordination, owing to the integration of new working methods, worker health, and safety obligations, as well as the lack of regulations or documents for the application of design specifications in three-dimensional (3D) models. The poor coordination in this phase will lead to more work accidents, some of which are fatal [7], and weaken safety plans, process productivity, and awareness among workers.

Few designers have sufficient knowledge of construction safety. Many do not understand how their designs pose risks through the lifecycle of building facilities, such as construction and maintenance [8]. To make matters worse, most safety design tools are text-based independent ones. Whether in paper or software format, these tools require designers to spend a lot of time to find applicable information [9]. The insufficient understanding of safety and construction, coupled with the limitation of relevant tools, hinder hazard mitigation in the design phase.

In fact, many construction accidents arise from design flaws. They are completely avoidable through proper design considerations. Active identification and elimination of hazards are safer and more cost-effective than passive management. To overcome the limitations of the current safety plan, this paper introduces safety knowledge into the design phase of 3D models, and verifies the applicability of our method from the perspective of construction managers and safety managers.

2. LITERATURE REVIEW

2.1 Construction accidents in petrochemical industry

The petrochemical industry involves various types of equipment and utilizes many toxic, flammable, and pyrophoric chemicals. The slightest error in design and maintenance might cause chemical leakage, which in turn brings accidents like explosion or fire. Repeating the same mistake will cause many accidents.

Any accident in oil refining operations will possibly lead to heavy casualties and property losses. Even a minor accident could damage properties worth millions of dollars, and suspend the production for days. The maintenance facilities not only face high risks, but also contain lots of harmful substances. Hence, the probability of accidents is very high in such facilities. Besides incurring additional cost, the accidents will negatively impact human health and the environment [10].

In general, there are two kinds of disasters in petrochemical industry: the general chemical disasters in factories induced by human factors, equipment factors and environmental factors; the chemical disasters caused by operational failures in manufacturing, e.g., unfamiliarity with the chemical reactions, improper engineering design, incorrect control, and unsuitable operating procedures and training [11].

To examine the mechanism of human damage, Chen et al. [12] analyzed the human factors and classified the fires and explosions in petrochemical industry, and identified violations, knowledge limitations, insufficient supervision, and weak safety culture as the key causes of fire and explosion accidents; although the accidents in the petrochemical industry in developing countries are mostly the result of mechanical failure, managers must pay attention to human error and external incidents, that is, company management must try to reduce potential accident and failure disaster.

Before the construction phase, it is essential for petrochemical industry to provide safety knowledge training to identify hazards and formulate preventive measures [13]. Nevertheless, many safety issues are latent, for not all conditions are included in the 3D design. In fact, there is no report on the accidents arising from 3D model design. For instance, loopholes like the risk of falling from the leading edge are rarely drew in paper-based or 3D models. Moreover, the safety requirements may change due to the dynamic nature of construction operations. Even for experts, it is difficult to determine the hazards of different construction stages and schedules based on drawings and 3D models.

2.2 Job safety of petrochemical industry

Compared with most industries, the petrochemical industry has a high probability of accidents. Therefore, it is essential for safety managers to identify and assess hazards and risks. Job safety analysis (JSA) provides a practical way to identify, evaluate, and control the risks in industrial processes [14].

Le et al. [15] created a social network system consists of a safety information module (SIM), a safety knowledge module (SKM), and a safety distribution module (SDM), and applied the system to popularize the safety and health knowledge of engineering. Li et al. [16] combined global positioning system (GPS) with radio frequency identification (RFID) to monitor the safety status of mobile tower cranes; starting from the conflict between man-made and dangerous sources, the application of these positioning techniques improved project quality and reduced safety risks. Navon and Kolton [17] proposed an automatic model to identify hazardous activities in the project schedule and the areas with falling from height risk in a building, based on the real-time data on the places in lack of guardrails.

The above studies established JSA as a technique for petrochemical construction and maintenance. Focusing on the relationship between workers, tasks, tools, and the work environment, JSA can identify the hazards in each step of the activity, and set up safety rules to prevent the hazards from turning into accidents.

The JSA can be implemented in three stages: (1) select a specific job or activity, break it down into multiple parts, and identify every out-of-control event that might occur during the work; (2) assess the relative risk level of each event; (3) take adequate measures to mitigate or eliminate the risks [18]. The JSA demands designers to assess the risks, and formulate construction plans/drawings during project development and design, with the aim to control the accident risk facing the workers and building/infrastructure users during the construction phase. The risk assessment can support the decisions leading to safe operations [19].

The Norwegian Oil and Gas Association described the best practices of the JSA, highlighting the importance of decomposing a work into sub-tasks. In any type of risk analysis, the object is systematically split into smaller parts, such that the analysis can cover as many relevant aspects as possible [20]. The risk assessment of JSA is gaining importance in the oil and gas industry, with the growing use of dangerous machinery, risk processes, and possibility of accidents in industrial environments. The materials, processes, and types of activities in that industry have been reshaped, adding to the dangers of workers [21].

Petrochemical plants usually operate under severe conditions, such as ultra-high pressure and temperature. The equipment ages rapidly in such a harsh environment [22], and the risk of maintenance is on the rise. The practice of safety strategies is needed to improve the quality and procedures of the JSA.

2.3 3D modeling combined with safety management

Recent years has seen great progress in the software tools for the realization of building safety knowledge design. After reviewing the relevant cases and implementing the building information modeling (BIM) tool, Zhang et al. [23] discovered the limitations of the developed safety rule inspection system: (1) It is impossible for the BIM tool to represent all the unsafe conditions in real time, for the environment of the construction site is constantly changing; (2) The rules cannot be explained automatically. Zhang stressed the necessity to select the best correction for unsafe conditions.

The dynamic construction work changes frequently, and gradually deviates from the original plan. During 3D modeling, the model should be as detailed as the design and engineering of permanently installed building components, which complicates the scheduling and model maintenance [24]. Based on the 3D model, additional safety knowledge, time and technical resources are required in the design phase, making the model difficult to implement. Before applying this 3D model-based tool for hazard detection and prevention in the field, practitioners should understand and benefit from the additional modeling requirements. But most of the current design models and safety management strategies solely rely on the experience of safety engineers [25].

Therefore, related researchers established a 3D model to prevent construction workers from falling from height in the design. However, such a model cannot prevent other types of hazards, as the rules are hard-coded into the algorithm [26]. In addition, safety management must be integrated with the 3D model platform, because 3D models are at the core of information management shared by all stakeholders involved in the lifecycle of every construction project, from design, construction, operation, maintenance to demolition [27].

Guerriero et al. [28] proposed a safety design based on regulations, which can be retrieved as an independent knowledge database, enabling designers to check the risks of their design elements against safety rules and use them before designing concepts and drawing 3D models. Currently, the information about construction safety management and design phase is highly scattered. Despite advances in information and knowledge management in construction, the link between safety management and information models is still missing.

Hence, designers are expected to play a major role in reducing the risks of construction, operation, and maintenance. Nonetheless, resolving risks in the design phase is no easy task, in the absence of proper safety knowledge and insufficient systems that support risk identification. At present, the safety knowledge and management model is being developed towards intelligent analysis, scientific decision-making, and refined management. Therefore, this paper suggests integrating safety knowledge in the 3D design stage.

3. METHODOLOGY

3.1 Research framework

Figure 1 illustrates our research framework. Firstly, the recent accidents in petrochemical industry were classified based on enterprise properties (e.g., class, scale, and safety and health management system), accident properties (e.g., time, location, and type), victim properties (e.g., gender, age, duty, work experience, injury level, and safety training experience), the events during the accidents, the conditions of the accident site, and the causes of the accident. Next, the factors, effects, possibility, and severity of each type of risk were assessed based on statistics. Further, the safety knowledge database was imported for JSA and construction safety assessment. During the importing process, some problems might arise and should be considered in the 3D design phase, such as safety evaluation of design plan, reference drawing plotting for safety facilities, preparing safety construction specifications, budget formulation, and compiling operation and maintenance manual for users.

After implementing the framework, 3D designers must fully understand safety knowledge, in order to test system functionality, and evaluate the practicality of the system before full development. The fully developed system will enable pipe maintenance workers to interact with design engineers to obtain a comprehensive security protocol for the required tasks. After that, the inspection procedures of the work environment should be improved, ensuring that workers comply with standard safety procedures. In addition, the combination of 3D models and safety knowledge helps to prevent injury or fall over accidental leakage during the maintenance and repair or replacement of damaged pipes. Overall, the framework could improve worker safety, operating efficiency, and knowledge transfer.

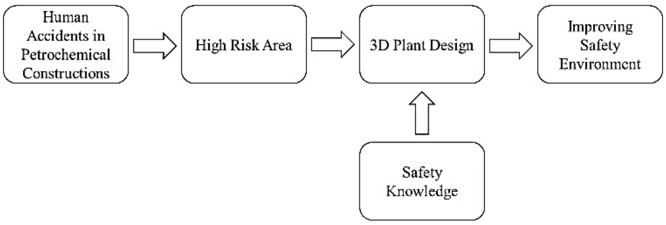

Figure 1. Research framework

3.2 Subjects and respondents

The subjects are employees in petrochemical industry, including project managers, pipeline design engineers, safety management personnel, and pipeline construction personnel. A total of 124 employees were randomly selected as respondents of our questionnaire survey.

3.3 Data collection

Uniformly designed questionnaires were distributed in written form to learn about the situation or solicit opinions from selected respondents. Before handling out the questionnaire, the authors explained the research purpose to petrochemical workers, and then asked them to fill in the questionnaire based on their experience and knowledge. Every questionnaire contains 25 questions about four influencing factors, namely, 3D design modeling, construction planning, safe operation, and safety knowledge.

3.4 Data analysis

The SPSS 22 statistical software package was adopted for statistical analysis on the collected data, including descriptive statistical analysis, reliability/validity test, correlation analysis, and regression analysis.

4. RESULTS

4.1 Descriptive statistical analysis

Table 1 presents the descriptive statistics of the respondents which are classified by gender, age group, position, work experience, and professional field. Obviously, males dominate the highly risky petrochemical industry, because they possess the technical skills required for this industry.

4.2 Reliability/validity test

To ensure the validity and reliability of subsequent data analysis, Cronbach's alpha (α) was used to test the internal consistency of measurement structure. As shown in Table 2, the Cronbach's α was greater than 0.7, indicating that the index measurement is reliable. In addition, the Cronbach's α was 0.794 for design modeling, 0.813 for construction planning, 0.812 for operation safety, and 0.807 for safety knowledge. All these scores meet the general requirements of the field, indicating that the reliability factor is higher than 0.7. According to the validity test, the Pearson correlation coefficients were from 0.212 to 0.769 (N=124), higher than the standard of 0.176 (N=125) required for the r-table.

Table 1. Descriptive statistics

Classes		Number of samples	%
Gender	Male	98	79
	Female	26	21
Age	≤30	24	19.4
	31~40	73	58.9
	41~50	22	17.7
	51~60	5	4
Position	Manager	20	16.1
	Engineer	78	62.9
	Basic level staff	26	21
Work experience	≤5 years	43	34.7
	6~10 years	52	41.9
	11~20 years	18	14.5
	21~30 years	10	8.1
	≥30 years	1	0.8
Field	Design modeling	34	27.4
	Construction planning	57	46
	Operation safety	33	26.6

Table 2. Reliability test results

Variables	Cronbach's α	Number of items
Design modeling	0.794	6
Construction planning	0.813	7
Operation safety	0.812	7
Safety knowledge	0.807	5
Total	0.932	25

4.3 Correlation analysis

As shown in Table 3, four variables had positive correlations with a moderate score. The closest correlation lies between design modeling and construction planning, suggesting that 3D model construction must fully consider the construction planning and its possible predicament, in order to promote the project. The second closest correlation is between construction planning and operation safety. This means, for different engineering features, it is necessary to improve labor safety and health equipment, optimize the working environment, and carry out inspections. Once identified, these correlations help to minimize the incidence of occupational disasters, ensure labor safety and health, and ensure effective operation of the management system.

It can also be inferred from Table 3 that the variables all have significant correlations with each other. Our research mainly focuses on the correlations of safety knowledge and another variable. The results of correlation analysis confirm that safety knowledge is closely correlated with 3D design modeling, construction planning, and operation safety in 3D model design of petrochemical industry.

Table 3. Correlation analysis results

Construct	Design modeling	Construction planning	Operation safety	Safety knowledge
Design modeling	1			
Construction planning	0.755^{**}	1		
Operation safety	0.669^{**}	0.714^{**}	1	
Safety knowledge	0.668^{**}	0.678^{**}	0.673^{**}	1

4.4 Regression analysis

Taking safety knowledge as independent variable and design modeling and construction planning as dependent variables, regression was performed to disclose the relationship between variables, which reflect the interaction between independent and dependent variables, and predict the mutual influence between variables.

As shown in Figure 2 and Table 4, the R-squared was significant between safety knowledge, design modeling, and construction planning. This means safety knowledge greatly affects the other two variables. In addition, the highest R-squared was observed between construction planning and design modeling. Thus, design modeling promotes construction planning. Similarly, safety knowledge was found to positively affect design modeling. Therefore, the value of safety knowledge is inseparable from the design of the initial model or the entry into construction planning.

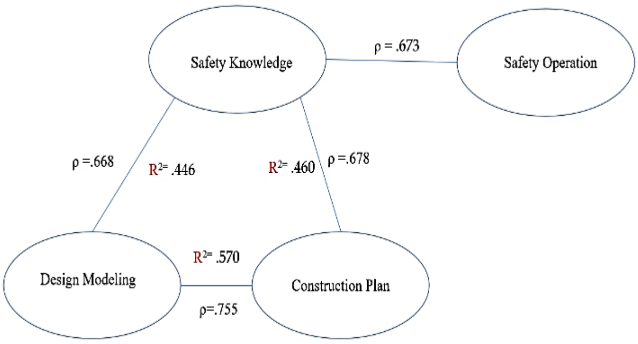

Figure 2. Correlation and regression analysis pathways

Table 4. Regression analysis results

	Design modeling			Construction planning		
	R-squared	F	Sig.	R-squared	F	Sig.
Safety knowledge	0.446	98.232	0.000^{b}	0.460	103.972	0.000^{b}
Construction planning	0.570	161.645	0.000^{b}			

5. DISCUSSION

The analysis results show that petrochemical employees hold that the safety knowledge in 3D design promotes the safety awareness and safety environment in the industry. Understanding the safety knowledge gives the designer an opportunity to learn and improve safety concept, and prepare protective facilities and construction progress in advance during the design phase. These measures will reduce repeated actions, and suppress cost and spending. During on-the-job tasks, the designer can be assisted by safety management personnel with the 3D model system. The safety knowledge can be derived from the analysis of safety operation procedures [29]. Therefore, our research framework can enhance the designer's understanding of safety knowledge to improve the safety quality in 3D model design. The improved design plan can minimize work risk and reduce the budget for engineering modifications.

Traditionally, workplace hazards are assessed mainly with written instructions to manage safety knowledge. But safety knowledge alone is insufficient [30].

Therefore, Yuan et al. [31] combined laws and regulations with the safety knowledge of experts, and established an automated construction safety inspection rule database system to improve the efficiency of traditional manual safety planning. By analyzing the information provided by the 3D model, Hallman [32] pointed out that the petrochemical industry needs to take safety protection measures during the design phase and construction phase, so that on-site operators, safety managers, and safety supervisors can acquire correct safety protection information in real time, which is critical to job safety management.

5.1 In petrochemical industry, 3D model designer should master the safety knowledge of the industry

The occupational hazards in petrochemical industry are affected by multiple factors. The records of major occupational accidents show that occupational accidents mostly stem from exposure to unsafe working environment, personal negligence, or damages to the working environment [33]. The workplace accidents have basically the same disaster status, and similar occupational disasters have occurred repeatedly.

Automatic rule checking is an important technology in the application of 3D models. The core concept is to translate the semantics of laws, standards, and specifications into logical relationships that can be understood by the computer, and rely on the computer to automatically find the components or spaces in the model that do not conform to the logical relationship (or violate the regulations and standards) [34].

In recent years, many have applied automatic rule checking to the safety and health management of engineering projects [35]. By analyzing the semantics and translating the logic of major risk events, the 3D model can identify potentially risky locations, areas, or spaces in the phase of construction planning. Then, measures and plans can be made in advance to eliminate intangible risks.

One of the key measures is to draw a plan of the safety signs. In actual operation, the safety sign plan [36] needs to cover the warning signs for all three layers of construction: foundation, main body, and decoration. If the layers are inconsistent in safety signs, the floor plan should be drawn in layers. Then, the complex information of safety signs might be discontinuous, if the 2D drawings are adopted. Thus, the traditional management of construction safety signs cannot effectively transmit information or support self-inspection [37].

In traditional workplace hazard assessments, the safety knowledge is usually managed with written descriptions, which only carry a very limited amount of information [38]. To enhance the efficiency of safety planning, some scholars [39, 40] built an automated construction safety inspection rule database system, which integrates laws, regulations, and expert knowledge of safety inspection. Based on the information provided by the 3D model, it is possible to pinpoint the situations in need of safety protection measures during the construction phase. Then, the on-site operators, safety management personnel, and safety supervisors will receive correct safety protection information in real time, and effectively improve the management of job safety [41].

5.2 Safety knowledge has the potential to improve the safety of construction plan

In petrochemical industry, it is an important issue to manage the safety of construction site. For construction site management, a crucial aspect rests with the management of safety signs in the construction site. Without proper safety signs, the construction personnel will have difficulty in preventing safety accidents [42, 43].

The conventional ways to manage the safety signs in the construction site include: (1) identifying construction hazards; (2) determining dangerous operations, points, and areas; (3) setting safety signs; (4) drawing a safety sign plan; (5) hanging safety signs; (6) safety disclosure; (7) inspection and maintenance of safety signs [44, 45].

In the planning phase, safety must be prioritized in construction activities. The safety and health requirements should be defined in view of the specific situation of construction activities in the work breakdown structure. Then, the safety-related activities must be included in the project schedule. As a result, the safety plan can proactively incorporate safety into the project as early as possible, before any harm emerges [46]. Looking at the project schedule, the project team can understand the safety requirements and their own tasks. The necessary resources required for safety performance can also be appropriately allocated and purchased in advance. Xia et al. [47] explored planning tools that integrate health and safety into buildings, and tried tools like safety information drawings, and responsibility maps to reduce bureaucratic paperwork [47].

As far as the petrochemical industry is concerned, there is a huge demand for the 3D platform, owing to the massive amount of data, the high density of equipment, and the strict requirements on model accuracy, authenticity, interactivity. Therefore, this paper preliminarily presents a model that solves the integrated management of multi-dimensional information, and facilitates equipment management, accident prevention, emergency response, and employee training.

The importance of safety management will further increase with the expansion of production scale. Therefore, the staff involved in preliminary design must be fully aware of safety. Our model provides them with a good tool to improve the quality of 3D drawings and enhance their capabilities in operation planning and protecting environment safety.

5.3 Integrating safety space in 3D model design promotes construction plan

The 3D model-based management of construction safety mainly considers the technologies of construction safety in the design and planning stage. Take special-shaped buildings which are not easy to construct for example [48]. 3D models can be called to design the construction frame, assess the feasibility of construction, and control project risks. If the building is particularly complex in shape, it is critical to eliminate risks before construction, thereby ensuring work progress and safety [49].

With the aid of 3D models, it is easy for construction managers to review the conflicts between construction interfaces in advance. For example, staff from different disciplines and fields can simulate the entire project with the 3D model. In this way, they can discuss every detail of the project, while executing the project [50]. Then, it is possible to control the construction method, the mobilization of each job, and manpower scheduling. The 3D model can also quantify the safety and health of hypothetical projects, judge the necessity of safety and health facilities, and confirm the integrity of the configuration of safety facilities [51].

In petrochemical industry, one of the stages of project construction is capacity improvement or area modification. Taking a Turkey project for example, 3D model design accounts for only 30% of the total project budget. The cost of 3D modeling is nothing compared to the huge cost of construction and management. Due to external factors, the project design needs to be changed during the construction. Any change to the design brings a huge pressure to the construction team. Many works must be reorganized according to the new design drawings, such as material procurement, personnel control, and work safety planning. With the help of 3D modeling, it is easy for 3D designers to make modifications, and minimize the pressure to the on-site team.

6. CONCLUSIONS

Through analysis and discussion, the authors learned that most on-site engineers and managers agree that integrating safety knowledge into model design at the beginning of the project greatly promotes the later planning. From the perspective of design engineers, how to improve the awareness of safety knowledge is a prominent issue to reduce work accidents.

In recent years, 3D models have been commonly applied in petrochemical industry. Our results show that, the framework of 3D model combined with safety knowledge was acceptable to project executors. Therefore, the follow-up research will collect and classify many unexpected dangerous behaviors, and then combine the classified items with the proposed 3D model system. To efficiently implement large-scale projects in future, designers must receive safety management courses, and management personnel must also participate in safety courses (e.g., seminars and on-the-job training). The staff in these two fields should supervise and communicate with each other.

Our research suggests that 3D design companies in petrochemical industry and related fields must effectively integrate the knowledge of petrochemical safety into 3D models. The integration can be realized by means of software and hardware. The software means is to incorporate safety data into the company’s safety knowledge database with big data and digital transformation tools. The hardware means include augmented reality (AR) / virtual reality (VR) facilities that enhances the overall model structure, changing the empirical mode into innovative mode.

As for employee candidates, they must receive safety knowledge training, and pass the relevant tests, before learning 3D modeling and designing 3D models. As for current employees, they should participate in trainings on risk/hazard identification, and risk assessment, in order to acquire the ability to predict potential accidents.

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Our 3D model design focuses specifically on petrochemical industry, under the setting of one of the biggest petrochemical companies in Taiwan.

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