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Developing a Tailored RBS Linking to BIM for Risk Management of Bridge Projects

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Abstract

Purpose – The purpose of this paper is to address the current theoretical gap in integrating knowledge and experience into BIM for risk management of bridge projects by developing a tailored Risk Breakdown Structure (RBS) and formalising an active link between the resulting RBS and Building Information Model (BIM).

Design/methodology/approach – A three-step approach is used in this study to develop a tailored RBS for bridge projects and a conceptual model for the linkage between the RBS and BIM. Firstly, the integrated bridge information model is in concept separated into 4 Levels of Contents (LOCs) and 6 technical systems based on analysis of the Industry Foundation Classes (IFC) specification, a critical review of previous studies and authors' project experience. The second step develops a knowledge-based risk database through an extensive collection of risk data, a process of data mining, and further assessment and translation of data. A critical analysis is conducted in the last step to determine on which level the different risks should be allocated to bridge projects and to propose a conceptual model for linking the tailored RBS to the 4 LOCs and 6 technical systems of BIM.

Findings – The findings suggest that the traditional method and BIM can be merged as an integrated solution for risk management by establishing the linkage between RBS and BIM. This solution can take advantage of both the traditional method and BIM for managing risks. On the one hand, RBS enables risk information to be stored in a formal structure, used and communicated effectively. On the other hand, some features of BIM such as 3D visualisation and 4D construction scheduling can facilitate the risk identification, analysis and communication at an early project stage.

Research limitations/implications – A limitation is that RBS is a qualitative technique and only plays a limited role in quantitative risk analysis. As a result, when implementing this proposed method, further techniques may be needed for assisting quantitative risk analysis, evaluation and treatment. Another limitation is that the proposed method has not yet been implemented for validation in practice. Hence, recommendations for future research are to: 1) improve the quantitative risk analysis and treatment capabilities of this proposed solution; 2) develop computer tools to support the solution; 3) integrate the linkage into a traditional workflow; and 4) test this solution in some small and large projects for validation.

Practical implications – Through linking risk information to BIM, project participants could check and review the linked information for identifying potential risks and seeking possible mitigation measures, when project information is being transferred between different people or forwarded to the next phase.

Originality/value – This study contributes to the theoretical development for aligning traditional methods and BIM for risk management, by introducing a new conceptual model for linking RBS to BIM.

Keywords: BIM (Building Information Modelling or Building Information Model), Safety, Risk Management, Risk Breakdown Structure (RBS), Level of Content (LOC), Bridge

Article Type: Research paper

1 Introduction

As core components constituting the infrastructure system, bridges are crucial to the public safety and national economy. They take a sizeable proportion in major railway and highway projects and need a large amount of investment (Marzouk and Hisham, 2014). However, building a modern long-span bridge is a challenging and complex long-term process in coordinating technology, people, cost, site conditions, natural forces (e.g. earthquake and typhoon), environment, etc. Various risks maybe present during the project life cycle and bridge construction has a poor reputation with a high accident rate. Furthermore, with the rapid development of society, risks are gradually growing because of the increase of structural complexity and project size, and the adoption of new and complex construction methods. From 1989 to 2000, it is reported that over 157 bridges collapsed in the United States (Wardhana and Hadipriono, 2003). Moreover, failure to manage risks may trigger chain effect and cause further risks. For example, in 2006 the collapse of an arch bridge in China not only killed 36 people but also led to adverse social influence and traffic inconvenience (BBC, 2007).

To avoid any serious accidents and assist in managing risks effectively, many risk assessment techniques have been introduced in practice, such as fault tree analysis (FTA) (Suresh *et al.*, 1996), decision trees (Dey, 2002), and neural networks (NN) (Khoshgoftaar and Lanning, 1995). These methods can be divided into two main categories: qualitative analysis techniques and quantitative analysis techniques. However, these are still static and traditional methods (Alaeddini and Dogan, 2011) and heavily reliant on multi-disciplinary knowledge and experience (Shim *et al.*, 2012). As a result, many researchers (Zhang *et al.*, 2014, Hartmann *et al.*, 2012, Shim *et al.*, 2012) point out that traditional methods can only play a limited role in the real world.

In recent years, Building Information Modelling (BIM) as an emerging digital technology has been adopted increasingly to support the project life cycle, and it is expected to play a significant role in facilitating risk management in the design, construction, and maintenance of a project. BIM is defined as *"a modelling technology and associated set of processes to produce, communicate, and analyse building models"* and allows a three dimensional representation of non-redundant data (Eastman *et al.*, 2011). A number of computer applications have been developed to support the use of BIM in practice, and also a new trend to use BIM and BIM-related digital tools for improving safety and risk management has been emerging (Zou *et al.*, 2016). For example, Liu *et al.* (2014) summarised the benefits and requirements of replacing the traditional 2D design method with 3D information modelling through the use of BIM tools to assist the design and construction of a long-span steel-box arch bridge project. Zhang *et al.* (2013) outlined an automated rule-based checking framework built on BIM for managing and preventing fall accidents on site. Wang *et al.* (2014) developed a BIM-based virtual environment and a game engine to simulate the fire evacuation of buildings. However, it has been observed that there is still a huge gap in applying these new initiatives into general use. To close this gap, an optimal solution is to align BIM with knowledge-based traditional methods for managing risks (Hartmann *et al.*, 2012, Ding *et al.*, 2016).

By taking bridge engineering as an example, this paper presents a new approach to integrate knowledge and experience in BIM for risk management by linking BIM to a tailored

RBS. It first summarises the developments and existing challenges in both traditional and BIM-based risk management methods followed by exploring the feasibility to separate BIM into different LOCs and technical systems. The paper then demonstrates a process of identifying and categorising major risks for bridge projects to develop a knowledge-based risk database. Lastly it develops a tailored RBS as an overall structural architecture to manage the risk database and presents a conceptual model to link the resulting RBS to BIM.

2 Background

2.1 The current status of risk management

According to ISO 31010:2009, risk management is a logic and systematic method that involves a set of activities and processes for establishing the context, facilitating risk communication, identifying, analysing, evaluating, treating risks, and recording and reporting the corresponding results properly in a timely manner (ISO, 2009). Architecture, Engineering and Construction (AEC) projects start with planning and design, followed by a construction stage that may last for many months, and eventually will come into the operation stage that may last for many decades before demolition. Different risks are present in the different stages of the project and product lifecycle. This means that regardless of the activity, there is always a possibility that hazards will occur and the whole project may be affected depending on the type of risk and how severe the consequences are. The scope of a risk consists of many issues: damage or failure of structures, injury or loss of life, budget overruns, delays to the construction schedule, etc. Consequently, all project participants need to improve their ability, knowledge and experience to manage risks during the project lifecycle to ensure a safe, successful, and sustainable project.

Zou *et al.* (2016) summarised a general risk management framework currently used in the UK AEC industry (Figure 1). The framework prescribes a long-term risk management strategy and a process that allows participants to work collaboratively to manage risks in a systematic way. The core philosophy of this framework, defined in the Risk Mitigation Model, is that the greatest scope for identifying and mitigating risks should be carried out as early as possible, especially in the design and planning phases, which are controlled in the UK by the Construction Design and Management (CDM) regulations (HSE, 2015). Therefore, ideally most of the foreseeable risks should be ‘designed out’ during the planning and design stages, and the residual risks should be managed during the construction and subsequent phases. Similarly, Gambatese *et al.* (2008) stressed that as many risks as possible should be considered and treated at the design phase because there is a strong link between the design of construction safety and construction site fatalities. The risk analysis process presents a typical analysis loop adapted from ISO Standard 31010:2009 which is broadly recognised in many industries. The model suggests that decision makers should establish the project context and an effective communication environment, make risks explicit, analyse them, take measures to control them, and review, record and report the results. Though the analysis loop looks the same in each project stage, the CDM Coordinator legislated by the CDM rules has the responsibility to track, control and manage the whole process and guarantee that it is running well during the project lifecycle. However, leading roles for risk management are defined differently at each stage. Specifically, in the planning and design stage, the designer is responsible for cooperating with other project participants to identify all foreseeable risks that may occur during the whole lifecycle and trying to mitigate them as far as possible. In the construction stage, the construction team takes the responsibility to work collaboratively with others to manage any risks on site to ensure a safe project is constructed within budget and time. When the project is handed over for use, the client is responsible for the daily use and maintenance as well as managing risks through hiring experts, technicians or others. Throughout the whole process, the CDM Coordinator acts as the coordinator to link different people, activities and processes on behalf of the decision makers.

[INSERT FIGURE 1 HERE]

The first step in the whole process is to identify potential risks (Zou *et al.*, 2007). Failure to identify risks at an early stage and treat identified risks in time may lead to further risks. As a project normally experiences many different phases and most of the participants may leave the process after completing their work, the unidentified risks may lead to a superimposed effect and the possibility of hazards will therefore increase.

2.2 Challenges in traditional risk management

Existing challenges in traditional risk management can be summarised:

- Traditional risk management is still a knowledge and experience based manual undertaking, and numerous investigations (Shim *et al.*, 2012, Hartmann *et al.*, 2012, Zhang *et al.*, 2014) have concluded it is time-consuming, error-prone and highly inefficient. In real projects many practitioners still work on two dimensional (2D) platforms and use 2D drawings and paper-based documents to convey the product information. In this process, though some simple techniques, such as checklists, could assist risk identification and analysis (HSE, 2015), it is a significant challenge to combine and link 2D drawings, on-site observations and paper-based documents together for identification and consideration of risks. Decisions are to a large extent made through a “brainstorming” exercise based on existing knowledge and previous experience.
- Risk knowledge management is fragmented and insufficient, and risk knowledge transfer from project to project is difficult. Multi-disciplinary knowledge and experience play a key role in traditional risk management and the corresponding decision making. Project participants, e.g. clients, architects and engineers, gain valuable knowledge and experience from every project and can use them to contribute to future work. In this case, the effective management of this large database of human knowledge and experience as well as flexible and accurate data extraction become a precondition for the success of risk management. However, unlike some manufactured products that can be made automatically, every AEC project has its unique characteristics that are distinguished from others (Clough *et al.*, 2000). In addition, the process of any AEC project is dynamic and new experience and new lessons come to light nearly every day. Consequently, another significant challenge is how to effectively manage the “database” of human knowledge and experience as well as extract the correct data flexibly and accurately.
- Communication and collaboration need to be improved in traditional risk management (Zou *et al.*, 2016). Since projects are completed by a team cooperatively, any common risks will be identified and treated individually, and the corresponding information will be documented and sometimes this work will be ignored or forgotten (Kazi, 2005). This may lead to the risk that information cannot be presented, shared, recorded, and updated effectively during the development process of a project. As the project is handed over from designer to contractor, and then from contractor to the client, people will normally leave the project after completing their tasks. Thus, large amounts of risk information may be lost if it is not recorded properly and communicated to other project participants.

2.3 Risk breakdown structure

To learn from and use past project knowledge and experience for managing risks, an effective way is to work out a comprehensive risk database containing all possible risks that may affect the project. The database could facilitate a systematic understanding of all project risks, and help the project team link risk information to real projects and make decisions

quickly, e.g. (Kartam and Kartam, 2001, Wang and Chou, 2003). As construction is by nature a dynamic process with unexpected changes and risks and new information is added into the project every day, it is crucial to use a logical and rapid approach for classifying and structuring the large amount of information. Currently a variety of tools have been developed for risk classification, e.g. risk list (PMI, 2004), risk matrix (Markowski and Mannan, 2008), risk maps (Dey, 2010) and RBS (Holzmann and Spiegler, 2011).

RBS in concept is a hierarchical structure that allows all types of risk factors and events to be well organised by groups and categories (Holzmann and Spiegler, 2011). It is an open, flexible and easily updatable tool and could offer a global view on risk exposure (Tah and Carr, 2001, Mehdizadeh *et al.*, 2013).The main advantages of RBS include: 1) to increase overall understanding of risks and facilitate risk communication; 2) to help locate identified risks into relevant places and make special strategies to treat them easily; 3) to provide an architecture for managing risk database and developing risk management software. So far the main approach to develop a RBS is mining risk data from academic publications, project reports, and past project experience and classifying risk factors into a number of logical groups according to the sources of risk (El-Sayegh and Mansour, 2015).

2.4 Adopting BIM for risk management

In recent years, BIM has seen a rapid increase in use and development in the AEC industry and offers the potential to enhance collaboration and communication, increase productivity and quality, and reduce project cost and delivery time (Azhar, 2011). In order to overcome the existing obstacles in traditional risk management method (e.g. in Sections 2.1 and 2.2), numerous attempts of the use of BIM and BIM-related technologies for risk management have been conducted globally. For instance, BIM itself has been proven as a systematic way to assist early identification and assessment of risks for design and construction through 3D visualisation (Grilo and Jardim-Goncalves, 2010), 4D scheduling (Zhang and Hu, 2011), and 5D cost estimating (Mitchell, 2012). The spatial visualisation and dynamic modelling of a project in a computer system could effectively facilitate early risk identification and communication (Liu *et al.*, 2014), and assist strategy and decision making to improve safety, time and cost management in construction (Hardin, 2011). Meanwhile, neutral data formats such as IFC that store standard and customised data for all project elements provide an interoperable digital representation of all project elements enabling interoperability between BIM software and applications (Laakso and Kiviniemi, 2012), which can increase the repeated use of data and reduce the possibility of errors. With the growing development of BIM in the AEC industry, some efforts that could further integrate BIM with risk management have been observed, e.g. automatic rule checking (Eastman *et al.*, 2009, Zhang *et al.*, 2013, Sulankivi *et al.*, 2013), proactive IT (Information Technology)-based safety systems (Forsythe, 2014), and safety training in a virtual gaming environment (Guo *et al.*, 2012). A critical review by Zou *et al.* (2016) summarised the latest developments of using BIM and BIM-related technologies for risk management.

Despite these considerable achievements, literature shows that BIM-based risk management has not been widely used in practice because of the following obstacles:

- Most of the current efforts relate to the design and construction stages and fail to support the development process of a project (Zou *et al.*, 2016).
- Because of technical limitations and the lack of “human factor” testing, most of these emerging technologies are still at a conceptual or prototyping stage (Forsythe, 2014).
- Most of these efforts focus on using or developing new digital technologies to manage particular risks in an ideally assumed scenario, e.g. prediction and prevention of fall accidents (Zhang *et al.*, 2013), and there is still a lack of methods to use new technologies for risk management systematically. In addition, Zhou *et al.* (2012) indicated that these considerations to manage safety risk on site are assumption-based actions.

Therefore, further investigations are needed to deepen the practical applicability of BIM-based risk management.

2.5 The need for aligning traditional methods with BIM for risk management

To strengthen the practical applicability of BIM-based risk management, an important solution is to align traditional methods with BIM and take advantages of both for managing risks (Zou *et al.*, 2016). A number of studies (Zou *et al.*, 2016, Hartmann *et al.*, 2012, Shim *et al.*, 2012, Ding *et al.*, 2016) have proved the feasibility and demonstrated the benefits including:

- Through visualising the project and simulating the construction scheduling virtually in a 3D computer environment, BIM could facilitate project team linking existing knowledge and experience with visualisation for identifying risks and making corresponding mitigation strategies.
- Knowledge and experience based traditional methods are still playing an important role in practice and could be further strengthened by combining with BIM.
- Risk data could be effectively stored, managed and reused through the project life cycle through merging traditional methods with BIM.

It is observed that there are two different development directions of aligning traditional method with BIM for risk management, i.e.1) product-oriented; and 2) process-oriented. For example, some studies, e.g. (Shim *et al.*, 2012, Zou *et al.*, 2015), demonstrated the feasibility and overall framework of developing a computer tool to visualise and link risk information to BIM while other researchers ,e.g. (Tomek and Matějka, 2014, Hammad *et al.*, 2012, Hartmann *et al.*, 2012), investigated the possibility of integrating BIM into the traditional workflow for risk management or develop a new implementation framework for BIM-based risk management. However, only limited research has been found in this area and new investigation is still needed.

3 Research Approach

3.1 Motivation and aim

As described in Section 2.5, to facilitate the practical applicability of BIM-based risk management, an optimal solution is to integrate knowledge and experience learned from the past into BIM for managing risks; however, no theory has been found to support this solution. To overcome this theoretical gap, this paper proposes a new method by establishing an active “link” between BIM and Risk Management System as shown in Figure 2. The Risk Management System consists of a knowledge-based risk database and a tailored RBS. The core principle behind the proposed solution is that a tailored RBS could be used as a knowledge-based approach to classify, store and manage the information of a risk database in a proper structure and risk information in RBS could be linked to different LOCs and different technical systems of BIM to support the development process.

[INSERT FIGURE 2 HERE]

This idea was motivated by several previous studies. For example, Zou *et al.* (2015) presented a conceptual model of the BIM and Knowledge based Risk Management System (BKRMS) and discussed the feasibility and potential of linking risk information into BIM. Kiviniemi (2005) demonstrated a methodology to manage user requirements during the life cycle of a project by establishing an active link between requirements models and building information models. Kiviniemi (2005) successfully illustrated that user requirement information can be divided into different levels and linked with BIM. Another study conducted by Shim *et al.* (2012) presented a conceptual diagram for visualising risk information in BIM

and pointed out that RBS has the ability to facilitate the understanding and communication of risks in risk identification and analysis processes.

3.2 Methodology

In order to develop a tailored RBS for bridge projects and formalise an active 'link' between RBS and BIM, a three-step approach was conducted. The scope of this research is limited to bridge projects; however, the basic methods and principles could be also applied to other AEC projects.

The first step of this study is to understand and identify the basic hierarchical structure of content of an integrated bridge information model. As only limited studies were found, a comprehensive analysis based on the existing primary element hierarchy of IFC models for buildings, existing studies, e.g. (Kiviniemi, 2005, Shim *et al.*, 2012) and the authors' project experience on bridge design and construction was conducted to separate an integrated bridge information model conceptually into different LOCs and technical systems. This separation was the theoretical basis in further steps for linking different groups of risk to the particular levels of a bridge information model.

The second step employed a data mining approach (Jun Lee and Siau, 2001, Gargano and Raggad, 1999) to collect, identify and categorise risk information. It started with an extensive collection of academic publications, bridge project risk assessment reports, and standards and guidelines that documented risk information in the past or potential risks that may affect bridge projects through a web-search approach. As construction projects share a large number of common risks and there are only a limited number of documents focusing on bridge related risks, the scope of collecting academic publications and related standards or guidelines was extended to all construction projects. A manual text mining process was then conducted through careful study of each document and interpreting and understanding the text in its relevant context to identify the valuable risk information (e.g. risk category, risk factor, risk description, and possible mitigation measures or strategies) in 80 collected documents. As currently there is no consensus on how to develop the RBS (Mehdizadeh *et al.*, 2013), a list of key words (e.g. project risk, external risk, global risk, design risk) were identified from previous studies (Tah and Carr, 2001, Choi and Mahadevan, 2008, Mehdizadeh *et al.*, 2013) to be an initial hierarchy for allocating and managing the collated risk information according to the source of risk. All identified risk information was stored in an initial database which is defined as the 'risk pool' in this research. After this, similar risks were translated to one format and all risk information was well structured to develop a knowledge-based risk database.

Built on the results obtained in the second step, the third step further categorised risks to generate a tailored RBS. The places of different types of risk in the RBS were classified according to their relationship with the 4 LOCs, e.g. structure-related risks are related to bridge-level while the financial risks are related to the project-level. To further improve the practical applicability of implementing the linked relationship between RBS and BIM, a critical analysis was then conducted to determine on which level the different risks should be allocated to bridge projects and 13 sub-models of linkage were developed. Finally, risks at the lowest level of the generated RBS were classified into 4 groups (i.e. project, surrounding environment, site, and bridge) and a conceptual model was established to link 4 LOCs and 6 technical systems of BIM to the tailored RBS.

4 Separation of the Integrated Bridge Information Model

In concept, data from different contents and disciplines is gradually defined and added to build the integrated bridge information model and BIM can be considered as a shared knowledge and information repository to support the whole project lifecycle. The data and their structure in a complete BIM are extremely complex, therefore some researchers, e.g. Fischer and Calvin (2002) and Haymaker *et al.* (2003), realised that there is a need for separation of the integrated information model to meet particular needs. In 2005, Kiviniemi

(2005) proposed a formal solution for dividing a project's data set into several sub-models and linking user requirements with these sub-models. Similarly, as current neutral information exchange formats such as IFC have limited supports on infrastructure structures such as bridges, Shim *et al.* (2012) divided the integrated bridge information model into five levels for different purposes of use, e.g. structural analysis, structural detailing, and construction simulation.

Level of Content (LOC) is defined in this paper as the primary hierarchical structure of content of BIM. LOC could be used for decomposing an integrated 3D information model into separated sub-models according to different information content and different disciplines, which could enable the 'correct' information to be extracted, used and communicated in an efficient way to meet particular requirements, e.g. structural analysis, construction scheduling simulation, and risk management. Currently there is no explicit method for separating LOC but the separation should meet particular needs and requirements. Kiviniemi (2005) defined the technical system as an aggregation of objects that have a common purpose or function or to provide a service, which originates from the definition of ifcSystem by buildingSMART. Though some researchers (Tah *et al.*, 1999, Shim *et al.*, 2012) tried to summarise the component objects for bridge information model, no study has been found to classify and group bridge component objects that have a common purpose or function or to provide a service to be a part of a technical system.

After a critical analysis, this paper separated the integrated bridge information model in concept into four LOCs (i.e. Project, Surrounding Environment, Site, and Bridge) and six technical systems (i.e. structural system, expansion joints system, decking system, drainage system, lighting system, and parapet system) for risk management, as shown in Figure 3.

[INSERT FIGURE 3 HERE]

The separation of BIM into four LOCs and six technical systems for risk management in this study is based on the following four observations:

1) IFC is a neutral and open data model specification describing AEC project lifecycle data, which is developed and managed by the buildingSMART International (formerly known as International Alliance for Interoperability or IAI). IFC can be used for data exchange by a number of software, e.g. ArchiCAD® and Revit®. An IFC model is composed of IFC Entities built up in a hierarchical order and the primary IFC element hierarchy is: Project, Sites, Buildings, Storeys, Spaces, Elements (Eastman, 1999). Though currently IFC still has some limitations in supporting bridge and other infrastructure projects and one of the latest ongoing projects is to develop a standard format of IFC-Bridge (buildingSMART, 2016), the principle of basic hierarchical structure of IFC is also applicable for separation of LOCs and technical systems of a bridge information model.

2) For establishing a linkage between user requirements and BIM, Kiviniemi (2005) suggested that a model for client requirements could be divided into five basic levels (i.e. project, site, building, building storey, space) and 12 technical systems (e.g. Building Envelope, Structural System, HVAC System) according to the IFC specification. This principle of separation could be an important guidance for this study for considering risks. The scope of risk is very wide – some, such as financial and political risks, may cause effects to the whole project and some others, such as the structural safety risks, may have a direct relation to part of the temporary structure or even a small component. Therefore, the core idea of this study is that risks from different sources could be divided into groups and linked to the four LOCs and six systems of an integrated information model, visualised in BIM and managed intelligently in a database during the development process.

3) Bridges share lots of common features with buildings. For example, both bridges and buildings are construction projects which will go through project phases such as briefing, design, construction, and maintenance. Though having different functionalities, both bridges and buildings are structures and need project participants (e.g. client, designer and contractor) to work collaboratively to complete the one-off endeavours. As a result, existing

hierarchical structures of BIM could be important references for developing the LOCs and technical systems of the bridge information model. For instance, a number of studies (Ji *et al.*, 2013, Yabuki and Li, 2006) investigated developing a neutral data model IFC-bridge by extending the current standard IFC to cover bridge components. In addition, Tah *et al.* (1999) used the levels of hierarchy such as project, product, in-situ, and bridge when describing the object classes of an integrated bridge information model. Therefore, in concept the bridge information models could also share some same LOCs with buildings, such as project, site and bridge.

However, for risk management, bridges are to some extent different from normal buildings. Liu *et al.* (2014) summarised that the characteristics of bridges include, for example, complex structural design, a large number of heavy components, and complicated site conditions. In addition, most bridges as part of transport system need more information of a relatively large area such as the local economy, the potential number of citizens to be benefited, surrounding topography and geology, and existing roads and tunnels. For example, the Mersey Gateway Bridge as part of a big highway project is a cable-stayed structure with three towers being constructed in the UK. The design and access report (HBC, 2008) indicated that the design and construction of the bridge needs to combine information of the surrounding environment all together for considerations, e.g. the project influence on the local community, possible restrictions from the local airport and power station. For instance, the height of bridge towers should be restricted to meet the height zoning map by Liverpool Airport for safety purposes. Therefore, considering not only risks but other project decisions for bridges, a surrounding environment level between project and site is needed for the LOCs of infrastructure projects such as bridges. The surrounding environment defined by this paper means in concept a relatively wide geographic area and opposites to the relatively narrow sense of site. In addition, as most bridges do not have complex requirements on space and storeys (Ryall *et al.*, 2000), LOCs such as space and storeys of buildings are not necessary for bridges.

4) Whatever the type of bridge is, according to Ryall *et al.* (2000), Zhao and Tonias (2012) and Fan (2012) bridge contains basically five major components (i.e. superstructure, bearings, pier and pier caps, foundations, piles) and five minor components (i.e. deck pavement, drainage system, parapets, expansion joints, and lighting). The main purpose of most bridges is to span physical obstacles such as rivers and valleys, which is heavily reliant on structural components. Liu *et al.* (2014) also highlighted that one significant feature of bridges is the complex structural design. Therefore, this paper grouped all structure-related components into the structural system and defined in total six technical systems as shown in Figure 3. The structural system includes bridge components such as girders, cross-beams, cables, towers (pylons), anchor blocks, bearings, abutments, piers.

5 Developing a knowledge-based risk database

This section demonstrates a knowledge-based approach of mining risk data to develop a knowledge-based risk database. As stated in Sections 2.2 and 2.3, a comprehensive risk database could be an important tool for helping the project decision makers develop an overall understanding of, quickly identify and effectively analyse and mitigate risks. Meanwhile, the knowledge-based risk database also provides information and theoretical basis for developing a RBS.

A number of existing studies have been conducted to obtain the ‘complete’ risk database, e.g. (Kartam and Kartam, 2001, Wang and Chou, 2003). Because the scope of risks is very broad, it is somehow difficult to obtain a complete risk database which can be applied to all industries and projects. As different risks are highly linked to certain type of projects and particular construction markets and conditions, most existing studies tend to apply some conditions to narrow the scope of the risk database and target particular types of project. For example, El-Sayegh (2008) summarised a list of 33 main risk factors for highway construction projects in the UAE through a critical literature review. Zayed *et al.* (2008) sent

a questionnaire to 17 highway construction experts in China to collect a list of risks and then classified them into company level and project level for further analysis.

This paper used a knowledge-based approach consisting of three basic steps (i.e. risk data collection, risk data mining, and risk data assessment and translation) to identify possible risks for bridge projects and develop the risk database, as shown in Figure 4.

[INSERT FIGURE 4 HERE]

5.1 Step 1: Risk data collection

The first step in developing a knowledge-based risk database is to collect and prepare risk data as the basis for the next step. In a construction project where people are from different disciplines and have various educational backgrounds and work experience, it is relatively difficult to identify a complete list of risks through a limited number of interviews or surveys of literature and there is a need to investigate a wide range of sources to develop the risk database.

This paper obtains risk data from 80 documents based on a web-search approach mainly from the following three sources: 1) academic publications, 2) bridge risk assessment reports, e.g. (Atkins, 2006, Structural-Safety, 1997), and 3) standards and guidelines on risk management, e.g. (HSE, 2015, Molenaar *et al.*, 2006, PMI, 2004). Reasons for choosing the three sources are: 1) the large number of published academic papers and books are easily accessed and contain research on the identification of risk factors for different countries and regions for all kinds of construction projects, which have summarised a relatively complete list of risks for construction projects; 2) risk assessment reports of bridges and related standards have recorded a number of identified risks in real environments and some are highly relevant to bridge projects, which are an important supplement for academic publications. However, there is a need to recognise that as construction projects, including not only bridges but also buildings, roads and industrial plants, share lots of common risks and there is only a limited number of publications focusing on bridge related risks, the scope of collecting academic papers and standards is extended to all construction projects.

5.2 Step 2: Risk data mining

The second step is to search for valuable risk information from the data collected in Step 1 by adopting a manual text mining approach. Specifically, a manual analysis through careful reading of each document and interpreting and understanding the text in its relevant context was conducted to identify and record the risk information. As the collected documents use different methods and standards to describe risks, e.g. ‘cost increase’ and ‘budget overrun’, it was then important to classify similar risks and put them into different risk groups individually according to the source of risk. Currently there is no consensus on how to develop the RBS (Mehdizadeh *et al.*, 2013), thus a list of key words (e.g. project risk, external risk, global risk, design risk) were identified from previous studies (Tah and Carr, 2001, Choi and Mahadevan, 2008, Mehdizadeh *et al.*, 2013) to be an initial hierarchy for allocating and managing the collated risk information. After this, all identified risk factors and corresponding information were organised into groups and stored in an initial database which is defined as a ‘risk pool’ in this paper.

5.3 Step 3: Risk assessment and translation

In the third step, the identified risk factors and information were further assessed group by group, where the same or similar risks described in different ways were translated to the same format to avoid duplicated data. A concise knowledge-based risk database was then structured and developed. An example of the knowledge-based risk database is shown in Table 1.

[INSERT TABLE 1 HERE]

6 Developing a tailored RBS linking to BIM

Built on the obtained knowledge-based risk database, this section further clusters data to develop a tailored RBS and proposes a conceptual model to link the resulting RBS to the four LOCs and six technical systems of an integrated bridge information model.

In this study, there are two major motivations for developing a tailored RBS. Firstly, although a number of RBS have existed, e.g. (Holzmann and Spiegler, 2011, Sigmund and Radujković, 2014, Tah and Carr, 2001), the current RBS vary in both form and content. Meanwhile, Mehdizadeh *et al.* (2013) stated that currently there is no consensus on the standards or general methods of developing a RBS and the RBS to be developed should satisfy the particular purposes and requirements. Furthermore, no existing studies have been found to develop a tailored RBS for linking it to BIM for risk management. Secondly, it was observed that a crucial role of RBS is to classify risks in a proper structure and the development of RBS is reliant on the collected risk data. However, only a limited number of studies have been found to focus on risks for bridge projects and most of them only partly summarise some of the major construction risks for their own country or local area (Li *et al.*, 2013).

Through a critical analysis, the resulting RBS and its basic relationship with BIM are proposed as shown in Figure 5. Specifically, project risks in this research are basically divided into two main groups – external risks and internal risks. The idea has also been adopted by other researchers, e.g. (Fang *et al.*, 2004, El-Sayegh, 2008, Tah and Carr, 2001).

[INSERT FIGURE 5 HERE]

External risks (Fang *et al.*, 2004, El-Sayegh, 2008, Tah and Carr, 2001) mean those risks that are outside the project and beyond the control of the project team. The external risks include political, economic, social and cultural risks. For example, the political risk may refer to the changes or variation of local laws and the economic risk could be the fluctuation of local currency. As external risks are at a macro level such as company or country levels and are not under the control of the project team, there is a need for a continuous scanning and forecasting through all phases of the project and drawing up company strategies to manage their effects (Tah and Carr, 2001).

Internal risks (Fang *et al.*, 2004, El-Sayegh, 2008, Tah and Carr, 2001) refer to those that are within the project and are more controllable by the project team. The scope of internal risks is much broader than external risks and there is a greater opportunity for the project team to manage them. The number of internal risks in the knowledge-based risk database is much larger than the number of external risks and the relation between different internal risks are inter-related and much more complex. Therefore, the internal risks were further divided into two groups – local and global – because some internal risks are related to the whole project whereas the others may cause effects local to the bridge or individual work packages (Tah and Carr, 2001).

To easily establish a conceptual relationship between 4 LOCs of BIM and RBS, risks at the lowest level in the RBS were further classified into 4 groups - project-level, surrounding environment-level, site-level and bridge-level. The purpose of this classification is that: 1) risks from different sources are grouped together to help the project team have a better understanding for risk classification and communication; 2) as BIM can be divided into different LOCs in concept, different groups of risk in the resulting tailored RBS have a direct relationship to the different LOCs of an integrated bridge information model. Meanwhile, this classification does not mean that the risks information in practice will be strictly put in a particular group. In fact, risks are highly inter-related and it has been found that some types of risk overlap in two different levels and could cause effects on both levels. For example,

material and equipment risks could refer to either risks in the material used in the bridge components or risks in transport and storage of material and equipment on site. Therefore, there is a need for detailed analysis of internal relationships between risks in the real environment.

The basic relationship of linkage shown in Figure 5 is that the four groups of risk in the RBS (project-level, surrounding environment-level, site-level and bridge-level) can be linked directly to 4 LOCs in the integrated bridge information model (project, surrounding environment, site, bridge). This linkage presents a general framework integrating BIM and RBS for risk management of bridge projects. There is a need to point out that the concept of 'surrounding environment' refers to a relatively wide geographic area, which is within the project environment as opposite to the relatively narrow sense of the concept of 'site'. For instance, bridge projects, especially those as a part of the major highway or railway project, have to deal with the potential risks in a relatively big surrounding environment area instead of only on site, e.g. potential conflicts between the bridge and existing road network, financial and legal risks in removal and demolition of existing facilities, or natural risks (e.g. debris flow) nearby.

To further improve the practical applicability of implementing the linked relationship between RBS and BIM, 13 sub-models of linkage were developed and one example is shown in Figure 6. In total, risks are classified into 16 main categories (e.g. structural, design, financial) and a number of sub-categories (i.e. risk factors in Table 1). These risks could have both direct links and indirect links to the 4 LOCs and 6 technical systems. The structural risks are used as an example to illustrate the detailed sub-model of linkage (see Figure 6). Structural risks as a part of bridge-level risks are directly linked to the bridge level and structural system. For example, potential damage or collapse of both temporary and permanent structures have immediate influence to the bridge structure and should be directly linked to the whole bridge or structural system. In addition, structural risks also have indirect links to expansion joints system, decking system, and drainage system. A practical example is that in the in-use phase rain may flow into the surface cracks of bridge deck slabs and corrode the steel reinforcement, which may influence the durability and safety of the whole bridge indirectly.

[INSERT FIGURE 6 HERE]

This section developed a tailored RBS and a conceptual model for linking RBS and BIM. The tailored RBS as a hierarchical structure can be used for categorising and managing data in the knowledge-based risk database and could provide a global view on project risks. In addition, through linking risk information to the BIM, risks can be visualised and managed in the BIM throughout a project lifecycle. This proposed method merges the RBS with BIM as an integrated approach and take advantage of both methods and could effectively facilitate identification, analysis, communication, and decision making of risks.

7 Discussions

This paper analysed the separation of integrated bridge information model and the hierarchical structure of different types of risk, and presented a new method to link RBS with BIM for bridge risk management. The RBS could help understand how risks may influence the project differently, and the linkage model provides evidence for the possibility of aligning traditional methods with BIM for risk management. Though the research scope is limited to bridges, the basic methods and principles could be also applied to other AEC projects.

Literature shows that the traditional knowledge and experience based method is still playing a significant role in project risk management. However, every project has its unique features and will go through different phases in a relatively long life cycle. For completing a project successfully, people should work collaboratively and use valuable knowledge and experience learned from academic studies as well as project practices for dealing with any

potential risks. In this process, RBS could be used as an advanced tool to help the project team have a clear understanding about risks at different levels and effectively facilitate risk identification and analysis. In the development process of risk database and RBS, this paper first identified a list of key words (e.g. project risk, external risk, global risk, design risk) from previous studies (Tah and Carr, 2001, Choi and Mahadevan, 2008, Mehdizadeh *et al.*, 2013) to be an initial hierarchy for allocating and managing the collated risk information. An important reason for doing so is that currently there is no consensus on how to develop the RBS (Mehdizadeh *et al.*, 2013) and most existing studies extracted risk data from academic publications, project reports, and past project experience and classified risk factors into a number of logical groups according to the sources of risk (El-Sayegh and Mansour, 2015). The idea of dividing project risks into external and internal risks has also been adopted by other researchers, e.g. (Fang *et al.*, 2004, El-Sayegh, 2008, Tah and Carr, 2001).

At the same time, BIM provides a new way of design, management and communication, and allows the project team to easily implement risk identification and analysis on daily work, e.g. in Section 2.4. Through establishing the linkage between RBS and BIM, two main practical advantages are summarised: 1) this solution can take advantage of both the traditional method and BIM for managing risks. On the one hand, RBS enables risk information to be stored in a proper structure, used and communicated effectively. On the other hand, some features of BIM such as 3D visualisation and 4D construction scheduling can facilitate the risk identification, analysis and communication at an early stage. Through this linkage, risks at different levels could be linked to the particular LOC and technical system in BIM for visualisation and management; and 2) risk information sharing and communication could be effectively improved by managing fragmented risk data using RBS and linking risk information to BIM. These data linked to BIM could provide important evidence for risk management and decision making at key stages. A practical example is that, when project information is being transferred between different people or forwarded to the next phase, project participants (e.g. client, principal designers, sub designers, and contractors) could check and review the attached information for identifying potential risks and seeking possible mitigation measures. Furthermore, conducting design review is a legal requirement in the UK for identifying and mitigating any foreseeable health and safety risks (HSE, 2015).

The knowledge gap of aligning traditional methods with BIM as an integrated solution for risk management was also documented by some other existing studies. For example, Shim *et al.* (2012) and Zou *et al.* (2015) discussed the benefits and theoretical methods for visualising and linking risk information to BIM for managing risks. Another empirical study conducted by Hartmann *et al.* (2012) illustrated how BIM could be implemented in the traditional project workflow for assisting risk management. Hence this paper further fills the knowledge gap by establishing an active link between RBS and BIM for risk management.

Some limitations also exist in this research. First, though RBS as a qualitative technique could be used to manage the risk database and facilitate risk identification and understanding, it provides limited support to quantitative risk analysis. Cagliano *et al.* (2015) stressed that RBS is mostly suited for the conceptualisation and planning stages in the risk management process (Figure 1). As a result, when implementing this proposed model, further techniques (e.g. brainstorming, sensitivity analysis) for strengthening risk analysis, evaluation and treatment are needed. One recommendation for the future research is to improve the quantitative analysis and treatment capabilities of this proposed solution.

There is a need here to point out the difference between the project process and the risk management process. The project process normally refers to phases such as briefing, design, and construction which are part of the project life cycle, while the risk management process means the steps such as risk identification, analysis, evaluation and treatment. Although RBS plays a limited role in the quantitative risk analysis in the risk management process, it could be used to support the project life cycle. For example, different risks may be present at different project phases and RBS could be used to classify and manage the risk information.

In addition, as described in Section 2.5, there are two main development directions for aligning traditional methods with BIM: 1) product-oriented, and 2) process-oriented. Hence, another suggestion for future research is to either develop BIM-based risk management software or integrate BIM into traditional risk management process. Hartmann *et al.* (2012) highlighted that one significant benefit of the latter is little disruption of existing work practices.

Secondly, though large amounts of theoretical and practical evidence are used to support this proposed method, it has not been yet validated in real projects. As a result, it is currently difficult to judge the real value of implementing the linkage model. Meanwhile, data collected in this research are from online sources (i.e. academic publications, bridge risk analysis reports, and standards) and have not been verified. Hence, for better implementation of the proposed method, future research may apply it into some small and large projects to 1) gain implementation experience, and 2) check and improve the reliability of risk data.

8 Conclusions

Risk management is a crucial activity in the AEC industry. Success of risk management is in a large degree reliant on effectively capturing, using, and communicating multi-disciplinary knowledge and experience in all project stages. Failure to do so may lead to further risks. In recent years, BIM as an emerging digital technology has been increasingly used to support the whole life-cycle of a project, and some features of BIM such as 3D visualisation, clash detection and construction simulation could facilitate identification, analysis and communication of risks. To improve the practical applicability of BIM-based risk management, a knowledge gap is documented in taking advantages of both traditional methods and BIM for risk management.

The paper fills the gap through establishing an active ‘link’ between knowledge learned from past lessons and BIM. An integrated bridge information model is separated into 4 LOCs and 6 technical systems. Valuable risk knowledge and experience are stored in a knowledge-based risk database which is developed through data collection, risk mining, and assessment and translation. Risk data referred here is mined from academic publications, risk assessment reports of real bridge projects, and related standards. Built on the results in risk database, a tailored RBS is then developed based on the separation of 4 LOCs and 6 technical systems of BIM. Specifically, the RBS has 3 basic hierarchical levels and risks at the lowest level are further divided into 4 groups (i.e. project, surrounding environment, site, and bridge). Lastly a conceptual model for the linkage between RBS and BIM is established and 4 groups of risks in RBS are linked to 4 LOCs and 6 systems of BIM.

The proposed solution would push risk management a step forward by aligning traditional methods with BIM to systematically support the development process of a project. The developed knowledge-based risk database, RBS, and the conceptual linkage model not only can be implemented manually as effective tools for understanding and managing project risks but have a practical value for developing BIM-based risk management software.

A limitation of the proposed solution is that it has not yet been validated in practice. Implementation methods and experience should be gained by applying this solution to some small and large projects. A possible future extension of this work would be to develop a computer tool based on existing BIM tools to support this proposed solution.

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Table 2 Example of knowledge-based risk database

Risk Category	Risk Factor	Risk Description	Possible Mitigation Strategy
Economic	Inflation	Price inflation of construction materials; Monetary inflation; Unanticipated local inflation and interest rates due to immature local economic and banking systems; Increase of wages and welfare	1) Escalation Clause; 2) Price Contingency in the Bid; 3) Project Financing by a Reputable Owner; 4) Owner Purchase of Equipment & Material; 5) Providing Performance Bond and Prequalification of Suppliers; 6) Forward Contracts for Hedging Exchange Rate Changes
	Currency	Rate fluctuation; devaluation; difficulty in converting foreign currency	
	National and international impacts	Changes by International Associations such as OPEC	
	Inadequate market demand	Inadequate forecast of market demand; Owners' unreasonable upfront capital demand	
Design	Unqualified or defective design	Insufficient planning; Incomplete design scope; Difficult and complex construction; Improper site estimation; Improper material use; Lack of experience and knowledge in design; Inadequate specifications	1) Changed Condition Clause (Delay); 2) Contractor Participates in Design; 3) Adoptable Design/ Construction Methods; 4) Changes to the Original Design
	Errors and mistakes	Carelessness; Lack of experience and knowledge in design; Inadequate specifications; Incorrect quantity calculation; Competence	
	Delays of design works	Low productivity; Work order change; Delays in design and regulatory approval	
Construction	Deviation between design and construction	Defective design and errors	1) Contingency in the Bid; 2) Insurance for Liability from accidents; 3) Contract Clause for Time Extension Due to Delays; 4) Safety and Training Programmes from Employees; 5) Planning Procurement Activities in Advance
	Inadequate construction planning	Inadequate consideration on the actual condition of the construction site; Unfamiliarity with the design drawings and design intention; Insufficient site information and unforeseeable circumstances underground; Unreasonable personnel organisation and arrangement; Unreasonable materials and unreasonable equipment allocation; Lack of knowledge and experience	
	Improper construction methods	Unfeasible construction methods; Lack of knowledge and experience	
	Construction changes and delay	Third party delays; Delay of drawing supply; changes in work; Owner changes; Construction delay; Delayed site access; Late drawings and instructions; Delays in material supply; Improper intervention	
	Poor construction quality	Unqualified workmanship and skills; Improper material use; Violating construction standards; Cutting corners	
	Increase of cost	Cost of tests and samples	
	Low construction productivity	Obsolete technology and practices by local partners; poor skills or inadequate supervision; Shortage of skilled and unskilled workers; Foreign firms face difficulties in hiring and keeping suitable and valuable employees; Insufficient labour; Productivity of equipment	
	Improper project management	Improper project budgeting; Inadequate project organisation structure; Incompetence of local project team; Incompetence of subcontractor	
	Failure to identify defects	Insufficient inspections	

Notes: Items in the database were imported and adapted from 80 documents.

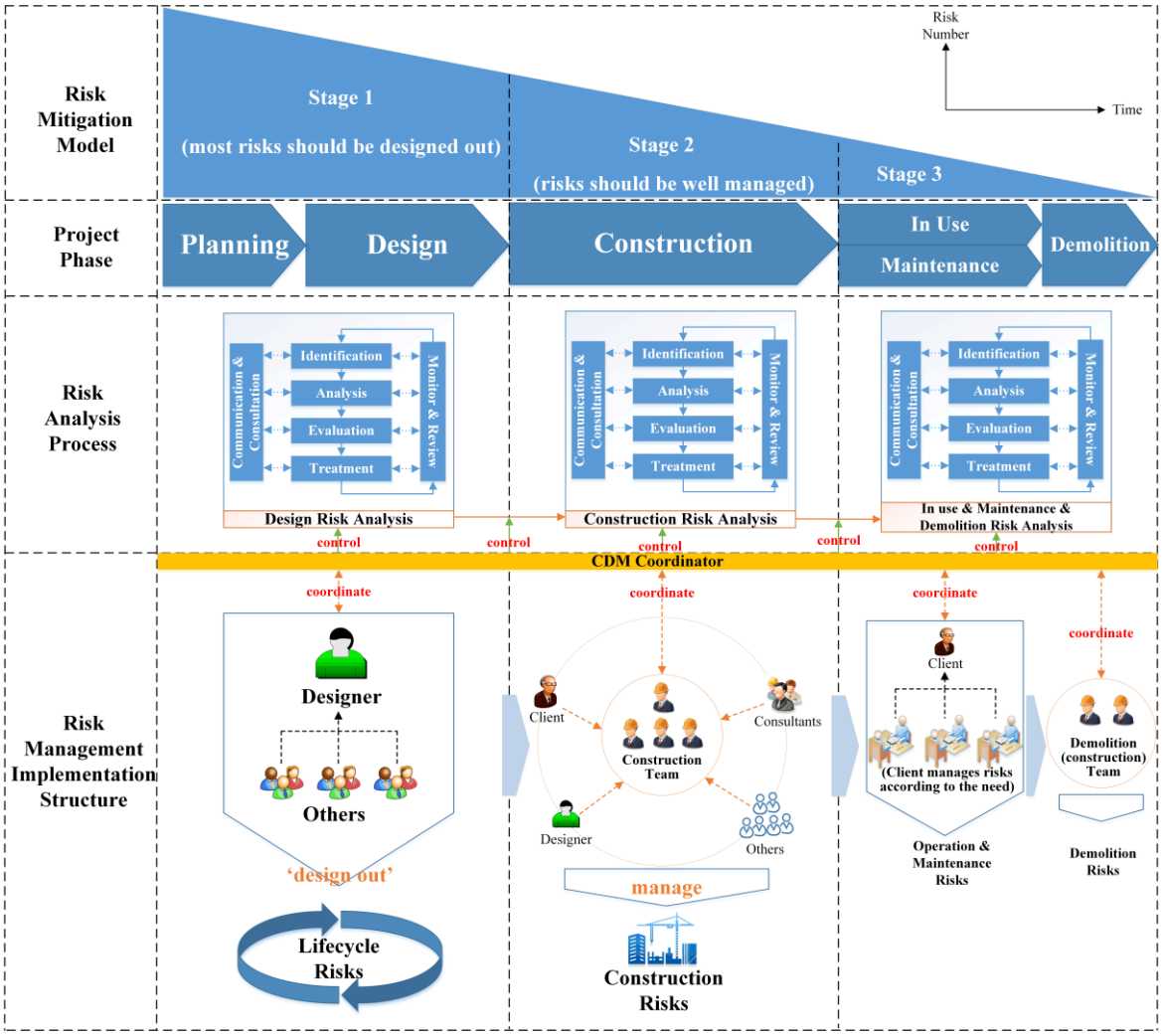

Figure 7 General risk management framework (Zou *et al.* 2016)

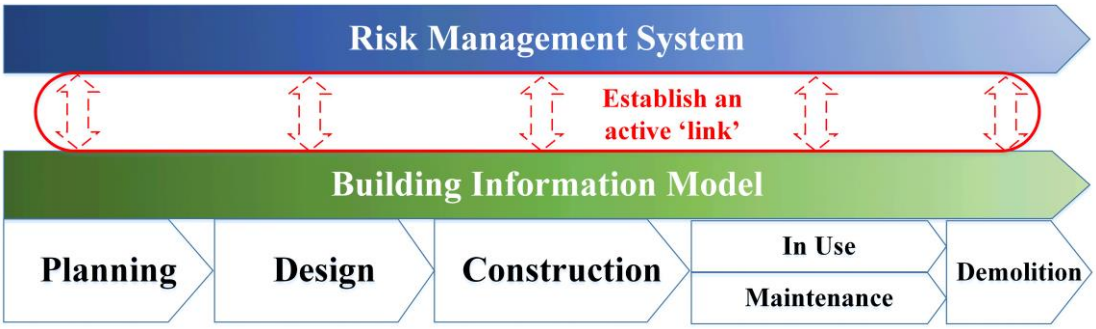

Figure 8 Link BIM to the Risk Management System (Zou *et al.* 2015)

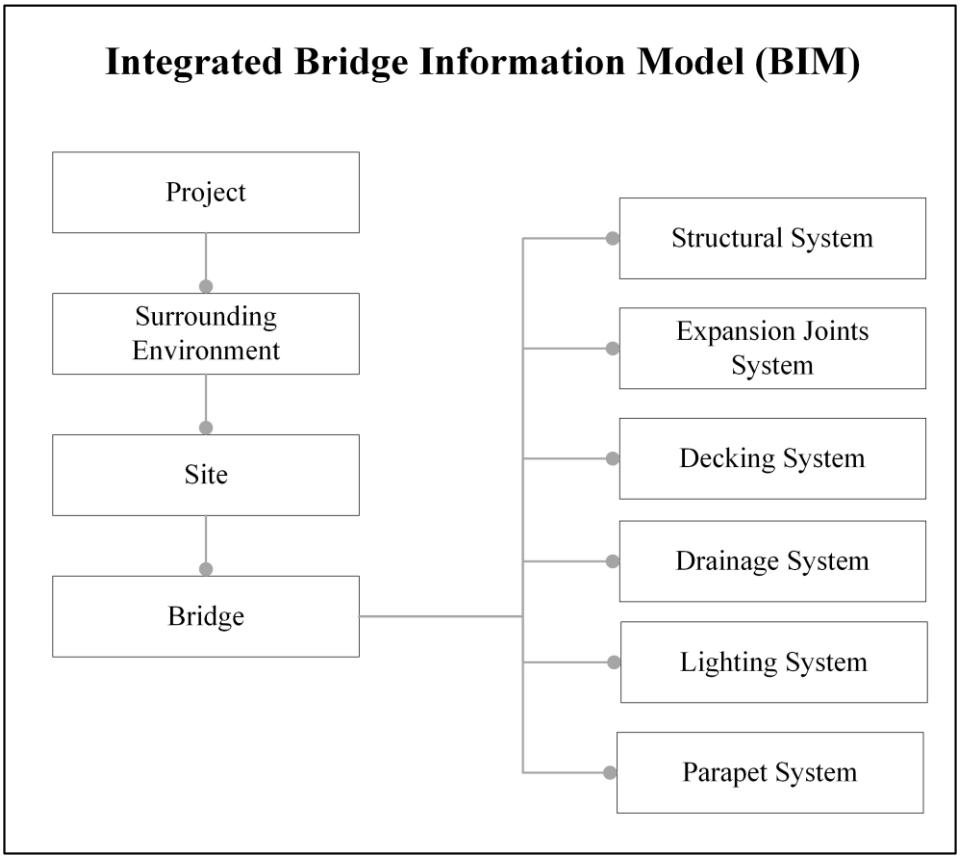

Figure 9 Separation of an integrated bridge information model

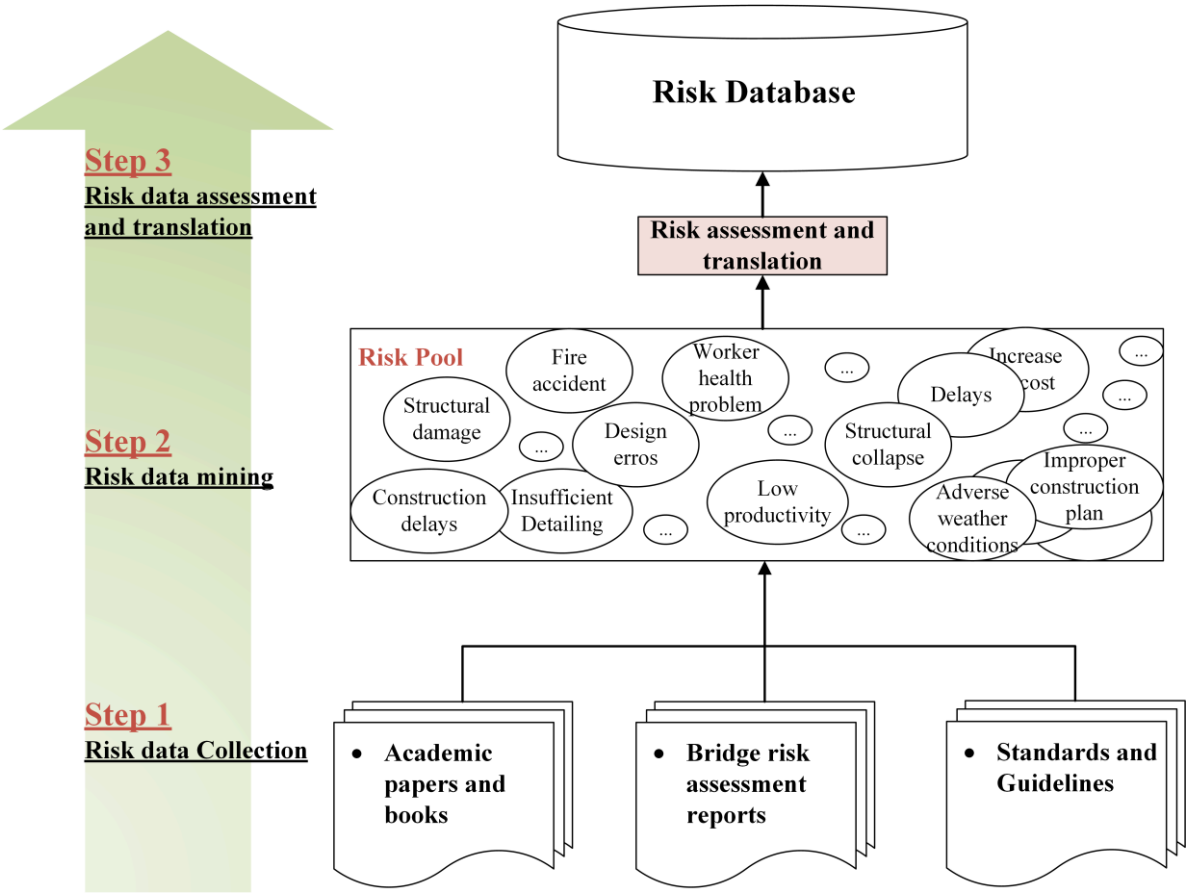

Figure 10 Process of developing a knowledge-based risk database

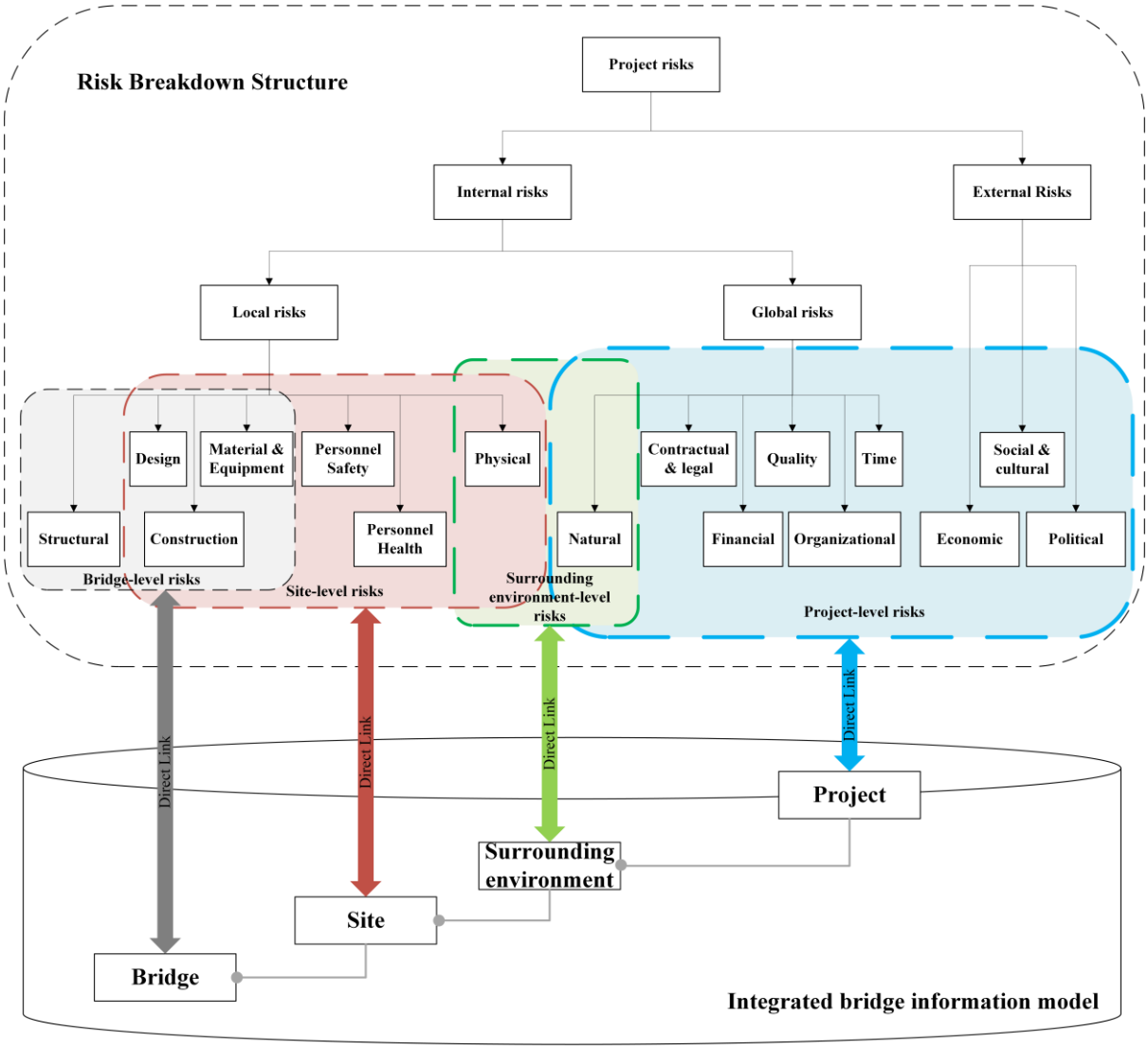

Figure 11 Basic linkage between RBS and BIM

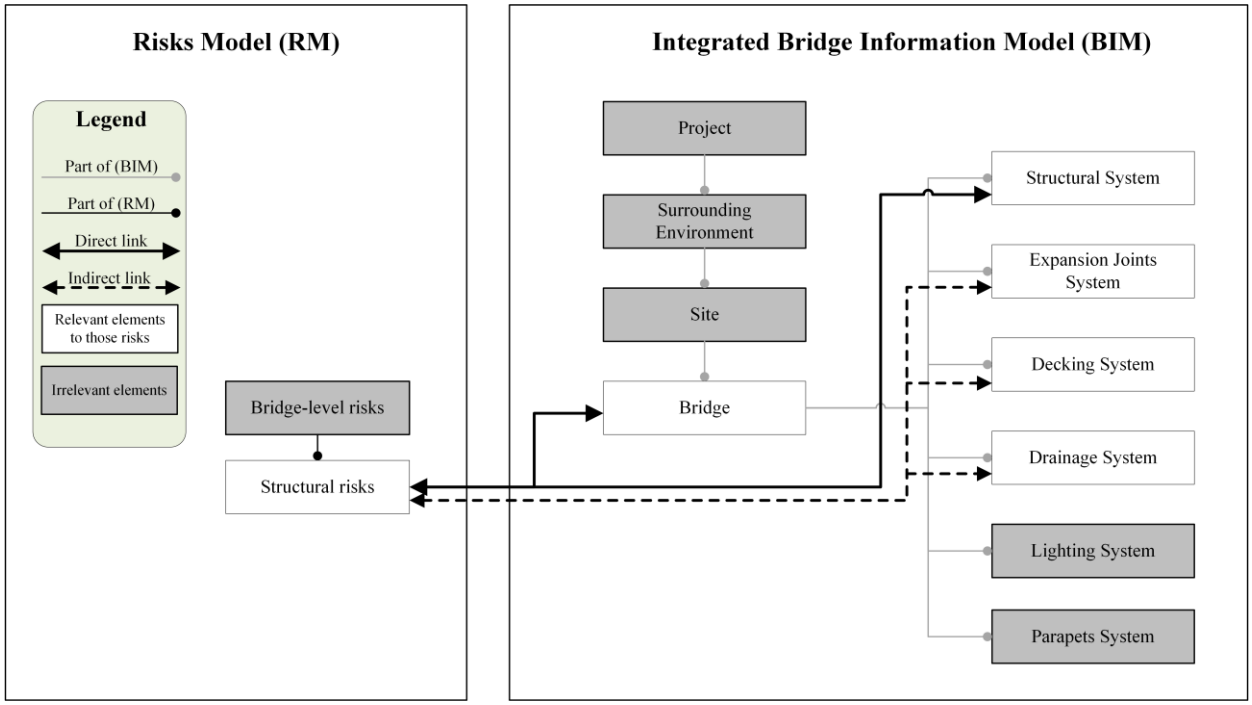

Figure 12 Linkage between structural risks and bridge information model