International Journal of Applied Science and Engineering

A knowledge management-based engineering design system for highway design projects

Wen-der Yu[1], Hsien-Kuan Chang[1*], Chien-Hung Lai[2]

[1] *Department of Construction Engineering, Chaoyang University of Technology, Taichung, Taiwan, R.O.C.*
[2] *CECI Engineering Consultants, Inc., Taipei, Taiwan, R.O.C.*

ABSTRACT

Construction engineering design is highly dependent on previous experience so experienced engineers normally produce the design. This practice allows the leakage of knowledge when experienced engineers leave and is costly in terms of the time required for design work. This study proposes a knowledge management–based engineering design system (KMEDS) that supports engineering design of highways and roads. A text mining technique using a vector space model (VSM) is used to retrieve documents. Nine historical design cases containing 1,683 engineering documents are collected as the knowledge base. A real-world express highway design project is used to test the feasibility of the proposed method. A questionnaire survey is then conducted to evaluate the proposed KMEDS. The approval rate is 88% in terms of system correctness and 86% in terms of time savings.

Keywords: Engineering design, Highway projects, Knowledge management, Document retrieval.

OPEN ACCESS

Received: November 29, 2018

Accepted: February 22, 2021

Corresponding Author:
Hsien-Kuan Chang
hkchang@cyut.edu.tw

Publisher:
Chaoyang University of Technology
ISSN: 1727-2394 (Print)
ISSN: 1727-7841 (Online)

1. INTRODUCTION

Engineering design processes are highly complex and dynamic inasmuch unforeseen changes occur frequently (Heer and Wörzberger, 2011). In addition to the problem of frequent changes, engineering design is also a transdisciplinary process that requires knowledge from multi-disciplines (Butt et al., 2018; Qureshi et al., 2013; Qureshi et al., 2014). The transdisciplinary process becomes more complicated when it is performed in a large-scale design project such as the civil engineering project, where the number of involved disciplines and organizations is usually much more than that of product design project in a product design project. It means that a streamline and standard engineering procedure should be developed. Moreover, a useful tool to cope with the transdisciplinary engineering knowledge needed in a civil engineering design project should be provided to better equip the design engineers.

The engineering design process for structures such as highways, bridges, tunnels, dams, airports, and buildings is critical for the successful delivery of a civil engineering project (Asteris and Neofotistos, 2014). However, there were very few reports existing in literature to address the practical method of an engineering design problem. Without such a method, it usually takes a long training period for a new design engineer to become a professional. Interviews with design engineers of the local leading consultant firms show that design engineers usually use very few historical design cases (Yu et al., 2014). If the new project is beyond the scope of the historical cases, the design engineers must find other similar cases. Only when there is no any relevant historical case available do the design engineers develop a time-consuming original design for the new project. Design using historical cases is a task that is perfectly suited to knowledge management.

In most cases, the design engineers refer to a few cases from the same department and the rest refer only to the cases conducted by other sections of the same department. This practice has several drawbacks: (1) the company's design knowledge is not shared with engineers in other departments; (2) it inhibits technological innovation because there are fewer idea intersections (Johansson, 2002); (3) it increases the cost of design work because the process involves reinventing the wheel and (4) it increases the time that is required for design work.

In response to the aforementioned challenges faced by the engineering design industry and the practitioners, this research aims at developing an engineering design assistant system for a highway design project, namely knowledge management–based engineering design system (KMEDS), which addresses the three principal problems in an engineering design project mentioned above. To achieve this objective, the current roles of knowledge management in design work and the drawbacks of the current engineering design practice suggest that a knowledge management-based computer-aided engineering design system that provides referable and reusable design documents retrieved from historical engineering design projects is desirable and useful. However, the detailed tasks in the process of engineering design that have complete input-process-output attributes must be identified in order to clarify the knowledge that is required for these tasks, engineering documents for these design tasks must be collected for reuse and an efficient document retrieval algorithm must be developed to retrieve the reusable historical cases. The methodology and the implementation process are described and demonstrated. In the evaluation process, senior design engineers are invited validate the proposed method in a real-world engineering project.

2. LITERATURE REVIEW

2.1 Engineering Design

Chen (2002) defined 'design' as "the process of drafting or modelling of the structures for specific purposes". Engineering design occurs as the result of a feasibility study (or a pre-study (Heer and Wörzberger, 2011)), which analyses the required technology, the construction cost, the resources required and the construction procedure in more detail (MBALib, 2018). Li et al. (2007) proposed a functional framework for computer-aided innovative design. In this framework, the designer generates design alternatives by exercising his/her imagination, based on previously learned knowledge and information, according to theory of cognitive science. This activity can be supported and aided by a knowledge-based computer system (Li et al., 2007). In the construction industry, the engineering design procedure is divided into two primary phases (Yu et al., 2014): (1) basic/preliminary design—proposing the preliminary design alternatives - and (2) detailed design/design development—developing design details for the selected design alternative.

Recently, sustainability has become an important issue in engineering construction projects (Rooshdi et al., 2014; Yu et al., 2010). Rooshdi et al. (2014) proposed an evaluation method for designing of a green highway by measuring the sustainability indicators of the design and construction activities. Yu et al. (2018) proposed an overall project sustainability index (PSI) to monitor the sustainability of a construction project for the 8 phases of a project lifecycle.

2.2 Engineering Problem-Solving

Problem solving is central to engineering consulting tasks (Yu et al., 2010), including engineering design. Li and Love (1998) developed a problem-solving framework for construction engineering and management. This study identified several characteristics of construction problems that must be addressed, in order to solve them quickly, correctly and cost-effectively, such as ill-structures, inadequate vocabulary, a lack of generalization and conceptualization, temporary multi-organizations, the uniqueness of problems and difficult in achieving the optimal solution. Yu et al. (2007) proposed an approach called a knowledge management integrated problem-solver (KMiPS) to solve emergent construction problems. The KMiPS uses a knowledge management system (KMS) and a specially designed community of practice (CoP), namely emergency problem-solving system (SOS), to solve emergent problems. The study demonstrates that the KMiPS achieves better quantitative and qualitative benefits than traditional problem-solving approaches.

2.3 Automatic Construction Document Retrieval System

Automatic document retrieval creates an information system that retrieves relevant documents that are stored in a database. There have been several studies of automatic document retrieval for construction engineering. The advanced construction technology system (ACTS) that was developed by Ioannou et al. (1992) provides a technology information system that allows construction planners and managers to select the most appropriate state-of-the-art construction technologies during the project planning stage. The architecture and engineering performance information centre (AEPIC) that was developed by Loss (1987) provides information on failures so that the mistakes are not repeated. The on-line reference library (OLRL) provides engineers with real-time reference manuals for specifications (SPECs) (Kartam and Flood, 1997).

Even though these systems provide some features of problem solving in engineering design process, none provides all of the functionalities that are required for construction design.

3. RESEARCH METHODOLOGY

In order to meet research objective described in the Introduction and deliver more practical and useful results, this study narrows down the scope to tackle only the highway engineering design, instead of developing a holistic engineering design system. However, the framework and methodology developed in this study will be applicable in development of the engineering design system for the other types of civil engineering projects.

The research methodology for this study is planned comprising of the following steps: (1) a local leading consulting firm, CECI Engineering Consultants, Inc. (www.ceci.com.tw) is selected as the industrial partner for consulting to collect the knowledge and information of practical operations in an engineering design project; (2) the required the detailed procedure of an engineering design project is analyzed with the senior design engineers of the selected industrial partner to layout the relevant activities required to complete an engineering design project using a focused group meeting with the industrial partner; (3) the necessary input information as well as the related deliverables of each activity are defined by the senior design engineers of the selected industrial partner; (4) after the identification of the required information for the relevant design activities, the historical project files with various documents for the required information are collected to provide the knowledge source for the proposed KMEDS; (5) the relevant document retrieving techniques and the related computational algorithms are developed for each types of the relevant engineering documents; (6) the system framework is planned to cope with the required functionalities for the proposed KMEDS; (7) the senior design engineers of the industrial partner are invited to verify the design functionalities of KMEDS; (8) an engineering design team of the industrial partner is asked to test the proposed KMEDS using the a real-world highway engineering design project, and the participants are surveyed with a questionnaire to validate the proposed KMEDS. The following sections show the details of the methodology adopted in this research.

4. ENGINEERING DESIGN PROCESS

A general engineering design may comprise of three primary processes (Heer and Wörzberger, 2011; Yu et al., 2014): (1) Design planning (or pre-study of a design problem)—analysis of an engineering problem to be solved; (2) Basic design—proposal of a couple of feasible alternatives; (3) Detail design (or design development)—development of detailed engineering analyses and drawings for manufacturing, installation, or construction works. In practice of the most consulting firms in Taiwan use 10 primary steps for engineering design: (1) In the principal department (PD), a project manager (PM) is responsible to the project sponsor; (2) the PM assigns a principal engineer (PE), who is usually a senior and experienced engineer, to take charge of the design work; (3) the assigned PE breaks down the work into design tasks for several associated departments (ADs) and the associated engineers (AEs) in these ADs; (4) the managers of the ADs assign the principal engineers from the ADs (PEAD) for the project; (5) the PEAD breaks down the assigned tasks for the associated engineers (AEs) in associated department (AEAD); (6) the AEADs complete assigned design tasks and deliver outcomes to the PEAD; (7) the PEADs collect and verify the design results and compile the assigned design tasks and deliver the finished work to the PE; (8) the AEs finish their assignments and deliver the finished work to the PE; (9) the PE compiles the finished work and report to the PM and (10) the PM reports to the sponsor (or client) with the finished design. This procedure for engineering design relies heavily on experienced senior engineers both in the PD and ADs (Kinney and Ra, 1995). The design engineers (either the PEs or AEs in the PD and ADs) usually refer to previous design cases for the design tasks. Modifications are made to the preliminary design according to the specific characteristics of the new project, if necessary.

Based on the literature review and interviews with senior design engineers from the industrial partner, a general engineering design process for a highway design project is shown in Fig. 1. This process consists of three major stages: (1) selection of the bridge type and the design principle (SBTDP); (2) preliminary design (PD) and (3) detailed design (DD). These three stages are described in the following sub-sections.

4.1 Selection of Bridge Type and Design Principle

The first stage in an engineering design project is to determine the most appropriate type of bridge and the type of road structure (viaduct, tunnel, embankment, etc.) for the project. Information that is required to conduct tasks at this stage includes: (1) a 1/5000 topographic map and (2) a drill plan from soil exploration (or a site investigation). The major outcomes of this stage are: (1) a bridge type and design principle report and (2) a value engineering analysis report (if applicable).

4.2 Preliminary Design

In the second stage, the design engineers generate a set of design alternatives, so that the project sponsor or client can determine which is to be developed. Information that is required to conduct the tasks for this stage includes: (1) a 1/1000 topographic map; (2) a surveying report; (3) a drilling report; (4) the bridge type and (5) the design principle report. The major outcomes of this stage are: (1) the preliminary design report; (2) the preliminary design drawings; (3) the conceptual cost estimation and (4) the map for right of way.

4.3 Detailed Design

The third stage develops the design so that the required documents for procurement can be generated. Information that is required at this stage includes: (1) a 1/1000 topographic map; (2) the preliminary design drawings; (3) the conceptual cost estimation; (4) the right of way map and (5) the soil drilling report. The major outcomes of this stage are: (1) the construction specifications (SPECs) and

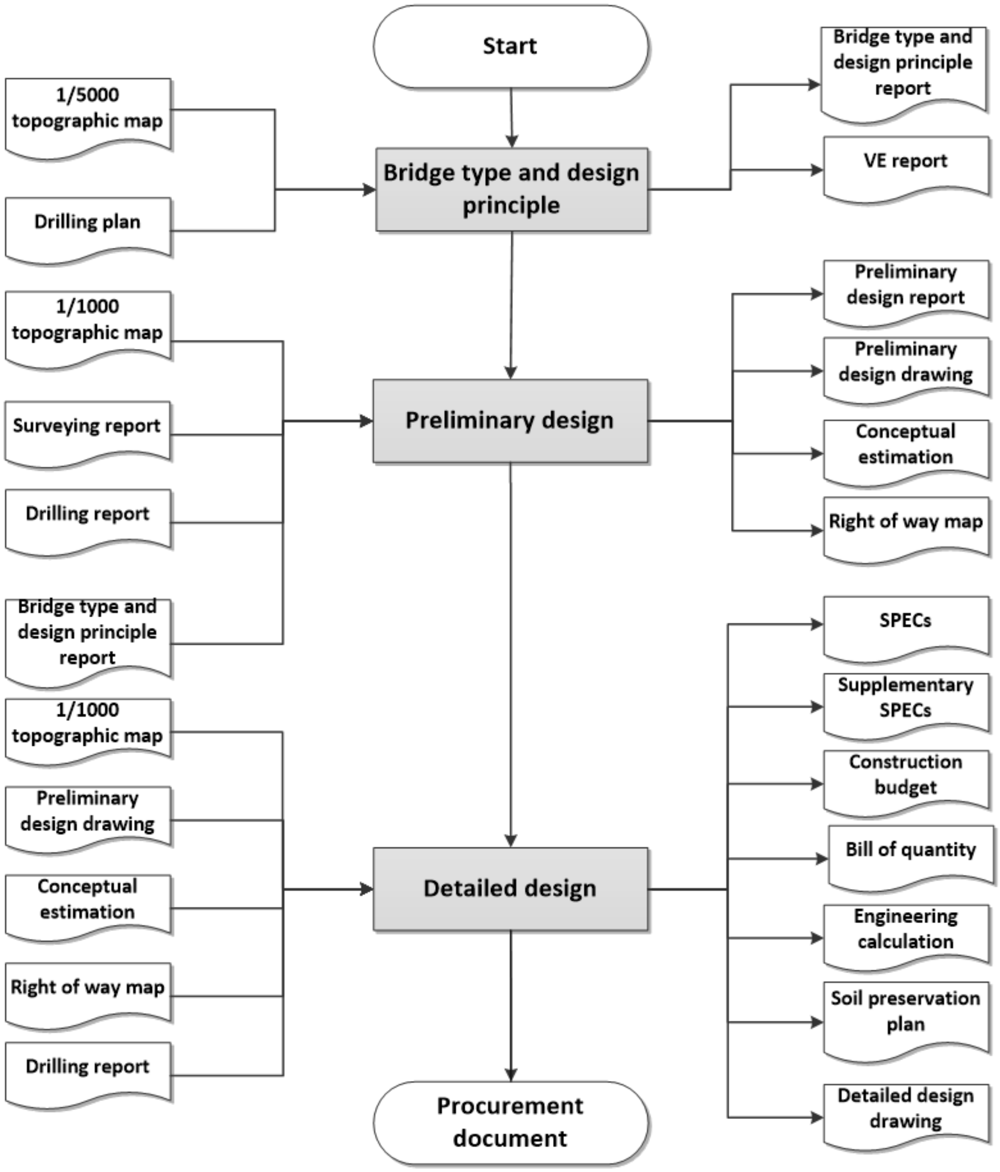

Fig. 1. General procedure for a highway design project

supplementary specifications; (2) the construction budget for the project; (3) the bill of quantities; (4) the engineering calculation report; (5) the soil preservation plan and (6) the detailed design drawings.

4.4 Procurement Documentation

When the detailed design is complete, the required procurement documents are prepared, including: (1) the construction budget; (2) detailed design drawings and (3) the SPECs. These documents are reviewed by the sponsor or client. If the sponsor or client approves the documents, the design procedure is completed and the project proceeds to the next step: procurement.

5. COLLECTION AND PROCESSING OF HISTORICAL DESIGN DOCUMENTS

Most previous knowledge of engineering design is preserved in design documents (e.g., reports, drawings, SPECs, calculations and estimations). This previous design knowledge is best accessed by an automated document processing system that can extract knowledge from historical engineering documents. However, the various types of historical engineering documents must be identified and a processing method is required.

5.1 Types of Historical Engineering Design Documents

To determine the types of engineering design documents, nine historical design cases for a highway construction project were collected by this study, including 1,417 CAD drawings, 126 Excel spreadsheet files, 8 PPT presentation files, 20 PDF reports and 112 Word files. Those documents are classified into 8 different types: (1) construction plans; (2) construction SPECs; (3) supplementary SPECs; (4) budgets; (5) structural and design calculations; (6) design drawings; (7) reports and (8) presentations.

5.2 Processing of Historical Documents

When processing the historical design documents for reuse, because there are five different formats of historical documents (CAD, PPT, PDF, Excel and Word), it is necessary to convert all to the same format for information processing. This study uses a text mining technique to process and retrieve the historical documents. All five types of documents are converted into text files and then the text files are processed using a vector space model (VSM) technique, which uses an algebraic model to represent text documents as vectors of identifiers. The original VSM was first proposed by Salton et al. (1975) and is described as follows:

For a document d_i and all words $w_l \in W$ (W is the corpus), the frequency $f(w_l \mid d_i)$ or probability $p(w_l \mid d_i)$, that characterizes the probability of the considered keyword (w_l) in the given document (d_i), are calculated using Equation (1).

$$p(w_l \mid d_i) = \frac{f(w_l \mid d_i)}{\sum_m f(w_m \mid d_i)} \tag{1}$$

where the numerator on the right-hand side counts the frequency with which a keyword w_l occurs in document d_i, and the denominator calculates all keywords in d_i.

Using a vector space of L ($= \|W\|$) dimensions, a document d_i is described as a vector $\vec{x_i}$ of word *probabilities,* as shown in Equation (2):

$$\vec{x_i} = [p(w_1|d_i), \ldots, p(w_L|d_i)]^T \tag{2}$$

Because there are many distinct words in any non-trivial corpus ($L \approx 10^5 \sim 10^7$) the vector space is extremely highly dimensional but sparsely occupied (Pullwitt, 2002). These very sparse vectors require another scheme to improve the processing efficiency.

5.3 Computational Algorithm

A computational algorithm for historical document processing is developed for this study and is shown in Fig. 2. The algorithm has six steps:

1. Historical documents (including all documents formats, e.g., MS® Word reports, PowerPoint files, Excel spreadsheets, and Autodesk® CAD drawings) are retrieved from the company's document base;
2. Textual information in the historical documents is extracted in the form of text files, namely a characteristic document (CD);
3. The CDs are processed using text mining techniques and converted into a VSM and saved to a VSM base;
4. The query input that is provided by the user KMEDS is converted into a VSM, namely Q-VSM;
5. Document matching involves matching the Q-VSM with all pre-stored VSM's in the VSM base, based on the inner product of q and W.
6. The VSMs with the greatest similarity are selected as the relevant design documents and reported to the user at the output interface.

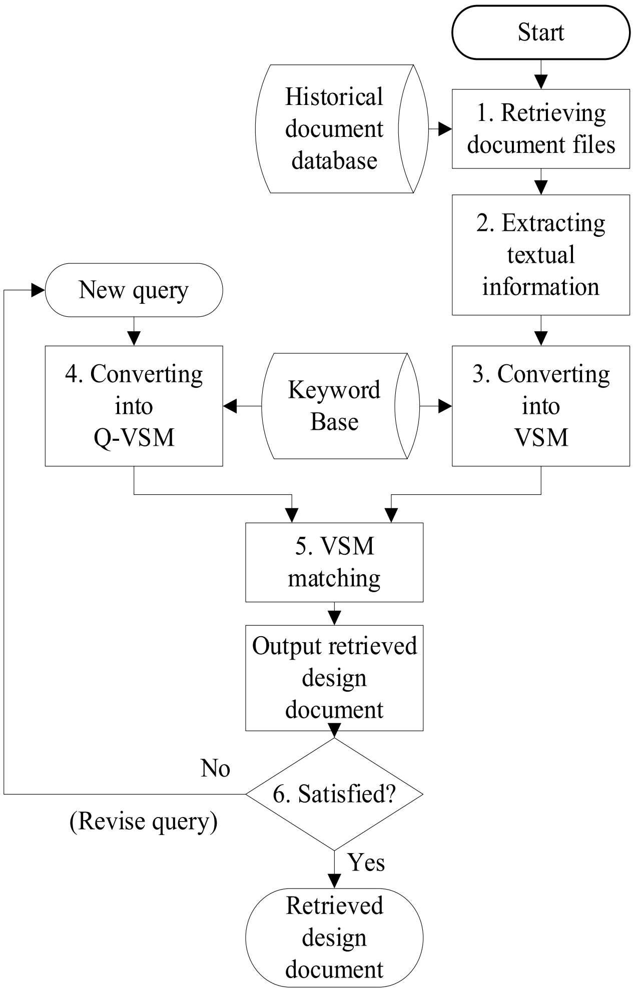

Fig. 2. Computational algorithm for document retrieval

6. DEVELOPMENT OF THE KMEDS SYSTEM

6.1 System Framework Planning

The proposed method is implemented in an engineering design assistant system, namely KMEDS. The system framework for KMEDS is shown in Fig. 3, where the historical design documents are processed and converted into VSM models and stored in the VSM base.

Seven modules are developed in the proposed KMEDS:

1. Project ID query (PIR)—query historical documents by project ID;
2. SPEC query (SRQ)—query historical SPECs;

Yu et al., International Journal of Applied Science and Engineering, 18(2), 2018172

3. Plan/report query (PRQ)—query historical plan and reports;
4. Engineering calculation query (ECQ)—query historical engineering calculation sheets;
5. Estimate/budget query (EBQ)—query historical cost estimation and budgets;
6. Design drawing query (DDQ)—query historical design drawings;
7. Presentation file query (PFQ)—query historical presentation files.

6.2 System Implementation

The proposed KMEDS is programmed and developed as an engineering design assistant for a highway design project. The entry interface for the KMEDS system is shown in Fig.4. The seven functional modules are listed in the left column, the query entry is located in the middle of the interface, which accepts a natural language query description or keywords and the retrieved documents are listed at the bottom of the right-hand side.

6.3 System Testing and Evaluation

6.3.1 Description of System Testing

The developed KMEDS system was tested using a real-world highway design project for which a leading local engineering consulting firm (CECI engineering consultants, Inc., Taiwan) was responsible, in order to verify its applicability. The selected case is part of the west coast expressway project from 297k+300~298k+613. Major work items include 1.3 KM of viaduct structure, a signal and lighting system, an interchange and 1.6 KM ramps. A total of 23 engineering design tasks—8 steps in bridge type selection and design principle (BTSDP), 7 steps in preliminary design (PD) and 8 steps in detailed design (DD)—were used.

6.3.2 System Application

1. Phase I: Selection of bridge type and design principle

(a) Description of design tasks in Phase I

The primary objective of the work in Phase I is to propose the bridge types and principles for road design for the sponsor or client. There are eight design tasks in this phase. For "Road Engineering Design", the

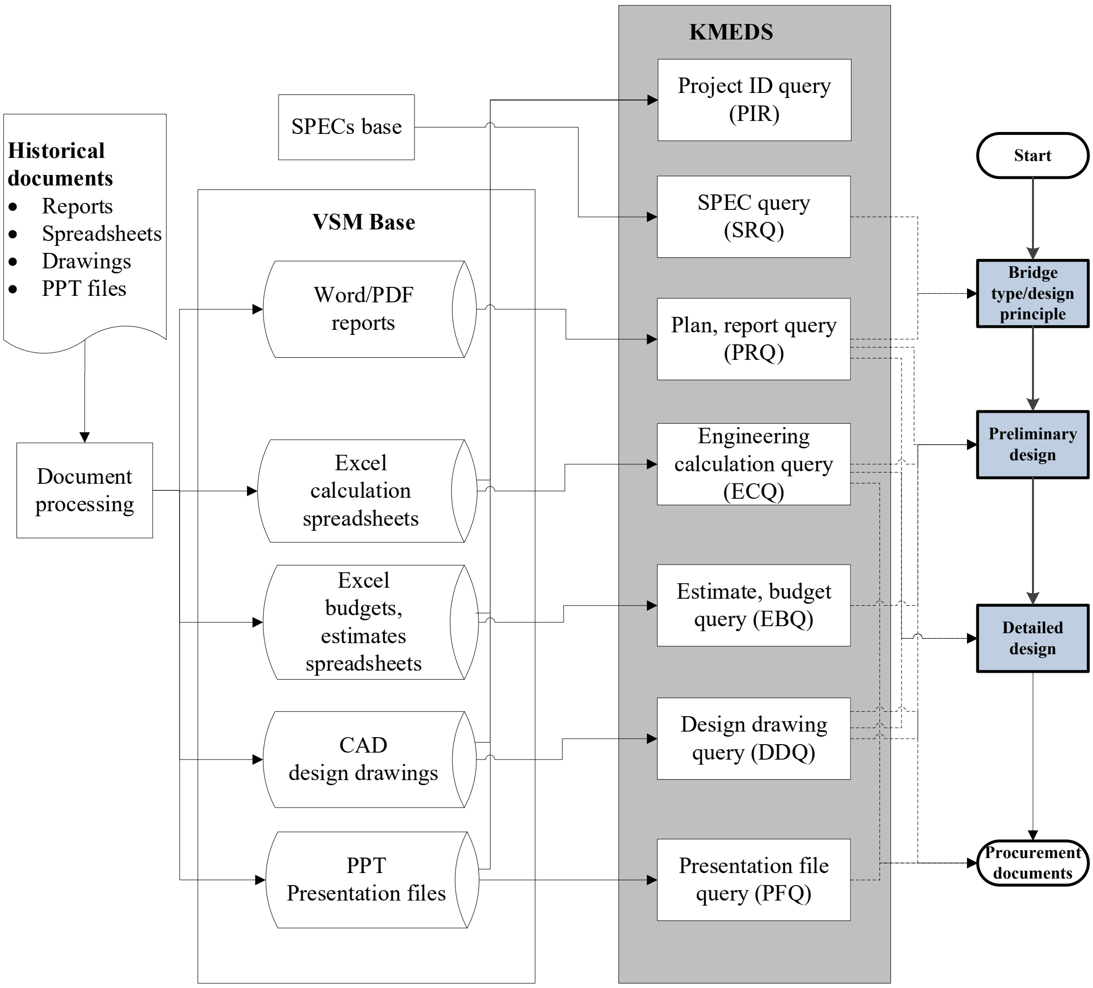

Fig. 3. Framework for the proposed KMEDS system

Yu et al., International Journal of Applied Science and Engineering, 18(2), 2018172

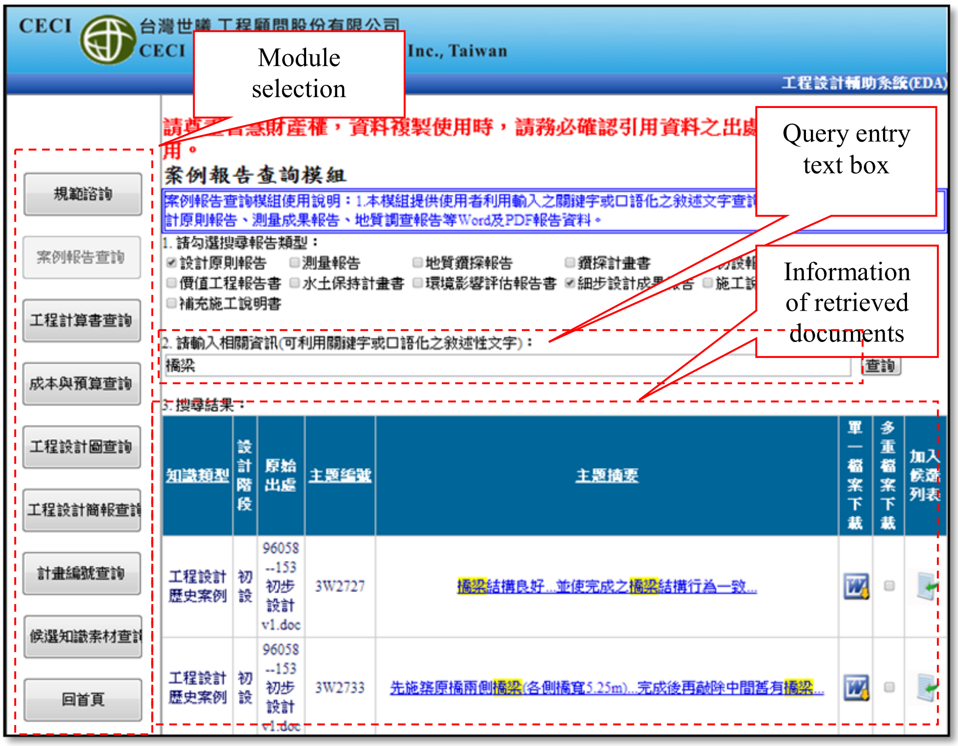

Fig. 4. Planned interface for the proposed KMEDS system

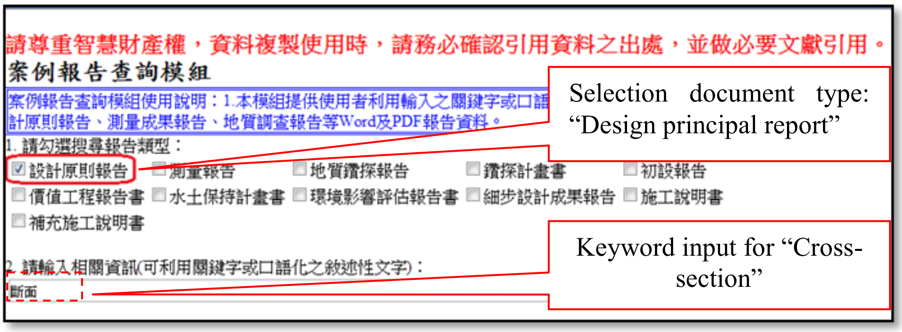

Fig. 5. The keyword query input interface

design engineer must determine the following parameters: the conceptual horizontal and the longitudinal alignment of the road, the conceptual layout of the interchange and the conceptual profile of the road cross-sections. The required inputs for this step are the SPECs for the horizontal and longitudinal alignment and a topographic map with a scale of 1/5000. The outputs include the horizontal and longitudinal alignment for the road, the interchange layout, and the cross-section profile of the road.

(b) System application

The user logs in using identity information (ID), including the staff ID No. and password. After the login process, the main interface of the KMEDS system is shown as that in Fig. 4.

For standard cross-section design, the user accesses historical design reports from the main interface of KMEDS using the key word “Cross-section”, as shown in Fig. 5. The search results are shown in Fig. 6. The user then clicks on “topic” (showing the short

Yu et al., International Journal of Applied Science and Engineering, 18(2), 2018172

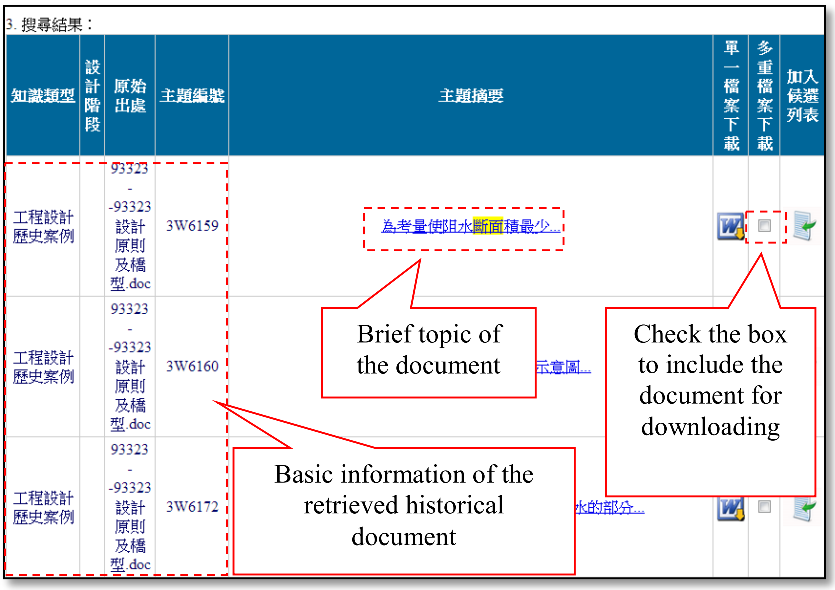

Fig. 6. The search results for historical design reports using KMEDS

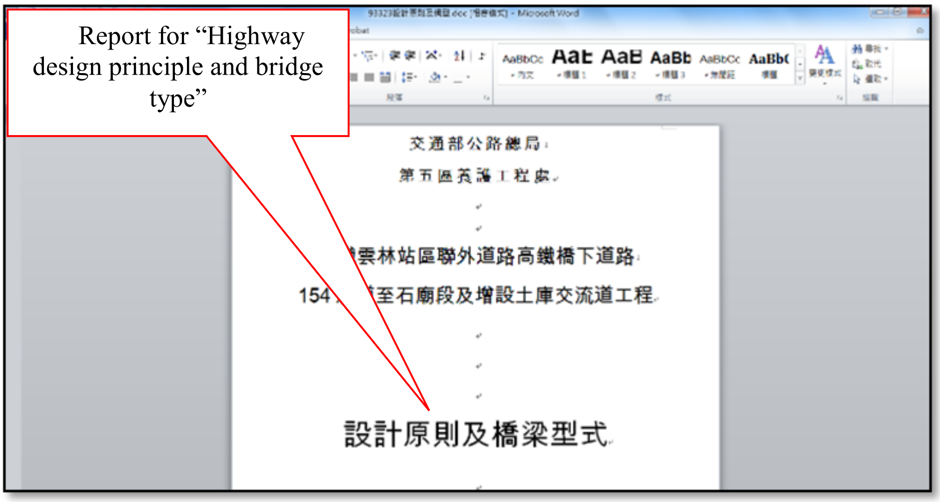

Fig. 7. An example of a downloaded report for "Highway design principle and bridge type"

abstract description of the document) for the associated document to see the content of the document. If the document is relevant, it is selected by clicking on the checkbox on the right-hand side of the retrieved document topic. The selected documents are then downloaded by the user for reference for the design tasks. An example of a downloaded design report for "Highway design principle and bridge type" is shown in Fig. 7. From this report, an example of a highway interchange layout is shown in Fig. 8. The design engineer refers to the historical design to generate alternatives for the new design project.

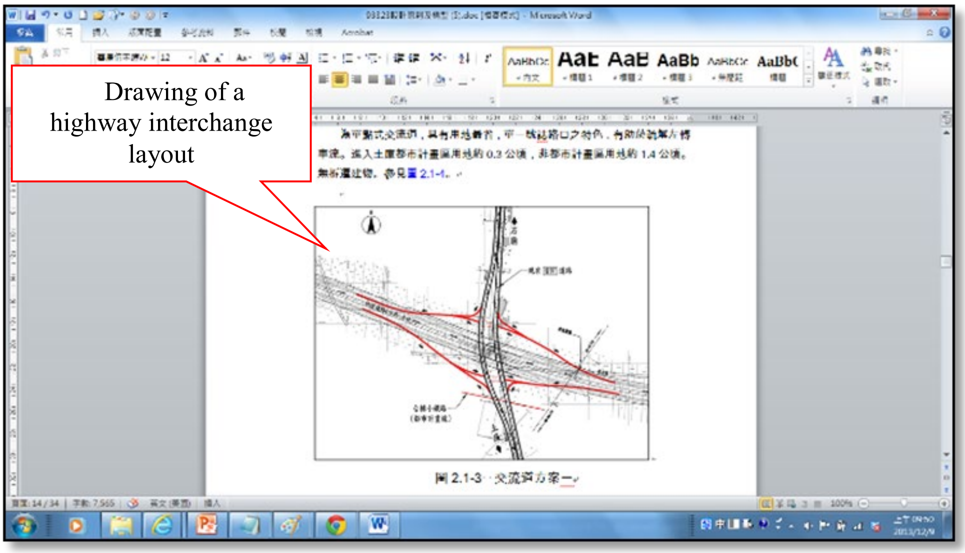

Fig. 8. An example of a highway interchange layout

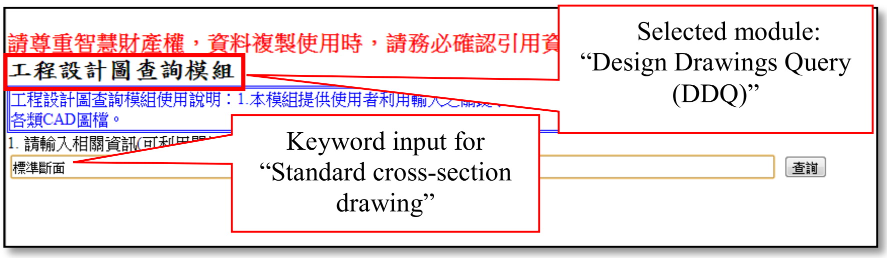

Fig. 9. “Road standard cross-section drawing”: retrieval information input interface

2. Phase II: Preliminary Design

(a) Description of design tasks in Phase II

The objective of Phase II (Preliminary design) is to propose preliminary design alternatives for the sponsor or client, who makes a final decision. The outputs of this phase are the preliminary design drawings. The primary design tasks include the preliminary design of the horizontal and longitudinal alignment, the preliminary layout design for the interchange and the preliminary profile of the road cross-section. The required inputs for the step are the SPECs for the horizontal and longitudinal alignment and a topographic map with a scale of 1/1000. The outputs include the preliminary horizontal and longitudinal alignment for the road, the preliminary interchange layout and the preliminary cross-section profile of the road.

(b) System application

In using KMEDS for preliminary design, the user first selects the appropriate functional module from Fig. 4. A sentence or keywords that describe the design task is input via an interface that is shown in Fig. 5. If an engineer wants to retrieve schematic design drawings from the historical project, the “Design drawing retrieval module” in Fig. 4 is used. The user types “Standard cross-section”, as shown in Fig. 9. The search results are shown in Fig. 10.

Similarly to Phase I, the user sees the results by clicking on the “topics” and selecting the relevant documents by checking the checkbox on the right-hand side. An example preliminary design drawing for road cross-section is shown in Fig. 11.

3. Phase III: Detailed Design

(a) Description of design tasks in Phase III

The objective of Phase III is to generate all documentation for the detailed design for the sponsor or client, who makes a final decision. This documentation includes the detailed design drawings, the calculation report and the budget for procurement. For “Road Engineering Design”, the primary design tasks include the detailed horizontal and longitudinal alignment for the road, the design of the standard cross-section, the design of the road super elevation, the design of the horizontal cross-section, the design of road use regulatory signs and the detailed design of the interchange layout.

The required inputs for the step are the SPECs for the horizontal and longitudinal alignment and a topographic map with a scale of 1/1000. The outputs include the horizontal and longitudinal section

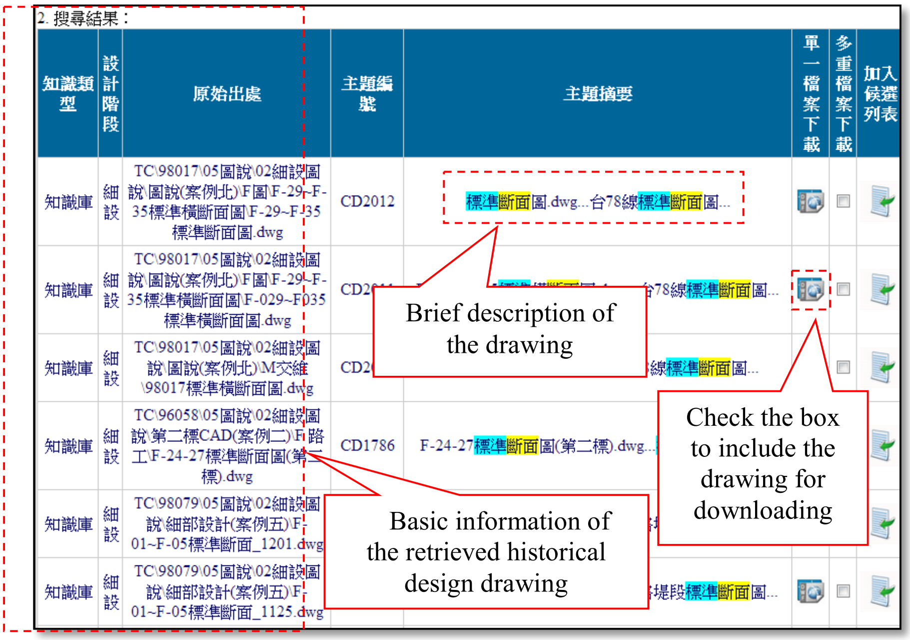

Fig. 10. Search results for “Road standard cross-section drawing” retrieval

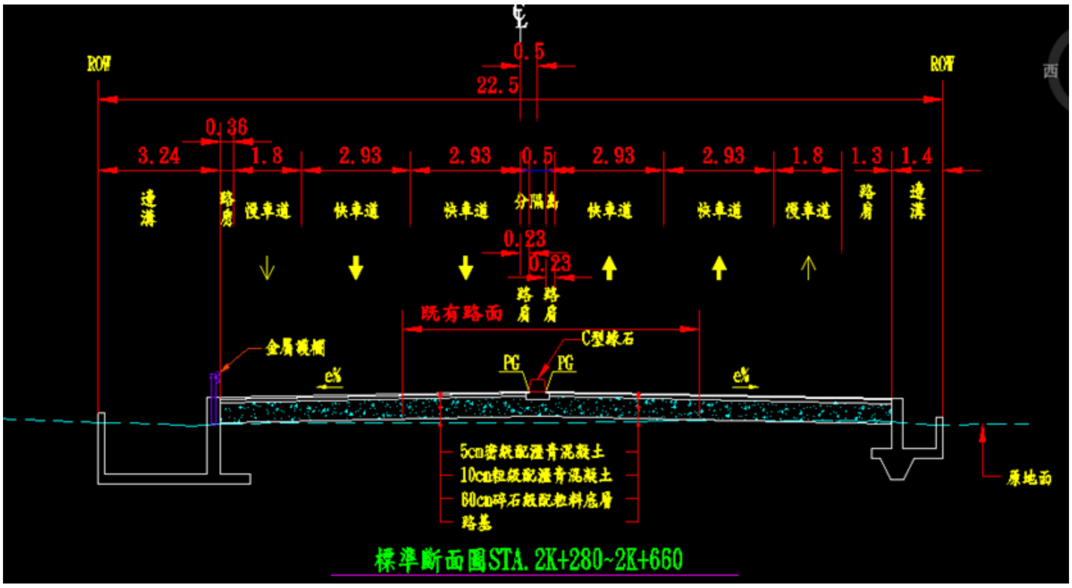

Fig. 11. Example of retrieved “Road standard cross-section drawing”

drawings for the road, the standard cross-section drawings, the detailed design drawings for road use regulatory signs, the detailed design drawings for the road super elevation, the detailed design drawings for the interchange layout and the cross-section profile of the road and the report for the construction budget for the works.

(b) System application

Similarly to Phase I and Phase II, the user chooses an appropriate functional module from the main interface (Fig. 5) of the KMEDS system. If the user is preparing the construction budget, the “Cost and Budget” functional module is selected and the relevant keywords are entered (for example, “asphalt pavement”) as shown in Fig.12. The search results are shown in Fig. 13.

The user can select the relevant reference document using a procedure that is described previously.

6.3.3 System Evaluation

In order to verify the search results and validate the proposed system, the KMEDS system was evaluated in terms of system correctness and time saving, based on Likter 5-point scale. The evaluation used five senior

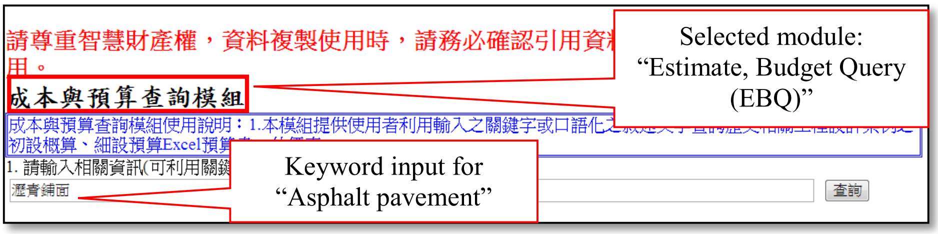

Fig. 12. Cost and budget search for "asphalt pavement"

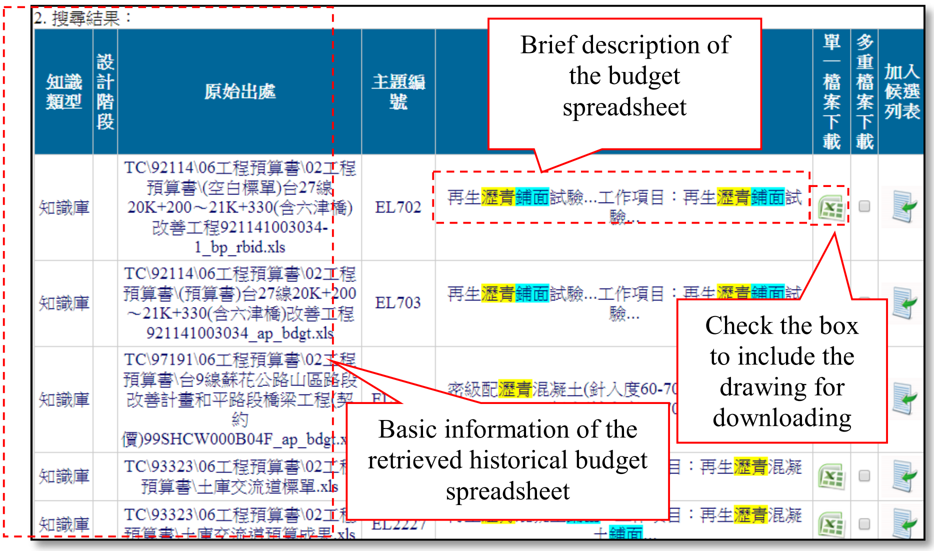

Fig. 13. Search results for cost and budget for "asphalt pavement"

Table 1. System approval rate, using a Likter 5-point scale

Stage	Correctness			Time benefit		
	Max	Min	Mean	Max	Min	Mean
BTSDP*	5	4	4.25	5	4	4.25
PD**	5	4	4.57	5	4	4.14
DD***	5	4	4.34	5	4	4.50

*BTSDP—Bridge Type Selection and Design Principle
**PD—Preliminary Design
***DD—Detailed Design

engineers from the department of transportation and civil engineering of CECI, Inc., who participated in the design tasks for the case project. The evaluation results are shown in Table 1, which shows that the system correctness and the time benefit for the proposed KMEDS are scored highly by the design engineers. The approval rate is 88% (4.4 of scale 5) for system correctness and 86% (4.3 of scale 5) for system benefit.

7. CONCLUSION AND RECOMMENDATIONS

7.1 Conclusions

Engineering design has been considered as highly complex and dynamic process, which does not only require multi-disciplinary domain knowledge but also involve many different functional organizations. Traditional practice of engineering design suffered in the leakage of knowledge when experienced engineers leave and is costly in terms of the time required for design work. This study proposes a highway design assistant that uses a knowledge management–based engineering design system (KMEDS), to support engineering design work. In order to develop such a system, the detailed procedure of an engineering design project is analyzed with the senior design engineers of the selected industrial partner to layout the relevant activities required to complete an engineering design project. The detailed engineering design procedure revealed in this paper has not been reported in the literature. Such a procedure, along with the identified required information and the relevant deliverables, has provided the engineering design consultants an invaluable reference in training the new design engineers.

A local leading consulting firm, CECI engineering consultants, Inc. (www.ceci.com.tw) was selected as the industrial partner to provide practical knowledge and experience of the firm in conducting an engineering design project. A real-world highway design project is used to test the proposed system. The system correctness and the time benefits of the proposed KMEDS score highly in a questionnaire survey of the design engineers.

It is concluded that the proposed method is a useful design assistant tool, from which historical design documents can be retrieved and reused effectively and which increases the efficiency with which design tasks are completed.

7.2 Recommendation

In order to meet research objective within the feasible timeframe and deliver more practical and useful results, the scope of the current study has been narrowed down to tackle only the highway engineering design, instead of developing a holistic engineering design system. Future research can adopt the framework and methodology developed in this study to develop the engineering design systems for the other types of civil engineering projects.

As the proposed KMEDS is based on the knowledge acquired from historical design cases, the sustainability issues related to green highway design were not considered due to the limitation of historical design cases on sustainability issues. Future direction can also be pursued in design of green highways and their related issues.

Engineering design is a highly creative work. The current research explores only the potential functions of the knowledge management system in assisting design engineers. Future research may explore the potential of recently developed generative design in the area of artificial intelligence (AI) for development of automated generative engineering design systems.

ACKNOWLEDGMENT

The funding for this research project was partially supported by the National Science Council, Taiwan, under Project No. NSC 101-2221-E-216-031-MY2. The project data for this study was provided by CECI engineering consultants, Inc., Taiwan, whose contribution and help are greatly appreciated.

REFERENCES

Asteris, P.G., Neofotistos, H.K. 2012. Engineering and design: Most central knowledge in architecture and engineering jobs. Leadership and Management in Engineering, 12, 6–11.

Butt, M., Sharunova, A., Storga, M., Khan, Y.I., Qureshi, A.J. 2018. Transdisciplinary engineering design education: Ontology for a generic product design process. Procedia CIRP, 338–343.

Chen, Y.S. 2002. The study on management of engineering design stage for projects. Master Thesis, Department of Construction Engineering, National Taiwan University of Science and Technology.

Heer, T., Wörzberger, R. 2011. Support for modeling and monitoring of engineering design processes. Computers & Chemical Engineering, 35, 709–723.

Ioannou, P.G., Liu, L.Y., Antonio, D. Jr. 1992. ACTS: Advanced construction technology system. Source Document 84, Construction Industry Institute, Austin, TX, U.S.A.

Johansson, F. 2002. The Medici effect: Breakthrough insights at the intersection of ideas, Concepts, and Cultures, Harvard Business School Press, Cambridge, MA, USA.

Kartam, N., Flood, I. 1997. Constructability feedback systems: Issues and illustrative prototype. Journal of Performance of Constructed Facilities, ASCE, 11, 178–183.

Kinney, J.R., Ra, J.W. 1995. Training Entry-Level engineers in civil engineering and design consulting firm. Journal of Management in Engineering, 11, 35–40.

Li, H., Love, P.E.D. 1998. Developing a theory of construction problem solving. Construction Management and Economics, 16, 721–727.

Li, Y., Wang, J., Li, X., Zhao, W. 2007. Design creativity in product innovation. International Journal of Advanced Manufacturing Technology, 33, 213–222.

Loss, J. 1987. AEPIC project: update. Journal of Performance of Constructed Facilities, ASCE, 1, 11–29.

MBALib. Engineering Design. Website: http://wiki.mbalib.com/zh-tw/%E5%B7%A5%E7%A8%8B%E8%AE%BE%E8%AE%A1, accessed 2018/02.

Pullwitt, D. 2002. Integrating contextual information to enhance SOM-based text document clustering. Neural Networks, 15, 1099–1106.

Qureshi, A.J., Gericke, K., Blessing, L. 2013. Design process commonalities in trans-disciplinary design. Proceedings of the 19th International Conference on Engineering Design (ICED13), 459–468.

Qureshi, A.J., Gericke, K., Blessing, L. 2014. Stages in product lifecycle: Trans-disciplinary design context. Procedia CIRP, 224–229.

Rooshdi, R.R.R.M., Rahman, N.A., Baki, N.Z.U., Majid, M.Z.A., Ismail, F. 2014. An evaluation of sustainable design and construction criteria for green highway. Procedia Environmental Sciences, 180–186.

Salton, G., Wang, A., Yang, C.S. 1975. A vector space model for automatic indexing. Communications of the ACM, 18, 613–620.

Yu, W.D., Cheng, S.T., Ho, W.C., Chang, Y.H. 2018. Measuring the sustainability of construction projects throughout lifecycle: A Taiwan lesson. Sustainability, 10, https://doi.org/10.3390/su10051523.

Yu, W.D., Hsu, J.Y., 2013. Content-based text mining technique for retrieval of CAD documents. Automation in Construction, 65–74.

Yu, W.D., Lin, C.T., Yu, C.T., Liu, S.J., Luo, H.C., Chang, P.L. 2007. Integrating emergent problem-solving with construction knowledge management system. Proceedings of the CME 25 Conference, University of Reading, Reading, UK, 10 pp.

Yu, W.D., Liu, D.G., Lai, C.H. 2014. KMS-based engineering design assistant for highway design projects. Proceedings of the Nineteenth International Symposium on Artificial Life and Robotics 2014 (AROB 2014), B-Con Plaza, Beppu, Japan, 671–674.

Yu, W.D., Yang, J.B., Tseng, J.C.R., Liu, S.J., Wu, J.W. 2010. Proactive problem solver for construction. Automation in Construction, 19, 808–816.