An Investigation of Constraint-based Risk Management for Collaborative Design

A thesis submitted for the degree of Doctor of Philosophy

by

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Abstract

In the context of internationally challenging economic, design has been regarded as a key factor in assisting design and manufacturing companies to survive. By using up-to-date computer-supported technology, the global design collaboration based on multidisciplinary and distributed environment is becoming a mainstream to new product development (NPD). However, during the process of collaborative design, risk is rarely mentioned. In particular, due to the complexity of design process and lack of efficient design decision-making, there have been some design collaboration failures across multiple companies. Some design projects cannot deliver the benefits as companies have expected through the collaboration. Moreover, a number of stakeholders, managers and designers expressed their disappointment at not seeing the projected savings in cost and time, which critically discredited the value of design collaboration.

Many studies in academia and commercial cases have suggested that risk assessment can be applied as an effective means in the realm of design. Nevertheless, few of them conducted risk management research associated with design constraints under a collaborative environment from both theoretical and practical perspectives. In current risk practice, many risk practitioners simply report key risks to their management teams and no further analysis, which might subsequently result in confusion with excessive discussions. Consequently, to prevent the failure of design collaboration and perform a satisfactory risk assessment, it is important to perform risk management with an upstream perspective and at an operational level.

An approach, called constraint-based design risk management (DRM) where a conceptual framework has been proposed on the basis of collaborative design features, risk management process and Theory of Constraints (TOC). Moreover, a DRM matrix has been developed to map, measure and mitigate collaborative design risk through evaluating the critical design constraints, and then specified design risk variables in the light of risk criteria. Design constraints are quantitative parameters that frequently affect main design processes and decisions. The combination of design constraints and risk criteria can be accessible and applicable by designers and design mangers. In addition, a Bayesian weighting method based on Bayesian theorem has been developed to measure collaborative design risk in a more efficient manner. Ultimately, a DRM tool has been created as a simulated scenario prototype, which incorporated with three case-study evaluations, to demonstrate the importance and effectiveness of using TOC and risk theory in the realm of design collaboration.

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Glossary

A glossary is presented to familiarise the reader with some of the terminologies that are repeatedly used throughout the course of this research. Most of these terms are consistent with the literature.

Accuracy/Safety: could be divided into two categories, one refers to accurate description, another indicate safety usage. A criterion of Accuracy/Safety is consistent with the progress of designing for availability and feasibility. More specifically, accuracy in industrial collaboration product design refers to the accurate description of the defined constraints resulting in corresponding design risk variables. Whilst safety indicated that defined constraints are used safely or not.

Availability: can be regarded as "the item's capability of being used over a period of time and the measure of an item's availability can be defined as the period in which the item is in a usable state" (Stapelberg, 2009, pp. 18).

Bayesian Risk Assessment: a risk analysis approach based on Bayesian theorem that extents the probability theory by a Bayesian estimation or inference.

Conceptual Design: segment of the product development process charged with identifying customer needs, developing possible concepts to explore, and selecting concepts for more detailed design. **(**Specification of principle concept solution)

Concurrent Engineering (CE): an approach used in new product development (NPD) that emphasises the need for the consideration of the manufacture process concurrently with regard to the product or service development. CE implies that a successful NPD will be achieved if functions of design engineering, manufacturing engineering and other functions are integrated.

Constraint: regards as factor or element that restricts and limits the range of a variable (Goldratt and Cox, 1992; Murthy *et al*., 2008).

Collaborative Design: defined as the process that various participators working together with collaboration of numerous activities to obtain a shared objective of designing and developing a service or product via task dependency, role interaction and resource integration. The definition includes time and space concept, which could be described as ‘synchronous’ and ‘asynchronous’. The ‘synchronous’ collaboration is termed co-design, while the ‘asynchronous’ one is named distributed design.

Criteria: the standard that “used to be able to focus on the investigation of the existing situation; to assess the contribution of the findings of such investigations for the research goal; to focus the development of support on the most relevant factors; to plan the appropriate evaluation; to focus the realisation of support on the evaluation; and to assess the evaluation results” (Blessing and Chakrabarti, 2009, pp.26).

Design: the activities that generate a concept and develop a product in terms of accomplish the requirements and the perceived desires of the users or stakeholders.

Design Constraints: refer to restrictions and limitations that constrain the implementation of a design project in new product design (NPD) and development context, including task, role and resource aspects, the concerns of schedule, cost, product quality, stakeholders, designers, legal, material, information and other inputs to the assessment.

Detail Design: refers to “a part of the design process that completes the embodiment of technical products with final instructions about the shapes, forms, dimensions and surface properties of all individual components, the definitive selection of materials, and a final scrutiny of the production methods, operating procedures and costs” (Pahl, *et al*., 2007, p.436).

Embodiment Design: refers to “a part of the design process in which, starting from the principle solution or concept of a technical product, the design is developed in accordance with technical and economic criteria and in the light of further information, to the point where subsequent detail design can lead directly to production” (Pahl, *et* *al*., 2007, p. 226).

Feasibility: refers to the capability of being done, accomplished or carried out. A criterion of feasibility incorporates a measurement of availability and an acceptable performance in terms of the specified constraints.

Maintainability: refers to the aspect of maintenance that considers the sustainability and "the probability that a failed item can be restored to an operational effective condition within a given period of time" (Stapelberg, 2009, pp.19). A criterion of maintainability requires an assessment of design alternative in case of breakdown, as well as of the demanding time and the integrated resources during the conducting maintenance.

Manufacturing Design: can be defined as "a stage that the characteristics of a product to allow an efficient high-quality manufacture. In principle, many manufacturing processes may be chosen for any product, and each manufacturing process shows different characteristics which must be considered during the design" (Filippi and Cristofolini, 2010, p.15-16)

New Product Development (NPD): refers to "a disciplined and defined set of tasks and steps that describe the normal means by which a company repetitively converts embryonic ideas into saleable products or services" (Belliveau *et al*., 2002, p.450).

Reliability: "a term that commonly described in terms of the probability of failure or a mean time to failure of equipment" (Stapelberg, 2009, pp.16). A criterion of reliability could be terms as the likelihood for the successful design activities related to design constraints, which secure the system or product by minimising the risk and failure. Reliability in this context could be regarded as "lower risk" or "not involved risk" (Murthy *et al*., 2008).

Resource-integration: represents the level that constraints restrictions on technology, material, legal, information, ergonomic. Resource-integration is a structural feature that resources are allocated in an integration way.

Risk: refers to "a combination of the likelihood of an undesirable event and the severity of the consequences of the consequences" (Hardy, 2010, p.1).

Risk Categories: refers to "a structure that ensures a comprehensive process of systematically identifying risks to a consistent level of detail and contributes to the effectiveness and quality of the identifying-risks process"(Project Management Institute, 2004, p.280).

Risk Criteria: the criteria against that the significance of a particular risk is assessed, which include availability, feasibility, accuracy/safety, reliability, and maintainability in this thesis.

Risk Management: refers to "a continuous, proactive and systematic process to understand, manage and communicate risk from a project or organisation perspective" (Kayis *et al*., 2007). It can be defined as a process of risk mapping (identification), measuring (assessment), and risk mitigation

Risk Mapping (Identification): defines as "a process to identify and to categorise risks that could affect a project" (Kayis *et al*., 2007).

Risk Measurement (Assessment): refers to "a process of quantifying the risk events documented in the preceding identification stage" (Molenaar, *et al*., 2007, p.25). In general, risk measurement includes two dimensions: risk frequency and consequence severity.

Risk Mitigation: refers to "the process of taking specific courses of action to reduce the probability and/or reduce the impact of risks" (Pritchard, 2001, p.42).

Role-interaction: represents the level that constraints of various design actors, linking to designer, knowledge, communication, conflict, performance, and customer. Actor-interaction is a structural feature that actors involved are working in an interactive manner.

Task-dependency: represents the level that constraints of the schedule, cost, product quality, function, manufacture, product life cycle. Task-dependency is a structural feature of work that tasks can be performed at varying levels of dependence.

Theory of Constraints (TOC): "a concept comes from the contention that any manageable system is limited in achieving more of its goals by a very small number of constraints, and that there is always at least one constraint that significantly determines the final success of goals" (Simatupang, *et al.*, 2004, p.58). The process intends to discover the crucial constraints from an upstream perspective and at an operational level in order to improve the performance by minimising the potential risks.

Probabilistic Risk Assessment (PRA): refers to **"**a comprehensive, structured, and logical analysis method aimed at identifying and assessing risks in complex technological systems for cost-effectively improving their safety and performance" (Ghaffarian, 2003, p. 697).

Product Life Cycle (PLC): "a term used to describe individual stages in the life of a product. It is an important aspect of conducting business, which affects strategic planning" (Maxi Pedia, p.9).

Chapter 1 Introduction

1.1 Overview

Design is increasingly regarded an effective approach or a strategic tool in new product development (NPD) (Cooper and Press, 1995; Priest and Sánchez, 2001; Ulrich and Eppinger, 2004; Ali *et al.*, 2008). In the globally challenging economic environment, design has been applied to add value in the process of designing innovative products and services, which helps manufacturing business to stay ahead of competition. The global design collaboration based on multidisciplinary and distributed environment is becoming mainstream to NPD (Yesilbas and Lombard, 2004; Li *et al.*, 2005; Emden *et al.*, 2006; Jiang *et al.*, 2008; Shen *et al.*, 2008).

As more and more companies allied by mergers or acquisitions, the majority are become cross-culture and globally distributed. In this regard, design and design collaboration are extremely essential rather than complex. The increasing competition are forcing firms to take account of design collaboration to cut costs and time during the new product design and development (Balzac, 2002; Wang *et al.*, 2002; Markeset and Kumar, 2003; Humphreys *et al.*, 2005; Chu *et al.*, 2006; Huang *et al.*, 2006; Jiang *et al.*, 2008). Thus, the concept of collaborative product design with Computer Supported Collaborative Work (CSCW) technologies has been adopted widely in NPD in order to reduce time-to-market and achieve competitive advantages against competitors (Markeset and Kumar, 2003; Bouchlaghem *et al.*, 2004; Shen *et al.*, 2008).

Nevertheless, the collaboration in the course of multidisciplinary and distributed design entails the complexity of the process of design and decision-making (Jeng and Eastman, 1999; Priest and Sánchez, 2001; De´tienne, 2006; Qiu, 2007; Zha and Du, 2006; Gonnet *et al.*, 2007; Ouertani and Gzara, 2008). The design activities are increased and the design interaction is more frequent in the process of collaboration. Despite plenty of collaborative design software being developed and implemented in

NPD, unfortunately most of them have overstressed the importance of collaborative design technology by focusing on the downstream design activities. On the contrary, upstream factors relating to task-dependency, role-interaction and resource-integration are neglected or even not being considered.

Accordingly, given the rising complexity of products and processes, plenty of researches have been undertaken in the field of collaborative design in attempts to enhance the effectiveness and efficiency of the collaborative product design process. Most researches focus on CSCW and address the significance of technology (Qin *et al.*, 2003; Chu *et al.*, 2006; Shen *et al.*, 2008). Others are relating to social issues, such as conflict management (Li, Zhou and Ruan, 2002; Yesilbas and Lombard, 2004; Ouertani and Gzara, 2008); design collaboration (Chiu, 2002; Hao *et al.*, 2006); knowledge management (Lang *et al.*, 2002; Zha and Du, 2006; Zha *et al.*, 2008); and design management (Lang *et al.*, 2002; De´tienne, 2006; Robin *et al.*, 2007).

Several studies in academia and commercial cases have suggested that risk assessment should be deployed in the process of NPD in order to avoid design failure, and improve the design quality and smoothness of the collaborative design process (Kayis *et al.*, 2007; Qiu *et al.*, 2007). Nevertheless, even though risk has been applied as an effective means in the design industry (Wertz and Miller, 2006; Lougha, Stonea and Tumerb, 2009), only a few researches have been conducted in association with risk management and collaborative design from theoretical or practical perspectives. It appears that there has been little research, which incorporates design constraints into the design collaboration. More specifically, risk factors have seldom been considered associated with design constraints for supporting the global design collaboration at an operational level.

However, these constraints could be “identified by considering the effects of failure of each identified performance variable in the realm of product design” (Stapelberg, 2009, p.16). In other words, design constraints can be used to “guard against failure or restrict the search to a preferred region of the design stage” (Gu and Renaud, 2002, p13.). As De Mozota (2003) suggested, every problem posed to a designer demands the constraints of technology, ergonomics, production and the marketplace be factored in and a balance be achieved. The finest performance with respect to relative constraints would have higher safety margin which give rise to more reliable product design (Rong *et al*., 2006; Stapelberg, 2009).

Thus, this thesis concentrates on investigating “how to improve design collaboration by means of a risk management approach”. More specifically, this research is focused on investigating a constraint-based design risk management (DRM) tool for mapping, measuring and mitigating collaborative design risks during the process of design collaboration.

In this chapter, the motivation and a general background of the research are presented in Section 1.2 and Section 1.3 respectively. The aim and objectives of this research are provided in Section 1.4, while the contributions and the overall thesis structure are given in Section 1.5 and Section 1.6.

1.2 Motivation

Despite the concept of collaborative design is widely adopted in the design Industry, there has been some design collaboration failure across multiple companies (Fuh and Li, 2002). In particular, some projects cannot deliver the benefits as companies have expected through collaboration during the process of NPD. Moreover, a number of stakeholders, managers and designers expressed their disappointment at not seeing the projected savings in cost and time, and critically discredited the value of design collaboration (Bauer, 2002). Besides, although various studies have been focused on improving collaborative design from diverse perspectives in academia, few researches has performed collaborative design improvement in association with a risk management approach.

Thus, there is a clear need to conduct risk management during the process of product design collaboration to prevent the potential hazards involved and ensure the success of the design project. Typically, the collaborative product process involves a variety of participators and teams who must coordinate their activities grounded on identical goal, available resources, shared information and various other constraints (Wang *et al*., 2006; Rong *et al*., 2006). The collaborative design risks can be represented as a set of design constraints that are assumed to be invariant and independent over the lifetime of a design project (Wang *et al*., 2006; Rong *et al*., 2006; Ruan and Qin, 2008; Stapelberg, 2009).

More specifically, failures and unexpected events emerge and threaten the design results during the course of design collaboration, which consequently influence on the overall design project's performance and efficiency. As collaboration becomes more complex based on characteristics of multi-disciplinary and global distributed environment, the design belief and the design audit are not adequate to interpret how the failures of different constraints during the process of collaboration would affect the entire design project. Therefore, to understand and complete an applicable and accurate risk management, it is important to model the structures and improve the overall collaborative product design in combination with the collaborative design features, Theory of Constraints (TOC) and the risk management process.

This research is focused on developing a constraint-based DRM tool to support the collaborative design projects and help companies to achieve success under a global collaboration environment. The DRM tool embedded with TOC and dominating collaborative features is an effective method for the design collaboration during the progress of NPD, which intends to explore the critical design constraints and identify key risk variables.

This research is similar to a proposal of the integrated risk management in industrial design. The proposal is funded by the European Research by Cooperation Work Program (www.euresearch.ch/.../Call-fiche_NMP_221206_01_SM.pdf). As the value chain based design and production activities have become more complex with more interrelations and interdependencies, and involve new technologies and materials that introducing new risks into a distributed and multidisciplinary environment, the development of integrated approaches and solutions for risk assessment and management is essential. These approaches and solutions are required to address the complexity and reduce the overall risk and impact. The consideration of social, technical, ergonomics, organisational, financial and environmental factors during the process of the risk assessment and management is highly recommended.

1.3 Research Background

While the previous section discussed the motivation of the study, this section will present the relevant background of the product design collaboration, and other current research in the domain of NPD.

1.3.1 Design and New Product Development (NPD)

Design is defined as “collaborative and can be optimised by allowing upstream integration of data, resources and knowledge” (Danesi *et al.*, 2006). It is a multi-disciplinary activity occurring in numerous application domains and involving a number of stakeholders (Blessing and Chakrabarti, 2009). In many worlds’ leading companies, design plays a fundamental role in the success of NPD.

Numerous researches have indicated that a good design is a substantial source of competitive advantage, which can facilitate NPD and lead to the success of business by improving their product or service quality and brand (Cooper and Kleinschmidt, 1995; Markeset and Kumar, 2003). More specifically, designs with high value-added are capable of improving product quality, delivering customised products, cutting time to market, and enhancing the business performance (Markeset and Kumar, 2003).

There are a variety of perspective and definitions of design in terms of diverse contexts. In general, as a commonly used approach in businesses and industries, design can be defined as a process that links creativity and innovation (HM Treasury, 2004).

Moreover, Morrison and Twyford (1994) presented an extensive discussion of the term “design”: “design is regarded as a creative process involving imagination and ingenuity, and usually expressed through visual images". In particular, design is associated with various domains including: product design, building design, interior design, landscape architecture, clothes and fashion, textile design, jeweller and graphics (see Figure 1.1).

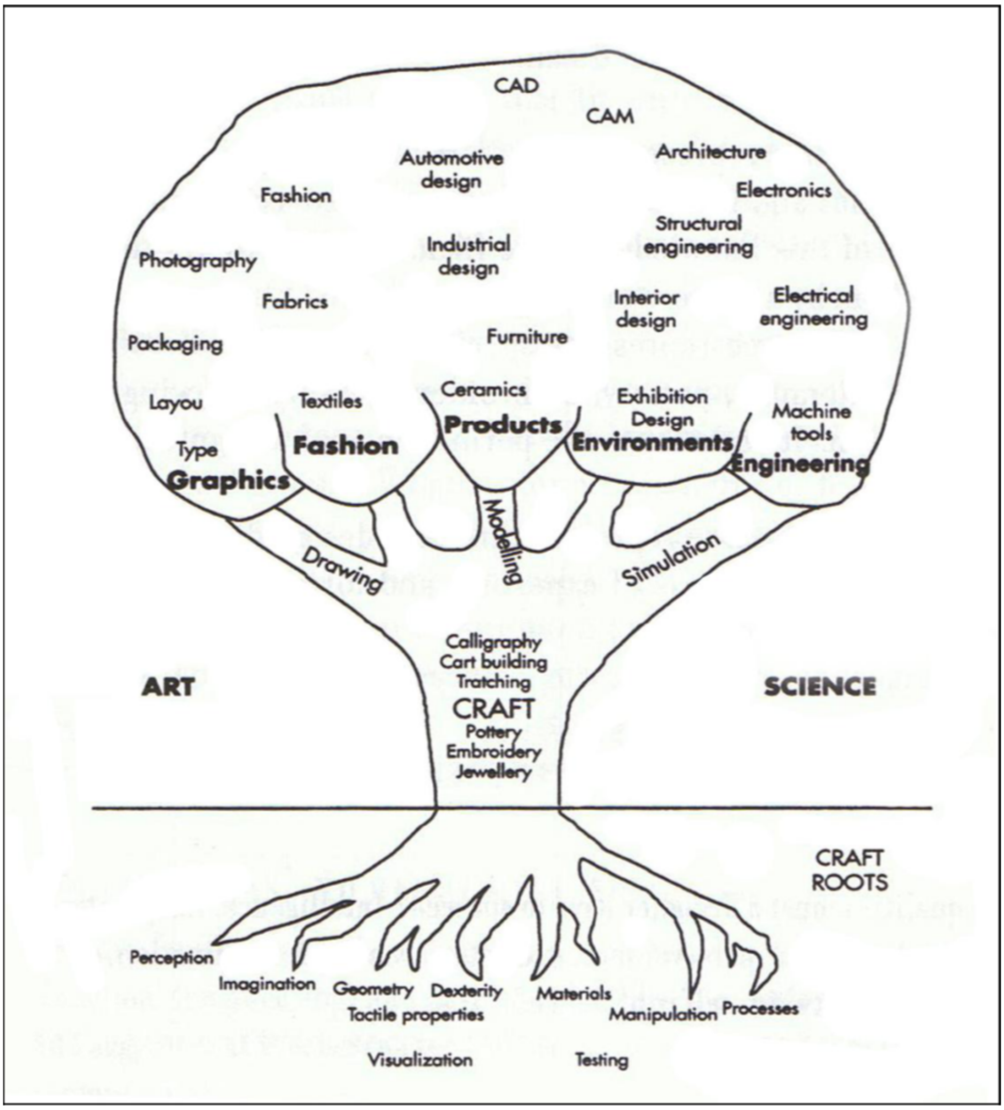


Figure 1.1 Design Tree (adapted from Cooper and Press, 1995).

In this research, design is referred to the activities that create and develop a product or service in order to fulfil the requirements and perceived desires of the users. The perceived desires could be financial, technical, social, ergonomics, and environmental. The impulse of design might come from: "1) the external market, such as desires of consumers and competing products; 2) the internal requests of companies, such as new product developments and cost reduction; or 3) from other sources, such as research results, legislation, environment, society and politics" (Blessing and Chakrabarti, 2009, p.1).

1.3.2 Product Design Process

In the last two decades, the increasing complexities of Computer Supported Collaborative Work (CSCW) technologies have led to significant changes in the process of new product design and development. Pugh (1990) put forth a concept of "total design", which provided a logical sequence and encompassed the entire product life cycle (PLC) in the process of NPD (see Figure 1.2). Besides, Pahl *et al*. (2007) has proposed that "a generic design process should include concept design, embodiment design, detail design, and manufacture design".

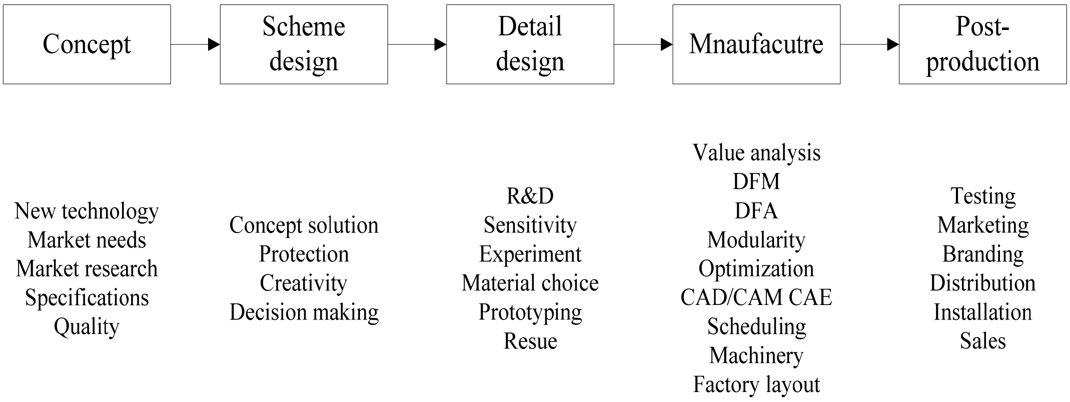


Figure 1.2 The Total Design Process (adapted from Pugh, 1990).

In this research, the process of product design can be described as "a thoughtful process grouped on the laws and insights of science, which generates the prerequisites for the realisation of products, processes, or systems, with specified constraints" (Pahl *et al*., 2007; Filippi and Cristofolini, 2010). It is compound and integrated with multi-stages and multi-disciplinary designers under a globally distributed environment (Robin *et al*., 2007; Ali *et al*., 2008). As design processes are often inefficient and ineffective (Gallaher *et al*., 2004; Young *et al*., 2007), a number of studies have been concentrated on an empirical identification and validation of product design process (Jeng and Eastman, 1999; Huang *et al.*, 2006; Scofield, 2002; Trappey and Yao, 2006; Flager and Haymaker, 2007; Pahl *et al.*, 2007; Navarro, 2009).

However, given that the sequence of the stages of product design development may differ to each other due to the diverse design objectives and strategies, no standard product design process has been acknowledged generically in design industry so far (Ali *et al.*, 2008). Priest and Sánchez (2001) indicated that "the design process should involve some functions: concept generating, conceptual design, detailed design, manufacturing design, assembly, testing, quality control, and product services".

In general, there are three sorts of models that could be applied for the demonstration of the design process in literature: "descriptive models, prescriptive models and integrative models" (Cross, 2000; Dym and Little, 2003; Filippi and Cristofolini, 2010). According to Filippi and Cristofolini (2010), "descriptive models represent the sequence of the activities occurring in the design process, while prescriptive models present algorithmic procedures with design methodologies; integrative models propose the understanding of the problem and the development of the solution in terms of the iterative nature of the product design process" (Filippi and Cristofolini, 2010, p.4).

Besides, the product design process could also be defined as "process-based, task-based, and parameter-based models" (Filippi and Cristofolini, 2010). More specifically, process-based models provide an upstream perspective of the design process and stress the design aims in manner of a clear and straight way. On the contrary, task-based models are corresponding to an explicit design process. The parameter-based models combine the merits of both process-based and task-based models by means of associating the design tasks with input parameters. However, during the design process, the parameters are usually unknown.

Thus, considering the complication of design process, and the importance of design collaboration (Chiu, 2002; Yesilbas and Lombard, 2004; De´tienne, 2005; Hao *et al.*, 2006; Robin *et al.*, 2007), the analysis of product design process is essential in managing design constraints (Yesilbas and Lombard, 2004; Huang *et al.*, 2006).

1.3.3 Features of Collaborative Design

The increasing complexity of new product development (NPD) brings challenging in design product and process, due to involved various technical and social issues. This requires “an effective collaborative design process model that can clearly depict the characteristics of collaborative design activities and provide methodologies to improve design productivity” (Lu and Jing, 2009, p. 3). Considering the involvement of multi-discipline stakeholders, design activities and decision-making are interacted with many constraints during the collaborative design process, such as technological, ergonomic, social, and manufacture factors (Rong *et al.*, 2006; Pahl *et al.*, 2007; Murthy *et al.*, 2008; Stapelberg, 2009). Thus, the design process should be modelled in terms of the identification and evaluation of the complex associations among these constraints.

Conventionally, for new product design and development, design processes used to apply a sequential model, which generally decomposes design requirement into subtasks. The subtasks could be fulfilled in a predefined model in a serial manner. Therefore, in order to achieve successful collaboration, task planning is required during the process of design (Li *et al.*, 2002). In general, task planning concludes two components: task decomposition and task assignment. As managing task-dependency is a crucial topic, which well identified in CSCW (Li *et al.*, 2002; De´tienne, 2006; Lu and Jing, 2009), the conventional design management is mainly focused on the management of design task-dependency.

However, researchers recently found that such a sequential design mode is inflexible that often requires frequent iterations (Wang *et al.*, 2002; Shen *et al.*, 2008). More importantly, these design iterations result in design expenses and time consumption, and decrease the amount of design alternatives. In addition, “the sequential design is usually practiced at a downstream level, which may cause insufficient design evaluation and inefficient NPD, due to the absence of manufacturability checks at the design stage” (Shen *et al.*, 2008, p.855)

Consequently, considering the advances in CSCW that have made product designers and design managers to coordinate and communicate by receiving and exchanging a variety of design information and resources in a more efficient way, modern global design collaboration requires more management from the view of role-interaction and resource-integration, apart from the perspective of task-dependency during the process of NPD.

More specifically, design roles or actors are required to collaborate closely in order to integrate design resource for the improvement of design effectiveness. During the process of collaborative, a wide range of roles or actors are involved with interactive design activities by linking to a new product or service with shared design information and resources. Product designers and design managers are required to adjust the work environment with the design process in order to enhance design performances and product quality.

Lu and Cai (2001) stressed the significance of collaboration among diverse design roles during the process of NPD. In particular, they highlighted design activities via task decomposition and representation (task-dependency), communication infrastructure (role-interaction) and collaboration support (resource-integration).

Girard *et al*. (2007) have concluded four types of actors' interactions and have evaluated the contextual factors for design process (see Figure 1.3) (Robin *et al*., 2007).

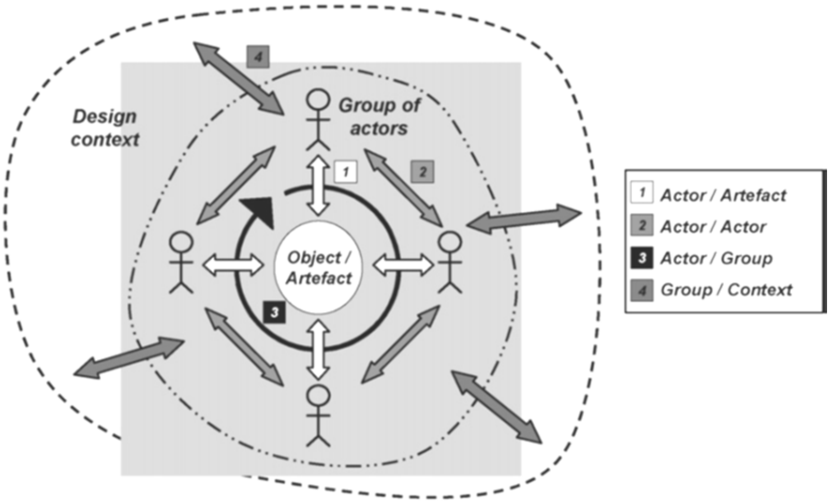


Figure 1.3 Design Actor's Interactions (adapted from Robin *et al*., 2007).

Zha and Du (2005) indicated that collaborative design may have two different types: in centralised design system, designers can achieve and exchange design information and resources by access to the main system despite in distributed place (see Figure 1.4 a) or distributed designers could assess the distributed resources via design models, internet, CSCW software applications, and database (see Figure 1.4 b and c).

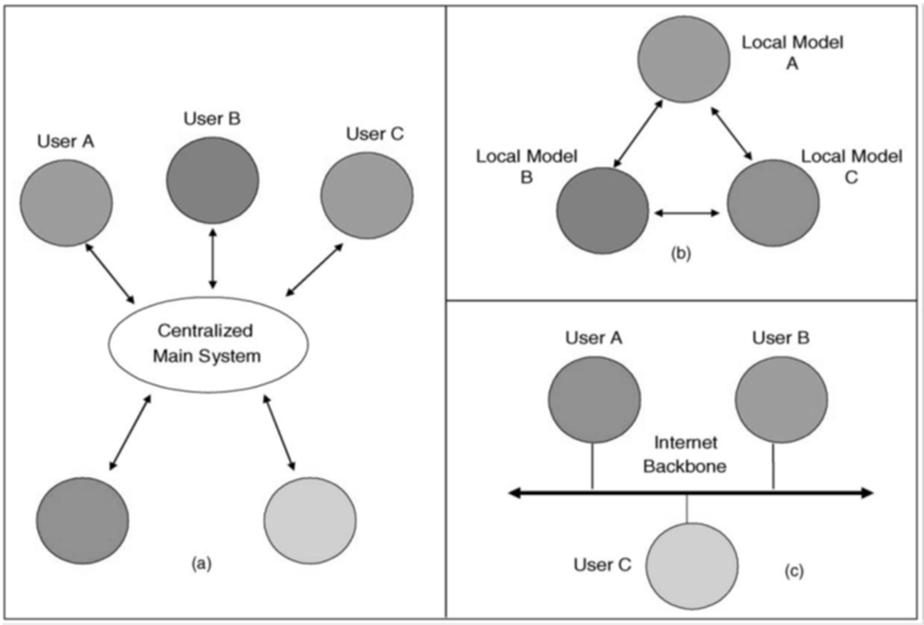


Figure 1.4 Interactions between modules exchange services (adapted from Zha and Du, 2005)

More specifically, ‘Centralised’ means that designers participate in design tasks, share the design resources and interact with each other based on centralised main system, whilst ‘Decentralised’ means that the coordination among designers are not centrally modelled or controlled (Zha and Du, 2005). Accordingly, with the assistance of technologies, the role-interaction and resource-integration can be achieved not only through the CSCW tools, but also can be facilitated by internet.

1.3.4 Roles of Design Management

From design management perspective, Lu and Cai (2001) indicated that there are many established approaches or models dealing with diverse aspects of NPD process in terms of the consideration of design thinking. In general, the design research could be summarised into three groups.

The first group focuses on the generation of formalized design theories or design methodologies, which based on the analysis of design activities and design decision-making. The design process frameworks implied in this group include General Design Theory (Yoshikawa, 1981), Axiomatic Design Model (Suh, 1990), Systematic Design Model (Paul *et al.*, 2007). These design frameworks and theories facilitate product designers' or design managers' decisions making.

The second group regards the design as a process or workflow with task dependencies. In this regard, design is only reckoned as task-dependency process with design alternatives and activities. The conventional design management mainly focuses on the management of task-dependency, in which generally decomposes the design task into subtasks that executed in a serial way. The design organisation is regarded as a stochastic processing network. Within this network, design resources are viewed as 'workstation', and design tasks are regarded as 'jobs' (Sanvido and Norton, 1994; Adler and Mandelbau, 1995; Lu and Cai, 2001). Accordingly, many techniques t has been developed in order to manage and optimise design alternatives and activities, such as Virtual Design Team (Jin and Levitt, 1996), Design Structure Matrix (Smith and Eppinger, 1997), Signal Flow Diagram (Eppinger, 1997), and Process Integration Design Optimization (Flager *et al.*, 2009).

The third group concerns about collaborative design. Numerous studies have stressed the significance of collaboration for multi-disciplinary product design under a global distributed environment (Chiu, 2002; Yesilbas and Lombard, 2004; De´tienne, 2005; Hao *et al.*, 2006; Robin *et al.*, 2007; Lu and Cai, 2009). The methods in this group are not only derived from technology, but also generated from business operation and project management.

Thus, these three groups of approaches present substantial contributions for understanding design and NPD by concentrating on different design aspects. More specifically, "design theory research provides a clearer picture of design rationale and the decision-making process" (Lu and Jing, 2009, p. 4). Design process and activity analysis characterises design alternatives and identify design task dependencies. Design collaborative management supports task-dependency, resource-integration and role-interaction, typically in a multi-disciplinary and global distributed design environment.

This research is concentrated on collaborative product design that mainly features task-dependency, resource-integration, and role-interaction. Design is viewed as one aspects of design collaborative management, which based on the perception that generates effective design coordination through scheduling design tasks, integrating design resources and information, and communicating design roles of stakeholders.

1.3.5 Collaborative Environment

The concept of collaborative design initially proposed as a potential means to enhance the communication of multi-disciplinary designers, to optimise the function of the product, and to minimise the production costs and time during the process of NPD. In the context of global competition, the design collaboration "has experienced some key technological innovations and paradigm shifts" (Li *et al.*, 2005).

There are various research efforts focusing on CSCW or management infrastructure to support designers and design managers in the context of global collaborative design. Some of them intend to collaborate via role interactions and design information and resources sharing. Others seek to construct management models or frameworks that improve workflow, manage conflicts or risks among design constraints, and support design decisions making.

More specifically, collaborative design is "a new concept of optimising engineering processes with objectives for better product quality, shorter lead-time, and cost that is more competitive and higher customer satisfaction" (Shen *et al.*, 2008, p.855). In literature, there are various definitions proposed in terms of diverse perspectives (see Table 1.1).

In this research, collaborative design refers to “various participators working together, with a certain degree of coordination of numerous activities to achieve a common purpose of designing and developing a product via task-dependency, role-interaction and resource-integration” (Wang *et al*., 2002; Yesilbas and Lombard, 2004; Robin *et al*., 2007; Ruan and Qin, 2008).

More specifically, it is “a process of designing a product through the collaboration among multi-disciplinary product developers associated with the entire product lifecycle” (Shen *et al*., 2008, p.855). This process is knowledge-intensive and cooperative that “design activities may involve many participants from diifferent disciplines and requires a team of designers and engineers with different aspects of knowledge and experience to work together” (Zha and Du, 2005, p.39).

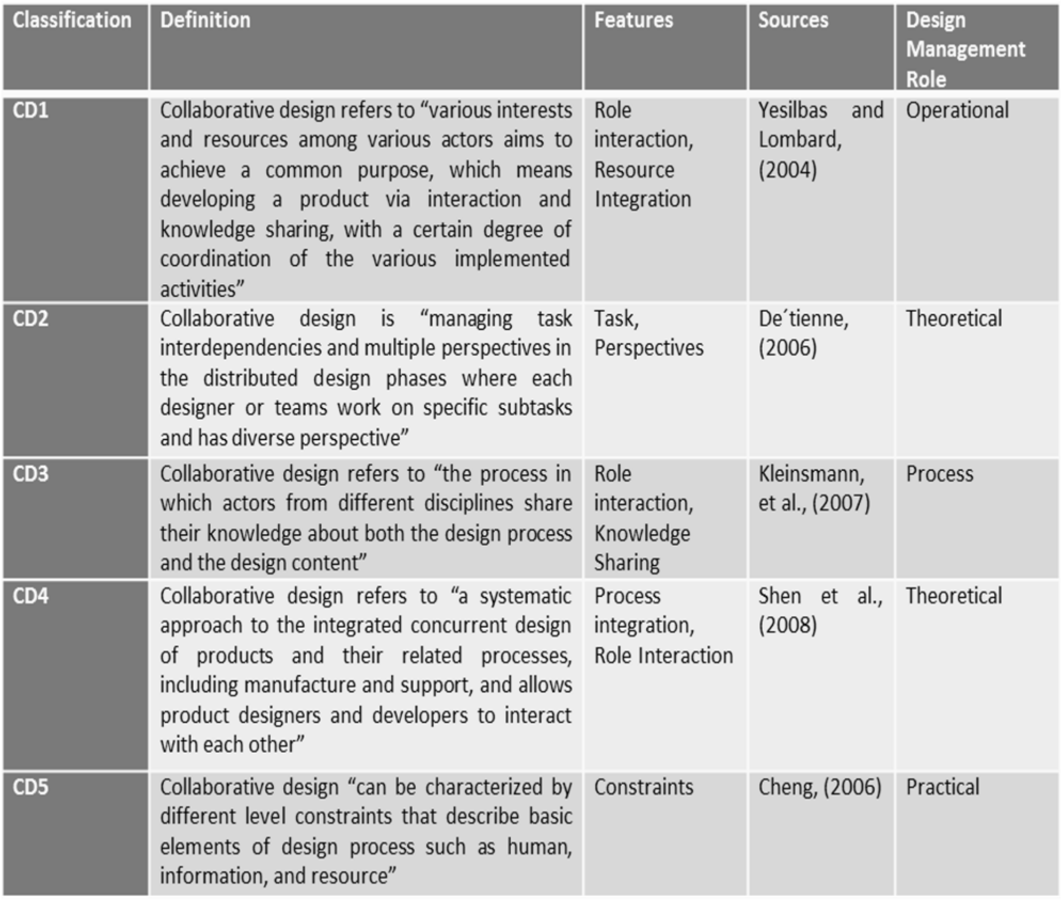
As a result, collaborative design plays a critical role in the process of NPD under a globally multidisciplinary and geographic distributed environment. Several researches have recently stresses the magnitude of the collaboration in CE (Chiu 2002; Yesilbas and Lombard, 2004; De´tienne, 2005; Hao *et al*., 2006; Robin *et al*., 2007).

However, the design risk is increased since the complexity and a variety of design collaboration correlated with communication, products, technologies, environments, etc. Although the risk management approach has been proved as an effective means to enhance design performance (Wertz and Miller, 2006; Lougha, Stonea and Tumerb, 2009), only a few theoretical researches have concentrated on improving design collaboration in combination with the risk analysis (Qiu *et al*., 2007). Therefore, there is a clear research gap that provides the motivation to conduct an empirical study associating the design collaboration with the risk management.

1.3.6 Theory of Constraints (TOC)

TOC is an overall management philosophy initiated by Dr. Goldratt in 1984. Instead of focusing on the management of process, TOC intends to provide a distinctive way of addressing the improvement and alteration from an upstream perspective and at the system level. More specifically, this theory adopts “a chain is no stronger than its weakest link as a new management paradigm, which means that organisations, systems or processes are vulnerable due to the weakest link that could fail or reduce the outcome” (Gupta and Boyd, 2008, p.993). This analytic approach comes from the contention that the success of management of any organisations, systems or processes is constrained by a limited number of constraints. Therefore, the TOC constraints perspective seeks to help designers and design managers at all levels to maintain proper concentrate on the elements that are most critical to overall success.

Table 1.1 Concept of Collaborative Design



Classification	Definition	Features	Sources	Design Management Role
CD1	Collaborative design refers to “various interests and resources among various actors aims to achieve a common purpose, which means developing a product via interaction and knowledge sharing, with a certain degree of coordination of the various implemented activities”	Role interaction, Resource Integration	Yesilbas and Lombard, (2004)	Operational
CD2	Collaborative design is “managing task interdependencies and multiple perspectives in the distributed design phases where each designer or teams work on specific subtasks and has diverse perspective”	Task, Perspectives	De´tienne, (2006)	Theoretical
CD3	Collaborative design refers to “the process in which actors from different disciplines share their knowledge about both the design process and the design content”	Role interaction, Knowledge Sharing	Kleinsmann, et al., (2007)	Process
CD4	Collaborative design refers to “a systematic approach to the integrated concurrent design of products and their related processes, including manufacture and support, and allows product designers and developers to interact with each other”	Process integration, Role Interaction	Shen et al., (2008)	Theoretical
CD5	Collaborative design “can be characterized by different level constraints that describe basic elements of design process such as human, information, and resource”	Constraints	Cheng, (2006)	Practical

The Five Focusing Steps

Goldratt (1986) created the five focusing steps as a way of improving management at the system level, which intends to make sure the ongoing efforts for the improvement are focused on the organisational constraints: “1) Identify the constraint (the constraints that prevents the organization from obtaining more of the goal); 2) Decide how to exploit the constraint (get the most capacity out of the constrained process); 3) Subordinate all other processes to above decision (align the whole system or organisation to support the decision made above); 4) Elevate the constraint (make other major changes needed to break the constraint); 5) If, as a result of these steps, the constraint has moved, return to Step 1" (Schragenheim and Dettmer, 2000).

The central insight of the TOC is that only a few constraints control the results of the entire organizations, systems or processes. The five focusing steps identify these constraints, and focus on simple, effective solutions to problems.

In literature, TOC can be used extensively in many domains, such as enhancing organisational performance (Gupta and Boyd, 2008; Inman *et al.*, 2009), improving competitiveness (Tony *et al.*, 2006), minimising the risk (Lee, 2008), overcoming difficulties in realising the potential benefits of supply chain collaboration (Simatupang *et al.*, 2004; Pahl *et al.*, 2007; Gupta and Boyd, 2008; Lin and Lai, 2009), dealing with design collaboration and management (De Mozota, 2003; Rong *et al.*, 2006; Pahl *et al.*, 2007; Murthy *et al.*, 2008; Filippi and Cristofolini, 2010).

1.4 Research Objectives

With the purpose of improving the performance of collaborative design through a design risk management (DRM) approach, the objective of this research is:

To explore and develop a "Design Risk Management (DRM) tool", which could be applied to map, measure, and mitigate the key design risk variables and improve the design decision-making during the process of collaborative product design.

Thus, the first primary objective of this research is to comprehend collaborative design characters and the concurrent design risk management in an attempt to verify the research gap.

The secondary primary objective is to investigate the design risk management under a collaborative product design environment. In this phase, a constraint-based DRM conceptual framework is proposed in order to manage the risk through the related design constraints. This new conceptual framework is presented for the identification of the key aspects of design constraints and risk variables, and for the assessment of impacts, values assignment, and the facilitation of the use of risks for design decision making during the process of the design collaboration.

The third primary objective is to explore design risk variables based on evaluated design constraints and risk criteria. A constraint-based DRM matrix is developed to integrate the Probabilistic Risk Assessment (PRA), which can be used to estimate the risk probability and consequence. It is central to develop an applicable tool that leads to identify and assess major risks instead of remediation after design failure. Capturing the critical design constraints accurately is essential if the associated risk variables vitally influence the design negotiations and the decision-making. Since the design negotiations and the decision-making have significantly affected design performance and cost, it is extremely essential that a constraint-based matrix can be applied to identify and capture key risk variables through design constraints and risk criteria.

The fourth primary goal is to explore a more appropriate and practical approach for design risk computation and simulate a DRM software prototype for further case study evaluation. After comparison with the conventional PRA method, a Bayesian weighting method is developed incorporating the constraint-based DRM matrix. This approach provides a better way to measure corresponding design risk variables. Moreover, a simulation software prototype is created based on the Unified Modelling Language (UML) and Visual Basic.NET. This prototype grounds on the conceptual DRM framework, and integrates with the constraint-based DRM matrix and the Bayesian weighting method.

The fifth primary goal is to evaluate the proposed DRM tool with the simulated prototype through case studies by participant observations and semi-structured interviews.

1.5 Contributions

This research has the contribution at both theoretical and practical aspects. The study contributes to the academic body of knowledge in collaborative design risk management (DRM) literature. Simultaneously, this research attempts to find answers to questions about how to develop a constraint-based DRM tool that would be used extensively for the improvement of design collaboration practice. Only a few empirical studies have been undertaken, and it appears that there has been little research linking design constraints to the risk management for design collaboration. More specifically, risk factors are seldom considered in association with design constraints with the purpose of supporting the global design collaboration at an operational level.

Theoretical Contribution

This thesis made a number of theoretical contributions. First, this research contributes to the literature on constraint-based design risk management (DRM) by extending the application of Theory of Constraints (TOC), as well as specifying design collaboration features and risk management process. Although the concept of using TOC as a basic risk analysis technique for product design is not new, there is no study directly related to collaborative design projects.

A constraint hierarchy is developed to map design constraints and risk variables in terms of the features of collaborative environment. As collaborative design refers to multi-disciplinary staffs spreading widely in a distributed environment, this hierarchy can be demonstrated based on three-dimensional levels: task-dependency, role-interaction and resource-integration (Wang *et al.*, 2002; Yesilbas and Lombard, 2004; Robin *et al.*, 2007; Ruan and Qin, 2008).

A constraint-based DRM conceptual framework is created as a useful theoretical model with the purpose of guiding design risk mapping, measuring and mitigating in incorporation with collaborative design features, Theory of Constraints (TOC) and risk management process for the improvement of collaborative design performance.

Second, the study identifies the critical design constraints and evaluates risk criteria that can be used to represent major risk variables involved in the collaborative product design context. These design constraints are grouped into three collaboration levels in a systematic manner. More importantly, the selected design constraints combined with risk criteria construct a valuable DRM matrix, which can be applied to diverse design stages based on risk management process. The DRM matrix establishes the dimensions of mapping design risks with reference to design constraints, and enables evaluation and refinement of the results that generated from the literature in order to achieve a better understanding for design constraints in collaborative design context. Besides, a Probabilistic Risk Assessment (PRA) method is implemented into the DRM matrix for risk measurement.

Third, a Bayesian weighting method is developed for improving risk computation. The modification of this calculation will significantly reduce the subjectivity and increase the accuracy to design risk measurement, whilst not notably increasing the cost and complexity of process. Thus, this study also adds to the current state of knowledge of design risk management as the research uses a modified form of Bayesian weighting method.

Practical Contribution

In addition, there are some practical contributions expected from the current research. First, a DRM simulation prototype is developed in terms of the previous research results, which aims at providing a demonstration of the application for further case study evaluation. The prototype tool combined with the constraint-based DRM conceptual framework and matrix based on the specified design collaboration levels and risk management process. The tool is developed with comprehensive risk management setting, flexible data input, automatic risk computation, and multi-presentation output. It can be operated in Windows XP or 7 systems, and used to determine the design risk at a project level. The DRM tool will be of benefit that supports the demonstration of overall research architectures. By applying the DRM tool, case study evaluations is greatly facilitated.

Second, case study evaluations through participant observations and semi-structured interviews were undertaken to validate the proposed DRM tool. These evaluations ensure that whether the establishments of DRM tool can provide assistance for design collaboration by setting an effective way to deal with the industry practice. The findings indicate that the proposed constraint-based DRM tool has a positive effect on the improvement of collaborative performance. These contributions will assist both designers and managers to understand the essential role of design constraints and risk management.

1.6 Structure of the Thesis

In Chapter 1, an introduction with research motivations and objectives is presented. In Chapter 2, a summary of literature related to collaboration design and risk management is reviewed. A research gap that the existing research leaves open is identified. Chapter 3 addresses an overall research methodology applied in this research, which combined with both quantitative and qualitative research methods in association with the design and management science. Chapter 4 proposes a conceptual DRM framework based on results of literature survey and industry interview. This framework provides a holistic and upstream perspective of design risk management for collaborative design environment. Chapter 5 develops a constraint-based DRM matrix in terms of the identification and evaluation of key design constraints and risk criteria. This matrix is mainly designed for mapping and measuring design risk variables in a more accurate and efficient manner. Chapter 6 provides a Bayesian weighting method for improving risk computation based on Bayesian theorem, which can be incorporated with proposed conceptual DRM framework and constraint-based DRM matrix. Moreover, a simulation prototype is developed by using Unified Modelling Language (UML) and Visual Basic.NET, which attempts to assist further case study evaluation. In Chapter 7, case studies consist of participant observations and industry interviews are conducted in order to evaluate the proposed DRM tool. Finally, in Chapter 8, a conclusion summarised with findings, contributions and limitations of overall research is provided.

Chapter 2 Literature Review

2.1 Introduction

The previous chapter introduced the research background including research motivation and objectives. This Chapter reviews the existing literature in the realm of collaborative design and risk management (DRM), which attempts to outline the scope and lay a foundation for the entire research.

Section 2.2 investigates collaborative design from both technology and management perspectives, and provides a holistic view of the significance of collaborative design in the process of new product development (NPD). An overview of general background with web-based and agent-based collaborative designs is presented. Moreover, a review with various research aspects from a management perspective is addressed.

Section 2.3 presents the existing research of risk management including risk sources, risk categories and risk management process. Section 2.4 explores relevant risk researches in association with modern global collaborative environment. Several researches indicate that risk management can be regarded as an effective means for the improvement of design collaboration. Ultimately, a summary has been concluded with a confirmation of the research gap.

2.2 Collaborative Design

2.2.1 Background

In general, collaborative design refers to “various participators working together with certain coordination of numerous activities to gain a common purchase of designing and developing a product via task-dependency, role-interaction and resource-integration” (Wang *et al*., 2002; Yesilbas and Lombard, 2004; Robin *et al*., 2007; Ruan and Qin, 2008). It can be regarded as “a synchronised asynchronous activity as in the case of concurrent engineering or a synchronous activity as in the case of platform projects” (Yesilbas and Lombard, 2004. p. 337).

Therefore, the definition of collaborative design incorporates time and space concept, which could be described as ‘synchronous’ and ‘asynchronous’. More specifically, the synchronous means design activities collaborated in the same time, whereas the asynchronous is usually described for different times. The ‘synchronous’ collaboration is termed co-design, while the ‘asynchronous’ one is named distributed design (Wang *et al*., 2002; Danesi *et al*., 2006). “The former supports the same ‘time-different place’ collaboration mode that mainly focuses on the technologies enabling real time communication for teamwork (such as dynamic task allocation and scheduling, real time data transmission, conflict management.), and the latter supports the ‘different time-different place’ collaboration mode that mainly focuses on workflow management for interior- or cross-organisational business collaboration” (Jiang *et al*., 2008, p.73).

Emden *et al*. (2006) made a summary of benefits that might derived from collaboration for new product development (NPD), including share research and development (R&D) costs and risks, provide multidisciplinary integration (Chesbrough, 2003), generate or explore new markets (Littler, Leverick, and Bruce, 1995), cut the time to customers (Bronder and Pritzl, 1992; Deck and Strom, 2002), and incorporate new technologies (Mohr and Spekman, 1994). Besides, a collaborative design environment also enhances data integration (Kleiner *et al*., 2003), facilitates the expansion of the knowledge (Wu and Duffy, 2002), and increases knowledge sharing (Vergeest and Horváth, 1999; Zha *et al*., 2008).

According to Huang *et al*. (2006), “research on the collaborative design can be classified into two main purposes: to assist users solving complex problems and to mediate cooperative activities in an efficient way”. On one hand, there are various researches efforts focusing on enabling technologies to aid designers in CSCW design environment, a number of emerging technologies in terms of agent and web are developed for collaborative design system (Shen *et al.*, 2008).

On the other hand, a great deal of researches focus on the aspect of management and social factors, such as conflict management (Li, Zhou and Ruan, 2002; Yesilbas and Lombard, 2004; Ouertani and Gzara, 2008), workflow management (Huang *et al.*, 2006; Jiang *et al.*, 2008), collaborative design process (Gonnet *et al.*, 2007; Ouertani and Gzara, 2008), design collaboration (Chiu, 2002; De´tienne, 2005; Hao *et al.*, 2005; Kleinsmann, Valkenburg and Buijs, 2007), knowledge management (Lang *et al.*, 2002; Zha, 2002; Zha *et al.*, 2008), and design management (Lang *et al.*, 2002; De´tienne, 2006; Robin *et al.*, 2007). Sections below will give more details from both the technical and management perspectives.

2.2.2 Web-based Collaborative Design

Nowadays, web-based collaborative design is "playing increasingly central roles in developing collaborative product development systems" (Huang and Mak, 1999, p.184). With the increasing developed of CSCW technology, competitive pressures are "forcing companies to consider strategies to reduce costs and compress time between each stage of the value chain" (Huang *et al.*, 2006).

In order to achieve competitive advantages, companies have been widely applied the concept of collaborative product design over the internet for the evaluation of product life cycle (PLC) and cutting time to market (Balzac, 2002; Wang *et al.*, 2002; Markeset and Kumar, 2003; Bouchlaghem *et al.*, 2004; Humphreys *et al.*, 2005; Chu *et al.*, 2006; Huang *et al.*, 2006; Jiang *et al.*, 2008). "Internet and Web-based technologies have created an 'information utility' that is accessible, cost-effective, and useful for a broad range of applications" (Hao *et al.*, 2006, p. 27). In order to achieve successful collaborative product design, CSCW technologies should not only be applied to facilitate the ability of the individual designers, but also improve the capabilities for interactive design collaborations (Wang *et al.*, 2002).

More specifically, in collaborative product design, each designer should not only be responsible for his own work and contribute expertise in diverse context, but also need to conquer the key weak point when communicated with conventional tools (Cheng *et al.*, 2006). Therefore, with the global design and manufacturing, there is "an ever increasing demand for collaborative designers over the Web and exploit the extensively available resources and enable collaboration among geographically distributed design teams" (Hao *et al.*, 2006, p.27).

According to Wang *et al.* (2002), "a collaborative design system developed with the Web as a backbone would primarily provide: 1) access to catalogue and design information on components and sub-assemblies; 2) communication among multidisciplinary design team members in multimedia formats; and 3) authenticated access to design tools, services and documents" (Wang *et al.*, 2002, p. 984). Moreover, Wang *et al.* (2002) have presented an overview of a number of Web-based tools and systems and listed a few frame works, which have been proposed and applied for Web-based collaborative design. In most cases, the Web is utilised as an intermediate for information, resource, knowledge and data sharing, while in other cases the Web incorporate with other CSCW technologies for design improvement. Besides, the Web may also be employed to observe and evaluate the design process.

However, the Web-based technologies just present basic infrastructures and only provide standardising interactions among individual systems. "The interaction among components is predefined and lack of capability in supporting the integration of multidisciplinary design environments, where collaboration sometimes is established through non-deterministic ad hoc interaction patterns" (Hao *et al.*, 2006, p.28). Thus, scattered designers and managers require more actively supports for coordination in a distributed context. The coordination "involves the translation of terminology among multi-discipline, locating and providing engineering analysis services, virtual prototyping services, and project management" (Shen, *et al.,* 2008, p.858).

Generally, "a Web-based collaborative design system usually uses a client and server structure, in which the interaction between components is predefined. This kind of approach is insufficient to support dynamic collaborative design environments, where tasks are usually involving complex and non-deterministic interactions, producing results that might be ambiguous and incomplete." (Shen *et al.*, 2008, p.858). Nevertheless, Web provides a repository of information and facilitating services to allow the implication of servers in support of users solving collaborative design problems.

2.2.3 Agent-based Collaborative Design

Agent is "software that can autonomously perform routine tasks with a degree of intelligence" (Turban *et al.*, 2004; Huang, 2006). Agents could be used to "filter data, interpret information, monitor activities, decision support" (Huang, 2006, p. 682). Given that agents typically consist of four key characteristics in application domains, such as "autonomy, reactivity, communication and goal driven", many researchers have focused on the integration of collaborative design with agent based technology (Huang, 2006; Shen *et al.*, 2008).

The term "agent" has been adopted broadly to develop intelligent software and provide Computer Supported Collaborative Work (CSCW) with the nature of collaborative design. More specifically, with the purpose of increasing "benefits of autonomy, social ability, pro-activeness, and reactivity", researchers could employ agent-based technology during the process of collaborative design (Xia and Li, 1999; Kuo, 2004; Huang, 2006; Shen *et al.*, 2008). For instance, in order to achieve successful business process coordination, agent technology can be applied for presenting autonomous solutions (Yan *et al.*, 2001). Thus, agent-based approaches play a critical role in support of design activities under a multi-disciplinary and distributed collaborative environment (Qiu, 2007).

Many R&D projects have demonstrated the application of agents in collaborative product design. Wang *et al.* (2002) presented "a detailed discussion on issues in developing agent-oriented collaborative design systems and a review of significant, related projects or systems". In order to support cooperation among designers, software agents are mostly used by means of increasing the "interoperability between traditional computational tools, or facilitating better simulations" (Shen *et al.*, 2008, p.858). Thus, the technologies based on Web or agents are constructive for the implementation of collaborative design tools or systems. The Web in combination with agents enables automatically access and exchange of design information, resources and knowledge. On one hand, the challenge is that the development of a Web-based collaborative design tools or systems that "enables seamless interactions between human designers, software agents, and Web servers using the available resources and emerging technologies" (Wang, Shen and Ghenniwa, 2003; Shen *et al.*, 2008). On the other hand, "an agent-based collaborative design system is a loosely coupled network that attempts to solve those design problems that are beyond their individual capabilities" (Shen *et al.*, 2008). More specifically, agents play coordinative, autonomous, and intelligent roles. Nowadays, most collaborative design systems are attempting to develop by using the combination of Web and agent-based technologies.

However, "although agent-based technology has been recognised as a promising approach for developing collaborative design systems, those agents that have so far been implemented in various prototype and industrial applications are actually not very intelligent" (Shen *et al.*, 2008, p.858). From this perspective, agent technologies for collaborative design are still facing some challenges. Thus, a number of studies have begun to analyse a collaborative design process in combination with aspects of social and technical. The efforts that dedicated from a management perspective are presented with details in next sections.

2.2.4 Management Perspective of Collaborative Design

In current collaborative design, "the number of project participants has been increased and the nature and means of collaboration has been changed with different participant backgrounds, interests, expertise, behaviours, cultural features" (Bayes *et al.*, 2007). The processes of collaborative design involves a variety of participators and teams who must coordinate their activities grounded on identical goal, available resources, shared information and various other constraints (Wang *et al.*, 2006; Rong *et al.*, 2006; Ruan and Qin, 2008). A successful collaborative design requires "the effectiveness in a number of areas: cognitive synchronization, developing shared meaning, developing shared memories, negotiation, communication of data and knowledge information, planning of activities, tasks, methodologies, and management of tasks" (Lang *et al.*, 2002, p.90).

However, contemporary design projects become to be large and complex, which cover a broad range of activities in different area: graphic design, engineering design, product design, human factors design, and software design (De´tienne, 2006). These complexities and challenges are significantly increased in a global e-manufacturing environment, due to the extensive application of internet and CSCW that "facilitates coupling, promotes conflicts and communication problems among design project teams with different educational, cultural and social backgrounds" (Tseng *et al.*, 2003).

Therefore, the challenge is how to handle the tremendous complexity involved in planning and executing a great volume of dependent and dynamic development tasks (Wang *et al.*, 2006). More specifically, significant levels of complexity highly require management to enhance the performance of design collaboration. These improvement usually involved product data management, conflict management, cost controlling, task planning, workflow management, and knowledge management.

For conflict management, "major conflicts in design process often stem from specification conflicts among the constituent design tasks" (Wang *et al.*, 2002). More specifically, "conflicts and disputes arise regularly in decision-making process during collaborative design, such as goal selection, proposal exchanging, task coordination, role-interaction, and allocation of the limited resources" (Wang *et al.*, 2002; Yesilbas and Lombard, 2004; Robin *et al.*, 2007; Ruan and Qin, 2008). Yesilbas and Lombard (2004) proposed a framework of conflict management, which "allows multi-disciplinary and distributed collaboration to be coordinated by defining a common repository for knowledge management in a collaborative design situation". Lu and Jing (2009) created a socio-technical negotiation method, which provides "a conflict resolution strategy by guiding software engineers to generate exchange and evaluate their argument claims in negotiation activities".

For workflow management, it includes "a set of tools that providing supports for the necessary services of workflow enactment services, process definition, administrative and monitoring tasks, workflow client applications, and other invoked applications (Huang *et al*., 2006, p.681)". In other words, the workflow systems comprise of the "coordinate mechanisms for a collaborative design environment with the benefits of flexible process definition, easy tracking of activities, and effective process management" (Huang *et al*., 2006, p.681).

Moreover, in recent years, there are increasing research considering risk as a method for evaluating and improving design performance under a collaborative environment.

2.3 Risk Management

2.3.1 General Background of Risk Management

Risk management refers to a "method of managing that concentrates on identifying and controlling the areas or events that have a potential of causing unwanted change. It is no more and no less than informed management" (Caver, 1985). Nowadays, there exists a growing need to have a strategic perspective during the project risk management in order to consider the holistic views of an organisation. It is not enough to define a project only in terms of schedule, costs, and product specifications (Sanchez *et al*., 2009). Therefore, it is necessary to take into account a comprehensive perspective that applies to project risk management.

According to Treasury Board of Canada Secretariat (2007), an integrated risk management could be viewed as "a continuous, proactive, and systematic process to understand, manage, and communicate risk from an organisation-wide perspective. It is about making strategic decisions that contribute to the achievement of an organisation's overall corporate objectives".

Risk is regarded as "an uncertain event or condition that might have a positive or negative influence on a project's objectives" (PMI, 2004). More specifically, according to Ward (1999), risk is "cumulative effect of the probability of uncertain occurrences that may positively or negatively affect project objectives". Moreover, Williams (1995) defined risk as "an uncertain event or set of circumstances that, should it occur, will have an effect on the achievement of the project's objectives". As a result, there are a number of risk definitions in literature. In general, risk is viewed "as an exposure to losses in a project or as a probability of losses in a project" (Webb, 1994; Chapman and Ward, 1997; Jaafari, 2001).

In this study, risk is regarded as "a probability of losses in a project", which is quantifiable and could be measure by using computational approaches. The nature of any given risk is consisted of three fundamental elements: event, probability, and severity. The higher probability or occurrence with higher severity or consequence means high risk (see Figure 2.1).

According to Clemen (1996), a situation where it is not possible to link a probability of occurrence to an item can be defined as uncertainty. However, because the uncertainty is not measurable, the risk can be predicted by means of subjective measurement approaches (Raftery, 1994). Once the risk items or variables have been defined, probability needed be assigned. Statistical data and probability theory play important roles in determining this value.

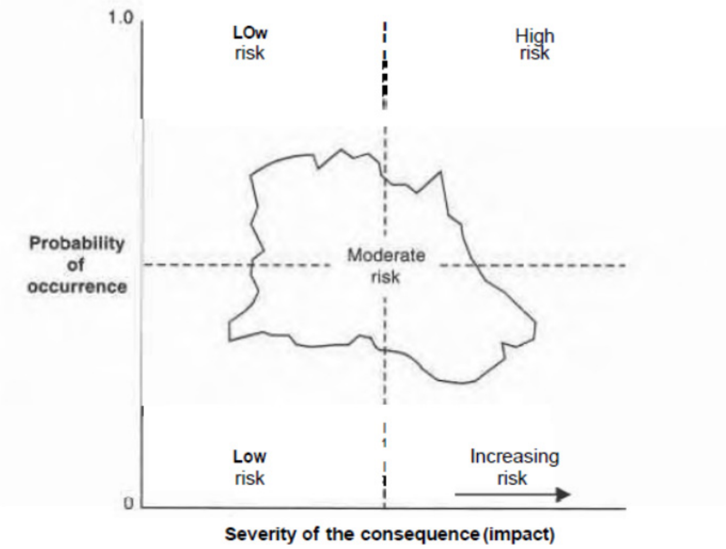
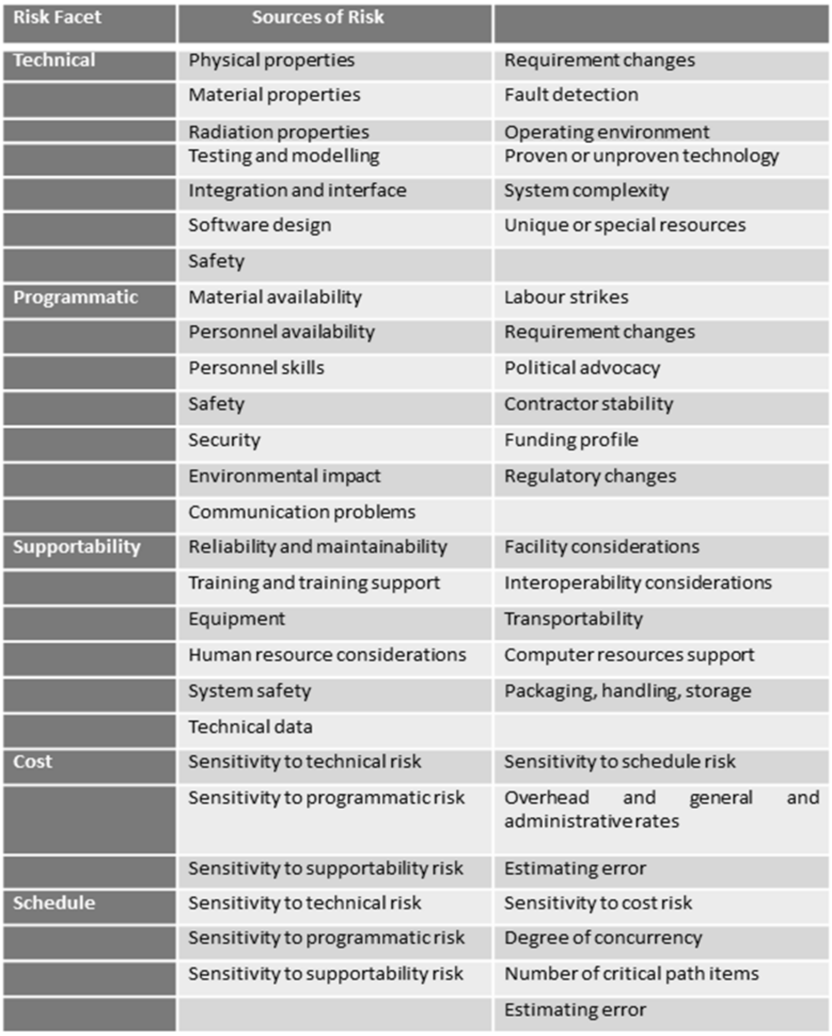


Figure 2.1 Concept of risk (adapted from Pritchard, 2001).

2.3.2 Risk Sources and Categories

Risk categories provide "a structure that ensures a comprehensive process of systematically identifying risks to a consistent level of detail and contributes to the effectiveness and quality of the identify risks process" (PMI, 2008, p. 280). However, classifying a risk into one or more categories requires examining the source of the risk. More importantly, "understanding the source of the risk and the affected areas, as well as providing a structure to examine risk, are critical elements if the risk is to be managed effectively" (Pritchard, 2001, p. 12). DSMC (1986) classified risk into five facets: technical, programmatic, supportability, cost, and schedule (see Table. 2.1).

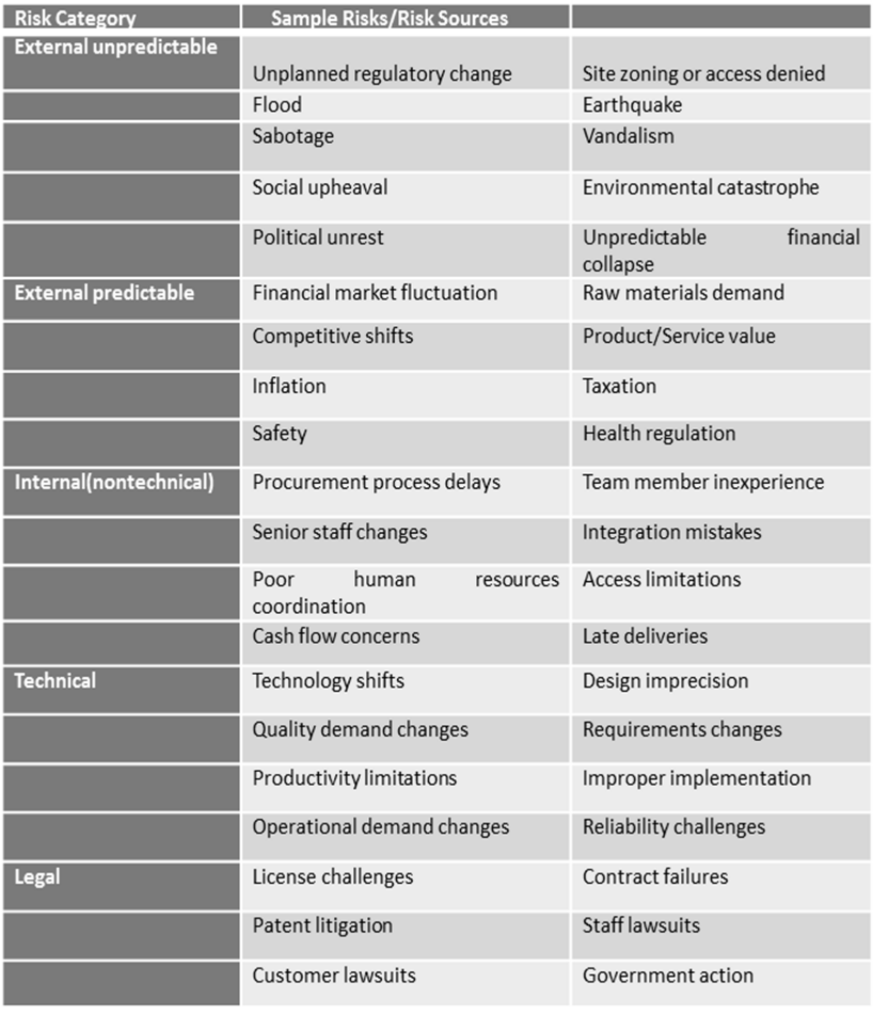
Table 2.1 Typical Sources of Risk by Facet (adapted from Defence Systems Management College, 1986)



Risk Facet	Sources of Risk	
Technical	Physical properties	Requirement changes
	Material properties	Fault detection
	Radiation properties	Operating environment
	Testing and modelling	Proven or unproven technology
	Integration and interface	System complexity
	Software design	Unique or special resources
	Safety	
Programmatic	Material availability	Labour strikes
	Personnel availability	Requirement changes
	Personnel skills	Political advocacy
	Safety	Contractor stability
	Security	Funding profile
	Environmental impact	Regulatory changes
	Communication problems	
Supportability	Reliability and maintainability	Facility considerations
	Training and training support	Interoperability considerations
	Equipment	Transportability
	Human resource considerations	Computer resources support
	System safety	Packaging, handling, storage
	Technical data	
Cost	Sensitivity to technical risk	Sensitivity to schedule risk
	Sensitivity to programmatic risk	Overhead and general and administrative rates
	Sensitivity to supportability risk	Estimating error
Schedule	Sensitivity to technical risk	Sensitivity to cost risk
	Sensitivity to programmatic risk	Degree of concurrency
	Sensitivity to supportability risk	Number of critical path items
		Estimating error

In the PMI (1987), risk categories included “external unpredictable, external predictable, internal (nontechnical), technical, and legal” (SamAbdou, Lewis, and Zarooni, 2004). Sample risks or risk sources from each category are shown in Table 2. 2.

Table 2.2 Risk Categories and Sources (adapted from PMI, 1987)



Risk Category	Sample Risks/Risk Sources	
External unpredictable	Unplanned regulatory change	Site zoning or access denied
	Flood	Earthquake
	Sabotage	Vandalism
	Social upheaval	Environmental catastrophe
	Political unrest	Unpredictable financial collapse
External predictable	Financial market fluctuation	Raw materials demand
	Competitive shifts	Product/Service value
	Inflation	Taxation
	Safety	Health regulation
Internal(nontechnical)	Procurement process delays	Team member inexperience
	Senior staff changes	Integration mistakes
	Poor human resources coordination	Access limitations
	Cash flow concerns	Late deliveries
Technical	Technology shifts	Design imprecision
	Quality demand changes	Requirements changes
	Productivity limitations	Improper implementation
	Operational demand changes	Reliability challenges
Legal	License challenges	Contract failures
	Patent litigation	Staff lawsuits
	Customer lawsuits	Government action

However, in PMI (2008), the risk categories shifted slightly: technical, external, organisational, and project management. PMI (2008) suggested that risk should be categorised in the form of a simple list of categories or might be structured into a Risk Breakdown Structure (RBS), which could be applied to identify the various areas and causes of potential risks. Sample risks and sources of risk are shown in the Figure 2.2.

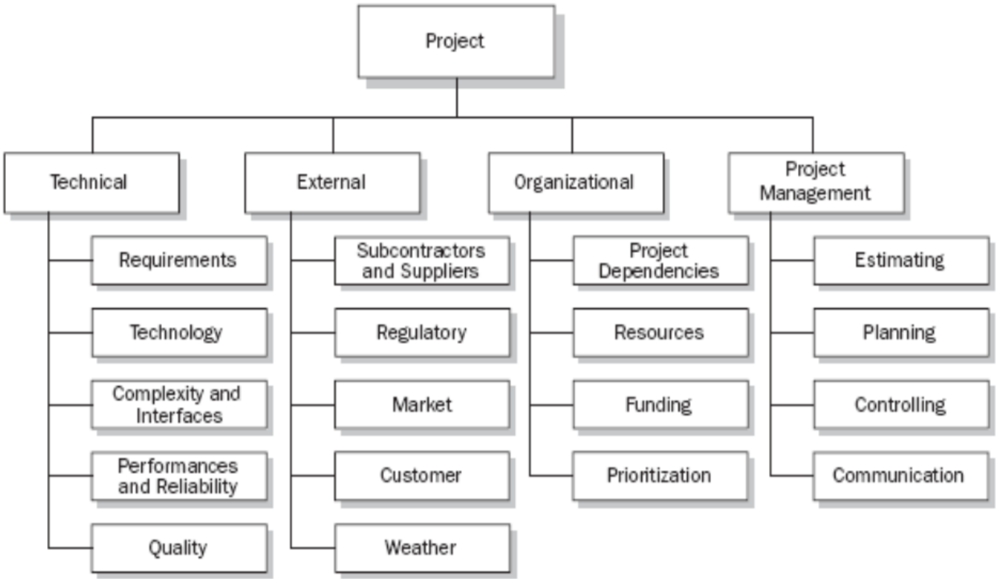


Figure 2.2 Example of Risk Breakdown Structure (adapted from PMI, 2008).

Several types of risks are discovered in new product design and development. According to Williams (1995), Chapman (2001), and Kayis *et al*. (2007), these risks could also be found in literature of project management. "Each risk in itself or combination of these risks can directly affect the deadline, cost and quality of the product design process" (Kayis *et al*., 2007, p.392). Consequently, it is crucial to identify and evaluate risks for the achievement of successful design collaboration in a distributed, complex, and multidisciplinary design team. "The enabling agents of design are essential ingredients to include in the whole risk management process" (Kayis *et al*., 2007, p.392).

2.3.3 Risk Management Processes

In the preceding section, the importance of identifying risk sources and generating risk categories are presented. These aspects provide a comprehensive, consistent and systematic way to facilitate the effectiveness of the risk management process.

In general, the process of risk management refers to "uncovering weaknesses in methods used in product development through a structured approach so that timely mitigation actions are initiated to avoid risk, transfer risk, reduce risk likelihood or reduce risk impact" (Pritchard, 2001).

Numerous literatures have been found focusing on the research of risk management process. For instance, Boehm (1991) indicated risk management is composed of two key aspects: "risk assessment (identification, analysis and prioritisation) and risk control (risk management planning, risk resolution and risk monitoring planning, tracking and corrective action)". Fairley (1994) provided a seven phases process for risk management: "identification, assessment, mitigation, monitoring, contingency planning, managing the crisis and recovery from the crisis".

Chapman (1998) presented nine steps during the process of project risk management: "definition, strategic approach, identification of risks, information structuring, ownership, uncertainty estimation, magnitude of risks, response, monitoring and controlling". Klein and Cork (1998) provided four steps: identification, analysis, control and reporting. The Software Engineering Institute identified four steps: "identification, analysis, response development and control" (Tseng *et al*, 2003; Kayis *et al*., 2007).

A risk management process proposed by the Australia and New Zealand Risk Management Standard (AS/NZ 4360) is shown in Figure 2.3 (AS/NZ Standard 4360, 1999). Ahmed *et al*., (2007) stressed that, the risk management process "is composed of seven iterative sub-processes of establishing the context of risk, identifying risks, analysing risks, evaluating risks, communication and consultation across stakeholders and monitoring and controlling risk events" (Ahmed *et al*., 2007, p.28).

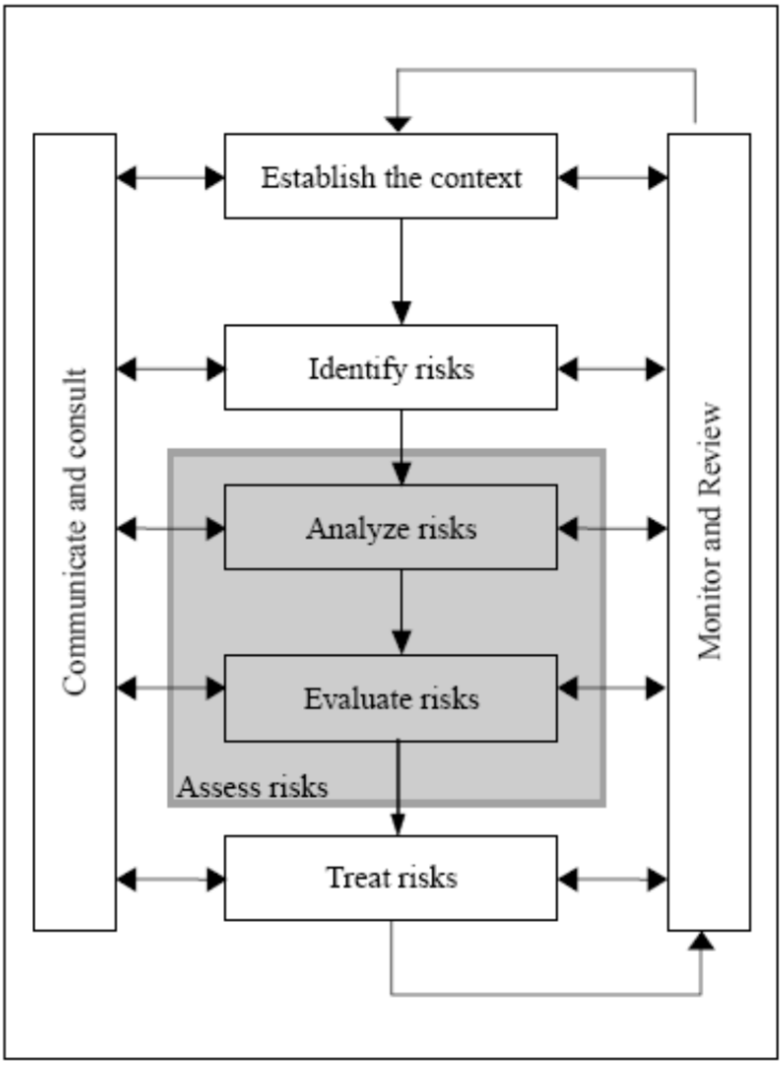


Figure 2.3 The Risk Management Process (adapted from AS/NZS 4360, 1999).

PMI (2008) suggested that project risk management encompassed six general steps, which constituted “the processes of conducting risk management planning, identification, analysis, response planning, and monitoring and control on a project”. The purpose of risk management is to achieve the success of project management by avoiding the risk that might caused by negative elements. Table 2.3 presents a review of project risk management processes.

Table 2.3 An Overview of Project Risk Management Processes (adopted from PMI, 2008).

Plan Risk Management	The process of defining how to conduct risk management activities for a project
Identify Risks	The process of determining which risks may affect the project and documenting their characteristics
Perform Qualitative Risk Analysis	The process of prioritizing risks for further analysis or action by assessing and combining their probability of occurrence and impact
Perform Quantitative Risk Analysis	The process of numerically analysing the effect of identified risks on overall project objectives
Plan Risk Responses	The process of developing options and actions to enhance opportunities and to reduce threats to project objectives
Monitor and Control Risks	The process of implementing risk response plans, tracking identified risks, monitoring residual risks, identifying new risks, and evaluating risk process effectiveness throughout the project

Despite several different structures and phases have been presented, some structures and definitions have used basically the same concept, which might results in continuing confusion (Pritchard, 2001). Therefore, the design risk management (DRM) should be in accordance with a strict process, which expects to make a significant improvement on the effectiveness and efficiency. In this research, a general risk management methodology composed of three stages is adopted: risk identification (mapping), assessment (measurement), and treatment (mitigation) (Raz and Michael, 2001; Kayis *et al.*, 2007). The explicit risk management process in association with collaborative design levels is articulated as a constraint-based DRM conceptual framework in Chapter 4.

2.4 Global Design Collaboration and Risk Management

In global competitive environments, “designers are increasingly faced with the challenges of interacting and integrating distributed multi-disciplinary collaborative product design and development teams and resources” (Fuh and Li, 2004, p.571). Moreover, “the ever increasing economy globalisation and product customisation have made the market more competitive and dynamic, companies have to enhance the collaboration among designers, design managers and stakeholders in an attempts to develop high-quality products at low cost and with quick response to market demands" (Markeset and Kumar, 2003; Bouchlaghem *et al.*, 2004; Humphreys *et al.*, 2005; Jiang, *et al.*, 2008). In addition, the rapid development of internet and CSCW facilitates the technologies among companies in the meantime, which make possible for design collaboration among multi-disciplinary design members under a global distributed environment.

As a result, "close collaborations with designers, customers, suppliers, and stakeholders have become imperative for most companies to meet time-to-market and reduce product development costs" (Balzac, 2002; Wang *et al.*, 2002; Markeset and Kumar, 2003; Bouchlaghem *et al.*, 2004; Humphreys *et al.*, 2005; Chu *et al.*, 2006; Huang *et al.*, 2006; Jiang *et al.*, 2008). Therefore, global design, supply and manufacturing demand high levels of design collaboration (Fuh and Li, 2004).

In addition, "with widespread use of a distributed product development environment designed to achieve desirable effectiveness and efficiency, collaborative design is becoming more complex" (Qiu, *et al.*, 2007, p.357). More specifically, contemporary design issues intend to be large and complex, which incorporates a wide range of design activities with diverse knowledge (De´tienne, 2006). Due to significant levels of complexity, it is impossible that collaborative design issues can be resolved by a single designer (Zha and Du, 2006).

Besides, consider the increasing globalisation, "participants of a design project are usually dynamic and geographically distributed" (Shen *et al.*, 2008). Thus, "current workflow management technologies have difficulties in solving the challenges of collaborative product design in a distributed environment with dynamic nature of product development, distributed knowledge and resources, and risks attached to design collaboration" (Huang *et al.*, 2006, p.168).

Thus, the process of collaborative design "inherits several risks due to knowledge sharing, decision making, role interacting, process increasing, and resources integrating in design projects" (Kayis *et al.*, 2007, p.389). However, only a few empirical researches have been conducted and it seems that there has been no study links design constraints to the design collaboration. More specifically, risk factors have seldom been considered in association with design constraints with the purpose of supporting the global design collaboration at an operational level.

This gap provides the motivation to explore risk as an underlying method in order to support design collaboration. In this work, risk criteria are associated with design constraints, which viewed as the primary sources of design risk variables, which can be used to maintain design risk management (DRM). The design constraints are mainly stemmed from the collaborative levels of task-dependency, role-interaction and resources-integration in an independent manner, which considered as the key aspects that play critical roles during the process of collaborative design.

To better understand the DRM, a constraint-based conceptual framework combined with the features of design collaboration, risk management process and Theory of Constraints (TOC) is proposed firstly. Then a following DRM matrix with evaluated design constraints and risk criteria is established for risk mapping and measurement. Ultimately, a Bayesian weighting method is implemented incorporating with the DRM matrix and a simulation is created in an attempt to support further case study evaluation.

2.5 Conclusion

In this chapter, an overall review is presented to describe the research field and the research gap is verified for the investigation of design risk management under a global collaboration environment. On the one hand, in the existing literature there has been an increasing volume of research for collaborative design with reference to both technology and management aspects. For the technology side, an overview consisted of web-based and agent-based collaborative design is described. While with regard to the management side, several aspects are related such as conflict management, workflow management, design collaboration and knowledge management. On the other hand, despite risk management being well developed and understood in other research areas, particularly the financial domain (Hood and Young, 2005), however, it has generally been ignored in the field of new product design, particularly collaborative design. In literature, the concept of risk source and categories is introduced which laid a foundation for overall design risk management. More importantly, several risk management processes are reviewed aiming at provide an essential guide to support design risk management.

Moreover, under a global competitive environment, few researchers have addressed risk management issues with regard to design collaboration (Xu and Wang, 2002; Kayis *et al.*, 2007; Qiu *et al.*, 2007). Only a few empirical studies have been undertaken. Additionally, risk factors have been rarely taken into account for the global design collaboration by linking with design constraints. Therefore, this research aims to investigate and develop a constraint-based Design Risk Management (DRM) tool, which can map, measure and mitigate overall risk of a design project under a collaborative environment. The next chapters will illustrate the design and development process of the proposed DRM tool.

Chapter 3 Methodology

3.1 Introduction

The preceding chapter provided an overview of related literature with reference to collaborative design and risk management under a global competitive environment. It seems that there exists a lack of empirical study of how to improve design collaboration by means of risk management. Thus, this research focuses on investigating and developing a design risk management (DRM) tool, which can be used to map, measure and mitigate key design risk variables and improve design decision-making during the process of collaborative product design. This chapter aims to clarify the differences among methodologies and present an outline of qualitative and quantitative methods applied in this research.

In general, research is designed to address a specific problem and find solutions based on scientific methods to gain knowledge or understanding. Jonker and Pennink (2010) introduced a "Research Pyramid" aiming to support for structuring appropriate research process (see Figure 3.1). The key function of this "Research Pyramid" is to assist researchers to structure the methodology to the study.

Particularly, in design science, with the aim of validating the results in manner of "some generic, theoretical as well as practical sense", research must be "scientific" (Blessing and Chakrabarti, 2009). In other words, a research methodology applied in a study or investigation should be "in a more scientific way" (Frankfort-Nachmias and Nachmias, 1996). More specifically, design research aims at improving rather than understanding, which requires "1) a model or theory applicable for the existing situation, 2) a model or theory of the desired situation, and 3) a vision of the support that is likely to change the existing situation into the desired situation, and maintain this" (Blessing and Chakrabarti, 2009, p.9). Thus, design researches have to design and develop in a systematic way.

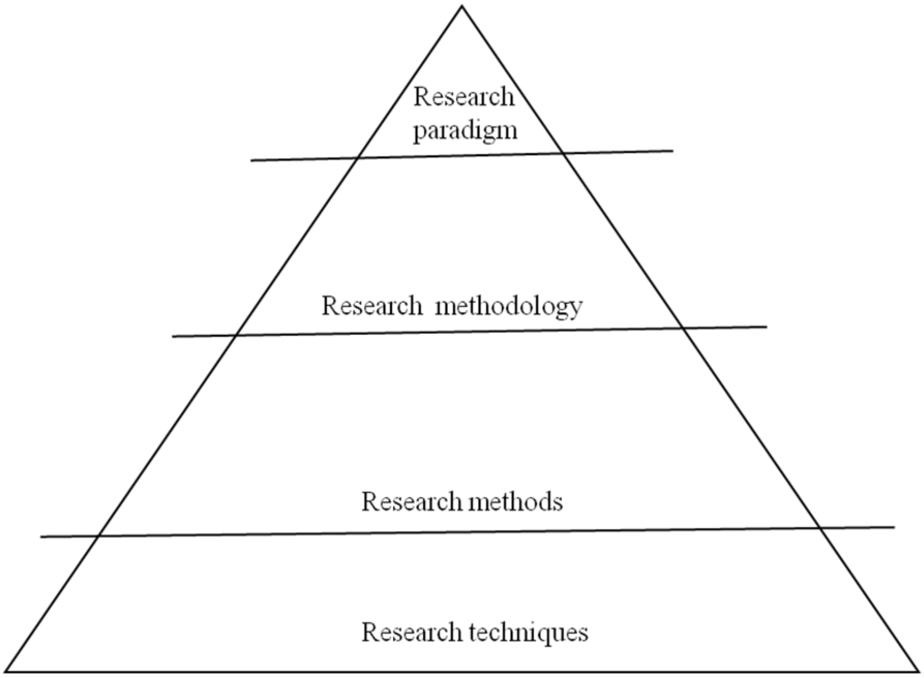


Figure 3.1 The Research Pyramid (adapted from Jonker and Pennink, 2010).

Consequently, in this chapter, a holistic review of methodology is illustrated in order to lay a comprehensive foundation for this research. In addition, the methods in combination with both qualitative and quantitative approaches are demonstrated, which were adopted specifically to develop a constraint-based Design Risk Management (DRM) tool.

3.2 Research Methodology

According to Jonker and Pennink (2010), "methodology is first and primary associated with conducting research, which assumes there is a logical order that the researcher needs to follow in order to achieve a certain predetermined result (e.g., knowledge, insight, design, intervention, change)". More specifically, a scientific methodology is required for designs and develops a serial of explicit tasks or procedures and attempting to obtain the research objective (Easterby-Smith *et al.*, 2002).

Moreover, "applying specific methodologies derived from a more scientific background to practical situations is in itself also a part of science" (Jonker and Pennink, 2010, p.10). Neuman (2006) concluded that "social research could be categorised into three groups: exploratory, descriptive and explanatory" (see Table 3.1). In particular, "a methodology for design research should guide the selection and application of a suitable approach and appropriate methods, and encourage reflection on the approach and methods to be used" (Blessing and Chakrabarti, 2009, p.9). Therefore, whether the selected research methods are appropriate determines the reliability of research results (Burns, 2000). It is more critical to select a suitable research methodology in the process of specific research development.

Table 3.1 Purposes of Research (adapted from Neuman, 2006; p.15).

Exploratory	Descriptive	Explanatory
Become familiar with the basic facts, setting, and concerns.	Provide a detailed, highly accurate picture.	Test a theory's predictions or principle.
Create a general mental picture of conditions.	Locate new data that contradict past data.	Elaborate upon and enrich a theory's explanation.
Formulate and focus questions for future research.	Create a set of categories or classify types.	Extend a theory to new issues or topics.
Generate new ideas, conjectures, or hypotheses.	Clarity a sequence of steps or stages.	Support or refute an explanation or prediction.
Determine the feasibility of conducting research.	Document a causal process or mechanism.	Link issues or topics with a general principle.
Develop techniques for measuring and locating future data.	Report on the background or context of a situation.	Determine which of several explanations is best.

3.2.1 Quantitative Research

Quantitative research involves complex experiments, many variables and treatments that are generally reflected in accurate figures. It is regarded as "being purely scientific, precise and grounded on facts" (Jonker and Pennink, 2010, p.38). More specifically, quantitative research is mainly used for “developing knowledge (i.e., cause and effect thinking, reduction to specific variables and hypotheses and questions, use of measurement and observation, and the test of theories), employs strategies of inquiry (such as experiments and surveys), and collects data on predetermined instruments that yield statistical data” (Creswell, 2009, p.18).

In general, quantitative research addresses the goals of conclusive study exploration, which usually applied for exploratory objectives. It is “based on the basic approach that knowledge about reality can be obtained through the eyes of the researcher” (Jonker and Pennink, 2010, p.69). More importantly, quantitative research “involves collecting data from relatively large samples; the data collected are usually presented as numbers, often in tables, on graphs and on charts” (Blessing and Chakrabarti, 2009). Besides, quantitative research also provides ideographic description that is rich in detail but limited to relatively few cases. Therefore, quantitative research usually “generates statistics with large-scale survey research, using methods such as questionnaires or structured interviews” (Dawson, 2002). “It is common to call this the expert approach.” (Jonker and Pennink, 2010, p.69)

3.2.2 Qualitative Research

Qualitative research can be regarded as “a research strategy that usually emphasise words, rather than quantification in the collection and analysis of data” (Bryman, 2008, p.28). More specifically, it is because “knowledge about reality can only be obtained through the eyes of someone else” (Jonker and Pennink, 2010, p.69). Qualitative research investigates “attitudes, behaviour and experiences through such methods as interviews or focus groups, which attempts to get an in-depth opinion from participants” (Dawson, 2002, p.168). In other words, it tends to explore “the importance of the subjective and experiential life world of human beings” (Burns, 2000, p.11). Especially, qualitative research plays a crucial role in “suggesting possible relationships, causes, effects and even dynamic processes in design development” (Crano, *et al.*, 2002, p.211). Therefore, qualitative research have been extensively operated in academia mainly in terms of the ways they provided which can lead to the deeper meaning of scientific discoveries.

Miles and Hubermans (1994) presented a “tree” diagram and made a clearly visible demonstration in order to help researchers to select appropriate mythology for the research design (see Figure. 3.2). The main qualitative methods include observation, interview, focus group, simulation, and case studies etc.

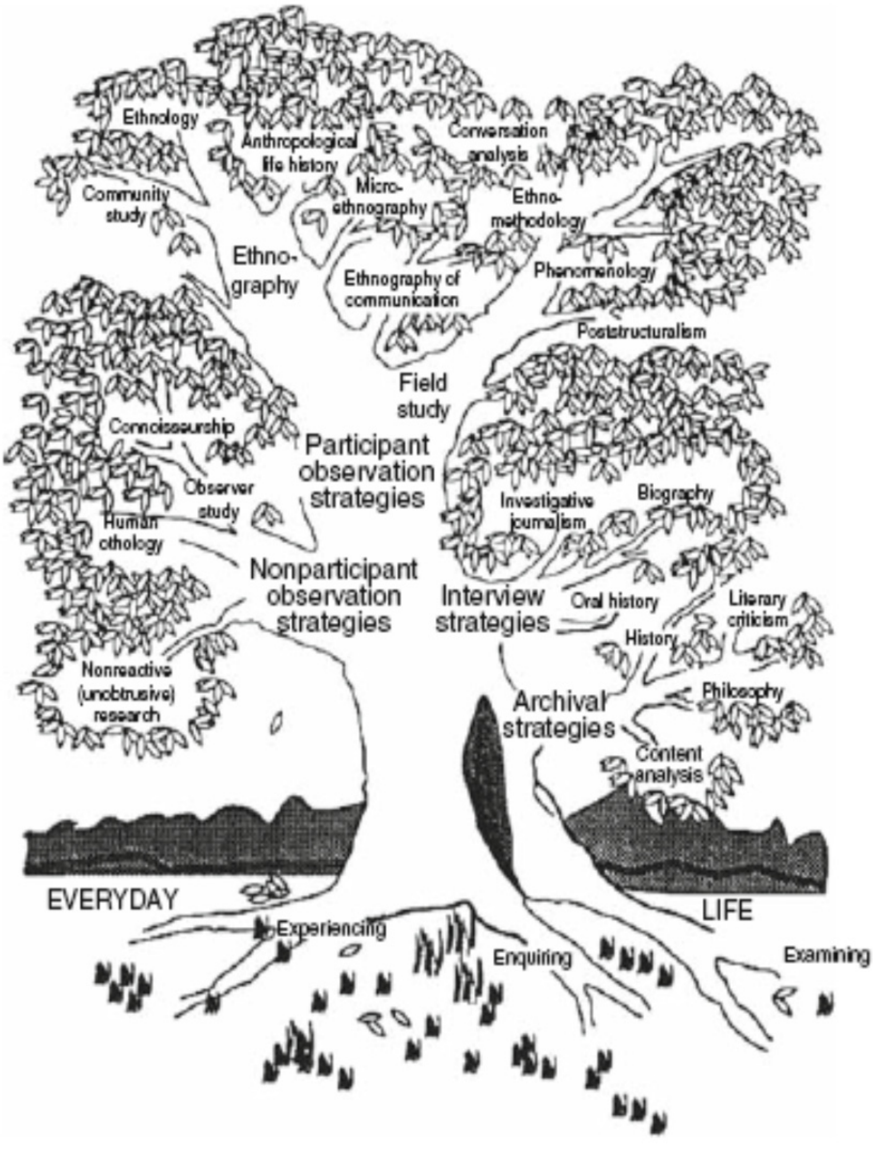


Figure 3.2 A “tree” Diagram for Qualitative Research Strategies (adapted from Miles and Huberman, 1994, p.6).

3.2.3 Distinction between Qualitative and Quantitative Research

In general, the most distinction between quantitative and qualitative research methods is the association with deductive or inductive respectively. Quantitative research analyse the data and statistically test the hypotheses by deriving hypotheses from theory in manner of a deduction way, while conversely, qualitative field research “collect data, formulate hypotheses based on data, test hypotheses by using data and attempt to develop theory” (Blessing and Chakrabarti, 2009, p.79).

More specifically, quantitative research is typically in line with objective fact, such as numbers or figures, whereas qualitative research is more concerned with the participants’ subjective perspectives, such as conversation, experience, opinion, behaviour. According to Casebeer and Verhoef, (1997) “quantitative research usually begins with pre-specified objectives focused on testing preconceived outcomes, whilst qualitative research usually begins with open-ended observation and analysis, looking for patterns and processes that explain how and why questions”.

As a result, quantitative research is often “adopted when the research wants to make quantifiable, “easy-to-generalise” statements” (Werner, 2008, p.27). On the contrary, qualitative research is used as method to “understand raw ‘experience’ (usually via in-depth interviews) … seeking to identify phenomena apart from these practices and the forms of representation” (Silverman, 2000, p. 224). A summary of contrasts of both methods is presented in Table 3.2.

3.2.4 Combining a Qualitative and Quantitative Approach

Owing to “the limitations and biases of the single method, which might be neutralized or cancelled by the other methods” (Crewell, 2009), a mixed method combined the merits of both qualitative and quantitative research is widely applied in the research domain. The mixed method is viewed as a multi-strategy research, which “implying the application of a number of different research strategies related to a complex range of research questions and research design” (Brannen, 2005, p.9). In particular, in order to explore design phenomenon, "Because of the variety of factors involved in design, the study of design often requires the selection and combination of research methods from various disciplines" (Blessing and Chakrabarti, 2009, p.102).

Table 3.2 A summary of Contrasts between Qualitative and Quantitative Research (adapted from Bryman, 2008, p.393).

Quantitative	Qualitative
Numbers	Words
Points of view of researcher	Points of view of participants
Research distant	Research close
Theory testing	Theory emergent
Static	Process
Structured	Unstructured
Generalisation	Contextual understanding
Hard, reliable data	Rich, deep data
Macro	Micro
Behaviour	Meaning
Artificial settings	Natural setting

More importantly, qualitative associated with quantitative approaches are aim to achieve the research objective and address the various factors. Therefore, design research in many instances requires "a combination of approaches and methods" to answer diverse research questions (Blessing and Chakrabarti, 2009, p.202). In addition, a mixed method is desirable due to the offset of the weakness that derived from each approach (Dawson, 2002). As a result, the use of a combination of methods is becoming an increasingly accepted research approach (Bryman, 2008). Figure 3.3 shows that the framework of incorporating qualitative and quantitative approaches applied in this Research.

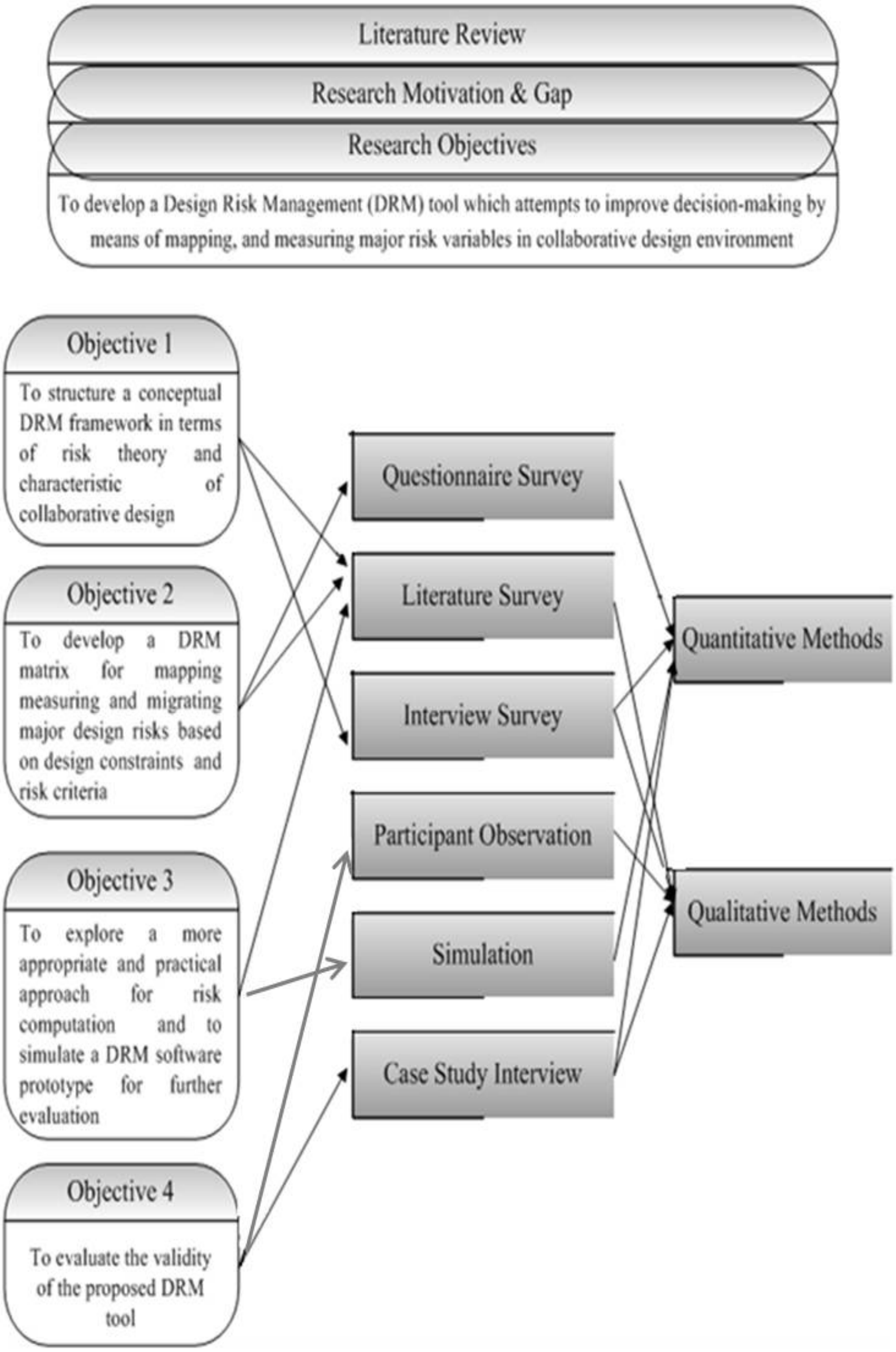


Figure 3.3 A Structure of the Mixed Method Applied in this Research.

3.3 Data Collection Methods

Existing literatures in the social sciences provide an overview of available strategies and methods for collecting, analysing, interpreting, and evaluating data (Blessing and Chakrabarti, 2009; Andrew and Halcomb, 2009). In particular, Halcomb and Davidson (2006) indicated that “many data collection strategies are commonly associated with either the positivist or naturalistic paradigm, which can be adapted to collect data across the spectrum from purely quantitative to purely qualitative data” (see Table. 3.3).

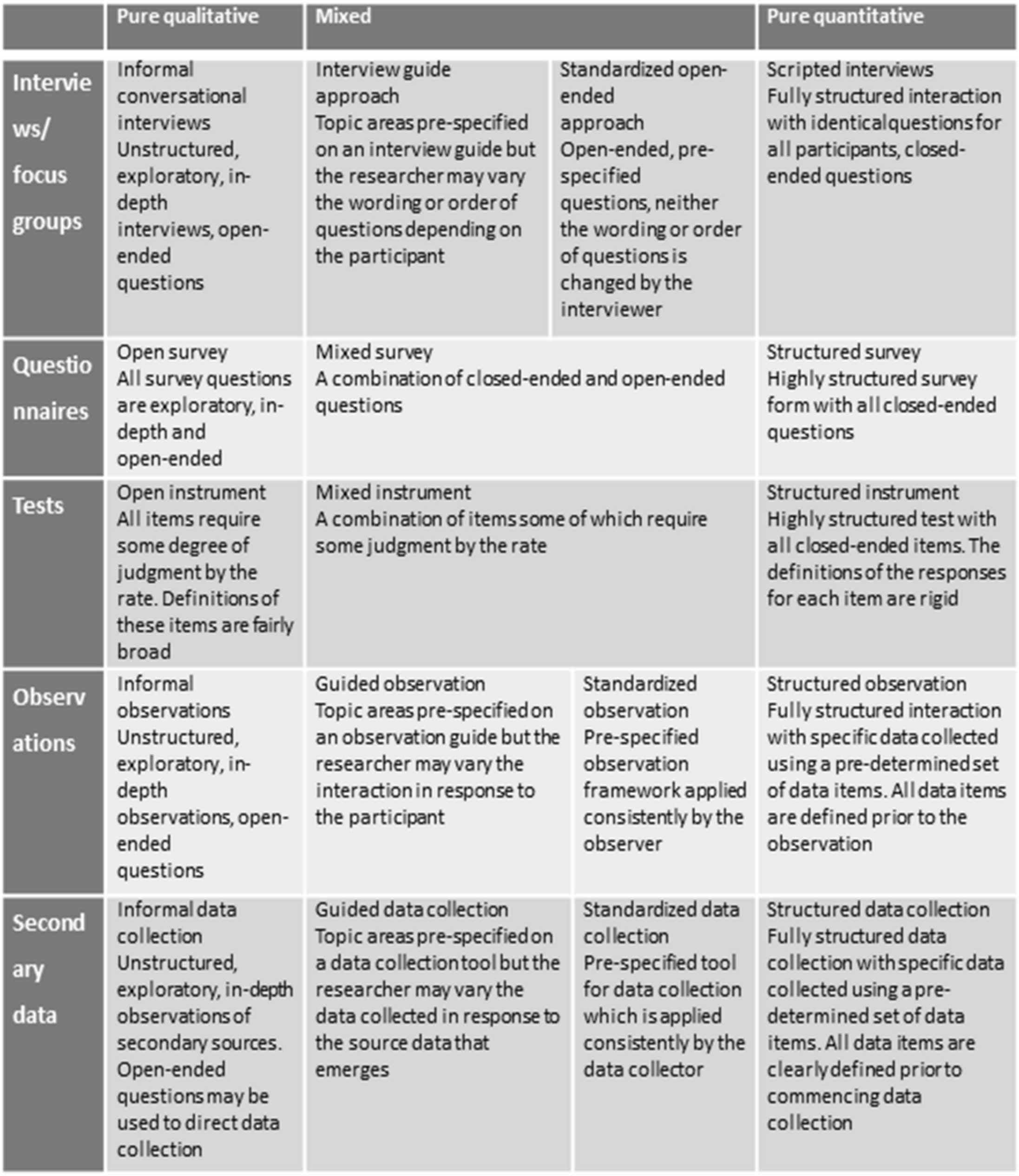
However, each research approach has some merits and limitations (see in Table 3.4). Therefore, in order to select appropriate data collection methods, an essential consideration is required “to ensure that the limitations of one method are balanced by the strengths of another” (Andrew and Halcomb, 2009). Moreover, it brings a chance for the researcher to design research method and optimise their selection in an active and creative manner (Andrew and Halcomb, 2009). Additionally, in most studies a combination of methods is used in manner of a parallel or sequence way (Blessing and Chakrabarti, 2009).

In this section, the main characteristics of some common data collection methods are presented with details, especially concerning their application in design research.

3.3.1 Questionnaire

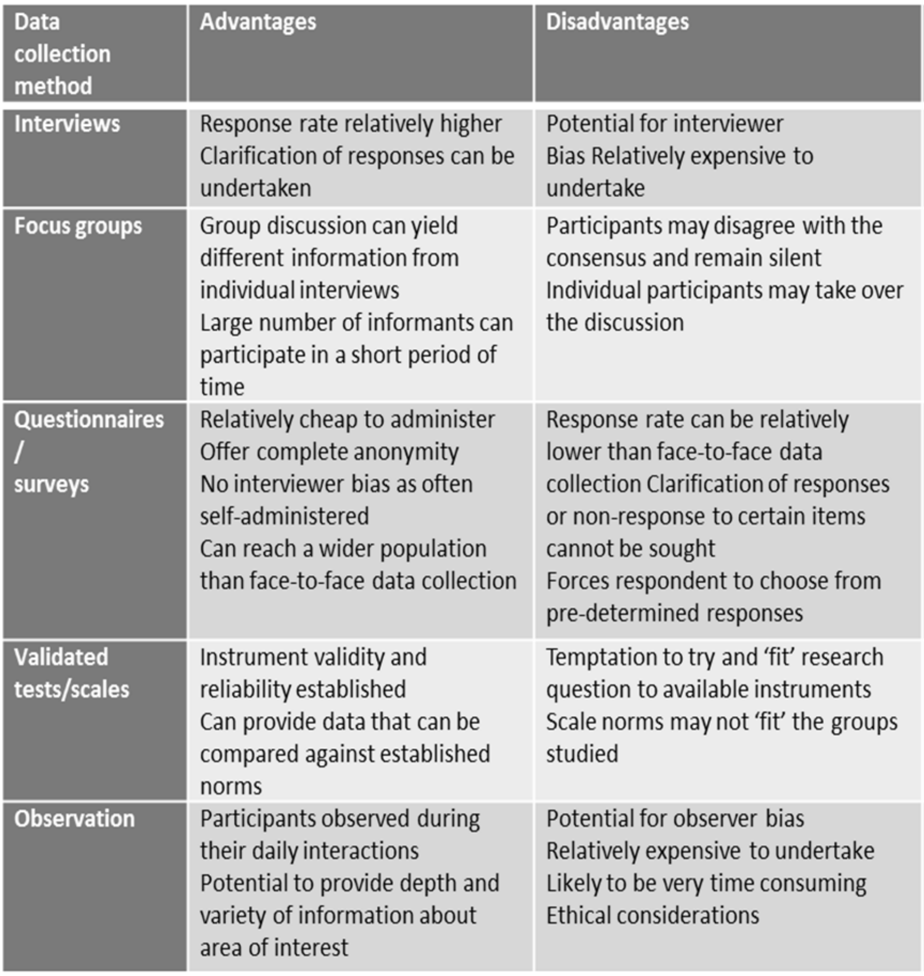
A questionnaire is an organised compilation of questions that information is desired from a targeted sampling of population. It is typically comprised of four parts: “an introduction, participant information section, the information section and an epilogue” (Stanton *et al*., 2005). In general, a questionnaire is often used to obtain information about the participants or organisations involved and their opinions (Blessing and Chakrabarti, 2009). This method of data collection is being adopted widely in order to collect thoughts, opinions, reasons, and preference from people by asking questions. Moreover, questionnaires “offer a very flexible way of quickly collecting large amounts of specific data from a large population sample” (Stanton *et al*., 2005, p.30).

Table 3.3 Data Collection Strategies (adapted from Johnson and Turner 2003; Halcomb and Davidson, 2006, p.71).



	Pure qualitative	Mixed		Pure quantitative
Interviews/ focus groups	Informal conversational interviews Unstructured, exploratory, in-depth interviews, open-ended questions	Interview guide approach Topic areas pre-specified on an interview guide but the researcher may vary the wording or order of questions depending on the participant	Standardized open-ended approach Open-ended, pre-specified questions, neither the wording or order of questions is changed by the interviewer	Scripted interviews Fully structured interaction with identical questions for all participants, closed-ended questions
Questionnaires	Open survey All survey questions are exploratory, in-depth and open-ended	Mixed survey A combination of closed-ended and open-ended questions		Structured survey Highly structured survey form with all closed-ended questions
Tests	Open instrument All items require some degree of judgment by the rate. Definitions of these items are fairly broad	Mixed instrument A combination of items some of which require some judgment by the rate		Structured instrument Highly structured test with all closed-ended items. The definitions of the responses for each item are rigid
Observations	Informal observations Unstructured, exploratory, in-depth observations, open-ended questions	Guided observation Topic areas pre-specified on an observation guide but the researcher may vary the interaction in response to the participant	Standardized observation Pre-specified observation framework applied consistently by the observer	Structured observation Fully structured interaction with specific data collected using a pre-determined set of data items. All data items are defined prior to the observation
Secondary data	Informal data collection Unstructured, exploratory, in-depth observations of secondary sources. Open-ended questions may be used to direct data collection	Guided data collection Topic areas pre-specified on a data collection tool but the researcher may vary the data collected in response to the source data that emerges	Standardized data collection Pre-specified tool for data collection which is applied consistently by the data collector	Structured data collection Fully structured data collection with specific data collected using a pre-determined set of data items. All data items are clearly defined prior to commencing data collection

Table 3.4 Advantages and Disadvantages of Data Collection Methods (adapted from Andrew and Halcomb, 2009, p.69).

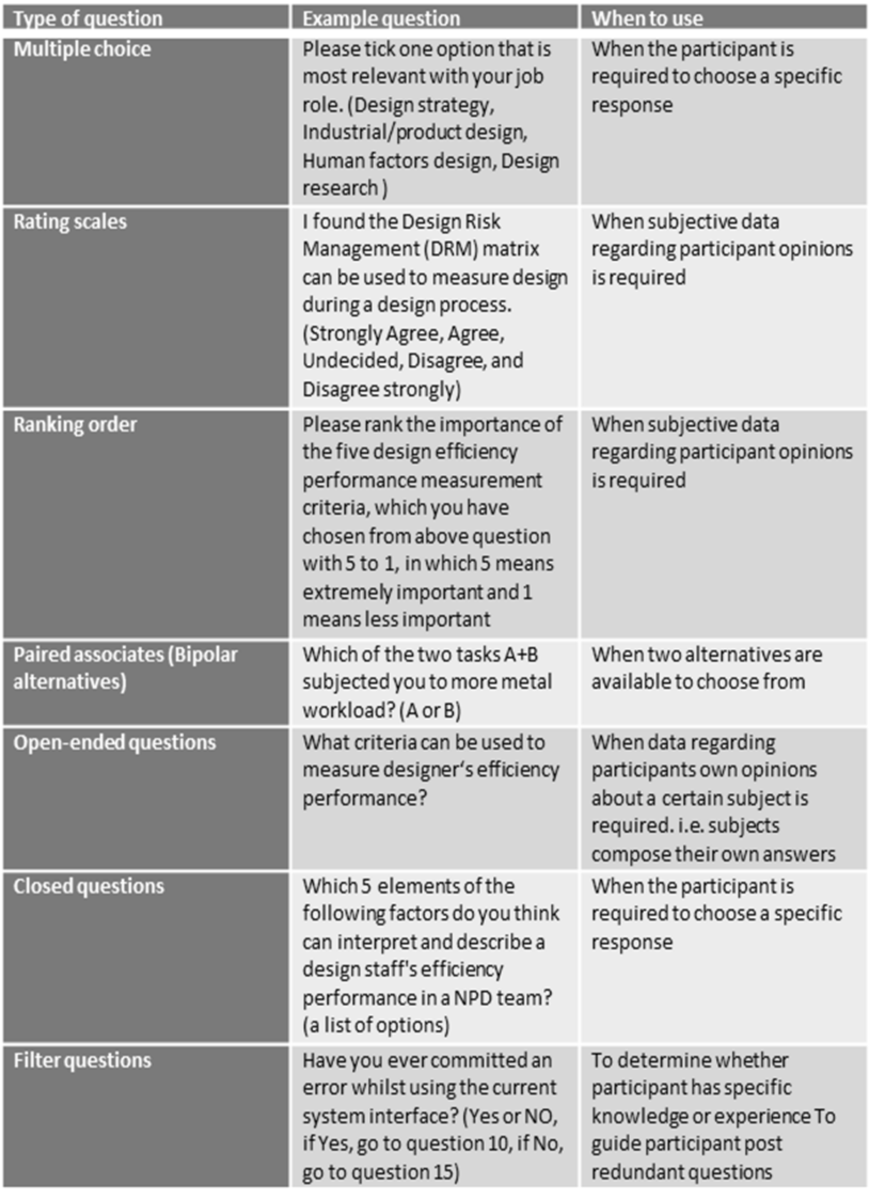


Data collection method	Advantages	Disadvantages
Interviews	Response rate relatively higher Clarification of responses can be undertaken	Potential for interviewer Bias Relatively expensive to undertake
Focus groups	Group discussion can yield different information from individual interviews Large number of informants can participate in a short period of time	Participants may disagree with the consensus and remain silent Individual participants may take over the discussion
Questionnaires / surveys	Relatively cheap to administer Offer complete anonymity No interviewer bias as often self-administered Can reach a wider population than face-to-face data collection	Response rate can be relatively lower than face-to-face data collection Clarification of responses or non-response to certain items cannot be sought Forces respondent to choose from pre-determined responses
Validated tests/scales	Instrument validity and reliability established Can provide data that can be compared against established norms	Temptation to try and 'fit' research question to available instruments Scale norms may not 'fit' the groups studied
Observation	Participants observed during their daily interactions Potential to provide depth and variety of information about area of interest	Potential for observer bias Relatively expensive to undertake Likely to be very time consuming Ethical considerations

In the realm of design, questionnaires are widely applied for data collection regarding user experience, feedback, participants' opinions and attitudes. More importantly, questionnaires could be utilised to "evaluate concept and prototypical designs, to explore user perceptions or attitudes, and to assess system usability during the design process" (Blessing and Chakrabarti, 2009). Besides, due to the absence of the researcher, questionnaires should also be self-explanatory and answerable by participator.

There are numerous categories of questions that can be employed in the constructing questionnaires, which are mostly depending upon the required data collection methods. Questions should be unambiguous, interesting, and quick to answer, because there is little incentive for people to spend their time and effort on answering a questionnaire (Blessing and Chakrabarti, 2009). Stanton *et al.* (2005) have summarised the types of questions used in questionnaire design (see Table 3.5).

Table 3.5 Type of Questions in Questionnaire Design (adapted from Stanton *et al.*, 2005, p.32)



Type of question	Example question	When to use
Multiple choice	Please tick one option that is most relevant with your job role. (Design strategy, Industrial/product design, Human factors design, Design research)	When the participant is required to choose a specific response
Rating scales	I found the Design Risk Management (DRM) matrix can be used to measure design during a design process. (Strongly Agree, Agree, Undecided, Disagree, and Disagree strongly)	When subjective data regarding participant opinions is required
Ranking order	Please rank the importance of the five design efficiency performance measurement criteria, which you have chosen from above question with 5 to 1, in which 5 means extremely important and 1 means less important	When subjective data regarding participant opinions is required
Paired associates (Bipolar alternatives)	Which of the two tasks A+B subjected you to more metal workload? (A or B)	When two alternatives are available to choose from
Open-ended questions	What criteria can be used to measure designer's efficiency performance?	When data regarding participants own opinions about a certain subject is required. i.e. subjects compose their own answers
Closed questions	Which 5 elements of the following factors do you think can interpret and describe a design staff's efficiency performance in a NPD team? (a list of options)	When the participant is required to choose a specific response
Filter questions	Have you ever committed an error whilst using the current system interface? (Yes or NO, if Yes, go to question 10, if No, go to question 15)	To determine whether participant has specific knowledge or experience To guide participant post redundant questions

For instance, multiple choice questions refer to the participants choosing the preferred answer after careful consideration of the alternatives. Closed-ended refer to questions "employed in an interview schedule or self-completion questionnaire that presents the respondent with a set of possible answers to choose from" (Jonker and Pennink, 2010, p.171). They are used to gather specific information and typically permit yes or no answers. “Multiple choice or closed questions have the advantages of easy handling, simple to answer, quick and relatively inexpensive to analyse but they are most amenable to statistical analysis” (Kothari, 2004, p.103).

Open-ended questions can be “used to elicit more than the simple yes/no information that a close question gathers, it allows the interviewee to answer in whatever way they wish, and elaborate on their answer” (Stanton *et al*., 2005, p.25). More specifically, open-ended questions provide an opportunity for the participants to present their opinions “as precisely as possible in their own words” (Jonker and Pennink, 2010, p.155). However, to many respondents, open-ended questions are difficult, which usually affected by their knowledge, experience and bias.

In practice, a combination of closed-ended and open-ended questionnaire is prevailing in most research areas. In general, a questionnaire is sent face to face in specific site such as university, supermarket or shopping mall. With the internet, questionnaire could also be sent through questionnaire websites in order to reach the targeted persons who qualified with the requirements to answer the questions. In this regard, the questionnaires are sent to the participants who are expected willing to read and provide more precise answers to the proposed questions.

Wilson and Corlett (1995) recommended that once the questionnaire construction stage is complete, an initial check of the questionnaire is required. The key purpose of an initial check is to examine the entire research method “from data collection to sampling test, to identify potential problems that may affect the quality and validity of the results, and to modify the method if required” (Blessing and Chakrabarti, 2009, p.114). As various problems might occur during the piloting stage, such as redundant questions, errors, or questions that might cause confusing to the participants (Stanton *et al*., 2005), an initial check should be conducted before perform questionnaire survey.

There are several reasons that questionnaires are quite popular and being adopted widely in research areas. First, the questionnaire is low cost. Questionnaires can be used as a convenient tool to get feedback economically when respondents are not easily approachable. Second, “when the questionnaire is properly designed, the data analysis phase should be quick and very straightforward" (Stanton *et al.*, 2005, p.33). Third, respondents have sufficient time to answer questions, so the results of questionnaire survey are more trustworthy (Kothari, 2004).

Conversely, the key disadvantage of questionnaire could also be specified. Most of all, lower rate of return or the dully filled in questionnaires (Kothari, 2004) are very disappointed, respondents may be unable to answer a questionnaire for various reasons. Furthermore, due to no-response is often encountered (Kothari, 2004) and respondents might have varied views or behaviour patterns, questionnaires are incline to involve individual biases. Thus, the reliability and validity of the results is questionable (Stanton *et al.*, 2005). In addition, despite the efficiency of questionnaire survey, it require more time to design questions, conduct pilot test, collect data, and perform some relevant data analysis (Stanton *et al.*, 2005; Blessing and Chakrabarti, 2009).

3.3.2 Observation

Observation is one of the most common ways of data collection whether in a laboratory or practical setting. It is regarded as a scientific tool and generally involved researchers either recording what is actually taking place by hand or using recording or measuring equipment (Blessing and Chakrabarti, 2009). More specifically, observation methods should "include the aspects of tasks (steps and sequence), the individuals performing the tasks (completion time, error made), the technology used by the system in conducting the tasks (controls, displays, communication technology), the system environment and the organisational environment" (Stanton *et al.*, 2005, p.38).

Observation is an approach of data collection with systematically plan and record. "The information is sought by way of investigator's own direct observation without asking from the respondent" (Kothari, 2004, p.96). In particular, observational methods could be applied during the design process in order to gather information regarding existing or proposed designs (Stanton *et al.*, 2005). The quality of observational data is highly depended on the skill, training and competency of the observer (Blessing and Chakrabarti, 2009).

In the context of social sciences studies, observation could be categorised into participant and non-participant. If the researcher observes by making himself and experiences by participation, the observation is called as the participant observation. According to Bryman (2008), participant observation is “more associated with qualitative research” and researchers “were required to engage in a social setting for a prolonged time”.

Conversely, when the observer observes in a detached manner, and does not take part in the process, this type of observation is regarded as non-participant observation. Therefore, the distinction between participant and non-participant lies in “the observer’s sharing or not sharing the life of the group he is observing” (Kothari, 2004, p.96).

Denzin (1978) views participant observation as a research strategy that simultaneously combines several data-collection methods, such as document analysis, interviewing, direct participation, observation and introspection. Yin (2009) views participant observation as a method of data collection based on a special mode of observation – namely one in which the observer participates in the observed process. Moreover, participant observation can help gain acceptance and increase familiarity with the field and the problems (Blessing and Chakrabarti, 2009). The data collected by participant observation can also be used as one source of evidence in, e.g., a case study.

The key benefit of observation is the elimination of subjective opinions and personal bias. More importantly, the data achieved through observation only concern recent experience, which not relates to either the past behaviour or the expectation of future. However, observation methods have some limitations. First, observation might cost and time consuming. Second, the data gathered might be limited. Third, some unexpected factors may affect during the process of observation.

3.3.3 Interviewing

Interviews have been used extensively in association with qualitative research for a number of different types of research (Stanton *et al*., 2005). It is one of the most useful methods for the understanding and investigation of participants' experiences and perspectives, individual attitudes and opinions,. The purpose of interviews is similar to that of questionnaires but is performed by way of face-to-face (Blessing and Chakrabarti, 2009).

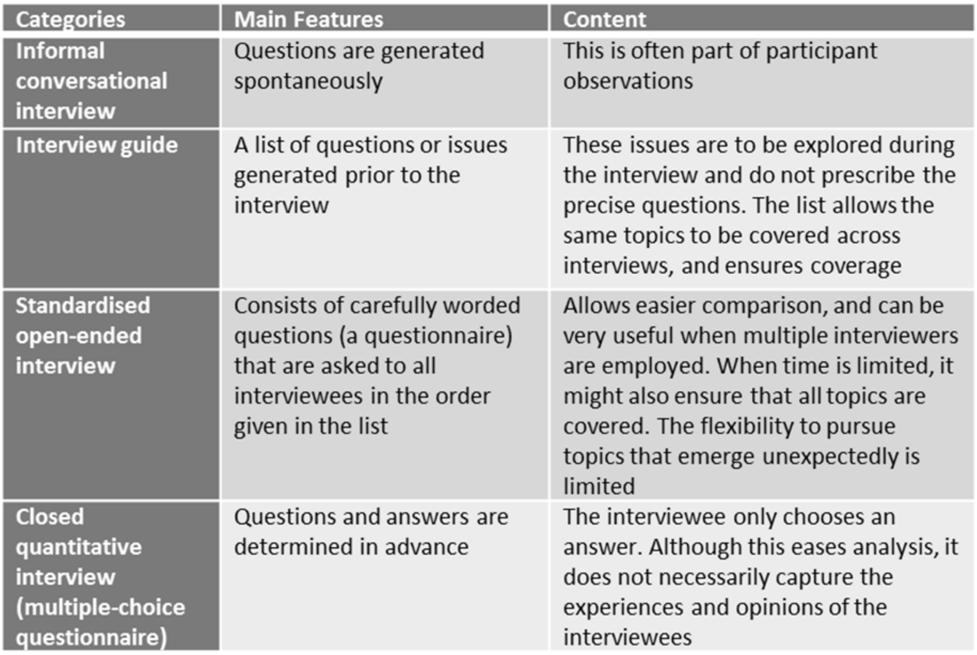
In general, interviews involve presentation and respond, which could be applied as the main data-collection method and in conjunction with real-time studies (Blessing and Chakrabarti, 2009). According to Easterby-Smith *et al*. (2002), interview method is typically appropriate for a research, which intends to investigate participant's opinions that concerning specific issues. Therefore, interviews usually used to collect thoughts, beliefs and opinions about past, present or future facts and events, with a focus on data that cannot be observed or was not captured in the past (Blessing and Chakrabarti, 2009).

During the process of interviews, participants are interviewed on a one-to-one basis and the interviewer uses pre-determined probe questions to elicit the required information (Stanton *et al*., 2005). Thus, interviews are potentially more confrontational and might require more effort compared to anonymous questionnaires (Blessing and Chakrabarti, 2009). However, although some of interviews conducted in one to one form, it could also be performed in from of a group of participants. The group interview could present an in-depth method to explore ideas and opinions from individuals with same background (Stone and Collin, 1984; Andrew and Halcomb, 2009). This is termed as "focus group interview", which require a skilled group facilitator (Andrew and Halcomb, 2009). However, although the group dynamics can enhance the overall outcome of the interview, but may have a negative effect on the contribution of some participants, depending on the person, the topic, and the differences in status of the participants (Blessing and Chakrabarti, 2009).

Patton (2002) distinguishes the four types of interview: "informal conversational interview, interview guide, standardised open-ended interview and closed quantitative interview” (see Table 3.6).

The latter three are often referred to as unstructured interview, semi-structured interview and structured interview respectively (Stone and Collin, 1984; Stanton *et al*., 2005, see Table 3.7) presented a brief description of these three types interviews. More specifically, “structured interview involves the use of a set of predetermined questions and of highly standardised techniques of recording which follows a rigid procedure laid down, asking questions in a form and order prescribed” (Gupta and Gupta, 2011, p.63).

Table 3.6 Distinction of Four Types of Interview (Patton, 2002, p.343).

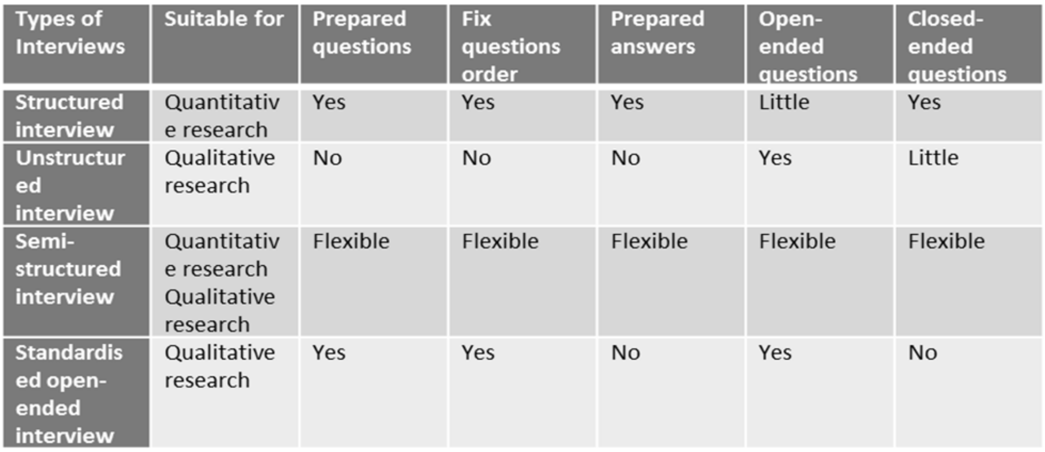


Categories	Main Features	Content
Informal conversational interview	Questions are generated spontaneously	This is often part of participant observations
Interview guide	A list of questions or issues generated prior to the interview	These issues are to be explored during the interview and do not prescribe the precise questions. The list allows the same topics to be covered across interviews, and ensures coverage
Standardised open-ended interview	Consists of carefully worded questions (a questionnaire) that are asked to all interviewees in the order given in the list	Allows easier comparison, and can be very useful when multiple interviewers are employed. When time is limited, it might also ensure that all topics are covered. The flexibility to pursue topics that emerge unexpectedly is limited
Closed quantitative interview (multiple-choice questionnaire)	Questions and answers are determined in advance	The interviewee only chooses an answer. Although this eases analysis, it does not necessarily capture the experiences and opinions of the interviewees

Thus, “the content of the interview (questions and their order) is pre-determined and no scope for further discussion is permitted” (Stanton *et al*., 2005, p.24). On the contrary, unstructured interview refers to a flexible questioning design that “no particular questions and no order of questions and responses are determined in advance” (Kothari, 2004; Yin, 2008). Thus, this allows the interviewer to explore different aspects of the subject under analysis on an ad-hoc basis (Stanton *et al*., 2005).

Compared to semi-structured interviews, structured interviews are easier to analyse and compare while unstructured interviews are more suitable for an exploratory study (Blessing and Chakrabarti, 2009). Moreover, "a structured interview is only used when the type of data required is rigidly defined, and no additional data is required. Whilst unstructured interviews are infrequently used, as their unstructured nature may result in crucial information being neglected or ignored" (Stanton *et al*., 2005, p.24).

Table 3.7 Types of Interviews (adapted from Stone and Collin, 1984).



Types of Interviews	Suitable for	Prepared questions	Fix questions order	Prepared answers	Open-ended questions	Closed-ended questions
Structured interview	Quantitative research	Yes	Yes	Yes	Little	Yes
Unstructured interview	Qualitative research	No	No	No	Yes	Little
Semi-structured interview	Quantitative research Qualitative research	Flexible	Flexible	Flexible	Flexible	Flexible
Standardised open-ended interview	Qualitative research	Yes	Yes	No	Yes	No

In addition, a semi-structured interview is regarded as a typical structure of interview, which incorporates both features of structured interviews and unstructured interviews. The semi-structured interview combines both structured and open-ended questions. "The structured questions are used to obtain information, such as age, education, position; and open-end questions are used when opinions, explanations or descriptions of behaviour or events are sought" (Stone and Collin, 1984). Thus, it is flexible for the research to manage and control the process of interviews and leads to the generation of meaningful results. Due to this sort of flexibility, the semi-structured interview is the most commonly applied type of interview (Stanton *et al*., 2005).

There are plenty merits of employing interviews in research. One of the major benefits of interviews is that interviews provide an effective way to collect a wide variety of data, ranging from user perceptions and reactions, to usability and error related data (Stanton *et al*., 2005).

Another main advantage is that, interviews offer “an opportunity for researchers to investigate deeply to uncover new clues, open up new dimensions of a problem and to secure vivid, accurate and inclusive information that, are based on personal experience” (Burgess, 1982). In other words, qualitative interviews could be “an important addition to a survey or clinical trial in order to gain a deeper understanding or explanation of the quantitative findings” (Andrew and Halcomb, 2009, p.70). The third major strength of interviews is that “samples can be controlled more effectively as there arises no difficulty of the missing returns; non-response generally remains very low. The interviewer can usually control which individuals will answer the questions. This is not possible in mailed questionnaire approach. If so desired, group discussions may also be held” (Kothari, 2004, p.98).

However, despite of benefits presents above, interviews have few limits: “First, given that the construction and data collection process, interview is time consuming. Second, transcribing data is also an arduous, time-consuming process. Third, the reliability and validity of the method is difficult to assess” (Stanton *et al.*, 2005).

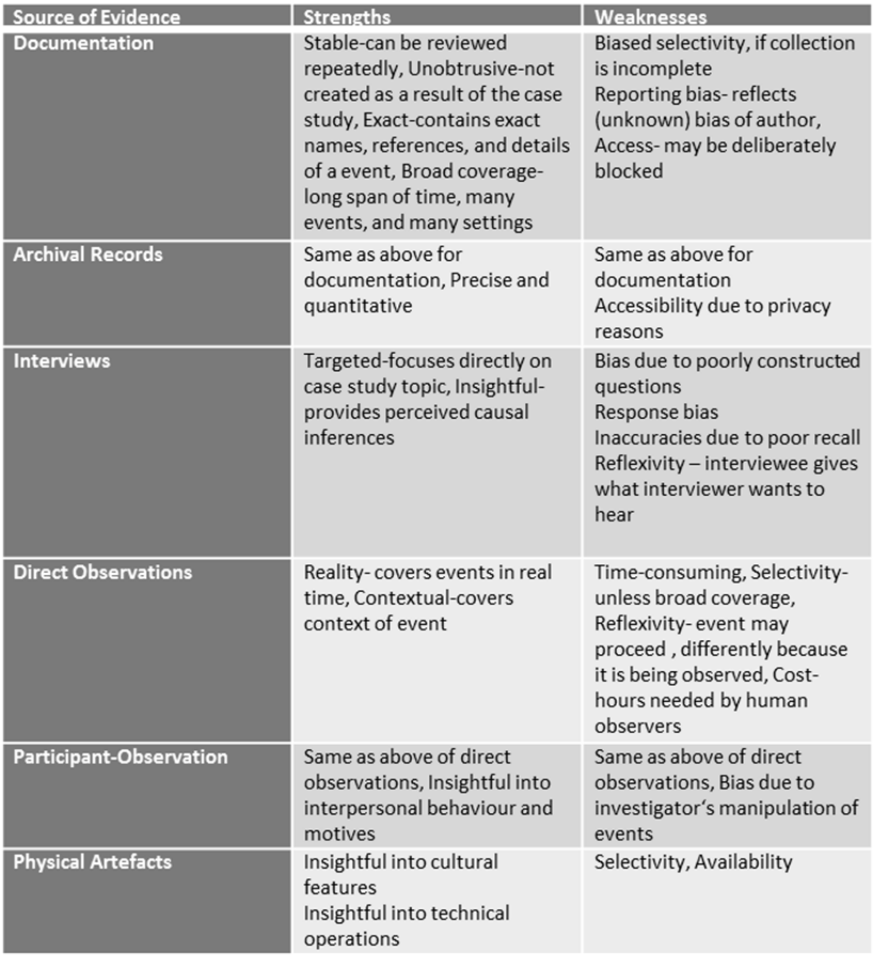
3.3.4 Case Study

Case study is refers to an empirical enquiry that explores a contemporary situation or phenomenon, which “allows investigators to retain the holistic and meaningful characteristics of real-life events” (Yin, 2009, p.2). It refers to a form of qualitative survey or evaluation in terms of careful and complete observation of a situation or an institution. In a case study, “the researcher explores a single entity or phenomenon and collects detailed information by using a variety of data collection methods during a sustained period of time” (Creswell, 2009, p.12).

In general, a case study “focuses on one instance of a particular phenomenon with a view of providing an in-depth account of events, relationships, experiences or processes” (Denscombe, 2003, p.35). Therefore, “case study places emphasis on a full contextual analysis of fewer events or conditions and their interrelations for a single subject or respondent” (Cooper and Schindler, 2001, p.13). It is particularly appropriate for the research that requires in-depth exploration of business processes or social issues.

Yin (2009) indicates that “a high quality case study can be characterised by rigorous thinking, sufficient presentation of evidence to reach appropriate conclusions, and careful consideration of alternative explanations of the evidence”. Case studies generally include multiple methods combined with both qualitative and quantitative approaches that could be best addressed. Yin (2009) identified six major sources of evidence in case studies: “documentation, archival records, interview, direct observations, participant-observation, and physical artefacts” (see Table 3.8).

Table 3.8 Six Major Sources in Case Study (adapted from Yin, 2009, p.83).



Source of Evidence	Strengths	Weaknesses
Documentation	Stable-can be reviewed repeatedly, Unobtrusive-not created as a result of the case study, Exact-contains exact names, references, and details of a event, Broad coverage-long span of time, many events, and many settings	Biased selectivity, if collection is incomplete Reporting bias- reflects (unknown) bias of author, Access- may be deliberately blocked
Archival Records	Same as above for documentation, Precise and quantitative	Same as above for documentation Accessibility due to privacy reasons
Interviews	Targeted-focuses directly on case study topic, Insightful-provides perceived causal inferences	Bias due to poorly constructed questions Response bias Inaccuracies due to poor recall Reflexivity – interviewee gives what interviewer wants to hear
Direct Observations	Reality- covers events in real time, Contextual-covers context of event	Time-consuming, Selectivity-unless broad coverage, Reflexivity- event may proceed , differently because it is being observed, Cost-hours needed by human observers
Participant-Observation	Same as above of direct observations, Insightful into interpersonal behaviour and motives	Same as above of direct observations, Bias due to investigator's manipulation of events
Physical Artefacts	Insightful into cultural features Insightful into technical operations	Selectivity, Availability

There are several reasons why the case study method is popularly applied in the field of research. First of all, the exclusive advantage of case study is that “the ability to deal with a full variety of evidence-documents, artefacts, interviews, and observations”

(Yin, 2009, p.8). Thus, case study facilitates the intensive and in-depth investigation with sufficient evidences, which is generally not possible to be conducted by other research methods.

Secondly, case studies play an important role in evaluation research (Patton, 2002; Yin, 2009). It provides a wide range of research methods to illustrate certain topics within an evaluation. The researchers can use the combination of research methods such as questionnaires, depth interviews, and participant observations. Thirdly, an investigator can acquire a real and enlightened record of personal experiences through case study (Kothari, 2004). Thus, it is specifically useful when the investigators are required to understand how is the organisational and environmental context and how much influence or impact on the case.

Nevertheless, the case study method also has some limitations. One of the primary weaknesses is that "case situations are seldom comparable and as the information gathered in case studies is often not comparable" (Kothari, 2004, p.116). Thus, it is quite difficult for the researchers to find an appropriate case under certain conditions. Another common concern about case studies is that, in comparing with other strategies, "the case study investigator has been sloppy and has not followed systematic procedures, and even worse has allowed ambiguous evidence or biased views to influence the direction of the findings and conclusions" (Yin, 2009, p.14).

A third frequent complaint about case studies is that "they provide little basis for scientific generalisation" (Yin, 2009, p.10). Kothari (2004) stressed that it cannot "consider the case data as significant scientific data since they do not provide knowledge of the impersonal, universal, non-ethical, non-practical, repetitive aspects of phenomena." In addition, case studies might time consuming and result in enormous and incomprehensible documents.

3.3.5 Simulation

According to Oxford English Dictionary (1989), simulation refers to "the technique of imitating the behaviour of some situation or process by means of a suitably analogous situation or apparatus" (Lenhard and Küppers, 2006, p.3). It is "a relatively new entity, whose usages are in flux and whose 'good practices' have not yet even been determined in full" (Lenhard and Küppers, 2006, p.5).

Harrell *et al*. (2004) defined simulation as "the imitation of a dynamic system using a computer model in order to evaluate and improve system performance". It is a particular type of modelling which is "simplification smaller, less detailed, fewer complexes, or all of these together of some other structure or system" (Gilbert and Troitzsch, 2005, p.2). Simulations are widely applied for training in science, technology, engineering, social, different sorts of research areas.

Nowadays, simulation "has increasingly become established as a new means of knowledge production and especially representation of complex dynamics in science and technology as well as a tool for the development of new and better technical artefacts in a rapidly expanding range of fields" (Lenhard and Küppers, 2006, p.4). Researchers can build relatively uncomplicated models by focusing on the major factors and discover the consequences of their theories through simulation. Thus, "the diversity of the sites of usage, applications, and practitioners connected with computer simulation today has turned it into a pervasive tool" (Lenhard and Küppers, 2006, p.4). More importantly, simulation introduces "the possibility of a new way of thinking about social and economic processes, based on ideas about the emergence of complex behaviour from relatively simple activities" (Simon, 1996; Gilbert and Troitzsch, 2005, p.1).

In comparison with other research methods, simulation focuses on questions like what if? Whilst other research methods investigate the questions such as what, how, and why? Moreover, simulation intends to explore research issues by way of moving forward into the future, while other research methods attempt to investigate research issues by looking backwards across history (Dooley, 2002). Thus, simulation "provides insights into the complex dynamics of a system that are unobtained using other analysis techniques" (Harrell *et al*., 2004, p.5). Gilbert and Troitzsch (2005) presents a logic of simulation as a method (as indicates in Figure 3.4), which develops a model through abstraction from the presumed research target. The model is built in the form of a software package, which can be run in computer by researcher, and its behaviour can be measured. Consequently, the simulation model is applied to produce the simulated data, which could be analysed, adjusted and compared with data that gathered in the common way. The simulation therefore is used to compare whether the two outcomes are similar or not.

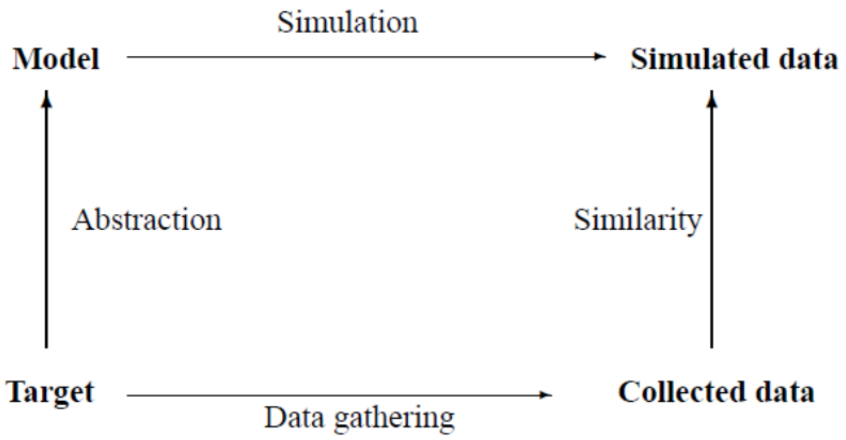


Figure 3.4 The Logic of Simulation as a Method (adapted from Greasley, 2004).

Pidd (2003) characterises three types of systems, which are most suitable to simulation: “dynamic, interactive and complicated”. Dynamic means “their behaviour varies over time”. Interactive refers to “a number of components interact with each other”. Complicated indicates that the systems “consist of many interacting and dynamic objects” (Greasley, 2004). Besides, Axelrod (1997) indicated that there are several uses or purposes of simulation for researchers: prediction, theory discovery, performance, training and education, entertainment and proof. More specifically, simulation is the main instrument for obtaining predictions (Lenhard and Küppers, 2006), which help forecast “the performance of project or system under a specified scenarios determined by the decision-maker” (Greasley, 2004). Besides, simulation could be applied as “a substitute for experimentation and intervention on the actual system when such experimentation is too dangerous, costly, untimely, or inconvenient to be applied” (Axelrod, 1997).

Moreover, simulation can be utilised for the development of new tools to replace human activities and used for training and entertainment (Axelrod, 1997). It can provide real-world experience in a controlled environment, which can be employed for training and education systems with dynamic activity. Furthermore, simulation can also provide a realistic representation for entertainment (John and Catherine, 2009). Thus, given that the process of collaborative design is in accordance with dynamic, interactive and complicated features, and simulation is more valuable for predication, a DRM simulation prototype is particularly appropriate for the assistance of application of case study evaluation.

The primary merit of simulation applications in the research area is that the simulation provides a powerful method of analysis that is not only formal and predictive, but is capable of accurately predicting the performance of even the most complex systems (Harrell *et al.*, 2004). Moreover, simulation promotes a try-it-and-see attitude which "gives manufacturers unlimited freedom to try out different ideas for improvement, risk free - with virtually no cost, no waste of time, and no disruption to the current system (Harrell *et al.*, 2004, p.5). It avoids the "expensive, time-consuming and disruptive nature of traditional trial-and-error techniques" (Harrell *et al.*, 2004). In addition, in the field of design, a simulation could make a rapid, uncomplicated, and non-expensive way for researchers to understand scenarios and make decisions that mimic reality.

However, although simulation has a variety of benefits and can be applied widely in many fields, some argued that simulation may lack full function due to unexpected issues and particularly complex environment.

3.4 Sampling Technique and Data Analysis

Sampling technique is "the technique or the procedure the researcher would adopt in selecting items for the sample" (Kothari, 2004, p.153). A sample design refers to an explicit plan for achieving a sample from a given population. A researcher can select methods from a number of samples designs in terms of the specific requirements.

Thus, in most cases, the researchers are prone to choose a more appropriate and reliable sample design for their study.

3.4.1 Sampling Technique

Sampling is regarded as a process of choosing units such as people, community, organisations from a targeted population. By observing the sample, certain inferences may be made about the population. Statistics analysis methods could be employed to examine the probability of the observation. In most the research work and surveys, sampling is used as a usual approach to make generalisations or to draw inferences. Thus, sampling provides a basis for research generalisation (Kothari, 2004).

Kothari (2004) provided a variety of reasons for sampling application in practice: First, sampling is lower cost and less time consuming. Second, sampling is generally conducted by trained and experienced researchers, which may enable measurements that are more accurate. Third, sampling offers a way when population is infinite. It assists in obtaining data in terms of some features of the population and enables the estimation of the sampling errors.

Kothari (2004) identified two distinct groups of sample designs: probability sampling and non-probability sampling (see Figure 3.5). The former focus on random selection, whereas the latter is "non-random" sampling. More specifically, probability sampling design refers to each unit has an identical opportunity to the contribution of conclusions, which "ensures the law of statistical regularity, and states that if on an average the sample chosen is a random one, the sample will have the same composition and characteristics as the universe" (Kothari, 2004, p.60). Therefore, random sampling usually uses to choose a representative sample.

Non-probability sampling refers to "a procedure that does not offer any basis for estimating the probability" (Kothari, 2004, p.59). Considering that every unit is incorporated in the sample, research can select sample items in a deliberate way. In this approach, investigators of the inquiry intentionally select the specific items from the population for constructing a sample. This sampling could representative or typical for the overall population. Thus, the investigators' judgement plays crucial role in non-probability sampling.

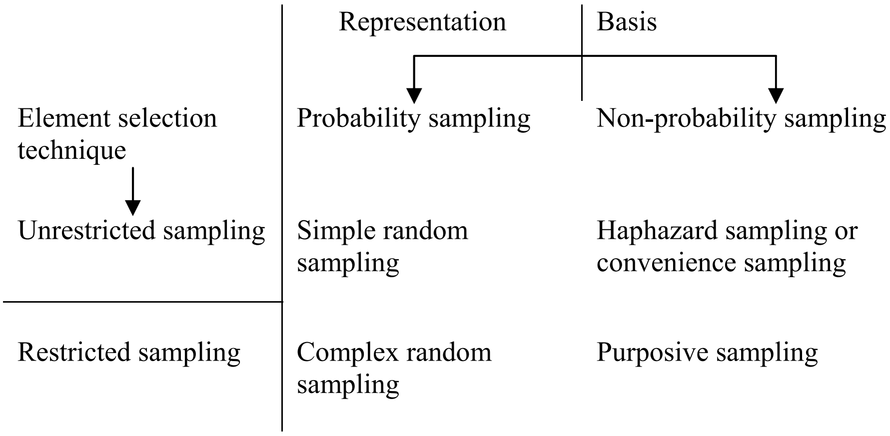


Figure 3.5 Two Different Types of Sample Designs (adapted from Kothari, 2004, p.59).

In this study, as the probability of participants are most relies on their availability, a non-probability sampling approach is selected. More specifically, the targeted population comprises managers (including design managers, project managers), and designers (including graphic designers, engineering designer, product designer).

3.4.2 Sampling Size

Sampling size plays a crucial role during the process of sampling design, the calculation of the sample size is essential to be able to draw conclusions (Blessing and Chakrabarti, 2009). Moreover, sampling size can be relevant for the data analysis, interpretation and generalisation, which might result in significantly influential research results. For instance, it may not represent entire data due to small size of sample.

Conversely, it may cause many expenditures and waste. The most suitable sample size depends on many factors, but primarily "depends on the research questions and hypotheses that need addressing" (Blessing and Chakrabarti, 2009). More specifically, in exploratory studies, the sample size should ensure that the estimates from the study have adequate precision (Blessing and Chakrabarti, 2009). As Creswell (2009) recommended, sampling size of 2-5 participants is appropriate for a case study research whilst 15-20 participants is apt for interview. Moreover, Bernard (1995) has suggested that 30-50 valid feedbacks are more suitable for questionnaire research. Therefore, in this research, the target sampling sizes are expected: 30-50 questionnaires, 2-5 case studies and 15-20 interviews.

3.4.3 Processing Data

Data processing is "essential for a scientific study and for ensuring that all relevant data are collected for making prospective comparisons and analysis" (Blessing and Chakrabarti, 2009, p.89). In general, the collected data is processed in terms of the research objectives and design. Quantitative data enables the statistic analysis that generates "summaries, comparisons, and generalisations quite easy and precise", whilst qualitative data is "typically meant to provide a forum for elaborations, explanations, meanings and new ideas" (Patton, 1987). In addition, "processing data often involves coding the data to abstract or index the collected data in order to facilitate retrieval, organisation and analysis" (Blessing and Chakrabarti, 2009, p.116). According to Kothari (2004), four steps are concluded for processing data: editing, coding, classification and tabulation.

Editing

Editing of data is "a process of examining the collected raw data in order to detect errors and omissions and to correct if possible" (Kothari, 2004, p.122). Therefore, editing "involves a careful examination of the completed questionnaires or interviews. Editing is done to ensure that the data are accurate and consistent with other facts gathered, uniformly entered and have been well arranged to facilitate coding and tabulation" (Kothari, 2004, p.122).

Coding

Coding refers to “a process of assigning numerals or other symbols to answers so that responses can be put into a limited number of categories” (Kothari, 2004, p.123). Thus, codes are “categories, which usually derived from research questions, hypotheses, key concepts or important themes” (Miles and Huberman, 1994; Blessing and Chakrabarti, 2009, p.117). More importantly, coding is essential for efficient analysis, and sampling may be abridged through coding. For instance, the researcher usually makes coding decisions when plotting the research methods. “The makes it possible to pre-code the questionnaire choices and which in turn is helpful for computer tabulation in comparison with raw data” (Kothari, 2004, p.123). In this research, quantitative data are directly or coded into categories while qualitative data are categorised in terms of structural and conceptual order.

Classification

According to Kothari (2004), “most studies result in a large volume of original data that must be categorised into homogeneous groups in order to generate meaningful relationships and results”. This requires classification of data and disposal of data in groups or classes based on general characteristics. Data having an identical feature are placed in the same class. For instance, there are several types of classification in questionnaires that generated in this research: quantitative data such as questionnaire or interview with close-questions, and qualitative data with open-questions..

Tabulation

Tabulation is referred to “a process of summarizing raw data and displaying the same in compact form (i.e., in the form of statistical tables) for further analysis” (Kothari, 2004, p.127). In this research, after coding and classification, the collected quantitative data will be inputted into Statistical Package for the Social Sciences (SPSS). Subsequently, tabulation could be generated from the raw data in a form of tables with frequency counts and percentages. Then, some relevant statistical tests can be applied for the analysis of the correlation or significance among each item. The results of finding and discussion could be derived from these useful evaluations.

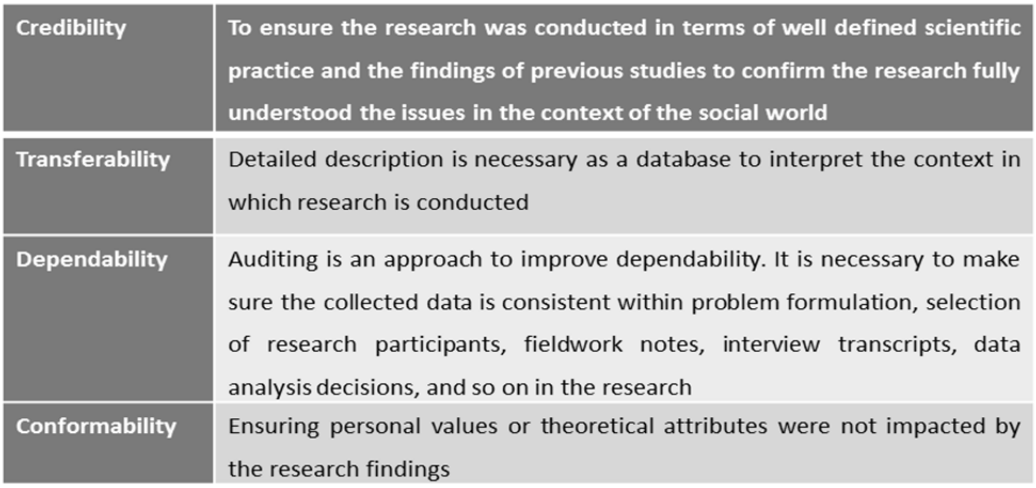
3.5 Reliability and Validity

Reliability indicates “the consistency of the measurements of the research and the application of particular research instruments” (Gomm, 2008, p.188). Thus, reliability is conducted to certify “measures are free from error and therefore yield consistent results” (Peter, 1979, p. 6), whereas validity inclines to “find the match between a construct, and how well a concept of reality fits with actual reality” (Neuman, 2006). In this regard, reliability refers to “whether the results of a study would be the same if the study were repeated”, whereas validity stresses “the integrity of the conclusions generated by a piece of research” (Bryman, 2008, p.25).

In general, “quantitative research tends to improve the reliability of measures by clarifying and conceptualising constructs, using a precise level of measurement, using multiple indicators and pilot tests” (Neuman, 2006). Nevertheless, qualitative researchers “focus on the standard, fixed measures that might limit the advantages from researchers and the application of other approaches” (Neuman, 2006). Quantitative researchers stress validity of measurements of the studies while qualitative researchers highlight the reliability in terms of observation consistency. Lincoln and Guba, (1985) suggests “to evaluate qualitative research from trustworthiness and authenticity”. More specifically, the trustworthiness including four aspects: “credibility, transferability, dependability, conformability” (Lincoln and Guba, 1985) (see Table 3.9)

Thus, in order to establish the linkage between literature and findings, and present meaningful description of research results, it is essential to evaluate the research reliability and validity.

Table 3.9 Trustworthiness of Qualitative Research (adapted from Lincoln and Guba, 1985).



Credibility	**To ensure the research was conducted in terms of well defined scientific practice and the findings of previous studies to confirm the research fully understood the issues in the context of the social world**
Transferability	Detailed description is necessary as a database to interpret the context in which research is conducted
Dependability	Auditing is an approach to improve dependability. It is necessary to make sure the collected data is consistent within problem formulation, selection of research participants, fieldwork notes, interview transcripts, data analysis decisions, and so on in the research
Conformability	Ensuring personal values or theoretical attributes were not impacted by the research findings

3.6 Research Design

In the preceding sections, a number of research methodologies, data collect methods, sampling techniques have been introduced. These provide a fundament for the entire research design. According to Jonker and Pennik (2010), research design is primary in relation to theory, methodology, question and context (see Figure 3.6). More specifically, a research plan could be defined as: “1) research goal and objectives for the study; 2) research questions and hypotheses; 3) data collection methods and setup; 4) method of data processing, data-analysis and data interpretation; 5) methods to validate the findings” (Blessing and Chakrabarti, 2009, p.138).

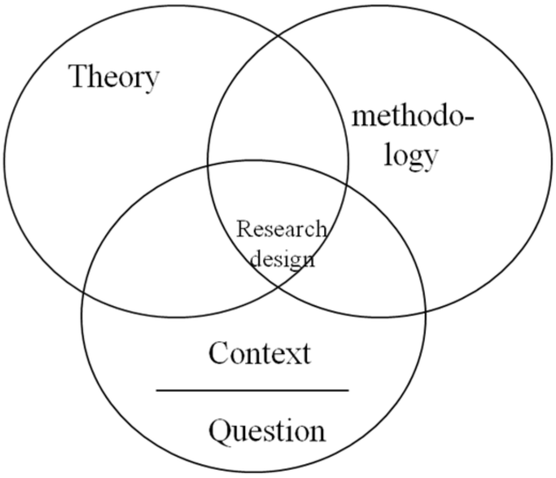


Figure 3.6 Research Design Model (adapted from Jonker and Pennik, 2010).

In this research, an overall framework is structured as shown in Figure 3.7. Besides, a justification of research methods employed is present in Table 3.10. Following objectives 1 - 5, the selected research methods for this research are identified. In summary, the first phase attempts to investigate "how to conduct design risk management (DRM) under a collaborative product design environment". The second phase intends to explore "how to map and measure design risk variables in relation with corresponding design constraints". The third phase focuses on discovers "how to compute overall design risk magnitude more appropriately and efficiently" and "how to simulate a DRM tool in terms of preceding integrated research results". Finally, the fourth phase concentrates on the evaluation whether the DRM tool can be implemented in industry practically.

More specifically, in the first phase, the research question focuses on developing a constraint-based conceptual DRM framework, which attempts to serve as a guideline for the overall DRM practice. A literature survey and a semi-structured interview are conducted in order to investigate the existing literature and the current industry in association with the DRM practice. The results compose of a constraint network technique in terms of generic characteristic of collaborative design, and a summary of the holistic risk management process in accordance with risk theory. Consequently, a constraint-based DRM conceptual framework is developed to provide a fundamental guideline for decision-making in context of a multidisciplinary and distributed collaborative product design.

The second phase attempts to create a constraint-based DRM matrix, which enables designers and design managers to map and measure design risk variables in an accurate and efficient manner. A literature survey is undertaken to explore general collaborative design constraints and essential risk criteria from a management perspective. Subsequently, in order to establish a more practical DRM matrix, questionnaire surveys are conducted to explore the most critical DRM design constraints and evaluate the proposed risk criteria. A constraint-based DRM matrix was constructed based on the above results.

The third phase concentrates on improving the efficiency and effectiveness of risk computation and creating a simulation prototype of DRM tool. A literature survey is conducted in order to review current risk weighting methods. As a result, after comparison, a Bayesian weighting method is developed and embedded for enhancing risk computation by means of incorporating with DRM framework and matrix. A visual-based prototype is created by Visual.Basic.NET in order to support further case study evaluation.

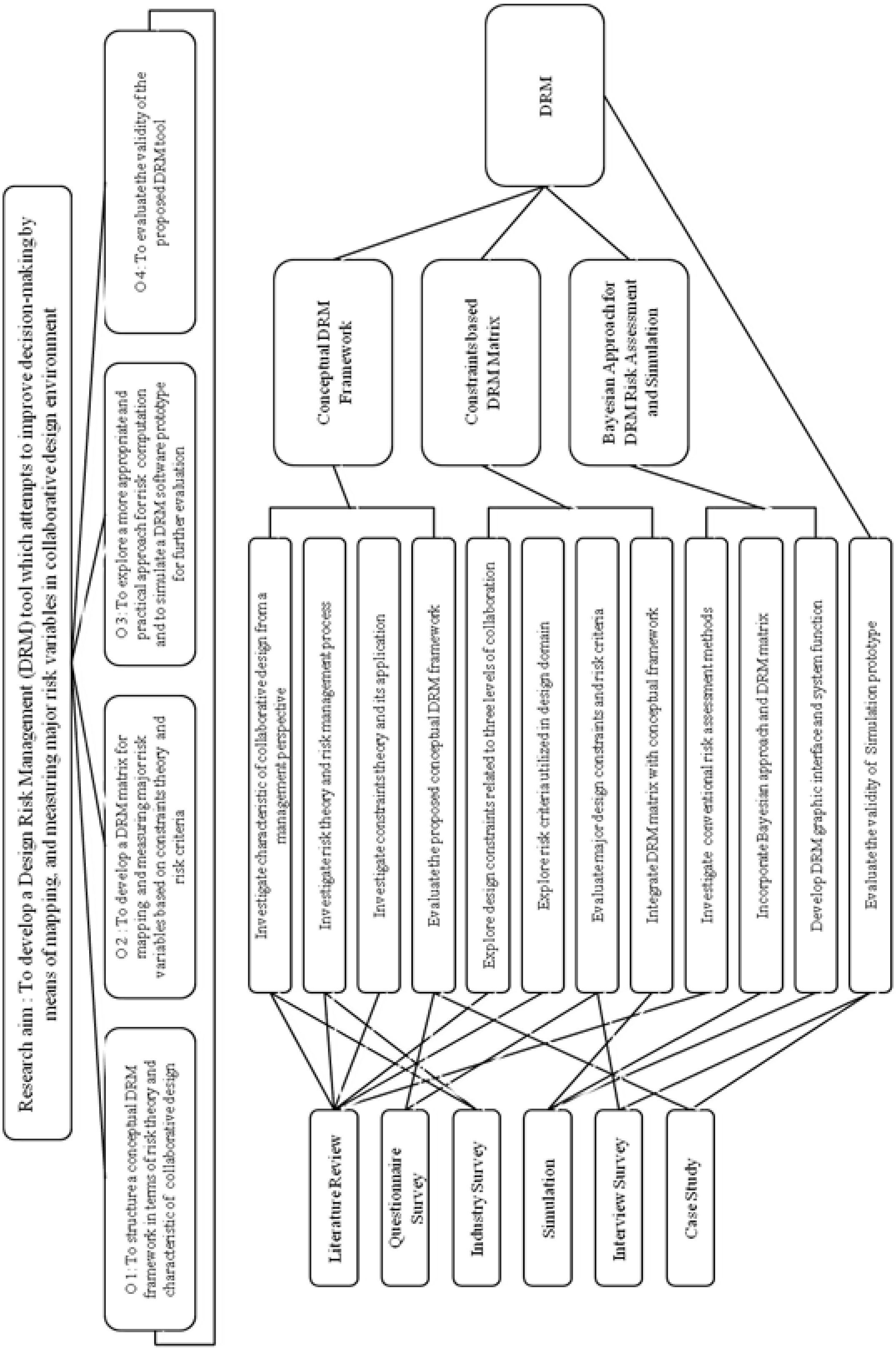


Figure 3.7 An Overall Framework for the Research.

Table 3.10 Justification of Research Methods in the Study

Methods	Purposes	Benefits
Literature survey	1)To investigate the generic features of collaborative design and identify the general process of risk management under a collaborative product design environment 2) To identify the potential design constraints and appropriate risk criteria relating to collaborative design 3) To investigate and compare the existing risk assessment techniques that can be utilised for enhancing measurement of collaborative design risk variables	Providing a comprehensive and critical review of the documentation of the published and unpublished work from secondary sources data in the specific areas These sources included books journals, conference proceedings, thesis Reviewing the literature on the specific topic that helps the researcher to focus further interviews or questionnaires in a more effective way on certain aspects
Semi-structured industry interview	1) To investigate how to conduct design risk management under a collaborative product design environment 2) To explore the current DRM practices in design industry 3) To collect some suggestions and implications as the references for further DRM development	Providing a most appropriate and flexible interview method to explore research questions in the field of design industry (Stanton *et al.*, 2005) Providing a suitable way for an in-depth investigation of the potential collaborative design features and the generic risk management process
Questionnaire survey	To explore the most critical design constraints and evaluate the measure feasibility of risk criteria in terms of the results of literature survey	Providing "a very flexible way of quickly collecting large amounts of specific data from a large population sample" (Stanton *et al.*, 2005, p.30) Providing a convenient tool to get feedback economically when respondents are not easily approachable Respondents have sufficient time to answer questions, thus the results are reliable (Kothari, 2004)
Simulation	To implement the selected risk mapping and measuring method and display the practical application for further evaluation. As the process of collaborative design is in accordance with dynamic, interactive and complicated features, and simulation is more valuable for demonstration and predication, a DRM simulation prototype is particularly appropriate for the assistance of application of case study evaluation	Providing a main instrument for obtaining predictions (Lenhard and Küppers, 2006), which can be "used as a substitute for experimentation and intervention on the actual system when such experimentation is too dangerous, costly, untimely, or inconvenient to be applied" (Axelrod, 1997) Simulation can be utilised to develop new tools with a realistic representation and provide real-world experience in a controlled environment with dynamic activity
Case study participant observation	To explore the status of collaborative design environment with cooperative design team structures and design processes in case studies, and to ensure whether the cases are appropriate for further evaluation	"The information obtained under participant observation relates to what is currently happening; it is not complicated by either the past behaviour or future intentions or attitudes" (Kothari, 2004) In comparison with interview or questionnaire, participant observation is "independent of respondents' willingness to respond and relatively less demanding of active cooperation on the part of respondents" (Kothari, 2004)

Case study semi-structured interview	To evaluate whether the DRM tool can be implemented on the basis of the DRM simulation software prototype demonstration, and whether the DRM can be operated effectively to map, measure and mitigate design risk under a collaborative design environment	Providing a "useful feedback" to increase correspondences between the world of concepts and reality in the field of the evaluation research (Grinnell and Unran, 2005) Offering an intensive, in-depth and rich research by using a variety of data collection methods to illustrate certain topics within an evaluation (Kothari, 2004; Creswell, 2009; Yin, 2009)

Finally, three case studies were undertaken based on the DRM simulation prototype. The case studies intend to evaluate whether the DRM tool can be employed to map, measure and mitigate design risk for the improvement of design collaboration in design industry. More details of the selected methods and the application in this research process are explained in the following chapters.

3.7 Potential User

The main research aims to provide a constraint-based design risk management (DRM) tool for collaborative product design. The potential users are targeted at both designers and design managers. From literature survey and industry practice, design managers generally take responsibility for the DRM in design industry, as their role mainly concern design management and decision-making, whilst designers usually play conceptual and creative roles.

However, in the context of collaborative product design and development, the main tasks of designers are not only concern concept creation and evaluation, but also need to "apply their scientific and engineering knowledge to the solution of technical problems" (Pahl *et al.*, 2007, p.1). In this regard, designers need to "optimise those solutions within the requirements and constraints set by the material, technological, economic, ergonomics, legal, and environmental considerations" (Pahl and Beitz, 1996, p.1).

In most design projects, designers have significant responsibility, as "their ideas, knowledge and skills determine the technical, economic and ergonomics properties of the product in a decisive way" (Wallace, 2007). To some extents, "designers determine the properties of every product in terms of function, safety, ergonomics, production, transport, operation, maintenance, recycling and disposal" (Pahl *et al.*, 2007, p.6). In addition, designers significantly affect the operation time and production quality and cost. Thus, designers are central in the process of NPD.

In summary, it can be concluded that both designers and design managers are important for DRM in the context of collaborative design. The DRM requires their valuable opinions and recommendations for further development and evaluation. Accordingly, both designers and design managers are selected as the initial participants during each primary research.

3.8 Conclusion

This chapter presents an overview of general research methodology with detailed demonstration of data collection methods, sampling techniques and data analysis, which intends to choose the most applicable methods for this study. For research methodology, both quantitative and qualitative research methods are reviewed and the distinction is presented for identifying merits and demerits between these two methods.

As a result, a mixed method, which combines both quantitative and qualitative approaches, is selected to provide a guideline for this research. To make a further illustration for how the mixed method is applied in this research, a holistic review of data collection methods, sampling techniques and data analysis is depicted and discussed. More specifically, five data collection methods consisting of questionnaire, observation, interview, case study and simulation is comprehensively described.

Moreover, sampling techniques, sampling size and processing data are addressed to show how the data is collected and processed. Ultimately, an overall research design framework is presented with details about research objectives and research questions. The potential users are also identified for further study. In summary, this chapter paid attention to the selection of methodology and the importance of research design, which provided fundamentals and guidelines for the entire research.

Chapter 4 A Constraint-based DRM Conceptual Framework

4.1 Introduction

The preceding chapter reviewed the research methodology and outlined the overall research design for the entire study. The objective of this chapter is to explore and investigate “how to conduct design risk management (DRM) under a collaborative product design environment”.

More specifically, this chapter focuses on the establishment of a DRM conceptual framework regarding collaborative design features, Theory of Constraints (TOC), and risk management process in order to facilitate design collaboration during the process of new product design (NPD) and development. Consequently, a constraint-based DRM conceptual framework is proposed based on the results of a literature survey and the evaluation of a semi-structured industry survey, which attempts to support designers and design managers for DRM under a multi-disciplinary and distributed collaborative design environment (see Figure 4.1).

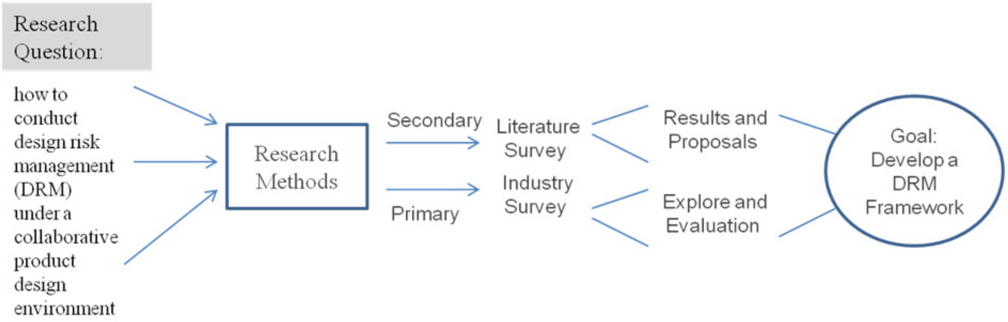


Figure 4.1 The Development Process of DRM Framework.

4.2 Research Method

In order to investigate generic collaborative design features and identify risk management process under a collaborative product design environment, a literature survey and a semi-structured survey were executed.

4.2.1 Literature Survey

A literature survey is performed in the field of collaborative design and design risk management domains by means of reviewing journal papers and textbooks. More specifically, the researcher uses Library and E-journals databases at Brunel University to search relevant books and journal articles. Given the perspectives of design and management, the Science Direct and Emerald databases are chosen as the key sources in search of relevant research papers. "Design collaboration", "Design risk" and "Design management" are used as key words in the process of literature survey.

4.2.2 Industry Interview

A semi-structured interview is regarded as the most appropriate and flexible method for the investigation in the realm of design industry (Stanton *et al.*, 2005). It could "direct the focus of the interview and use further questions that are not in the original part of the planned interview structure" (Stone and Collin, 1984). Thus, the semi-structured interview is appropriate and useful for a deep exploration of the potential collaborative design features and the generic risk management process.

In this study, the semi-structured interview attempts to investigate how to conduct design risk management under a collaborative product design environment. More specifically, the current DRM practices in design industry are investigated. The situation of current design risk management is presented. Some suggestions and implications are also provided as the references for further DRM development.

Consequently, a constraint-based DRM conceptual framework is proposed in the light of the results of the semi-structured industry interview.

4.2.3 Design of Industry Interview

The close-ended and open-ended questions are used in the construction of the semi-structured interview. The close-ended questions are applied to discover participants' background, whilst the open-ended are employed to investigate the practitioners' opinions of the current practices of design risk management, and suggestions for DRM development. As a result, the semi-structured interview is constructed into three key sections: general background information of participants, current practice of DRM, and suggestions for DRM development.

In the first section, close-ended questions are used to explore participants' background, comprise age, gender, occupation, job experiences and related responsibilities. Questions in this section include "What is your occupation?", "Which functional group you are responsible for in your profession?", "How many years have you been taken of this job", and "What kind of organisation do you work for?" These kinds of information can be used to identify the interviewees' professional focal point and evaluate survey quality accordingly.

In the second section, questions are concentrated on related collaborative design and explore the existing practice of design risk management in terms of interviewees' understandings and opinions. More specifically, collaboration, design risk management participants, risk management methods and processes are investigated in depth. The main questions conclude "Among current and recent design projects, what percentage of design practice involves collaboration?"; "Among current and recent design projects, are there any DRM tool or method used to support design management?"; "Do you find it is important to bring the DRM tool or practice into Collaborative Product Design?"; "Who are in charge or responsible for DRM practice?"; and "What kinds of process is being taken in your DRM practice?" The information gathered in this section can be used to analyse the problems and challenge of the present design risk practice in relation to a collaborative environment.

In the third section, questions are concentrated on investigation of the participants' suggestions and comments for the development of DRM in the future. These questions include: "Who should be involved in the operation of collaborative design risk management?", "To what extent do you agree with a constraint theory related to design practice should be introduced into design risk management field". The results of these questions are used to identify respondents' suggestions, which can be considered as the references for designing and developing the proposed DRM tool.

4.2.4 Initial Check of the Semi-Structured Interview

An initial check is performed to improve design of the semi-structured interview. The key benefit of undertaking an initial check is it "allows any potential problems or discrepancies to be highlighted" prior to the execution of the major research (Stanton *et al.*, 2005, p.26). In this research, the initial check comprises conducting a trial interview with research group members, which "allows any potential problems in the data collection procedure to be highlighted and removed" (Stanton *et al.*, 2005). More specifically, it indicates the collection of the desired type of data and the modification of the appropriate interview questions.

Therefore, an initial check is conducted the purpose of finding out if some questions are unnecessary or over-elaborate for the industry interview. Finally, the semi-structured interview is improved in terms of the results of the initial check. Some redundant questions are removed, some questions are recomposing, and some new questions are added (see Appendix A).

4.2.5 Interview Implementation

As described in Section 3.7, both design managers and designers are chosen as the appropriate interviewees in this research. Internet is adopted as the main way to collect data from the targeted populations. All the targeted population were contacted by emails or phones. Consequently, interviews were arranged grounded on their willingness and availability. 100 interview requests were sent out, and 12 design experts included 4 design managers and eight designers accepted the invitation. All 12 participants had rich working experience in the field of product design and project management. The interviews were performed in a face-to-face manner.

More importantly, a brief is presented to the participant by the researcher before the implementation of each interview. This brief is an essential introduction that represented the research aims and structures. It is essential to conduct the brief before conducting the semi-structure industry interview. More specifically, the brief highlights the main aims of the primary research, and ensures the participants are able to comprehend the overall purpose of the interview. Moreover, the brief helps the participants to interpret the questions posed during the process of interview and the terms used in each interview questions, which make sure the participants could provide more accurate and more valuable answers.

4.3 Results and Discussion

This section summarises the finding and discussions from the literature and the semi-structured interview and presents a conclusion and suggestions for the development of the DRM conceptual framework.

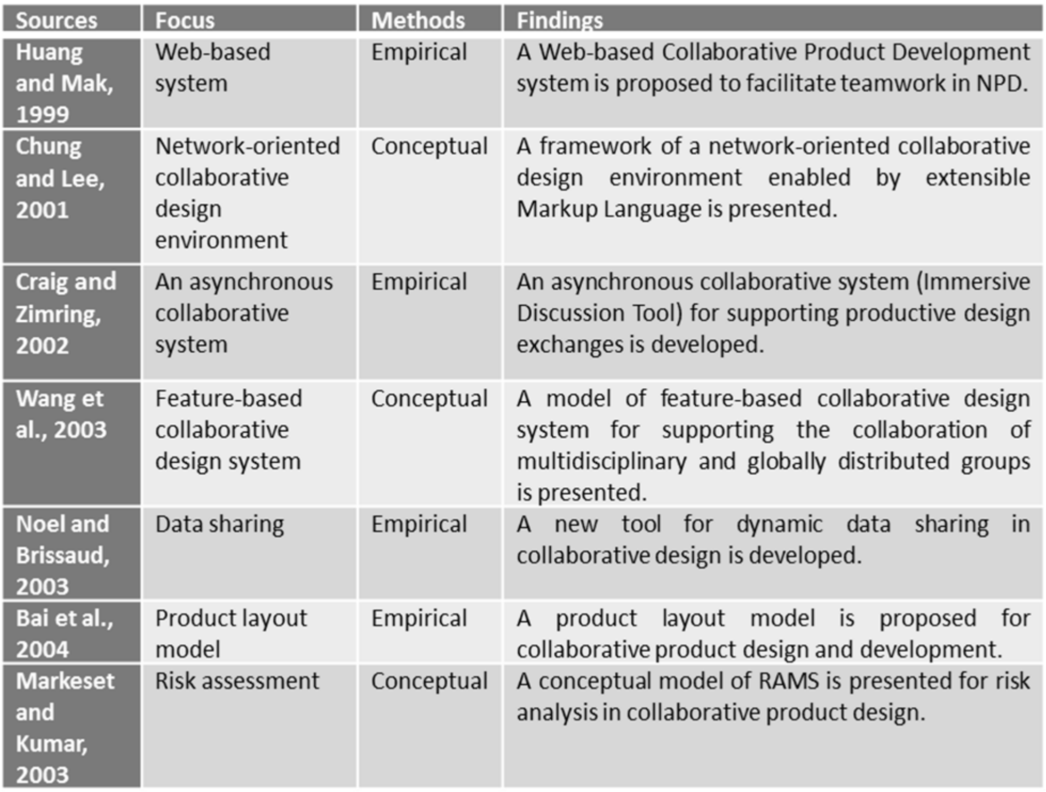
4.3.1 Related Research on Design Collaboration

A considerable literature has accumulated on the subject of design collaboration, which is widely seen as the basis of new product development. This literature can be separated from perspectives of up-to-date technology and management aspect.

From the aspect of technology, numerous researches concentrate on the application of computer technology and the development of collaborative design tools (Robin *et al*., 2007). Example could be found in web-based (Huang and Mak, 1999; Craig and Zimring, 2002; Tseng and Abdalla, 2004); agent-based (Liu *et al*., 2004; Maher, 2006), and grid technology (Li *et al*., 2006).

For instance, many collaborative product design tools are incorporated with web-based technology. In particular, most of multidisciplinary team members incline to use the web for sharing design resource, information and data. Additionally, web is usually integrated with other relevant technologies for design project management and product data management. Table 4.1 and 4.2 shows an overview of web-based tools.

Table 4.1 Related Technology Research for Web-based Collaborative Design.

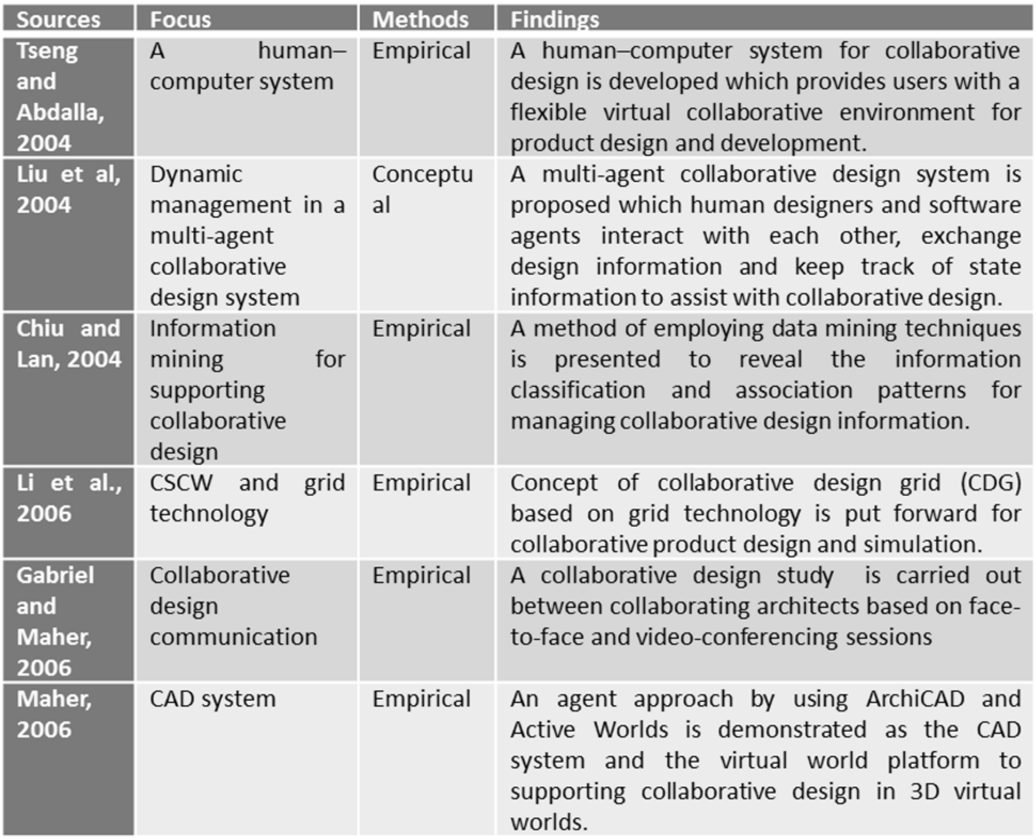


Sources	Focus	Methods	Findings
Huang and Mak, 1999	Web-based system	Empirical	A Web-based Collaborative Product Development system is proposed to facilitate teamwork in NPD.
Chung and Lee, 2001	Network-oriented collaborative design environment	Conceptual	A framework of a network-oriented collaborative design environment enabled by extensible Markup Language is presented.
Craig and Zimring, 2002	An asynchronous collaborative system	Empirical	An asynchronous collaborative system (Immersive Discussion Tool) for supporting productive design exchanges is developed.
Wang et al., 2003	Feature-based collaborative design system	Conceptual	A model of feature-based collaborative design system for supporting the collaboration of multidisciplinary and globally distributed groups is presented.
Noel and Brissaud, 2003	Data sharing	Empirical	A new tool for dynamic data sharing in collaborative design is developed.
Bai et al., 2004	Product layout model	Empirical	A product layout model is proposed for collaborative product design and development.
Markeset and Kumar, 2003	Risk assessment	Conceptual	A conceptual model of RAMS is presented for risk analysis in collaborative product design.

For agent-based collaborative design, “agents are mostly used for supporting cooperation among designers, enhancing interoperability between traditional computational tools, or allowing better simulations” (Shen, *et al*., 2008, p.858). Jin *et al*. (2003) proposed “an agent-supported framework to facilitate conflict management and streamline workflows, which provides knowledge infrastructure to support knowledge representation, sharing and exchange”. Liu *et al*. (2004) developed “a multi-agent collaborative design system for dynamically creating and managing design tasks in widely distributed and ever-changing design environments”.

Jia *et al*. (2004) developed“an adaptive and upgradeable agent-based system for coordinated product development and manufacturing”. Tang (2004) presented “a multi-agent-based system to integrate designers’ activities into product development process within a distributed, collaborative and concurrent environment”.

Table 4.2 Related Technology Research for Web-based Collaborative Design (Continued).

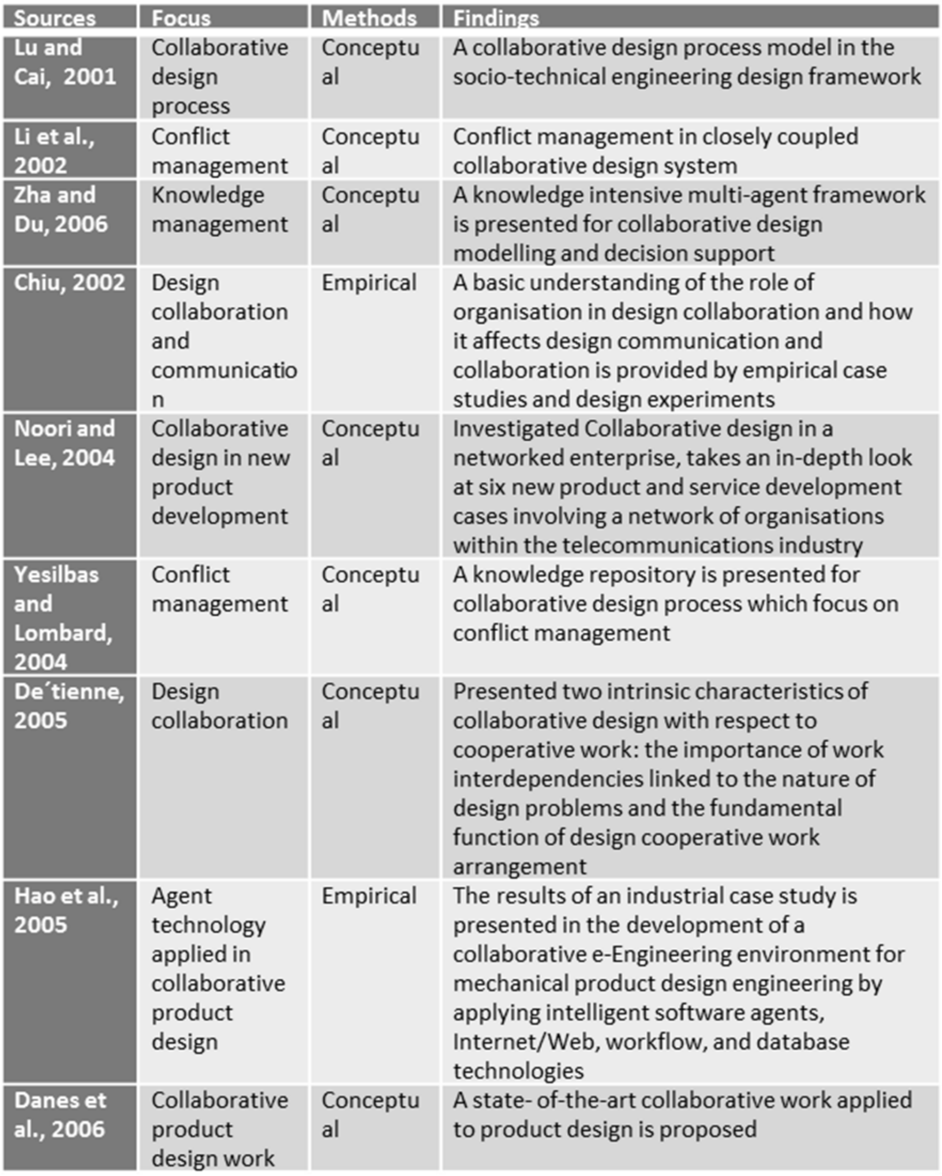


Sources	Focus	Methods	Findings
Tseng and Abdalla, 2004	A human–computer system	Empirical	A human–computer system for collaborative design is developed which provides users with a flexible virtual collaborative environment for product design and development.
Liu et al, 2004	Dynamic management in a multi-agent collaborative design system	Conceptual	A multi-agent collaborative design system is proposed which human designers and software agents interact with each other, exchange design information and keep track of state information to assist with collaborative design.
Chiu and Lan, 2004	Information mining for supporting collaborative design	Empirical	A method of employing data mining techniques is presented to reveal the information classification and association patterns for managing collaborative design information.
Li et al., 2006	CSCW and grid technology	Empirical	Concept of collaborative design grid (CDG) based on grid technology is put forward for collaborative product design and simulation.
Gabriel and Maher, 2006	Collaborative design communication	Empirical	A collaborative design study is carried out between collaborating architects based on face-to-face and video-conferencing sessions
Maher, 2006	CAD system	Empirical	An agent approach by using ArchiCAD and Active Worlds is demonstrated as the CAD system and the virtual world platform to supporting collaborative design in 3D virtual worlds.

From management perspective, most studies focus on research area such as conflict management (Li *et al*., 2002; Yesilbas and Lombard 2004), workflow management (Huang *et al*., 2006; Jiang *et al*., 2008), collaborative design process (Gonnet *et al*., 2007; Ouertani and Gzara, 2008), design collaboration (Chiu 2002; De´tienne, 2005; Hao *et al*., 2005; Kleinsmann *et al*., 2007), and knowledge management (Zha, 2002; Robin *et al*., 2007) (see Table 4.3-4.4).

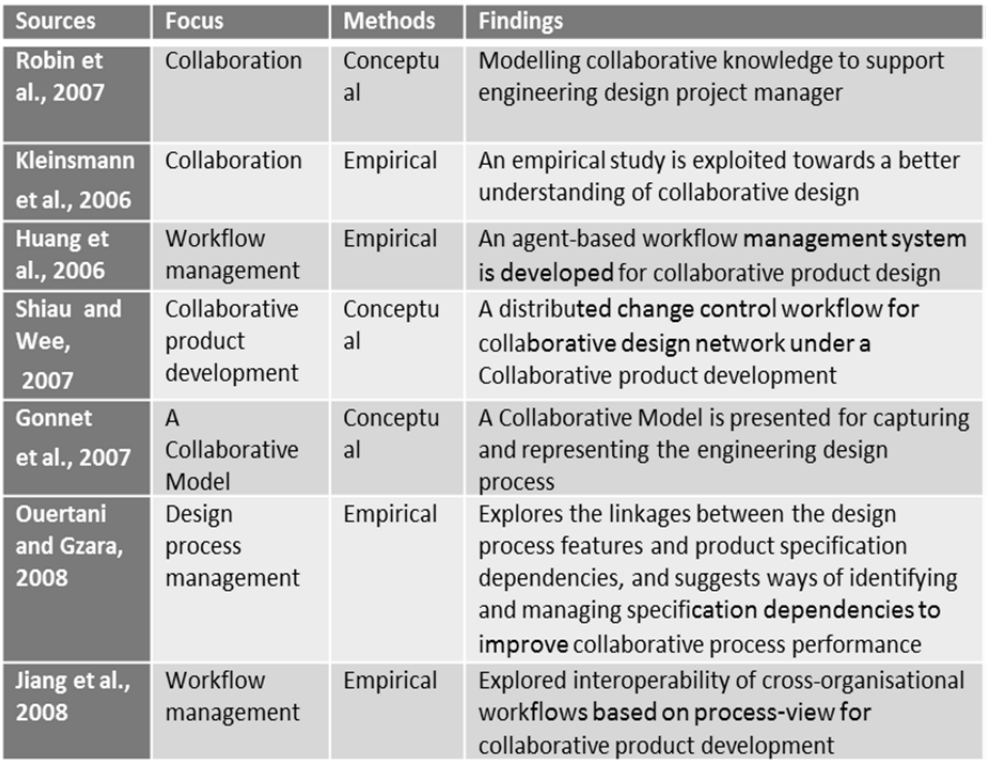
Lu and Cai (2001) developed a socio-technical framework for collaborative design management. Within the study, they regarded engineering design as a technical activity involved human factors. Li *et al*. (2002) put forward a conflict management method for closely coupled collaborative design. As the experts are usually multidisciplinary, globally distributed and design modern products cooperatively, the conflict is unavoidable.

Table 4.3 Related Management Research on Collaborative Design.



Sources	Focus	Methods	Findings
Lu and Cai, 2001	Collaborative design process	Conceptual	A collaborative design process model in the socio-technical engineering design framework
Li et al., 2002	Conflict management	Conceptual	Conflict management in closely coupled collaborative design system
Zha and Du, 2006	Knowledge management	Conceptual	A knowledge intensive multi-agent framework is presented for collaborative design modelling and decision support
Chiu, 2002	Design collaboration and communication	Empirical	A basic understanding of the role of organisation in design collaboration and how it affects design communication and collaboration is provided by empirical case studies and design experiments
Noori and Lee, 2004	Collaborative design in new product development	Conceptual	Investigated Collaborative design in a networked enterprise, takes an in-depth look at six new product and service development cases involving a network of organisations within the telecommunications industry
Yesilbas and Lombard, 2004	Conflict management	Conceptual	A knowledge repository is presented for collaborative design process which focus on conflict management
De´tienne, 2005	Design collaboration	Conceptual	Presented two intrinsic characteristics of collaborative design with respect to cooperative work: the importance of work interdependencies linked to the nature of design problems and the fundamental function of design cooperative work arrangement
Hao et al., 2005	Agent technology applied in collaborative product design	Empirical	The results of an industrial case study is presented in the development of a collaborative e-Engineering environment for mechanical product design engineering by applying intelligent software agents, Internet/Web, workflow, and database technologies
Danes et al., 2006	Collaborative product design work	Conceptual	A state- of-the-art collaborative work applied to product design is proposed

Table 4.4 Related Management Research on Collaborative Design (Continued).



Sources	Focus	Methods	Findings
Robin et al., 2007	Collaboration	Conceptual	Modelling collaborative knowledge to support engineering design project manager
Kleinsmann et al., 2006	Collaboration	Empirical	An empirical study is exploited towards a better understanding of collaborative design
Huang et al., 2006	Workflow management	Empirical	An agent-based workflow management system is developed for collaborative product design
Shiau and Wee, 2007	Collaborative product development	Conceptual	A distributed change control workflow for collaborative design network under a Collaborative product development
Gonnet et al., 2007	A Collaborative Model	Conceptual	A Collaborative Model is presented for capturing and representing the engineering design process
Ouertani and Gzara, 2008	Design process management	Empirical	Explores the linkages between the design process features and product specification dependencies, and suggests ways of identifying and managing specification dependencies to improve collaborative process performance
Jiang et al., 2008	Workflow management	Empirical	Explored interoperability of cross-organisational workflows based on process-view for collaborative product development

Therefore, “managing task interdependencies is an important issue that is well identified in computer supported cooperative work” (Li *et al*., 2002; De´tienne, 2006). More specifically, traditional design usually applies a sequential model for design generation that design task can be broken into a number of subtasks. Therefore, the conventional design management is mainly focused on management of interdependency task.

However, researchers recently found that such a sequential design mode is inflexible which often requires frequent iterations (Wang *et al*., 2002; Shen *et al*., 2008). More importantly, these design iterations result in design expenses and time consumption, and reduce design alternatives numbers. In addition, the sequential design is commonly applied at a downstream level, which may “cause insufficient design evaluation and inefficient new product development, due to the absence of manufacturability checks at the design stage” (Shen *et al*., 2008, p.855).

Consequently, “advances in computer networks and information technology have enabled product designers more effectively to communicate, collaborate, obtain and exchange a wide range of design resources during product development” (Deitz, 1996, p. 84). Modern global design collaboration requires more management from the view of role-interaction and resource-integration apart from the perspective of task-dependency.

De´tienne (2005) proposed a collaborative design framework, which presents two intrinsic characteristics of collaboration: “collaborative design as managing task interdependencies” and “collaborative design as managing multiple perspectives”. More specifically, collaboration characteristics that stressed “specific cooperative processes: coordination processes in order to manage task interdependencies that are linked to the nature of design problems; establishment of common ground and negotiation mechanisms in order to manage the integration of multiple perspectives in design” (De´tienne, 2005).

Besides, De´tienne (2005) indicated that “managing task interdependencies is most central in distributed design, managing multiple perspectives is most central in co-design”. In collaborative design, actors or team who involved role-interaction and resource-integration have their own work to complete. Therefore, the aims are pursued through not only by conducting task interdependencies, but also by sharing integrated resources. All these design activities are also needed to be coordinated in the process of role-interaction.

In addition, De´tienne (2005) presented that there are some basic socio-technical solutions that are possible for collaborative design: “1) at the task and organisational level: matching organisation structure with task decomposition; 2) at the cooperation level: facilitating coordination mechanisms through informal communication, and awareness”. Owing to involves multidisciplinary designers and concerns competing PLC, modern engineering design becomes more complicated with socio-technical issues (Lu and Cai, 2001; De´tienne, 2005; Kayis *et al.*, 2007; Lu and Jing, 2009).

In current collaborative design environments, there are increasing participants has been involved in the process of design collaboration with multidisciplinary background. "The complexity is greatly multiplied in the e-manufacturing economy, because the internet and CSCW facilitate coupling, promote conflicts and communication problems among project teams with different educational, cultural and social backgrounds" (Tseng *et al.*, 2003). In the context of e-manufacturing, "the design style must be changed from the "Design OF" in the past, through the "Design FOR" at present, to the "Design WITH" in the future" (Tseng *et al.*, 2003; Kayis *et al.*, 2007). The main feature of "Design WITH" method supports design managers and individual designers to communicate and negotiate with each other by using the web and computer in a constant and collaborative manner. Compared with traditional design approaches, the present CSCS requires the communication and negotiation through data exchange, information transferring and knowledge sharing which mostly relies on technology and iterations.

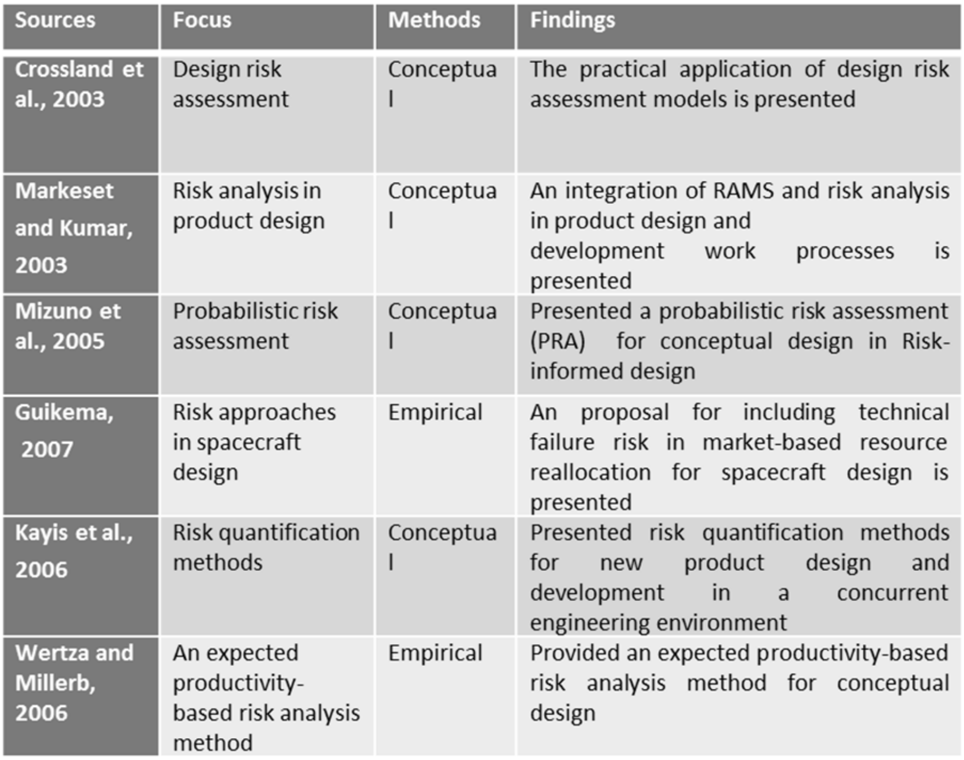
To sum up, the above results can be explained by the fact that collaboration becomes crucial for the success of collaborative product design (Chiu, 2002). Design collaboration refers to "various interests and people put together to achieve a common purpose", which can consider three main features: task-dependency, role-interaction and resource-integration (Wang *et al.*, 2002; Yesilbas and Lombard, 2004; Robin *et al.*, 2007; Ruan and Qin, 2008). The process of product design via collaboration should be associated with the entire product lifecycle (Shen *et al.*, 2008).

4.3.2 Related Research on Design Risk

A number of researches have been found on the exploration of the success of new product development (NPD) in association with risk factors (Prasad, 1996; Haque, 2003; Kayis *et al.*, 2007; Qiu *et al.*, 2007). Existing work has examined that risk can be regarded as a useful means for design improvement (see Table 4.5-4.6), and for supporting a multi-disciplinary and distributed design collaboration (Qiu *et al.*, 2007).

Crossland *et al.* (2003) conducted three cases studies with design risk assessment for the practical application, which paid much attention to task criticality and task duration in relation to design risk. This research presented a general review of the process of risk management with the demonstration of how risk was identified, how risk assessment was evaluated, and how risks were observed.

Table 4.5 Related Research on Design Risk.

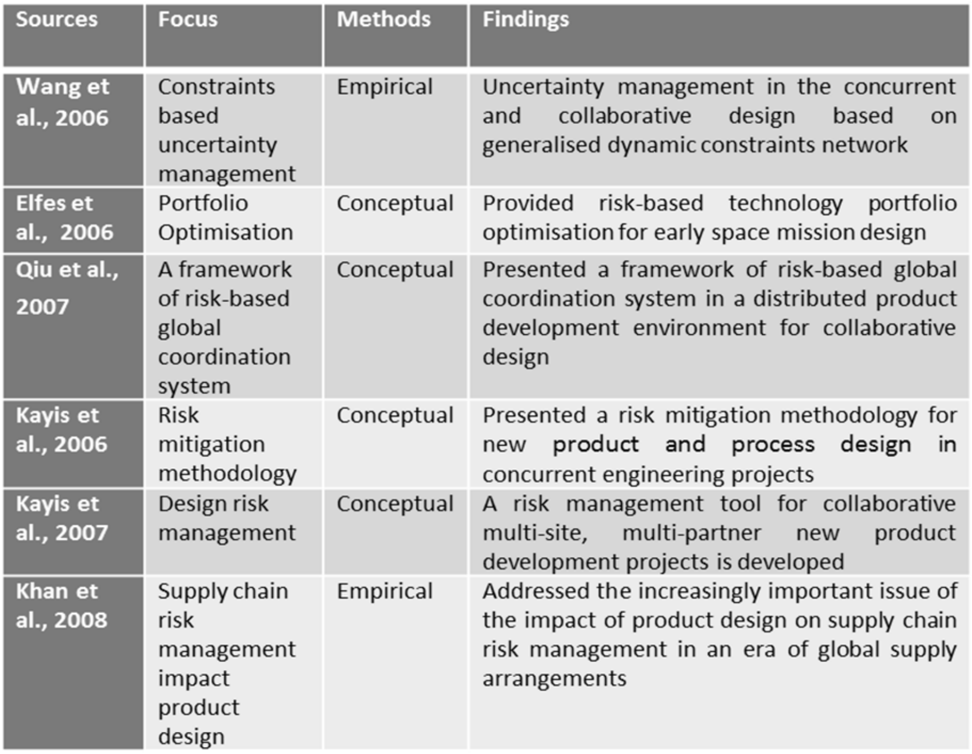


Sources	Focus	Methods	Findings
Crossland et al., 2003	Design risk assessment	Conceptual	The practical application of design risk assessment models is presented
Markeset and Kumar, 2003	Risk analysis in product design	Conceptual	An integration of RAMS and risk analysis in product design and development work processes is presented
Mizuno et al., 2005	Probabilistic risk assessment	Conceptual	Presented a probabilistic risk assessment (PRA) for conceptual design in Risk-informed design
Guikema, 2007	Risk approaches in spacecraft design	Empirical	An proposal for including technical failure risk in market-based resource reallocation for spacecraft design is presented
Kayis et al., 2006	Risk quantification methods	Conceptual	Presented risk quantification methods for new product design and development in a concurrent engineering environment
Wertza and Millerb, 2006	An expected productivity-based risk analysis method	Empirical	Provided an expected productivity-based risk analysis method for conceptual design

Mizuno *et al*. (2004) utilised Probabilistic Risk Assessment (PRA) to support the evaluation of International Reactor Innovative and Secure design. The results showed that "the use of PRA in the early stages of the design allowed a selection of design and performance features and an optimisation of the design of several systems to reduce the potential for events that could lead to core damage".

Meshkat and Voss (2005) put forward a risk assessment method integrated PRA for concurrent design. The PRA is used as a scenario based methodology for the evaluation of major risk items. However, this approach scores the likelihoods and impacts by a 5x5 matrix. It merely provides a basic analysis for the enhancement of risk communication in design process.

Table 4.6 Related Research on Design Risk (Continued).



Sources	Focus	Methods	Findings
Wang et al., 2006	Constraints based uncertainty management	Empirical	Uncertainty management in the concurrent and collaborative design based on generalised dynamic constraints network
Elfes et al., 2006	Portfolio Optimisation	Conceptual	Provided risk-based technology portfolio optimisation for early space mission design
Qiu et al., 2007	A framework of risk-based global coordination system	Conceptual	Presented a framework of risk-based global coordination system in a distributed product development environment for collaborative design
Kayis et al., 2006	Risk mitigation methodology	Conceptual	Presented a risk mitigation methodology for new product and process design in concurrent engineering projects
Kayis et al., 2007	Design risk management	Conceptual	A risk management tool for collaborative multi-site, multi-partner new product development projects is developed
Khan et al., 2008	Supply chain risk management impact product design	Empirical	Addressed the increasingly important issue of the impact of product design on supply chain risk management in an era of global supply arrangements

Qiu *et al*. (2007) presented a risk-based global coordination system for collaborative product design. A risk-based approach is developed to enhance the collaboration and negotiation under a multidisciplinary and global distributed environment. However, although this approach is generated by a practical observation, the whole research is entirely relied upon a theoretical scenario which simplifies social dynamics and assumes the availability of risk solutions. Moreover, the conducted risk analysis merely focuses on stakeholder's communication and negotiation which ignores the importance of other factors such as schedule, legal, environmental, financial, ergonomic, which might have significantly influences on design collaboration.

Kayis *et al*. (2007) developed a risk management approach for NPD in a collaborative multi-site, multi-partner context. The risk analysis is conducted in terms of eight risk categories: "schedule, technical, external, organisational, communication, location, resource and financial" (Kayis *et al*., 2007, p.398). However, these eight risk categories are summarised in an imprecise way, which also lack of sufficient consideration of collaborative characteristic such as task-dependency, resource-integration and role-interaction.

Thus, although so many studies focus on risk management, only a few researchers began to address risk issues in association with collaborative design (Markeset and Kumar, 2003; Rong *et al.*, 2006; Kayis *et al.*, 2007; Qiu *et al.*, 2007). In particular, there is little empirical studies were undertaken and it appears that there is no research linking collaborative design risk with TOC.

4.3.3 Related Research on Theory of Constraints (TOC)

TOC has been broadly acknowledged as a management philosophy, which intends to initiate and implement significant improvement for achieving a higher level of performance (Simatupang *et al.*, 2004). Numerous research of TOC can be found in literature (Kim *et al.*, 2008). More importantly, TOC has been developed into "a prevailing and versatile management theory with a set of theoretical frames, methodologies, techniques and tools, which is applied as a general theory in the domain of operations management" (Mabin and Balderstone 2003, pp. 569-570).

In general, TOC is regarded as "a systemic problem-structuring and problem-solving methodology which can be used to develop solutions with both intuitive power and analytical capability in any environment" (Mabin and Balderstone, 2003, pp. 569-570). In particular, "TOC emphasises the cross-functional and interdependent nature of organisational processes by viewing an organisation as a chain of interdependent functions, processes, departments or resources" (Gupta and Boyd, 2008, pp.993)

In view of TOC, it is essential to evaluate the role of operations or management from an upstream perspective. Besides, a constraint perspective from the TOC provides a useful way from which researchers and practitioners can anticipate and resolve a variety of design problems (Dym and Little, 2003; Pahl *et al.*, 2007; Whitney, 2008; Murthy *et al.*, 2008; Stapelberg, 2009). Therefore, given that the nature of collaborative design process, it is potential to introduce TOC into design area and provides a specific guideline for design research.

Moreover, “only a few points, the constraints, which have a significant, immediate impact on the whole system” (Gupta and Boyd, 2008, p.997). These sorts of constraints can be regarded as the source of weakest link or risk variable, which might greatly affect the performance of overall results. More specifically, when viewed from an operational management perspective, “the chain analogy suggests that not all problems can be the weakest link in the chain; some problem has to be the most significant with respect to the organisation’s ability to move in the direction of its goal” (Gupta and Boyd, 2008, pp.993).

Thus, TOC is essential and valuable for the proposed DRM conceptual framework. It specifies a more efficient way for design risk mapping, measuring and mitigating by means of exploring of key design constraints involved in the process of collaborative design.

4.3.4 Results of Semi-Structured Industry Survey

In this section, the results of the semi-structured interviews is presented, including participants’ profiles, results of the current practice, and results of suggestions of DRM for collaborative design.

Results of the Current Design Risk Practice

In the second section of industry survey, the concern is focused on the current design risk practice, interviewees’ opinions are collected and the results are presented as below.

1) *Most design project involves risk analysis are generally in charged by project or design manager*

According to the industry survey, 75% (N=9) of the interviewees claimed that their current design project involved risk analysis which served as a tool for design decision-making improvement. For instance, some interviewees emphasised that, as design plays a central role in NPD, risk management approaches are capable of assisting design managers to improve their decision-making and avoid major design failure. Therefore, design risk analysis should be considered and well evaluated. In other words, a DRM tool is required to advance design function in NPD. In addition, these design risk practices are generally conducted by project managers. Some interviewees indicated that project managers are the key executants who involved risk analysis, and should take responsibility for the success of the design project. Therefore, in the current design risk practice, there is usually no specific crew or panel, which is designated to the comprehensive design risk management. The project managers or design managers are coordinated and facilitated the product design process and interacted with the customers in terms of design belief or requirement. This would assure the achievement of design project aims.

2) *Current design risk practice do not consider collaborative factors*

66.67% (N=8) of the interviewees indicated that current design risk practice did not consider collaboration factors. As some interviewees suggested, most current design risk practice concerning with task or workflow management due to conventional experience. It is common that risks are mainly defined as cost and time-scale, and technical cause or simply defined as the designed artefact cannot meet functional requirements. Moreover, comparing to analysis technique failure and task failure, it is too complex and complicated to bring collaboration factors into action. Hence, in the current design risk practice, generally collaboration factors are excluded.

3) *Most design risk analysis adopted PRA method but too subjective*

58.33% (N=7) of the interviewees indicated that PRA are utilised as the primary method when conducting risk analysis in the process of design. Some of interviewees stressed that risk is commonly measured by risk probability and risk consequence in current design risk practice, and the PRA is frequently used as the major method to evaluate risk magnitude in terms of probability and consequence of risk items. Although some interviewees complained that PRA is too subjective and inaccurate which may affected by individual preference, expertise and bias, most them claimed that PRA presents a basis means for risk measurement. Consequently, PRA is still being considered as a more important and appropriate way to assess risk items so far.

4) All design risk practice is strictly in accordance with risk management process

In addition, 91.67% (N=11) of the interviewees highlighted that all risk practice involved in design activities are strictly in accordance with risk management process. From most interviewees' perspective, risk management is fixed and should be performed in the form of certain procedures. The experience of financial risk management can be used in the field of engineering and design. This standpoint is consistent with Crossland *et al*. (2003), who demonstrated "the importance of understanding risk should be recognised and much has recently been published on the theory behind the discipline of risk management". Kayis *et al*. (2007) concluded that risk management methodologies include three steps: "risk identification (mapping), assessment (measurement), and treatment (mitigation)" (Conroy and Soltan, 1998; Raz and Michael, 2001; Kayis *et al*., 2007). Thus, risk practice, which complies with strict process, would strength the efficiency of design risk management. Moreover, some interviewees 58.33% (N=7) indicated that most the design risk analysis were conducted before the commencement of design project.

Results of the Suggestions for DRM

According to the semi-structured interview results, some suggestions are concluded for the development of conceptual DRM framework.

1) Collaborative characteristics

91.67% (N=11) of the interviewees indicated that DRM tool under a collaborative design environment should comprise of all of main collaborative design characteristics, in spite of collaborative factors are not included in the current design risk practice. More specifically, some interviewees suggested that the three levels of collaboration should be considered comprehensively and respectively, given that global collaboration plays crucial role in concurrent NPD. Modern global design collaboration requires more management from the view of role-interaction and resource-integration apart from the perspective of task-dependency (Wang *et al*., 2002;

Yesilbas and Lombard, 2004; Robin *et al*., 2007; Ruan and Qin, 2008).

However, even though the concept of product collaborative design is extensively adopted in the process of NPD, some interviewees still insisted that bringing the concept of collaboration into DRM might give rise to conflict and make DRM practice more complicated and complex. Nevertheless, with the wide use of the internet and rapid development of web and agent technology, both academia and practitioners have reached a broad consensus which point out that global collaboration in terms of multidisciplinary and distributed environment is a mainstream for NPD.

More importantly, some interviewees emphasised that the DRM practice without considering collaboration factors are not intact and lack of accuracy, which might significantly influence the outcome of design decision-making and ultimately result in failure of product design. In addition, some interviewees indicated that the attempt to incorporate collaborative characteristics into the DRM practice is to deliver all aspects of design collaboration to the risk management process. Only in this way, the DRM can be implemented comprehensively for mapping, measuring and mitigating the major design risk variables during the course of product design development.

Thus, as the significant characteristics of design collaboration, role-interaction and resource-integration should be taking into account apart from task-interdependency (Wang *et al*., 2002; Yesilbas and Lombard, 2004; Robin *et al*., 2007; Ruan and Qin, 2008). The exploration of these three levels of collaboration characteristics were detailed in section 4.3.1.

2) DRM process and PRA

With regard to the DRM process, 91.67% (N=11) of the interviewees suggested that the operation of the DRM practice should be in light of the generic risk management process which had been generated from risk theory and practice. Some of interviewees stressed that there is no difference between conventional design and collaborative design regarding to the DRM process. Furthermore, as mentioned by a respondent, nearly all of design projects, which attempt to perform risk management practice, should conform to proper risk management process. Therefore, the recommended risk management process should be regarded as a basis for the DRM practice. Moreover, some interviewees also mention that PRA can be applied as an evaluation method for design collaboration risk assessment embedded in the DRM tool. Despite of the fact that PRA might not objective and imprecise, some interviewees emphasised that PRA provides a basic means for risk assessment. At present, PRA is still being regarded as the most effective method for design risk management. In addition, as indicated by most interviewees, only project managers are involved in the process of current design risk practice. However, 66.67% (N=8) of the interviewees also recommended that designers and stakeholders should be involved as main participants apart from project manager. This result is also in accordance with Qiu *et al*. (2007), who highlights that "risk is an important factor, which affects stakeholders and designers to effectively, coordinate, and is widely considered in designing engineering systems".

3) A Constraints perspective

Although some of interviewees admitted that, they are not familiar with the TOC, but most of them recognised that design constraints play a vital role during the process of product design. As indicated by the interviewees, constraints are usually described as restrictions and limitations that constrain the implementation of a design project in NPD. This viewpoint is in accordance with Pahl *et al*., (2007), who stressed that designers and managers must consider a multitude of technical, economic, social, environmental, and political constraints in the process of design projects. In other words, "design is a process of balancing functional requirements against various constraints such as material, technological, economical, physical, functional, operational, environmental, legal, and ergonomical factors" (Voland, 1999; Pahl *et al*., 2007, p. 395).

Moreover, some of interviewees also recognised that design constraints could be used as an approach to identify risk variables in product design. Gu and Renaud (2002) shared the identical opinion that design constraints typically could be used to "guard against failure or restrict the search to a preferred region of the design stage" (Gu and Renaud, 2002, p13.) As the design process is a cross-functional process that integrates constraints from all aspects of design management, cooperation and management among these constraints increase chances of success (Griffin and Huser, 1996). Thus, given that the risk analysis associated with design constraints could enhance the risk identification, most interviewees strongly recommended that Theory of Constraints should be introduced into DRM practice.

To sum up, the main purpose of the primary research in this stage is to explore the current DRM practices in design industry, investigate the opinions of designers, and design managers for the development of DRM. A semi-structured industry survey was conducted to evaluate the results of literature survey and gather the valid data. These finding has indicated the desire to integrated collaborative product design with risk management in terms of TOC. The empirical evidence derived from the analysis of industry survey is in compatible with the results of literature review.

Moreover, it is evident from the finding that risk management approaches are capable of assisting design managers to improve their decision-making and avoid major design failure. DRM are recommended to be adopted and well evaluated. In addition, as DRM is operated based on a collaborative product design project, collaborative factors such as task-dependency, role-interaction and resource-integration need to be considered. More importantly, as most of interviewees indicated, DRM practice should strictly in accordance with certain risk management process, in order to ensure the risk analysis is conducted in a comprehensive and accurate manner.

Thus, the primary research made an evaluation for the identification of the features of collaborative design and the general process of risk management by linking theoretical research to industry practice. The TOC is also confirmed during the process of the industry survey in order to ensure whether the perspective is useful and valuable for DRM practice under a collaborative design environment. These suggestions and implications were investigated and analysed as the references for further DRM development.

In the next section, a conceptual DRM framework is proposed on the basis of the results of the pertinent literature survey and industry semi-structured interview. The framework has developed an in-depth understanding of the core constructs underlying risk and constraints in a global collaborative product design context. The review of the literature and the results of semi-structured industry survey support the development of the conceptual DRM framework, which resolved some conceptual and structural issues, and supported the future study with a fundamental platform.

4.4 A Constraint-based DRM Conceptual Framework

Based on the result of the literature survey and the semi-structured industry interview, a constraint-based DRM conceptual framework is proposed. In describing the structure of the framework, a perspective of TOC is adopted to illustrate the interactions and relationships within collaborative product design and risk management. Constraint mapping is “a technique, which can manage the uncertainty, constraint relationships, and all of the objects related to the constraints in a concurrent and collaborative multi-disciplinary design project” (Wang et *al.*, 2006; Ruan and Qin, 2009).

Moreover, collaborative design faces numerous restrictions, such as design tasks, designers, design resources and the up-to-date design techniques, etc. These restrictions under design environment can be characterised as constraints, and those classified constraints during the collaborative design process can construct a constraint network or database. From the risk point view, a constraint must have relationships with risk variables. The emergence of risk variables will result in straight constraint violation, thus the risk variables can be derived and identified by using the constraint mapping.

4.4.1 A Constraint Network Technique

The constraint mapping can be used to check whether the results are compatible with the overall constraint network. If not, the risk variables must exist, and then we must track them and register the constraints. There are three ways to input constraints by capturing, classifying and registering.

In order to accelerate the constraint mapping, a constraint network technique is used in this study. The constraints can be generalised into three levels: task-dependency level, role-interaction level and resource-integration level (Yesilbas and Lombard, 2004; Rong, 2006; Ruan and Qin, 2009).

The task-dependency level constraints represent constraints of schedule, quality, manufacture, product, safety, and so on (Rong, 2006). The role-interaction level constraints articulate the design constraint of various design roles, which link communication, conflict, designers, knowledge, performance, etc. The resource-integration level constraints represent restrictions on legal, technical, material, environmental, etc.

For example, in the conceptual design phase, the task-dependency level constraints are the most key factors, therefore, the constraint network of this level is propagated to derive and identify risk variables in the first place. When the design goes further, the role-interaction level constraints are more important, and the constraint network in this level has the priority for detection. Whilst at manufacturing phase, designers and managers are required to pay more attention to the resource-integrated level constraints. More details about design constraints categories are described in Section 5.3.1. Thus, with the help of the hierarchy constraint network, risk variables can be identified in a prompt and efficient way.

4.4.2 A Flow Chart of Mitigation Strategy

In order to eliminate risk by mitigation, it requires feasible mitigation strategies and sufficient resources to execute the risk mitigation plan. In general, all mitigation strategies could be generated by risk analysts, in view of their adequate knowledge and experience. Thus, from a perspective of database, the proposed mitigation strategies can be saved, altered and reused on the basis of iterative processes or inherited experience. By combining inductive learning method and reasoning consistency approach, a flow chart of risk mitigation strategy is presented in Figure 4.2.

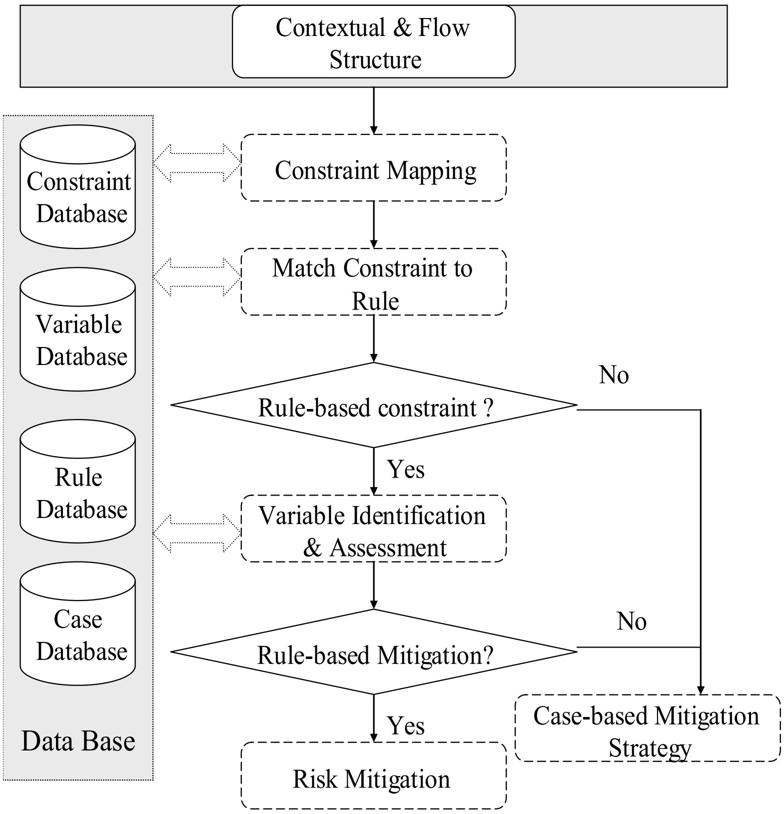


Figure 4.2 A Flow Chart of Risk Mitigation Strategy.

In the proposed chart, following the initial contextual and the flow structure, two reasoning consistency methods are adopted to match a series of given design constraints and risk variables to rules or cases through database. The design constraints and risk variables are collected as a set of data bank in the database by an iterative or inherited manner. If the risk analyst cannot handle the design constraints and risk variables properly, the case-based reasoning consistency approach would be called to deal with the risks by matched cases. Else, the design constraints and risk variables will be disposed of by a rule-based reasoning consistency method.

A corresponding rule-based or case-based mitigation strategy will be implemented appropriately if matching is successful. After the complete of risk mitigation, rules or cases inherited during the mitigation process would be added to the rule or case database by inductive leaning manner ultimately.

4.4.3 A Constraint-based DRM Conceptual Framework

Under a concurrent multi-agent collaborative design environment, the advanced technologies in computer networks “have enabled collaborative designers more effectively to collaborate and integrate with a wide range of design agents and resources” (Wang *et al.*, 2006). Computer Supported Cooperative Work (CSCW) provides researches in the context of multi-agent interaction under multidisciplinary task dependencies that could be supported by computer and web networks. Collaborative design involves many aspects from multiple perspectives due to a multidisciplinary and distributed product design environment. Owing to distinct domain perspectives, discipline knowledge and evaluation standards in a collaborative design system, the collaborative risk evaluation is critical and needs to be further considered.

A constraint-based DRM conceptual framework is proposed on the basis of the constraint network technique and the flow chart of risk mitigation strategy (see Figure 4.3). The framework is designed as a conceptual risk evaluation model in the context of design collaboration, which provides a basis for further research. More specifically, it incorporates with the collaborative design features, the risk management process and TOC.

In the first phase, a contextual or flow structure needs to be selected with specified design stages. Then, in the stages of risk mapping, design constraints are identified by using the constraint network technique. These design constraints can be evaluated by capturing, classifying and registering, and can be saved into constraints database for future tracking and analysis. As in view of risk perspective, a design constraint must have relationships with risk variables (see Section 4.3.3).

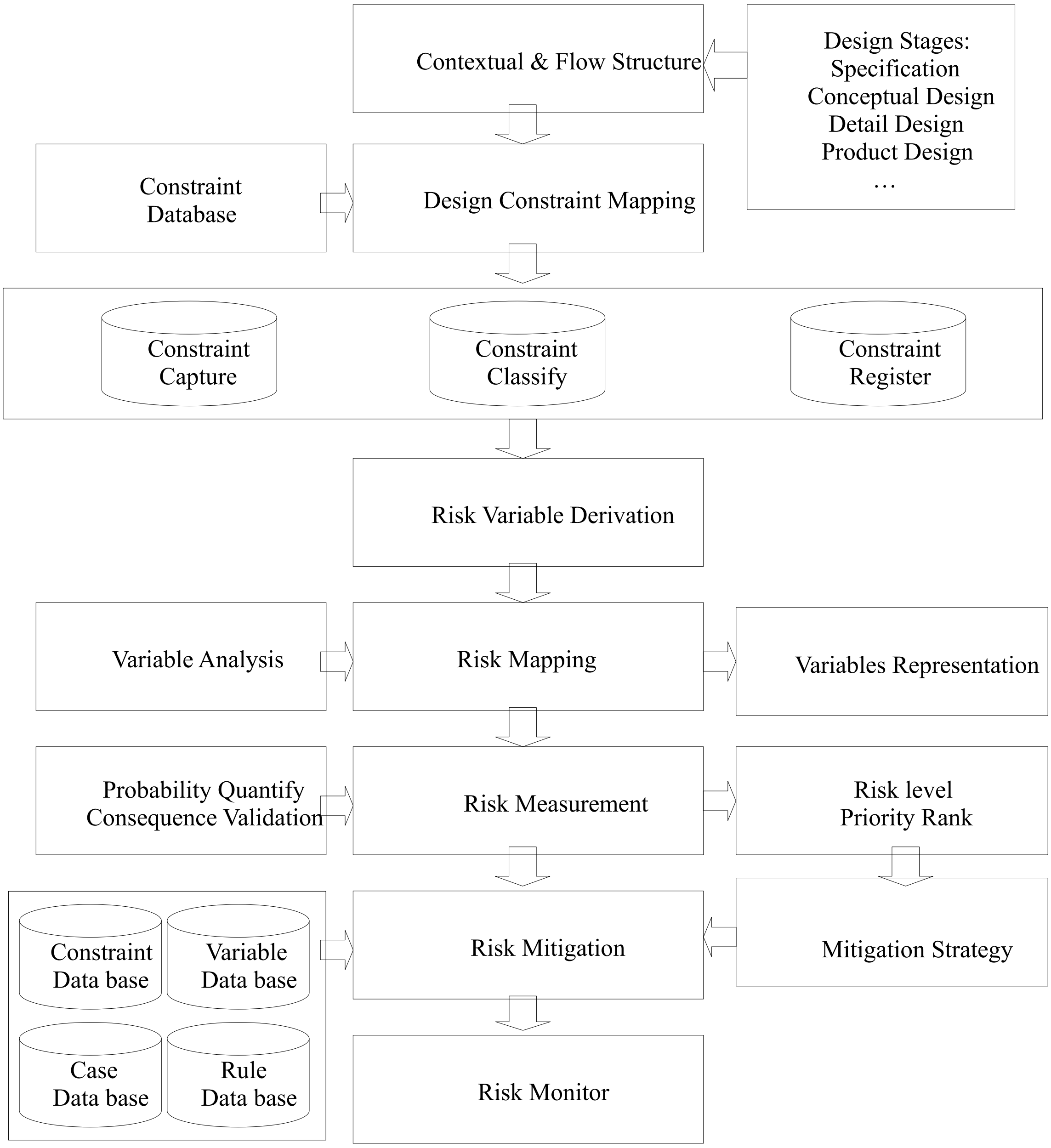


Figure 4.3 Architecture of Constraint-based DRM for Collaborative Design.

Thus, design risks can be identified by analysing and representing the evaluated design constraints. Moreover, after the risk mapping, the risk measurement needs to be conducted by using a Probabilistic Risk Assessment (PRA) method for probability quantity and consequence validation. Design risks can be evaluated and presented by risk level and priority rank. Finally, in order to eliminate risk variables, it requires more operations according to the flow chart of risk mitigation strategy. It is presumed that all mitigation strategies can be generated by risk analysts who have adequate knowledge and practice. These proposed mitigation strategies can be saved, altered and reused on the basis of iterative processes or inherited experience.

4.5 Conclusion

This Chapter presents a constraint-based DRM conceptual framework for the improvement of design collaboration under a multidisciplinary and distributed collaborative design environment. A constraint hierarchy is proposed to map design constraints and risk variables in terms of the features of collaborative environment. As collaborative design refers to multidisciplinary staffs spreading widely in a distributed environment, this model can be demonstrated on the basis of three dimensional levels: task-dependency, role-interaction and resource-integration (Wang *et al.*, 2002; Yesilbas and Lombard, 2004; Robin *et al.*, 2007; Ruan and Qin, 2008). A constraint-based DRM conceptual framework is created as a useful theoretical model with the purpose of guiding design risk mapping, measurement, and mitigation in incorporation with the design collaboration features, TOC and risk management process for the improvement of collaborative design performance. Then, a PRA method is adopted to evaluate risk level and rank priority after probability quantification and consequence validation. In addition, a flow chart of mitigation strategy is expanded to deal with risk mitigation in an inductive learning manner with feasible solution strategies.

However, as the proposed DRM framework is in a conceptual stage, the methods of risk mapping, measuring and mitigating required to be improved for further application in industry practice. In the next chapter, a constraint-based matrix is developed with the purpose of mapping, measuring and mitigating design risk variables in an accurate and efficient manner.

Chapter 5 A Constraint-based DRM Matrix for Risk Mapping and Measuring

5.1 Introduction

The previous chapter presents a constraint-based DRM conceptual framework based on the collaborative design features, the risk management process and TOC. The aim of this chapter is "how to map and measure design risk variables in relation to the corresponding design constraints".

As TOC can be used to emphasis the cross-functional collaborative design processes from a chain perspective of tasks, functions, processes, roles and resources, a constraint perspective provides a useful way from researchers and practitioners that can anticipate and resolve a variety of design problems (Dym and Little, 2003; Pahl *et al.*, 2007; Whitney, 2008; Murthy *et al.*, 2008; Stapelberg, 2009). However, there is an uncertainty in the first phase of DRM, which is the identifying of main design constraints among different design stages, where most of constraints are critical to the success of NPD.

Typically, these sorts of design constraints can be regarded as the source of weakest link or risk variables, which might greatly affect the performance of overall results. Thus, considering that "only a few points, the constraints, which have a significant, immediate impact on the whole system" (Gupta and Boyd, 2008, p.997), it is essential to identify and evaluate these constraints in order to support designers and managers for mapping, measuring, and mitigating design risk variables in an accurate and efficient manner.

An initial study was undertaken into existing literature for exploring the design constraints and relevant risk criteria. Design research prescribes that in order to understand collaborative design risk variables, design constraints must be generated from an upstream level and should be evaluated appropriately in terms of a wide range of design domains. These constraints after the identification and the evaluation can be used in line with risk criteria for the development of proposed constraint-based DRM matrix (see Figure 5.1). This means that the evaluated design constraints should not only aid for mapping design risk variables, but also facilitated the measuring of these risk variables by using a wider set of relevant risk criteria.

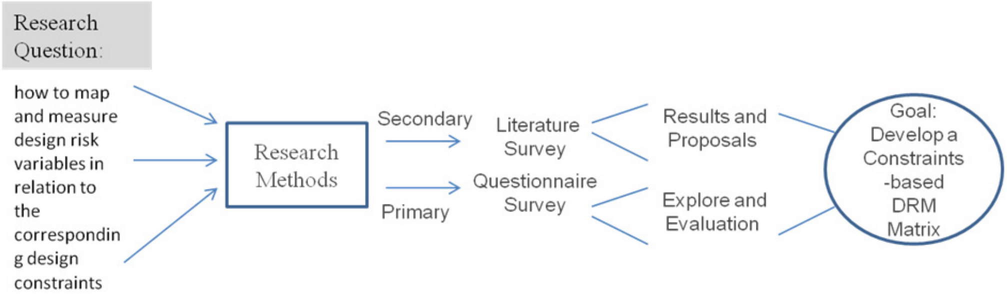


Figure 5.1 The Development Process of DRM Matrix.

In this Chapter, Section 5.2 presents some basic research methods used in the development of the DRM matrix. Then, Section 5.3 describes the results of literature review relating to design constraints and risk criteria. Section 5.4 discusses the results of industry questionnaire related to theoretical and methodological issues of the DRM matrix. Section 5.5 specifies a process focusing on the implementation of the DRM matrix with the DRM conceptual framework.

5.2 Research Methods

In order to capture the potential constraints of the DRM and develop the method of mapping and measuring collaborative design risk variables, a literature survey and a questionnaire survey are designed as research methods employed to support the development of the constraint-based collaborative risk variables matrix.

5.2.1 Literature Survey

With regards to the aim of identifying the potential constraints and appropriate risk criteria relating to collaborative design, a literature survey is conducted in the realm of TOC, risk theory and product design management. This survey is mainly based on E-Journal databases. In particular, Science-Direct and Emerald were selected as a main source because of the focusing on both engineering and management research field. Moreover, the International Journal of Operations and Production Management, the Journal of Quality in Maintenance Engineering and the Journal of Manufacturing Technology Management are selected as key sources for the literature survey due to many associated research are concluded.

In addition, some published books are reviewed, such as “Product Reliability: Specification and Performance” (Murthy, Rausand and Østerås, 2008) ; “Handbook of Reliability, Availability, Maintainability and Safety in Engineering Design” (Stapelberg, 2009); “The Design Guidelines Collaborative Framework: A Design for Multi-X Method for Product Development” (Filippi and Cristofolini, 2010); “Engineering design: a systematic approach” (Pahl *et al*., 2007). As a result, 30 design constraints are summarised and categorised into three collaborative levels: task-dependency, role-interaction and resource-integration (Wang *et al*., 2002; Yesilbas and Lombard, 2004; Robin *et al*., 2007; Ruan and Qin, 2008).

5.2.2 Questionnaire Survey

Questionnaire Survey Objective

The objective of the questionnaire must be clearly defined before questions design (Stanton *et al*., 2005). This questionnaire survey attempts to explore the most critical design constraints and evaluate the measure feasibility of risk criteria in terms of the results of literature survey. These critical design constraints and related risk criteria have significant effects on the reliability of DRM risk variables representation and value outputs. More specifically, the questionnaire strongly focuses on the selection of specific design constraints and mainly relies on the accuracy and reliability of generated risk criteria.

Questionnaire Survey Design

Questionnaires “offer a very flexible way of quickly collecting large amounts of specific data from a large population sample” (Stanton *et al.*, 2005, p.30). In order to explore participant’s profile, identify the critical design constraints for DRM and evaluate the feasibility of risk criteria, close-ended questions, open-ended questions, and ranking questions are used as a mixed method attempting to build a well-designed questionnaire. The close-ended questions are used to explore participants’ general background information. The ranking questions play major roles in the selection of the top six critical design constraints and in the evaluation of the feasibility of generated risk criteria. Moreover, the open-ended questions are designed to investigate the participants’ opinion of the critical design constraints, which encourage them to suggest more critical design constraints related to different levels of collaborative design.

Initial Check of the Questionnaire Survey

An initial check is conducted in order to identify the feasibility of the questionnaire survey. The aim of an initial check is “to try out the research approach to identify potential problems that may affect the quality and validity of the results” (Blessing and Chakrabarti, 2009, p.114). Moreover, the major advantage of undertaking an initial check is that it “any potential problems or discrepancies” prior to the execution of the major research (Stanton *et al.*, 2005, p.26). Therefore, the initial check is applied with five senior design researchers, which attempts to find out whether 30 design constraints are correctly categorised into three collaboration levels, whether risk criteria are selected accurately, whether all the questions are clear and easy to comprehend, and whether some questions are not necessary in the questionnaire survey. The questionnaire could be improved based on the results of the initial check. Some redundant questions are removed, some questions are recomposing, and some new questions are added (see Appendix A).

Performing Questionnaire Survey

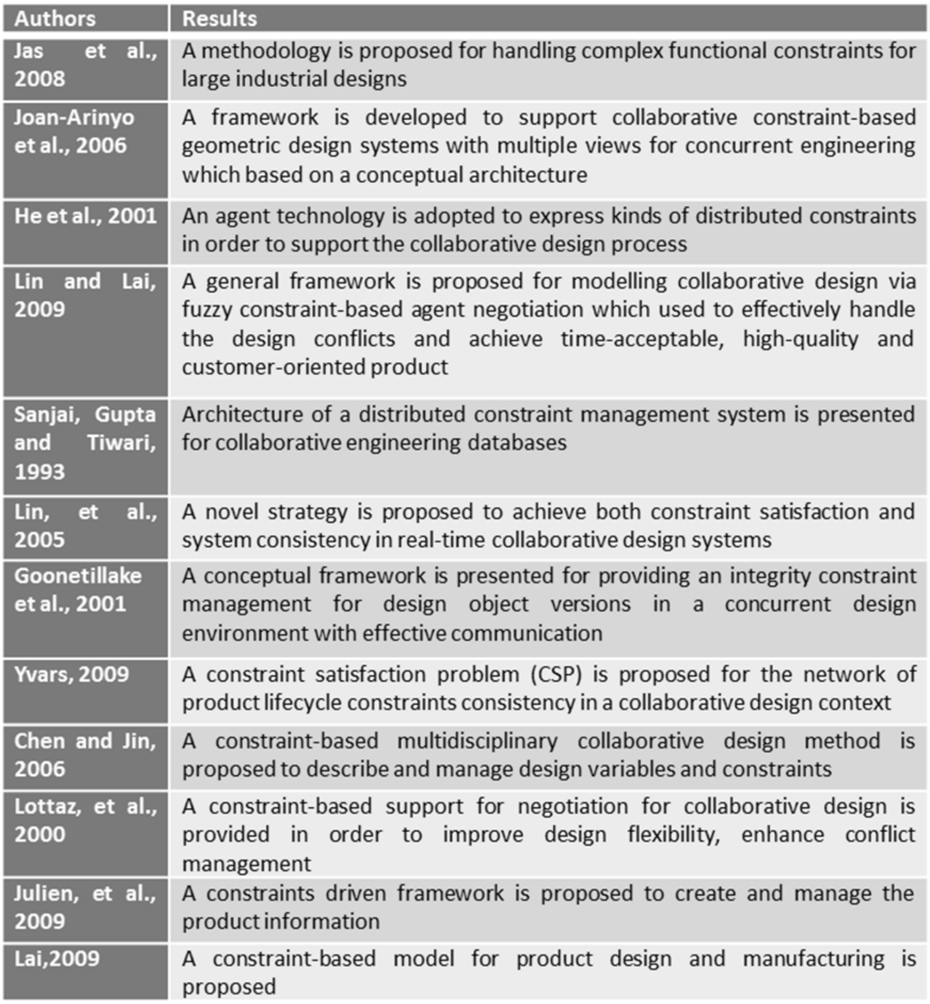
The questionnaire survey is performed based on a web-based questionnaire survey system (www.suverymonkey.com), which allows diverse types of questions could be constructed, such as close-ended questions, open-ended questions and ranking questions. After uploading the questionnaire, it can be distributed to the targeted population by email. Participants can answer questionnaire by click the link and the data will be saved. One of the main merits of this approach is that the researcher can created the questionnaire in a flexible and easy way in terms of research objectives and deliver to targeted participants. Moreover, the data collected from web can be exported and inputted into SPSS or Excel, which usually can be applied for statistical analysis. In this questionnaire survey, designers and design managers are targeted as main participants. The contact details of these participants are explored from design company and research institute directories in terms of internet. More importantly, the samples are carefully selected in terms of several criteria. First, the respondents must have strong design or design management background. Second, the respondents should have more than three years related working experience. Third, the samples should be filled out without missing data.

5.3 Results of the Literature Survey

5.3.1 Design Constraints

Existing literature on design constraints are not only produced from a technological side, but also generated from a management side (Rong *et al.*, 2006; Pahl *et al.*, 2007; Murthy *et al.*, 2008; Stapelberg, 2009). Some of these constraints are profoundly influence on performance and results of collaborative design project. A number of studies related to the design constraints are listed in Table 5.1.

Table 5.1 Related Studies for Design Constraints.



Authors	Results
Jas et al., 2008	A methodology is proposed for handling complex functional constraints for large industrial designs
Joan-Arinyo et al., 2006	A framework is developed to support collaborative constraint-based geometric design systems with multiple views for concurrent engineering which based on a conceptual architecture
He et al., 2001	An agent technology is adopted to express kinds of distributed constraints in order to support the collaborative design process
Lin and Lai, 2009	A general framework is proposed for modelling collaborative design via fuzzy constraint-based agent negotiation which used to effectively handle the design conflicts and achieve time-acceptable, high-quality and customer-oriented product
Sanjai, Gupta and Tiwari, 1993	Architecture of a distributed constraint management system is presented for collaborative engineering databases
Lin, et al., 2005	A novel strategy is proposed to achieve both constraint satisfaction and system consistency in real-time collaborative design systems
Goonetillake et al., 2001	A conceptual framework is presented for providing an integrity constraint management for design object versions in a concurrent design environment with effective communication
Yvars, 2009	A constraint satisfaction problem (CSP) is proposed for the network of product lifecycle constraints consistency in a collaborative design context
Chen and Jin, 2006	A constraint-based multidisciplinary collaborative design method is proposed to describe and manage design variables and constraints
Lottaz, et al., 2000	A constraint-based support for negotiation for collaborative design is provided in order to improve design flexibility, enhance conflict management
Julien, et al., 2009	A constraints driven framework is proposed to create and manage the product information
Lai,2009	A constraint-based model for product design and manufacturing is proposed

In general, a constraint can be regards “as any element or factor that restricts and limits the range of a variable” (Goldratt and Cox, 1992; Murthy *et al*., 2008). In the context of product design, projects are performed and delivered under certain constraints. Suh (2001) defines “a constraint as a bound on either 1) a single external or internal product property, or 2) the relationship between two or more product properties and identifies two types of constraints: i) input constraints that are identified at the onset of the new product development process (e.g., constraints on size, weight, materials, cost) and ii) system constraints that arise as the development progresses (e.g., the choice of a particular electronic part in one sub-system may impose constraints on the temperature generation in another part of the system)” (Murthy *et al*., 2008, pp. 55).

More specifically, constraints can be generally described as restrictions and limitations that constrain the implementation of a design project in new product development (NPD). Designers and design managers should consider a multitude of schedule, technical, financial, social, and environmental constraints during design process (Design Constraints Report; Rong *et al*., 2006; Pahl *et al*., 2007; Murthy *et al*., 2008). Thus, “design is a process that balances needs and functional requirements against various constraints such as material, technological, economical, physical, functional, operational, environmental, legal, and ergonomics factors” (Voland, 1999; Pahl *et al*., 2007, p. 395).

More importantly, these constraints could be “identified by considering the effects of failure of each identified performance variable in the realm of product design” (Stapelberg, 2009, p.16). In other words, design constraints can be applied to “guard against failure or restrict the search to a preferred region of the design stage” (Gu and Renaud, 2002, p.13). As De Mozota (2003) suggested, every problem posed to a designer demands that the constraints of technology, ergonomics, production and the marketplace be factored in a balance way. The finest performance with respect to relative constraints would have higher safety margin which give rise to more reliable product design (Rong *et al*., 2006; Stapelberg, 2009).

Thus, the feasible design solutions with no violated constraints would result in an acceptable or satisfied outcome. With the purpose of achieving the success of a design project, designers and managers should accommodate certain constraints such as financial, operational, technological and environmental factors. In essence, the design is a cross-functional process that integrates constraints from all aspects of design management. Thus, collaboration and management among these constraints are highly recommended (Griffin and Huser, 1996; Goonetillake, 2001; Chen and Jin, 2006).

In addition, “in any complex design process, there are only a few points, the constraints, which have a significant, immediate impact on the whole system” (Gupta and Boyd, 2008, p.997). Besides, as Cushman and Rosenberg (1991) suggested, design constraints must be identified as early as possible because they limit the options available to product designers. Therefore, it is crucial to identify the critical design constraints in the earlier stage collaborative design in order to meet the success of NPD.

Hubka (1988) concluded constraints into several categories: “industrial, ergonomic, aesthetic, distribution, delivery, planning, design, production, and economic”. Pahl *et al.* (2007) generates a constraints guideline for quality control during the design and development (see Figure 5.2).

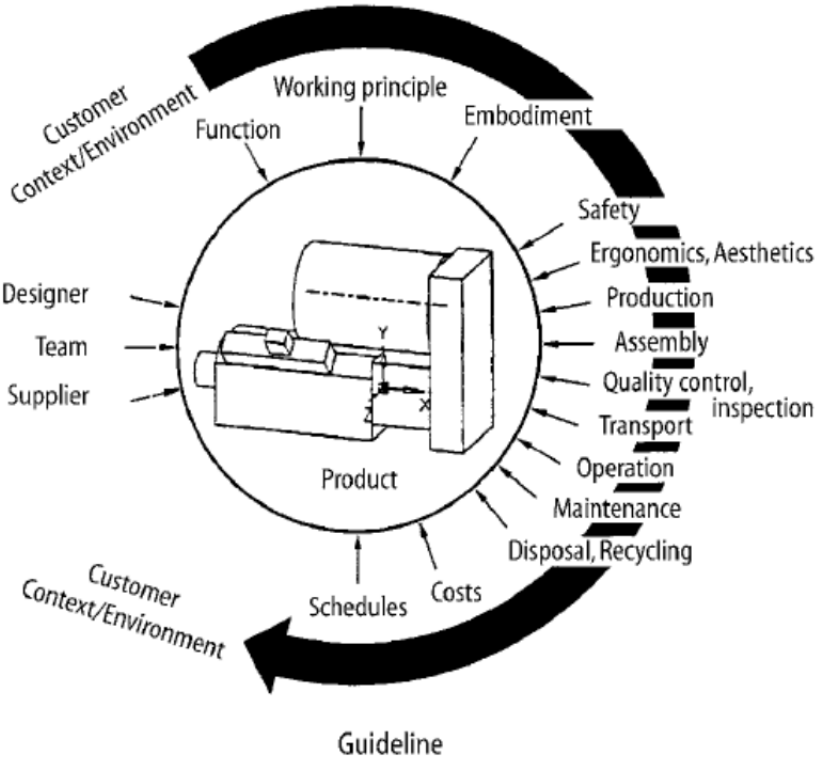


Figure 5.2 Influences and Constraints during Design and Development (adapted from Pahl *et al.*, 2007, p.44).

Rong *et al.*, (2006) indicated that “collaborative design process could be identified and represented by several aspects of constraints ranging from customer needs to legal factors”. These constraints can be characterised into three different levels: “the technical level, the social level, and the collaboration level” (Rong *et al.*, 2006). In each level, the constraints involved during the design process could be used to describe the basic constructs or elements. Murthy *et al.*, (2008) identified that there are various constraints in the process of collaborative design, such as “financial constraints (ability to raise funds for the new project), resource constraints (labor), and time constraints (new product must be launched by some specified date)” (Murthy *et al.*, 2008, p.39).

As Ruan and Qin (2009) proposed, the constraints that could be used to restrict and limit design collaboration can be categorised into three levels: the task-dependency level, the role-interaction level and the resource-integration level. More specifically, design specification and requirements are usually formulated in terms of the features that derived from these constraints. This significantly affects the collaborative design function and the success of the design project.

In this study, totally 30 constraints are collected through literature survey. The identified design constraints were organised and presented in Table 5.2-5.4. These constraints are treated as guidelines in design risk management in association with risk variables during the entire design process. All types of these constraints can be used for mapping and measuring design risk variables in the context of the collaborative design project.

5.3.2 Risk Criteria

"For design research, with the ultimate aim of improving a situation, formulating criteria for success is essential to be able to determine whether the results help achieve this aim" (Blessing and Chakrabarti, 2009, p.26). More specifically, **"**criteria are used to be able to focus the investigation of the existing situation; to assess the contribution of the findings of such investigations to the research goal; to focus the development of support on the most relevant factors; to plan the appropriate evaluation; to focus the realization of the support on this evaluation; and to assess the evaluation results" (Blessing and Chakrabarti, 2009, pp.26). In other words, criteria are required and selected for the support and judgement of the outcome in the process of design evaluation.

Table 5.2 Task-dependency Related Design Constraints.

	Design Constraints and Scope	**Resources**
Task-dependency level	**Schedule constraints:** Design schedule (project planning, project control), Development schedule (design detailing, compliance tests), Production schedule (manufacture, assembly, packing, transport), Delivery schedule (delivery date, distribution network, supply chains)	Hubka,(1988); Pahl *et al*., (2007); Murthy *et al* .,(2008); Kerzner,(2009); Stapelberg, (2009)
	Quality constraints: Quality assurance (regulations, standards, codes), Quality control (inspection, testing , labelling), Quality management tool, Design audit	Hubka , (1988) ; Voland, (1999); Albano *et al*., (1999) Markeset and Kumar (2003); Pahl *et al*., (2007)
	Manufacture constraints: Components production (factory limitations, means of production, wastes) Components purchase (supplier quality, reliability, quality control, inspection) Assembly (installation foundations, bolting, welding Transport (material handling, clearance, packaging)	Kevin ,(1996); Voland, (1999); Skander *et al*., (2008); Stapelberg, (2009)
	Functional constraints: Over all geometry (size width space, arrangement Control system (electrical, hydraulic, mechanical, pneumatic) Information flow(inputs outputs form display Material selection (flow, transport, properties) Energy system (heating cooling conversion)	Hubka,(1988); Albano *et al*., (1999); Voland, (1999); Cather *et al*., (2001); Markeset and Kumar (2003);Pahl *et al*., (2007); Jas *et al*.,(2008); Gupta and Boyd, (2008)
	Product life cycle constraints: Distribution(means of transport, nature and conditions of dispatch, rules, regulations) Maintenance (servicing intervals, inspection, exchange and repair, cleaning, diagnostics) Disposal (recycle, scrap)	Albano *et al*., (1999) ;Tichkiewitch and Brissaud , (2000); Murthy *et al* .,(2008); Yvars, (2009)
	Cost constraints: Budget, machines, material, labour costs , consumable materials costs, manufacturing costs)	Hubka (1988); Voland, (1999); Pahl *et al*., (2007); Murthy *et al*., (2008); Kerzner,(2009); Stapelberg, (2009)

However, most the problems encountered in collaborative design due to lack of a proper evaluation. Although there exists plenty of literature conducting criteria analysis associated with diverse types of design under varying circumstances (Markeset and Kumar, 2003; Murthy *et al*., 2008; Stapelberg, 2009). Little literature concerns the implementation of criteria and design risk analysis. One of exception is

Markeset and Kumar (2003), which "presented an approach for integration of reliability, availability, maintainability and supportability (RAMS) and risk analysis in design, development and manufacturing and emphasises the importance of these characteristics for ensuring failure-free operations of industrial products". Moreover, Markeset and Kumar (2003) also argued that "the integration of RAMS and product life cycle in combination with risk analysis in the design and manufacturing process is fundamental in accomplishing and ensuring the success of new product design and development".

Table 5.3 Role-interaction Related Design Constraints.

	Design Constraints and Scope	**Resources**
Role-interaction level	**Conflict constraints:** Conflict detection, conflict analysis , conflict presentation, conflict resolution, conflict mitigation	Lottaz *et al*., (2000); He *et al*., (2001); Chen and Jin, (2006); Lin and Lai, (2009)
	Communication constraints: Message transfer , communication tool, culture diversity, individual difference	Albano *et al*., (1999) ; Chen and Jin, (2006)
	Negotiation constraints: Objective, terms and rules, skills, agreement and achievement	Albano *et al*., (1999); Lottaz, *et al*., 2000; Chen and Jin, (2006); Lin and Lai,(2009)
	Decision-making constraints: Scientific Standards , expert opinion and assessment , risk assessment, outcome	Chen and Jin, (2006); Rong *et al*., 2006; Gupta and Boyd, (2008)
	Knowledge constraints: Domain, sharing, experts, experience, database	Rong *et al*., 2006; Vanda, (2008); Zha *et al*., 2008; Lin and Lai, (2009)
	Performance constraints: Operational performance, financial performance, management performance, production performance	Gandikota, and Davis, (1990); Puigjaner, (1993); Markeset and Kumar (2003); Simatupang *et al*., (2004); Kerzner,(2009); Inman *et al*., (2009); Stapelberg, (2009)
	Designer constraints: Absence, experience, leadership, motivation	Hubka, (1988)； Albano *et al*., (1999);Pahl *et al*., (2007);Murthy *et al* .,(2008)； Lin and Lai, (2009);
	Customer constraints: Customer appeal (shape, color, texture, form, feel, smell, surprise and delight features) Fashion (culture, history, trends) Future expectations (rate of change in technology, trends, product families)	Hubka (1988) ; Albano *et al*., (1999); Rong *et al*., 2006; Pahl *et al*., (2007)
	Supplier constraints: Logistics, capability, performance, numbers, delivery**,** substitute	Simatupang *et al*., (2004);Lin and Lai, (2009); Pahl *et al*., (2007)
	Stakeholder constraints: Participation, investment, empowerment	Lin and Lai,(2009); Pahl *et al*., (2007)

Thus, in order to verify the integrity of a product design need, RAMS is applied for "determining the complexity and consequent frequent failure of the critical combination and complex integration of large engineering processes and systems, both in their level of technology as well as in their integration, the integrity of their design needs to be determined" (Stapelberg, 2009, p.5).

The design integrity implies "determining reliability, availability, maintainability and safety design criteria of the design's inherent systems and the related process" (Stapelberg, 2009, p.5). However, the importance of risk criteria associated with the critical design constraints is not fully understood in the field of design domain. It seems that there is no research, which reports on how to integrate design constraints and risk criteria for design collaboration.

According to Markeset and Kumar (2003) and Stapelberg (2009), in total five measurable risk criteria are formulated from literature review. These measurable risk criteria include availability, feasibility, accuracy/safety, reliability and maintainability, which would significantly influence the results of DRM results. The scale of these risk criteria can be weighted up in terms of their magnitude of influence. Moreover, these selected risk criteria of critical design are in accordance with the "RAMS" which presented by Markeset and Kumar (2003) and Stapelberg (2009). The identification of risk variables is performed in terms of the combination of specific design constraints and risk criteria.

Therefore, the integrity of design constraints and risk criteria can be used to constitute a matrix-based methodology that ensures the accuracy of mapping and measuring of the appropriate design risk variables with the a desired probability value and the assigned consequence rank. These values are input mainly on the basis of design experts, knowledge, and experience. The method allows the complex process of collaboration design can be analysed appropriately, which not only from upstream project management but also with a perspective of combination of designers, design managers and related stakeholders.

Table 5.4 Resource-integration Related Design Constraints.

	Design Constraints and Scope	Resources
Resource-integration level	**Legal constraints:** Patents, trademarks, copyrights , regulations, ethics	Lewis (1993) ; Voland, (1999); Markeset and Kumar (2003); Rong *et al*., 2006; Pahl *et al* ., (2007)
	Financial constraints: Design costs (design team computing, information retrieval) Development costs (design detailing, supplier costs, testing costs) Manufacturing cost (tooling, labour, overhead, assembly, inspection) Distribution costs (packing, transport, service centres, spare parts, warranty)	Pahl *et al* .,(2007); Murthy *et al*., (2008); Markeset and Kumar (2003); Inman *et al*., (2009)
	Ergonomic constraints: User needs (type of operation, instructions, warnings) Ergonomic design (man -machine relationships, operation, height, layout, comfort, lighting) Cybernetic design (controls, layout, clarity, interactions)	Hubka (1988); Voland, (1999); De Mozota, (2003); Rong *et al*., 2006; Murthy *et al*., (2008) ; Pahl *et al* ., (2007)
	Information constraints: Communication, control, data, form, instruction, knowledge, meaning, mental stimulus , pattern, perception, representation	Hu, (2002); Rong *et al*., 2006; Joan-Arinyo *et al*., (2006) ; Rong *et al*., 2006; Pahl *et al*., (2007)
	Technical constraints: Hardware equipment, software installation, data management, information sharing, application	Suh, (1990); Voland, (1999); De Mozota, (2003); Markeset and Kumar (2003); Rong *et al*., 2006; Pahl *et al*., (2007); Murthy *et al* .,(2008); Gupta and Boyd, (2008)
	Market constraints: Size, distribution, segments, production	De Mozota, (2003); Murthy *et al*., (2008)
	Ecological constraints: General Environment impact , Sustainability (political and commercial consequences) , resource optimisation health act, public safety	Pahl *et al*., (2007); Gupta and Boyd, (2008); Murthy *et al*., (2008)
	Material constraints: Material selection (solid, liquid, gas, stability, protection, toxicity)	Suh, (1990); Lewis, (1993); Voland, (1999); Cather *et al*., (2001); Markeset and Kumar (2003); Murthy *et al* .,(2008)
	Tool constraints: Design tool, communication tool, programming tool	Pahl *et al*., (2007); Gupta and Boyd, (2008); Murthy *et al*., (2008)
	System constraints: Process, procedures, routines structures, components, entities, factors, properties inputs, outputs, internal environment, external environment, feedback	Goldratt, (1984); Suh, (1990); Lin *et al*., (2005); Rong *et al*., 2006; Murthy *et al* .,(2008); Gupta and Boyd, (2008); Inman *et al*., (2009)

In general, the abovementioned concepts of risk criteria are not new and have been increasingly evaluated (Markeset and Kumar, 2003; Murthy *et al.*, 2008; Stapelberg, 2009). Industrial designers and managers have been paid much attention to product design in terms of their theoretical and practical experiences and knowledge. In summary, five risk criteria implemented in the proposed constraint-based matrix are described into details as below:

Availability is regarded as “the item’s capability of being used over a period of time”, and the measure of availability can be viewed as “the period in which the item is in a usable state” (Stapelberg, 2009, p. 18). More specifically, a criterion of availability refers to the aspect of defining constraints that takes account of the notion of utility and time. If the overall risk is presumed as value (1.0), design risk variables relating availability to constraints can be assigned to the fixed risk values with (0.2, 0.8). In other words, if corresponding design constraints are not available, collaboration risk variables will encounter the most severe consequence (0.8). Conversely, if design constraints are available, the risks are relatively lower (0.2).

Feasibility refers to the capability of being done, accomplished or carried out. A criterion of feasibility combines “an assessment of availability and expected performance with respect to the performance measures of the specified constraints” (Stapelberg, 2009), in relation to the feasible of capabilities. More importantly, the feasibility implies “the ability to perform within the prescribed limits quantified by the defined constraints on the acceptable performance that is identified by considering the consequences of the failure of each identified design risk variable” (Stapelberg, 2009). The value of feasibility can be assigned to the fixed risk value with (0.3, 0.7). In other words, if matching design constraints are not feasible, the collaboration risk value is (0.7). On the contrary, if the design constraints are feasible, the risk value is (0.3).

Accuracy/Safety can be divided into two groups, one is accurate description, another concerns safety usage. A criterion of Accuracy/Safety is consistent with design availability and feasibility. More specifically, accuracy in industrial design, particularly in collaborative product design, refers to the accurate description of the defined constraints resulting in corresponding design risk variables. Whilst safety indicated that defined constraints are used safely or not. The value of Accuracy/ Safety can be assigned to the fixed risk value with (0.4, 0.6). If the related design constraints are not accurate/ safe, the collaboration risk value is (0.6). However, if the design constraints are Accurate/Safe, the risk magnitude is medium (0.4).

Reliability is commonly defined as “in terms of the probability of failure or a mean time to failure of equipment” (Stapelberg, 2009, p. 16). A criterion of reliability can be viewed as “the probability of successful operation related to design constraints, with minimum risk of the loss or disaster or of the system failure” (Stapelberg, 2009, p.635). In this regard, reliability could be regarded as “lower risk” or “not involved risk” (Murthy *et al.*, 2008). Moreover, under a collaborative product design environment, reliability can also be considered as “whether a particular design has inherently obtained certain attributes of reliability, brought about by the properties of the components of the design, or whether the design has been configured at systems level to meet certain constraints” (Stapelberg, 2009, p.44). The value of reliability can be assigned to the fixed risk value with (0.3, 0.7). If the design constraints are not reliable, the collaboration risk value will be (0.7). In addition, if the design constraints are reliable, the risk value will be (0.3).

Maintainability concerns the sustainability, which refers to “the probability that a failed item can be restored to an operational effective condition within a given period of time” (Stapelberg, 2009, pp.19). A criterion of maintainability requires an evaluation of design alternative in the event of failure, as well as of the demanding time and the integrated resources during the process of design. The value of Maintainability can be assigned from (0.2, 0.8). Thus, if design constraints are not maintainable, collaboration risk value will be (0.8). Conversely, if design constraints are maintainable, the risk value will be lower (0.2).

To sum up, the application of these risk criteria requires a combination of the defined design constraints, and the critical design risk variables mostly rely on participant’s knowledge and experience. In this study, five risk criteria are evaluated by a questionnaire survey. More specifically, designers and design managers will bring their opinions to agree or disagree with the employment of these risk criteria.

5.4 Development of a Constraint-based Matrix for Risk Variables Mapping, Measuring and Mitigation

This section presents the development of the DRM matrix. A questionnaire survey is performed intends to identified the most critical design constraints and evaluate the measure feasibility of risk criteria in terms of the results of literature survey. These critical design constraints and related risk criteria have a significant effect on the reliability of DRM risk variables representation and value outputs. More specifically, the questionnaire strongly focuses on the selection of specific design constraints and mainly relies on the accuracy of generated risk criteria.

5.4.1 Background Information

In total, 39 applicable samples are collected from this online questionnaire survey after initial check. Participants of the survey include 22 designers and 17 design managers. Among them 41 percentages are from research organisations, 48 percentages are from design companies and 11 percentages are from engineering companies. Additionally, 34 percentages of them are working For-Profit Medium companies, 34 percentages from For-Profit Small companies and 11 from Non-Profit organisations. Moreover, 38 percentages of participants have 2-3 years working experience while 62 percentages claimed that they have 4-5 working experience. Among all these participants, their job responsibilities are range from research, design management, engineering management and product development. More specifically, 18% of them are majored in research, 36% concentrate on engineering management whilst 46% focus on design management.

5.4.2 Questionnaire Results

The questionnaire creates a database of the identification of the critical design constraints and the evaluation of the measureable feasibility of risk criteria. A method of combination of selecting frequency and average ranking is used to evaluate the samples results. More specifically, selecting frequency refers to the proportion of participants who select a specific design constraint as the most critical design constraints for design risk management. Average ranking means calculation of mean value for each specific design constraint over its summation of ranking value. These are illustrated in a descending sequence way (see Table 5.5).

Task-interdependency Design Constraints

De´tienne, (2006) stressed that "managing task interdependencies are becomes more crucial during the distributed design phases where each designer or teams work on specific subtasks". The solution of design tasks and alternatives bring certain constraints that might be derived from the schedule, the manufacture methods, the product life cycle, the intended operation.

As it shows in Table 5.5, schedule constraints are considered as the top critical constraints in the task–dependency level of collaborative design.

Table 5.5 Results of Task-dependency Level of Design Constraints.

Design Constraints	**Frequency (%)**	**Ranking Average**	**N**
Schedule constraints	87.17	4.23	34
Cost constraints	84.62	3.78	33
Quality constraints	79.48	3.22	31
Function constraints	74.35	2.96	29
Manufacture constraints	64.10	2.67	25
Product life cycle constraints	58.97	2.58	23
Operation constraints	48.71	2.32	19
Safety constraints	43.58	2.11	17
Operational constraints	35.89	1.97	14
Maintenance constraints	23.07	1.47	9

More specifically, in view of the selecting ratio, 87.17% of 39 participants reckoned that schedule constraints would significantly restrict design management and influence the final project results. Moreover, ranking average analysis also shows the same results. This result is consistent with Murthy *et al.* (2008) and Stapelberg (2009), who indicated that schedule constraints play fundamental roles in design projects.

In addition, cost, quality, function, manufacture, and PLC are selected as the most critical design constraints in line with schedule in the task – dependency level of collaborative design. The importance of influence of schedule, quality control, manufacture, etc in design has been identified by Pahl *et al.* (2007). In general, designers are required to analyse these constraints and to evaluate design alternatives accordingly.

Role-interaction Constraints

Collaborative design involves designers from multiple disciplines with various expertises. Design is the business that includes "diverse participants with different competencies, responsibilities and interest" (Bucciarelli, 2002). The importance of role-interaction characteristics in collaborative environment design is fully discussed in literature (De´tienne, 2006). The participants share an identical objective for the achievement of design success by optimising role-interaction. Design constraints of this level direct cooperation to assure a desired solution.

Results in Table 5.6 indicated that designer constraints are regarded as the most critical constraints in the role-interaction level of collaborative design. According to selecting ratio, 82.05% (N=32) of 39 participants assumed that designer constraints can profoundly restrain design management and affect the ultimate results of project in this level. Designer constraints are used to take into account of absence, experience, leadership. Curtis *et al.* (1988) found that "a significant success factor for large design projects is the presence of a super designer, a person who is responsible for holding and supporting the project vision". In other words, lack of key designers can lead to serious consequences.

In addition, decision, conflict, performance, communication, and knowledge are selected as the most critical design constraints as well as designer constraints in the role–interaction level of collaborative design. Lubars *et al.* (1993) emphasised that decision, communication, performance, conflict and customer are crucial for design collaboration. For instance, collaboration might not be successful due to designers' lack of collaboration willingness and ability for making decision (Olson, 2000). Potts and Catledge (1996) confirmed that "the depth of domain knowledge is critical to the success of early stages in a project".

Table 5.6 Results of Role-interaction Level of Design Constraints.

Design Constraints	Frequency (%)	Ranking Average	N
Designer constraints	82.05	4.19	32
Knowledge constraints	76.92	3.84	30
Communication constraints	74.35	3.68	29
Conflict constraints	71.79	3.56	28
Performance constraints	69.23	3.41	27
Customer constraints	51.28	2.79	20
Decision constraints	46.15	2.53	18
Stakeholder constraints	43.58	2.46	17
Negotiation constraints	43.58	2.31	17
Supplier constraints	41.02	2.27	16

As a result, managing role-interaction is most central issues in collaborative design in order to establish the common ground and improve communication and negotiation mechanisms in support of final decision regarding the corresponding constraints.

Resource-integration Design Constraints

"Design is increasingly a multi-site, multi-cultural, globally distributed undertaking. Design projects tend to become more and more geographically distributed" (De´tienne, 2006, p.5). Therefore, design constraints associated with the resource-integration level are crucial issues, which greatly influence design collaboration.

Table 5.7 presents the results of the importance of resource-integration level design constraints. Legal constraints are selected as the most critical constraints in the resource-integration level of collaborative design. As we can see from selecting ratio column, 89.74% (N=35) of 39 participants convinced that legal constraints can significantly restrain design management and impact the ultimate results of project at this level.

Table 5.7 Results of Resource-integration Level of Design Constraints.

Design Constraints	Frequency (%)	Ranking Average	N
Financial constraints	89.74	4.56	35
Technical constraints	79.48	3.94	31
Legal constraints	76.92	3.77	30
Information constraints	69.23	3.42	27
Ergonomic constraints	66.66	3.22	26
Material constraints	56.41	2.79	22
System constraints	48.71	2.46	19
Market constraints	43.58	2.27	17
Tool constraints	38.46	1.92	15
Ecological constraints	30.76	1.76	12

The legal constraints of products usually contain with several overlapping categories i.e. patents, trademarks, copyrights, regulations, ethics (Lewis, 1993). A working knowledge of intellectual property rights is clearly a pre-requisite for good design. Legal constraints are more critical in designing in case of failure for new product development.

Additionally, legal constraints are just one facet of the design constraints placed by the law upon designers. Others factors include financial, technical, information, ergonomic, and material are chosen as the most critical design constraints together with legal in the resource-integration level of collaborative design. Studies of these constraints give detailed guidelines on design activities that are the keys to success.

To sum up, the primary research aims to explore the most critical design constraints and evaluate the measure feasibility of risk criteria based on the results of literature survey. These design constraints in combination with risk criteria could help risk analysts to indicate the risk sources and to identify the related risk consequence in terms of its risk probability of individual item. Thus, the questionnaire survey was conducted mainly focusing on explicating design constraints and evaluating the accuracy and reliability of generated risk criteria.

The finding shows that as design projects are performed under certain constraints, some critical design constraints and related risk criteria have significant effects on the reliability of DRM risk variables representation and value outputs. It is apparent that these constraints are more important for the specified risk variables given the influence of failure in the realm of collaborative product design. Consequently, more critical design constraints are selected for the construction of the DRM matrix whilst the others are excluded. These empirical results drawn from the analysis of questionnaire survey are echoed with Gupta and Boyd (2008), who claimed that in any complex design process, “only a few points, the constraints, which have a significant, immediate impact on the whole system” (Gupta and Boyd, 2008, p.997).

Besides, as the matrix is operated based on critical design constraints and a set of risk criteria, the accuracy and reliability of generated risk criteria are also evaluated.

The finding provides a better way to understand of collaborative design risks in terms of critical design constraints and risk criteria from an upstream perspective. These constraints after the identification and the evaluation can be used in line with risk criteria for the development of proposed constraint-based DRM matrix.

More importantly, the evaluated design constraints should not only aid for mapping design risk variables, but also facilitated the measuring by using a wider set of relevant risk criteria. Thus, the results of questionnaire survey have a contribution for the development of the DRM matrix, which provided a useful way to map and measure design risks based on the corresponding design constraints and risk criteria.

5.4.3 Formulate a DRM Matrix

According to the questionnaires results and analysis, 18 design constraints were identified as the most crucial variables, and being categorised into three collaborative levels. The formulated DRM matrix incorporated design constraints with five evaluated risk criteria can be show as below (Table 5.8-5.10):

Table 5.8 The Constraint-based DRM Matrix (Task-dependency Level).

Risk Criteria / **Design Constraints**	**Availability**	**Feasibility**	**Accuracy /Safety**	**Reliability**	**Maintainability**
Schedule constraints	Schedule constraints available (Not)	Schedule constraints feasible (Not)	Schedule constraints accurate/safety(Not)	Schedule constraints reliable (Not)	Schedule constraints maintainable (Not)
Cost constraints	Cost constraints available (Not)	Cost constraints feasible (Not)	Cost constraints accurate/safety (Not)	Cost constraints reliable (Not)	Cost constraints maintainable (Not)
Quality constraints	Quality constraints available (Not)	Quality constraints feasible (Not)	Quality constraints accurate/safety (Not)	Quality constraints reliable (Not)	Quality constraints maintainable (Not)
Function constraints	Function constraints available (Not)	Function constraints feasible (Not)	Function constraints accurate/safety (Not)	Function constraints reliable (Not)	Function constraints maintainable (Not)
Manufacture constraints	Manufacture constraints available (Not)	Manufacture constraints feasible (Not)	Manufacture constraints accurate/safety (Not)	Manufacture constraints reliable (Not)	Manufacture constraints maintainable (Not)
Product life cycle constraints	Product life cycle constraints available (Not)	Product life cycle constraints feasible (Not)	Product life cycle constraints accurate/safety (Not)	Product life cycle constraints reliable (Not)	Product life cycle constraints maintainable (Not)

Table 5.9 The Constraint-based DRM Matrix (Role-interaction Level).

Risk Criteria Design Constraints	**Availability**	**Feasibility**	**Accuracy /Safety**	**Reliability**	**Maintainability**
Designer constraints	Designer constraints available (Not)	Designer constraints feasible (Not)	Designer constraints accurate/ safety (Not)	Designer constraints reliable (Not)	Designer constraints maintainable (Not)
Knowledge constraints	Knowledge constraints available (Not)	Knowledge constraints feasible (Not)	Knowledge constraints accurate/ safety (Not)	Knowledge constraints reliable (Not)	Knowledge constraints maintainable (Not)
Communication constraints	Communication constraints available (Not)	Communication constraints feasible (Not)	Communication constraints accurate/ safety (Not)	Communication constraints reliable (Not)	Communication constraints maintainable (Not)
Conflict constraints	Conflict constraints available (Not)	Conflict constraints feasible (Not)	Conflict constraints accurate/ safety (Not)	Conflict constraints reliable (Not)	Conflict constraints maintainable (Not)
Performance constraints	Performance constraints available (Not)	Performance constraints feasible (Not)	Performance constraints accurate/efficient (Not)	Performance constraints reliable (Not)	Performance constraints maintainable (Not)
Customer constraints	Customer constraints available (Not)	Customer constraints feasible (Not)	Customer constraints accurate/efficient (Not)	Customer constraints reliable (Not)	Customer constraints maintainable (Not)

5.5 Implement Matrix into Conceptual Framework for Risk Mapping and Measuring

According to the conceptual design risk management (DRM) framework which was presented in Chapter 4, the collaborative design risk management principally takes account of four major design stages: “conceptual design, embodiment design, detailed design and manufacturing design” (Pahl *et al.*, 2007, p.4). The process of DRM can be concluded into three major aspects: “risk identification, risk assessment and risk mitigation” (PMI, 2008). The analysis of collaborative design risk variables are mainly conducted through three distinctive collaborative levels: task-dependency level, role-interaction level and resource-integration level (Wang *et al.*, 2002; Yesilbas and Lombard, 2004; Robin *et al.*, 2007; Ruan and Qin, 2008). Sources of collaborative design risks are generated from potential design constraints that concluded from these collaborative levels.

Table 5.10 The Constraint-based DRM Matrix (Resource-interaction Level).

Risk **Criteria Design Constraints**	**Availability**	**Feasibility**	**Accuracy /Safety**	**Reliability**	**Maintainability**
Financial constraints	Financial constraints available (Not)	Financial constraints feasible (Not)	Financial constraints accurate/ safety (Not)	Financial constraints reliable (Not)	Financial constraints maintainable (Not)
Technical constraints	Technical constraints available (Not)	Technical constraints feasible (Not)	Technical constraints accurate/ safety (Not)	Technical constraints reliable (Not)	Technical constraints maintainable (Not)
Legal constraints	Legal constraints available (Not)	Legal constraints feasible (Not)	Legal constraints accurate/ safety (Not)	Legal constraints reliable (Not)	Legal constraints maintainable (Not)
Information constraints	Information constraints available (Not)	Information constraints feasible (Not)	Information constraints accurate/ safety (Not)	Information constraints reliable (Not)	Information constraints maintainable (Not)
Ergonomic Constraints	Ergonomic constraints available (Not)	Ergonomic constraints feasible (Not)	Ergonomic constraints accurate/ safety (Not)	Ergonomic constraints reliable (Not)	Ergonomic constraints maintainable (Not)
Material constraints	Material constraints available (Not)	Material constraints feasible (Not)	Material constraints accurate/ safety (Not)	Material constraints reliable (Not)	Material constraints maintainable (Not)

The function and development of the risk matrix is to helps designers and design managers to map design risk variables accurately and measure risk values in terms of estimated risk probability and consequence. The mapping and measuring are mainly based on the identified design constraints and evaluated risk criteria. The estimated risk probability and consequence mainly rely on designers and design managers experiences and knowledge.

Based on the DRM framework, the risk matrix can be incorporated to map and measure design risk variables during a design process in accordance with the following procedures:

1. Participants should choose design stage to set out DRM practice. In this study, Design stage is composed of four aspects: “conceptual design, embodiment design, detailed design and manufacturing design” (Pahl *et al.*, 2007).

2. Based on the proposed DRM matrix, in each specific design stage, design risk could be mapped and measured at three distinctive collaborative levels respectively: task-dependency level, role-interaction level and resource-integration level. More importantly, in each selected level, the mapping and measuring of design risk variables are entirely complies with a common risk management methodology which includes three phases: “risk identification (mapping), assessment (measurement) and treatment (mitigation)” (Conroy and Soltan, 1998; Raz and Michael, 2001; Kayis *et al.*, 2007).

3. In the risk identification stage, participants should present corresponding design risk variables. These are captured according to identified design constraints and evaluated risk criteria. These design risk variables are intended to be demonstrated primarily by relating to TOC and concerning a set of criteria: availability, feasibility, accuracy/safety, reliability and maintainability.

4. Then in the risk assessment stage, participants should assign a potential

probability value and an estimated consequence value for each identified design risk variables in terms of their knowledge and experience. Risk is assessed by two dimensions: “risk probability and risk consequence” (Ward, 1999; Baccarini and Archer, 2001; Pyra and Trask, 2002; Ahmed *et al.*, 2007; Kayis *et al.*, 2007). More specifically, risk probability indicates “a chance of a risk variable occurring while risk consequence represents an outcome generated from the risk variable” (Ahmed *et al.*, 2007). Note that varying degrees of probability and consequence values can influence the whole result of the design risk variables. Risk probability and consequence constitutes for the risk assessment function (Patterson and Neailey, 2002).

5. Then, a calculation of overall risk magnitude in each level should be conducted in term of the DRM calculation formula: $R=\sum (P_n * C_n) / \sum (C_n)$, n=1, 2, 3… In this formula, P_n represents risk probability; C_n represents risk consequence. Subsequently, a corresponding mitigation solution for each collaborative design risk variable should be given.

6. With regard to three distinct levels’ risk values, participants should calculate overall collaborative risk magnitude in each design stage and create risk report. $R= (R_1+R_2 +R_3)/3$, which R_1, R_2, R_3 represents risk magnitude in task-dependency level, role-interaction level and resource-integration level respectively.

7. Ultimately, a calculation of overall project risk magnitude should be conducted: $R_p= (R_c+ R_e +R_d+ R_m)/4$, where R_p represents overall project risk value, R_c represents conceptual design stage overall risk value, R_e represents embodiment design stage overall risk value, R_d represents detailed design stage overall risk value, R_m represents manufacturing design stage overall risk value.

5.6 Conclusion

This chapter describes the development of a constraint-based DRM matrix, which provides a structured and proactive approach to map and measure design risk variables in an accurate and efficient manner. The development of the matrix caters for collaborative design projects by viewing the accumulative design constraints as a result of risk variables within the level of tasks-dependency, role-interaction and resources-integration (Wang *et al.*, 2002; Yesilbas and Lombard, 2004; Robin *et al.*, 2007; Ruan and Qin, 2008). This constraint-based risk analysis could not be tackled in a traditional way of risk management. The design constraints and risk criteria are generated from literature review. Moreover, they are evaluated appropriately by conducting a questionnaire survey after an initial check. By performing the DRM matrix, these design constraints are utilised in association with risk criteria for the generation of specific design risks and facilitating the measure of risk probability and consequence. In addition, with regard to these assigned probability and consequence value, an overall project risk magnitude can be calculated.

However, probability indicates “a chance of a risk event occurring, while risk consequence represents an outcome generated from the risk variables” (Ahmed *et al.*, 2007). The above weighting method is mainly based on probabilistic risk assessment, which is usually regarded as subjective, often affected by individual preferences, knowledge and bias expertise. In the next chapter, a Bayesian weighting method is introduced which attempts provide a more objective and accurate way for risk computation, and a simulation prototype is developed for further case study evaluation.

Chapter 6 A Bayesian Weighting Method for Risk Computation and Simulation

6.1 Introduction

The preceding chapter presented a constraint-based DRM matrix for mapping and measuring crucial design risk variables within a collaborative design context. Design constraints and risk criteria are evaluated attempting to aid design risk analysis at three collaboration levels in four design domains respectively. PRA is used for risk computation, in which risk is assessed in two dimensions: “risk probability and risk consequence” (Patterson and Neailey, 2002; Pyra and Trask, 2002, Ahmed *et al.*, 2007). More specifically, risk probability specifies an odd of risk variables occurring, whilst risk consequence presents the impact or severity that resulting from the corresponding risk variables.

However, although this approach can provide a basis for risk assessment, it mostly relies on the assessment of individual perspectives and judgments, which might be significantly affected by in preferences and bias. In addition, quantitative data “is hard to achieve and is restricted to very small domain of the problem where historical trends could be sustained” (Ahmed *et al.*, 2007, p.28). Thus, it is indispensable to find a more appropriate risk assessment method for DRM, which can combine subjective assessment techniques and quantitative approaches together.

The objective of this chapter is to explore and investigate “how to measure the design risk magnitude in a more appropriate and efficient way”. A Bayesian weighting method is developed for risk computation by means of incorporating with the proposed DRM matrix. In addition, a visual-based prototype is developed by Visual.Basic.NET for simulation which attempts to assist further objective industry practice (see Figure 6.1).

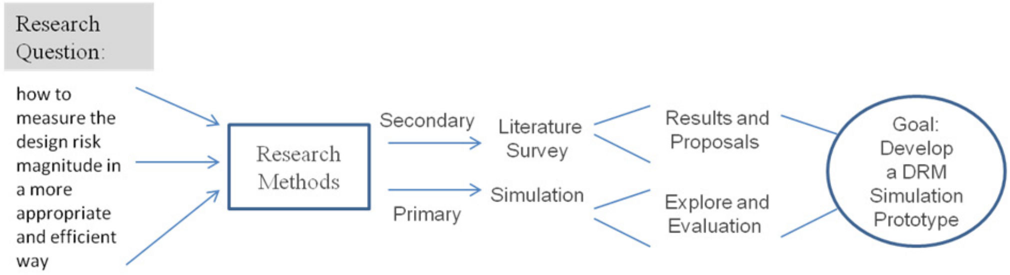


Figure 6.1 The Development Process of DRM Simulation Prototype.

6.2 Research Method

In this chapter, a literature survey and a prototype simulation are conducted for the exploration of the proposed research question. More specifically, the literature survey is performed to explore and compare the existing risk assessment techniques that can be utilised for enhancing measurement of collaborative design risk variables in the realm of design management, and the prototype simulation is developed to implement the selected risk mapping and measuring method and display the practical application for further evaluation.

6.2.1 Literature Survey

The relevant literature that applies to assessing risk in the field of design management is reviewed for informing the enhanced risk analysis approach. Both qualitative and quantitative techniques of assessing risk in design are summarised. Moreover, the limitations of conventional methods in the literature are discussed. A Bayesian weighting method based on Bayesian theorem is proposed.

6.2.2 Simulation

Simulation provides an effective way for analysing complex processes and system. Normally, simulation for prediction is “used as a substitute for experimentation and intervention on the actual system when such experimentation is greatly time consuming, costly, and inconvenient” (Gilbert and Troitzsch, 2005). More specifically, simulation could provide realistic feedback before designing real systems. Consequently, the researchers may explore or compare the merits of design alternatives in design stage rather than in manufacturing stage. Thus, the cost of design can be decreased significantly. Moreover, “by approaching a project at a higher level of abstraction, simulation can help the researchers for enhancing comprehensive understanding of project’s structures and components regardless of its inherent complexity” (Harrell *et al.*, 2004).

In this study, a simulation incorporated with the constraint-based DRM matrix and the enhanced weighting method is developed to evaluate the DRM tool. Unified Modelling Language (UML) and Visual Basic.NET have been utilised within this development. More specifically, UML is applied to generate an UML User Case Diagram in order to provide a holistic guide. Visual Basic.NET is employed for creating a structured graphic interface and fulfilling the interactive information flows of the DRM simulation software prototype.

6.3 Results of Literature Survey

A number of researches are found in the relevant design risk measurement area. After the identification of risk variables, the features will be assessed and evaluated in order to assist further analysis for mitigation (Ahmed *et al.*, 2007). “Measurement metrics for risk need to be determined so that the metrics can be used for computation of risk magnitude and risk analysis leading to risk mitigation plans” (Amornsawadwatana, 2002). The state-of-the-art risk assessment methods for the design industry can be categorised into two groups: qualitative risk approaches and quantitative risk analysis. Table 6.1 shows that there are several conventional risk assessment methods used in the analysis of design area. More specifically, most these approaches are based on qualitative or quantitative analyses, which essentially rely on inputs and outputs. They are intended to estimate and identify the major sources of risk variables involved in the design process.

6.3.1 Qualitative Risk Analysis Methods

Qualitative methods of risk analysis in design are the most widespread in practice. They are mainly determined by expert knowledge and experience that concluded from a previous system and practice (Walton, 2002). Most organisations use quantitative methods that rely on qualitative approaches as inputs to their analysis. The goal of the qualitative methods in managing risk is to estimate the sources of risk that provides the greatest exposure of risk variables to a design project.

Table 6.1 Conventional Risk Assessment Methods.

Probabilistic Risk Assessment	Engineering and design (Stewart and Melchers, 1997;Pritchard, 2001; Wertz,2002; Chapman and Ward, 2003; Crossland *et al*., 2003; PMI, 2008; Ahmed *et al*., 2007)
Probability and Impact grids	All (Stewart and Melchers, 1997; Royer, 2000; Pyra and Trask, 2002; Ahmed *et al*., 2007)
Fuzzy Approach	Engineering and design (Wood and Antonsson, 1990; Thurston and Carnahan,1992; Antonsson and Otto, 1995; Vanegas and Labib, 2005)
Risk exposure analysis	All (Roberts, 2000)
Portfolio Theory	Financial domain (DeMaio *et al*., 1994; Clarke and Varma, 1999; Dickinson *et al*., 2001; Archer and Ghasemzadeh, 1999; Caron *et al*., 2007; PMI, 2008)
Utility Theory	Engineering Systems (Thurston and Carnahan,1992; Walton, 2002)

Risk Exposure Analysis

The most commonly-used type of qualitative analysis is through the use of exposure charts, such as the one presented in Figure 6.1 (Roberts, 2000). As shows in the exposure chart, sources of risk variables are identified and evaluated individually based on their probability of occurrence and impact of consequence. Designers and decision makers can then concentrate the majority of their consideration on the area of anxiety as indicated in the Figure 6.2. Furthermore, Roberts suggested relevant extensions to the classical risk exposure approach by using the exposure Chart as a tool to focus on sources of risk that should be considered for more detailed analysis techniques (Roberts, 2000). These more detailed techniques would include some of the quantitative techniques that are presented in next section.

Probability and Impact Grids

Risk events "represent on a grid consisting of probability on one axis and impacts on another are often used to define the threshold regions on the grid" (Risk Management Standard AS/NZS 4360, 1999; Chapman and Ward, 2003; Stewart and Melchers, 1997; Royer, 2000; Pyra and Trask, 2002; Ahmed *et al.*, 2007). Probability and impact grids present "a simple format for showing relative importance of risk events. Figure 6.3 shows an example of a probability and impact grid" (Royer, 2000).

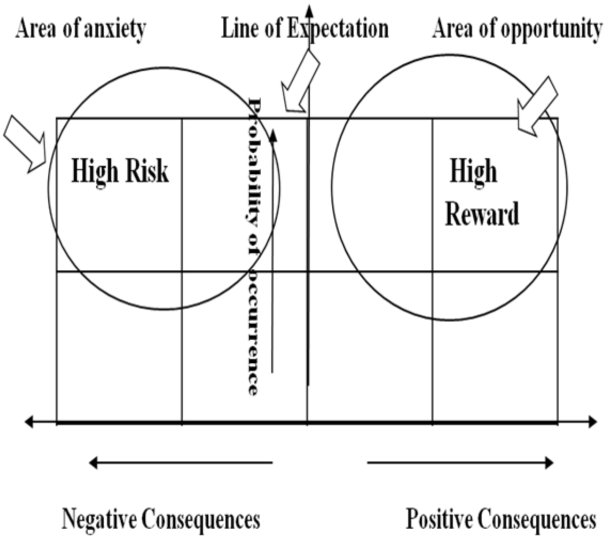


Figure 6.2 Probability and Consequences Exposure Chart (adapted from Roberts, 2000).

6.3.2 Quantitative Risk Analysis Methods

In addition to qualitative risk assessment, a number of quantitative risk analysis methods are investigated in the engineering design industry. Several techniques are found in the literatures that are currently applied for risk analysis in the project level. They are summarised in this section.

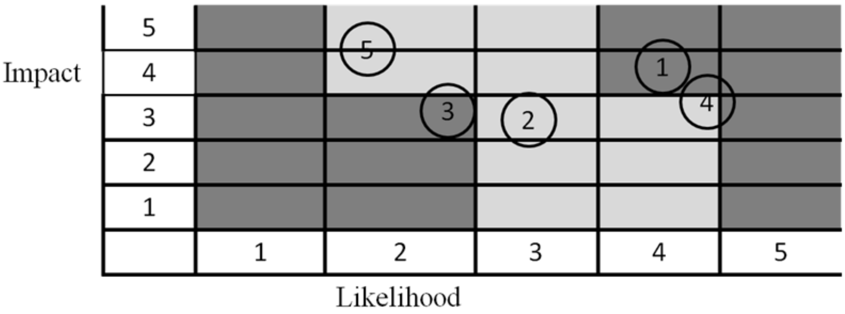


Figure 6.3 A Probability and Impact Grid (adapted from Royer, 2000).

Probabilistic Risk Assessment (PRA)

Probabilistic Risk Assessment (PRA) is "an approach to calculating a final probability of failure, and relies on component probabilities of failure and event probabilities to be accurate" (Wertz, 2005, p.28). The field of probabilistic risk analysis has evolved into a standard of systems analysis (Stewart and Melchers, 1997). The most common implementation of PRA is through quantifiable fault trees and hazard modes and effects analysis. More specifically, the process of conducting probabilistic risk analysis is contained in Figure 6.4 (Modarres and Kaminskiy, 1999). Therefore, PRA is generally accepted as a useful method of assessing risk for engineering design at the project level. More importantly, it has been successfully implemented in systems development (Walton, 2002). As Paulos (2005) stressed, PRA is "a structured, disciplined approach to analysing system risk".

Utility Theory

The foundations of utility theory were developed by von Neumann and Morgenstern and Savage in 1950s (Thurston and Carnahan, 1992). Numerous successful applications are implemented, some of which are extended to the multi-dimensional design problems (Thurston and Carnahan, 1992). Generally, Utility theory is introduced as a method sometimes employed in Probabilistic Risk Assessment (PRA) to deal with inconsistent outcomes by the normalising consequences of events in order that individual event risks can be understood readily. Utility theory provides a means to map relative preference to an attribute at different levels, thus defines a trade-off curve of worth of achieving an attribute in a number of different states (Walton, 2002). More details of application to the design problems and the superiority of utility analysis over weighted averaged methods can be found in Thurston and Carnahan (1992).

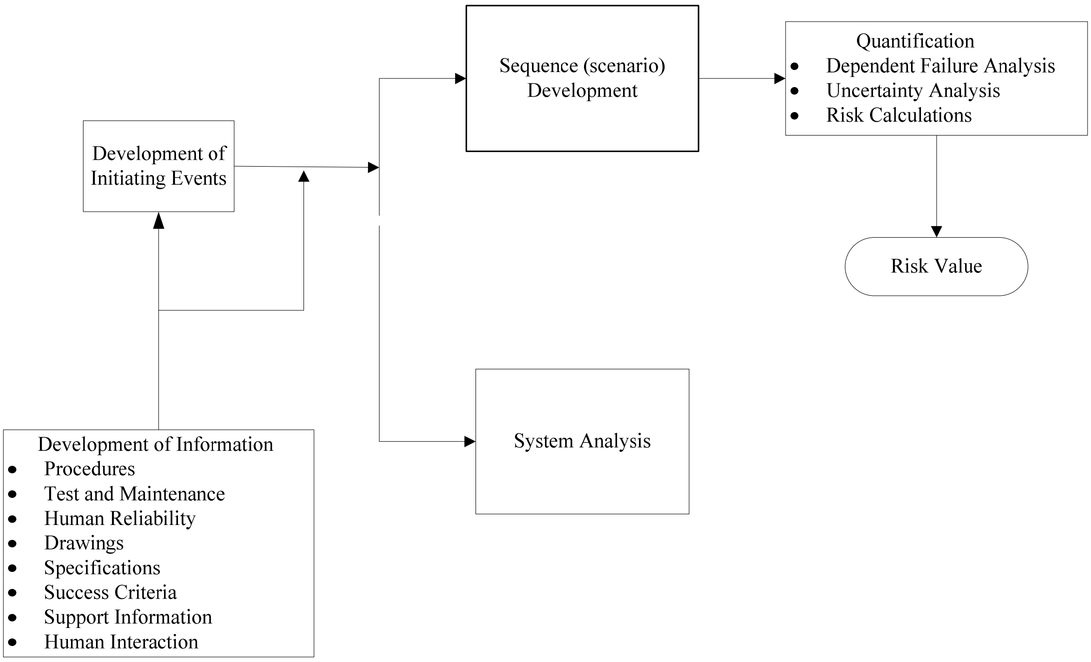


Figure 6.4 The Probabilistic Risk Assessment (PRA) Process (adapted from Modarres and Kaminskiy, 1999).

Fuzzy Approach

Fuzzy approach is applied in design by several researchers (Wood and Antonsson, 1989; Thurston and Carnahan, 1992; Antonsson and Otto, 1995). Particularly, fuzzy approach is introduced by some researchers in risk analysis for design evaluation

(Vanegas and Labib, 2005). Anotonnson and Otto (1995) provided an approach to manage uncertainties and risk in design by using the fuzzy approach applied to design. This method provides one of the first quantitative approaches to create input ranges to set based design, but is only supported during the preliminary design stage.

Thurston and Carnahan (1992) compared two approaches for design evaluation, fuzzy set theory, and multi-attribute utility analysis. It is concluded that multi-attribute utility analysis is preferred in preliminary design, where performance levels can be expressed quantitatively; whereas fuzzy set theory is appropriate in the earliest stages of conceptual design that are based on linguistic performance levels. In addition, Maglaras (1995) applied fuzzy set theory to the design process and explain how results differ from results obtained using probabilistic techniques. He demonstrated that probabilistic optimisation could result in a better design than the result from fuzzy set optimisation.

However, these researches are in their infancy; while some investigations have very useful proposals, others have failed to treat their problems effectively (Vanegas and Labib, 2005). Moreover, fuzzy approach is only appropriately utilised in the preliminary design stage where the information is incomplete, imprecise, and vague (Vanegas and Labib, 2005).

Portfolio Theory

Portfolio theory compares “multiple projects with respect to risk in investment and returns” (DeMaio *et al.*, 1994; Clarke and Varma, 1999; Dickinson *et al.*, 2001; Ahmed, 2007). More specifically, projects are positioned on a matrix of risk magnitude and return, with high risk and low return projects being located at a different location to low risk and high return projects (DeMaio *et al.*, 1994).

In portfolio management, researches focus on “analysing the probability of the success or failure of projects and on analysing risks generated by the selection of a project ensemble during the balancing of a portfolio” (Archer and Ghasemzadeh, 1999; Caron *et al.*, 2007; Sanchez *et al.*, 2009). Walton (2002) used portfolio theory as potential organising method to manage uncertainty and guide decision makers in space systems conceptual design.

6.3.3 Limitation of Conventional Methods

As mentioned above, it describes a number of techniques included both qualitative and quantitative methods in the literatures, which are currently applied for design risk analysis. However, in practice, quantitative approaches are too intricate when encounter a large volume of risk items. Moreover, in most cases, quantitative data is “hard to achieve and is restricted to very small domains, some of them are not always available” (Ahmed, 2007).

In particular, some risks analyses attempt to predict risks impact in association with hypothetical situations, which might results in “impractical, unethical, or even impossible” of empirical data collection. This interprets that “scientific understanding of the underlying processes may itself be in doubt” (Ferson, 2005).

On the other hand, despite providing a basis method for risk assessment in the process of design, qualitative approaches are too subjective, and mainly rely on the assessment of designers’ perspectives and judgments. Considering an expert’s suggestions and opinions are the best information, most design employs qualitative assessment techniques for risk identification and evaluation. In this regard, using qualitative assessment techniques are usually more applicable for design risk management.

To sum up, the literature and current approaches to manage risk for collaborative design fall short in three main areas. Firstly, there is little understanding of methods to quantify the risk variables in the process of collaboration design from an upstream prospective. Secondly, there is no method to provide a more objective assessment for conducting risk management under a collaborative design environment. Thirdly, there is no method in literature that quantifies the potential risk variables by carrying multiple aspects of design collaboration. The current methods are focused on how to manage risk within the context of a single design process. Therefore, a more appropriate risk assessment method named Bayesian theorem is selected, which combines both subjective prediction and quantitative probabilistic computation.

6.3.4 A Bayesian Weighting Method

In current literature, several studies suggesting that Bayesian theorem can be valuable when applied during the process of risk analysis (Aven, 1997; Alexander, 2001; Pillai, 2004; Ferson, 2005; Castrup, 2007). Bayesian theorem provides a mathematical framework for performing inference, or reasoning, using probability (Olshausen, 2004), which certainly presented “an important way to select inputs for a risk analysis” (Ferson, 2005, p.4).

More importantly, the Bayesian weighting method might be useful in addressing complex and complicated issues under the circumstances that are similar to the process of collaborative design: “1) there may be little or even no empirical data available for some variables, 2) it may be necessary to employ subjective information from the analyst’s judgment or expert opinion, and 3) uncertainty about the mathematical model used in the assessment may be substantial” (Ferson, 2005, p.3).

Thus, Bayesian theorem for risk analysis “overcomes some limitations of the classical approach for parameter and model selection” (Chick, 2001; Draper, 1995). In particular, recent Bayesian studies are concentrating on “the potential significance of model uncertainty and how it can be incorporated into quantitative analyses. The Bayesian method is often recommended as the proper way to make formal use of subjective information such as expert opinion and personal judgments or beliefs of an analyst” (Ferson, 2005, p.3). Unlike other conventional quantitative methods, Bayesian computation is more flexible and data can be easily collected and analysed. The combination of Bayesian weighting method and DRM matrix would be applicable for the computation of the specified collaborative design risk variables.

Derivation of Bayesian Theorem

In general, Bayesian theorem is underpinned by the manipulation of conditional probabilities. For two variables x and y, with probabilities P (x) and P (y) $\neq 0$ respectively, the calculation of the conditional probability of x given y can be expressed as:

$$P\,(x/y) = P\,(xy)\,/\,P\,(y) \tag{1}$$

Where xy denotes the occurrence of both event x and y, P (xy) indicates the joint probability. The quantity P (x/y) implies the chance of occurrence of event x given the occurrence of B .

In Bayesian theorem, one of these "events" is the hypothesis x (i.e. probability risk), and the other is data y (i.e. estimated probability). The Bayesian theorem is used to judge the relative truth of the hypothesis a given the data y (Ferson, 2005):

$$P\,(x/y) = P\,(y/x)\,P\,(x)\,/\,P\,(y) \tag{2}$$

This equation simple denotes that the probability of x, given the condition y is equivalent to the probability of y, given the knowledge of a multiplied by the probability of x. The term P (x/y) is regarded as the posterior, which reflects the hypothesis probability after consideration of the data. P (y/x) is represented the likelihood, which assesses the probability of the observed data y resulting from the hypothesis a. In general, P (y/x) could be judged by the experts, who have sufficient knowledge and experience.

In this formulation, the term P (x) is called the prior probability in terms of hypothesis, which reflects prior knowledge before the data are considered. The specification of the prior is often the most subjective aspect of Bayesian theorem. The term P (y) is called the normalization factor, which derived from integrating P (y/x) P (x) over all x. It can be calculated by the law of probability as (Ferson, 2005):

$$\begin{aligned} P(y) &= P(y/x)\,P(x) + P(y/\text{not } x)\,P\,(\text{not } x) && (3)\\ &= P(y/x)\,P(x) + (1 - P\,(\text{not } y/\text{not } x))\,(1 - P(x)) && (4) \end{aligned}$$

Application with the DRM

In collaborative design risk management, after the identification of risk variables, the features are required to be evaluated in order to assist further analysis for risk mitigation (Ahmed *et al.*, 2007). The enhanced Bayesian weighting method is an extension of PRA, which combined estimated probability and Bayesian' rule and provide a unified approach for DRM. Moreover, Bayesian theorem requires incorporating prior beliefs into the estimation process other than simply considering the likelihood density. In addition, Bayesian theorem applies widely in many research areas by incorporating with simulation experiments and modelling.

In this study, the Bayesian weighting method refers to the application of parameter inference via observations probability of data in accordance with Bayesian' rule. The details of the method incorporated with DRM matrix is strictly in accordance with Section ***Derivation of Bayesian Theorem****,* which can be demonstrated as below:

1. Assumed that consequence resulting from the identified risk variables is known, and denoted as Probability Risk$_1$ (PR$_1$) and Probability Risk$_2$ (PR$_2$) (both value from 0 to 1), where PR$_1$ refers to P(y/x), which indicates risk magnitude when risk variables occurred. Whereas PR$_2$ refers to 1-P (not *y*/not *x*), represents risk magnitude generated when risk variables not occurred.

2. Designer needs to assign a value of estimated probability (E_p) for a risk variable in terms of their judgments, experience and knowledge, where E_p refers to P(*x*).

3. Calculate the estimated risk (E_r) by formulation :

$$E_r = PR_1 * E_p + PR_2 * (1 - E_p)$$

   Where the estimated risk (E_r) refers to P(*y*), which represents risk summation, involved both situations whether risk variable arises or not.

4. According to Bayesian's rule, compute Bayesian probability (B_p), or names

posterior probability , which refers to P (*x/y*) given that a risk variable occurred, then

$$B_p = E_p * PR_1 / E_r$$

5. Calculated Bayesian risk (B_r) : $B_r = B_p * PR_1 + (1 - B_p) * PR_2$

6.4 Develop a Prototype for Simulation

The previous section proposed a Bayesian weighting method to reinforce risk assessment for the DRM tool based on the Bayesian theorem. In order to evaluate DRM tool, a simulation prototype incorporated with the DRM matrix and enhanced weighting method is developed. Due to simplification smaller, less detailed, less complex, simulation prototype can be applied to conduct a verification of the DRM implementation in practical design companies in convenient manner of less time consuming, lower cost and no risk. Simulation for evaluation or prediction is employed as an alternative for many research experimentations on the real system (Axelrod, 1997). In this research, UML and Visual Basic.NET are adopted to create a DRM simulation prototype with structured interface and interactive information flows.

6.4.1 Simulation Fundamentals

Unified Modelling Language (UML)

UML is viewed as “a versatile and principal tool in software development” (Brittion and Doake, 2005). It provides “an industry standard for the analysis and design of software” (Fowler and Scott, 1997).

In comparison with other modelling language, “UML not only offers a standard means to write a software system’s blueprints, including conceptual things such as project processes and system functions, but also concrete things, such as programming language statements, database schemas, and reusable software components” (Booch, 2000). Besides, UML can be incorporated with many programming languages, such as Java, C++, and Visual Basic. In addition, UML provides “a set of graphical elements that allows the user to structure a prototype in a more efficient manner” (Brittion and Doake, 2005). As a result, UML is adopted to structure and complete the interactive information flows of the proposed DRM simulation prototype.

Visual Basic.NET

With the developing of computer technology, various programming languages can be utilised to structure a software prototype. In the process of software design and development, Visual Basic.NET, C, C++ and Java are the prevalent and commonly used programming languages. In attempting to readily create a user-centred interface, fulfil multi-functional of the DRM tool evaluation, a rapidly applicable and database accessible programming language needs to be selected “as a simple and friendly interface that can increase the usability of the system” (Lynch and Cross, 1991).

Visual Basic.NET is an object-oriented computer programming language with simple structure and executable code. More specifically, Visual Basic.NET enables Dynamic Language Runtime (DLR), Graphical User Interface (GUI) and Rapid Application Development (RAD) applications. The GUI of VB brings “intuitively appealing perspectives for the management of the program structure in the lager and various types of entities, such as classes, modules, procedures, forms and so on” (Holzner, 2003). Visual Basic.NET is highly optimised to support RAD. Moreover, Visual Basic.NET is regarded as an integrated, interactive development environment (IDE). In addition, Visual Basic.NET offers a more efficient way to access databases by using Data Access Objects (DAO). Thus, Visual Basic.NET is widely used as an appropriate method for the development of a prototype due to owing to its applicability, accessibility, and simplicity.

UML Use Case Diagram (UCD)

UCD is the starting point for UML-based software development projects. It consists of actors and use cases, which illustrates the functionality that is provided by the system. The key objective of UCD is to aid users to communicate with the system, which allows the development programmer to visualise the systems functional requirements. The requirements include the relationship of interactive users and the core design and development processes. In general, UCD can be applied in two ways: "one is that all use cases used for the complete system; another is a breakout of a particular group of use cases with related functionality" (Xie *et al*., 2008).

According to the conceptual DRM framework, a DRM tool is recommended to integrate the features of collaboration with design risk management process in a manner of a closed management loop. Designers and managers execute a DRM tool to make a more appropriate decision for avoiding chief risk of design project. Consequently, the DRM tool should be simulated for the capability of providing a holistic analysis for individual designers, as well as project managers and stakeholders. A UML Use Case Diagram is created in Figure 6.5.

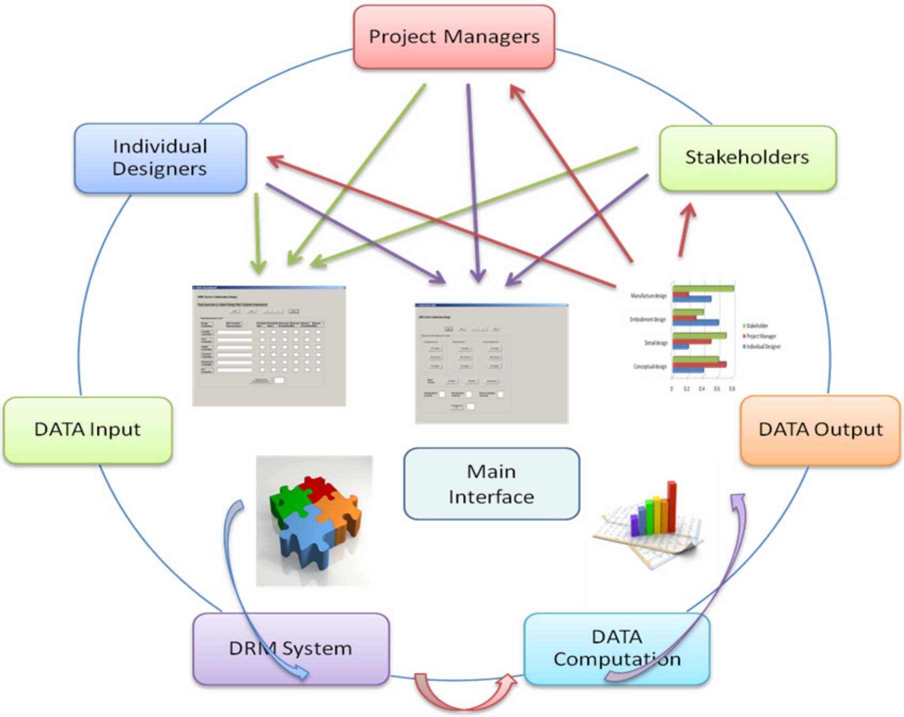


Figure 6.5 A UML Use Case Diagram for DRM Prototype.

This UCD is typically applied for the construction of the DRM prototype. As shows in Figure 6.5, the flows and functions that the example system provides are clearly presented. Both project managers, individual designers and other stakeholder are considered as potential users for the proposed DRM tool. The diagram indicates the explicit way of data input and output of DRM system.

6.4.2 Simulation Development

According to Gilbert and Troitzsch (2005), simulation with a particular type of modelling is simplified, less detailed, less complex. During the process of the development of the DRM prototype, there are three tasks needs be simulated: First, a comprehensive DRM structure need to be simulated based on risk management process and collaborative design features. Second, the process of DRM data collection, saving and analysis is required to be simulated in the software prototype. Third, the DRM results presentation needs to be simulated for further analysis and discussion.

Comprehensive Risk Management Setting

Concerning the nature of collaborative design, an effective risk management structure should involve not only project managers but also individual designers and project stakeholders. Moreover, a normal product design process encompasses four design stages: “conceptual design phase, detail design phase, embodiment design phase, and manufacture design phase” (Pahl, 2007, p.4). Participants should choose design stage to set out the DRM practice. An entire risk assessment should be conducted incorporating all these four phases. In each phase, an analysis must follow three collaborative levels in terms of the proposed DRM conceptual framework (see Chapter 4): task-dependency level, role-interaction level, and resource-integration level. In addition, a completed risk management process includes three phases: risk mapping, measurement, and mitigation, which also needs to be considered during the process of DRM software prototype development (Conroy and Soltan, 1998; Raz and Michael, 2001; Kayis *et al.*, 2007).

Data Input and Saving

After all the risk management processes were structured for DRM prototype, the following tasks become how to simulate input, computation and saving of the DRM data for each participant separately. Based on the DRM conceptual framework and DRM matrix, users need to input data in four design stages individually in terms of collaborative level. First, in each specific design stage, users need to identify and represent crucial risk variables in an accurate manner with the aid of constraint-based DRM matrix. Second, users need to assign probability risk value and estimated risk probability for each identified risk variable according to their own experience and knowledge. Third, users need to recommend corresponding risk mitigation suggestions with the purpose of providing solutions for future risk analysis. Data should be entered, saved and altered easily and simply in terms of graphic interface.

Multiple Form of Output

The output is presented in the form of reports and graphs. According to the design DRM computation formulae, the overall risk for different collaborative levels in each design stage can be calculated in terms of assigned probability risk and estimated probability. Thus, for each design stage, three reports are generated in accordance with three collaborative levels, which encompassed overall risk value; six identified risk variables, assumable probability risk values and estimated occurrence probability. Moreover, the estimated risk value and Bayesian probability and Bayesian risk are generated automatically by means of the established formulae (see section 6.3.4). In addition, a recommended risk mitigation strategy is also contained in the report. In light of these accessible reports, users can print them out for further risk analysis and group discussion.

A presentation of two types of graphic diagrams for output is also provided in the simulated prototype. One graphic diagram shows the comparison of overall risk values of different collaborative levels in each design stages for a single user. Another graphic diagram presents the comparison of overall risk values of all users for each design stage. With the aid of these graphic diagrams, users can visualise and compare the results from different users straightforwardly.

6.4.3 DRM Simulation Prototype

A DRM simulation prototype is created in terms of UML and Visual.Basic.NET. This section presented a detailed process of how the DRM tool can be implemented in context of virtual design collaboration.

Initial Risk Management Guide

In general, three types of users are involved in the DRM virtual practice: designer, design manager and stakeholder. Participators can choose his or her role by clicking on the matching button in the entrance interface of DRM simulation prototype. After that, the user needs to input his/her personal details in order to build a profile for data saving (see Figure 6.6). This profile can be deleted, saved or altered in case of further inquiry. Thus, basic information is generally required in this step for subsequent data tracing and reference. Besides, four design stages are provided for collaborative design stage modelling: conceptual design, detailed design, embodiment design and manufacture design.

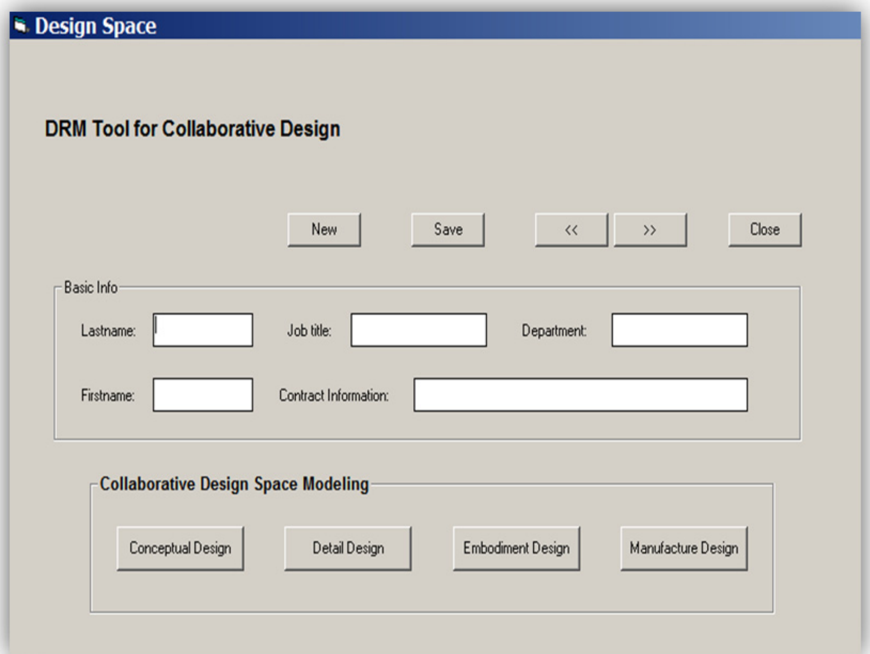


Figure 6.6 The Profile Interface of the DRM Tool for Collaborative Design.

Subsequently, an interface fulfilled with DRM functions is displayed in Figure 6.7. Based on the proposed DRM matrix, in each specific design stage, design risk can be mapped and measured in three distinctive collaborative levels correspondingly: task-dependency level, role-interaction level and resource-integration level. More importantly, in each selected level, the mapping and measuring of design risk variables are entirely compliant with common risk management methodologies and processes, which include three phases: “risk identification (mapping), assessment (measuring), and mitigation” (Conroy and Soltan, 1998; Raz and Michael, 2001).

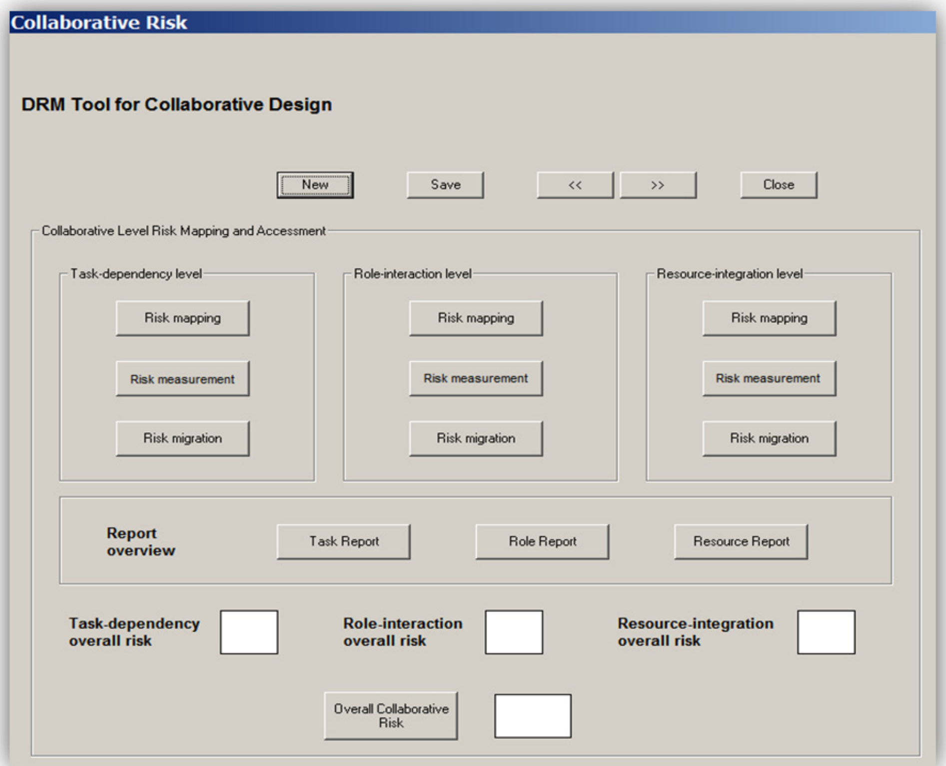


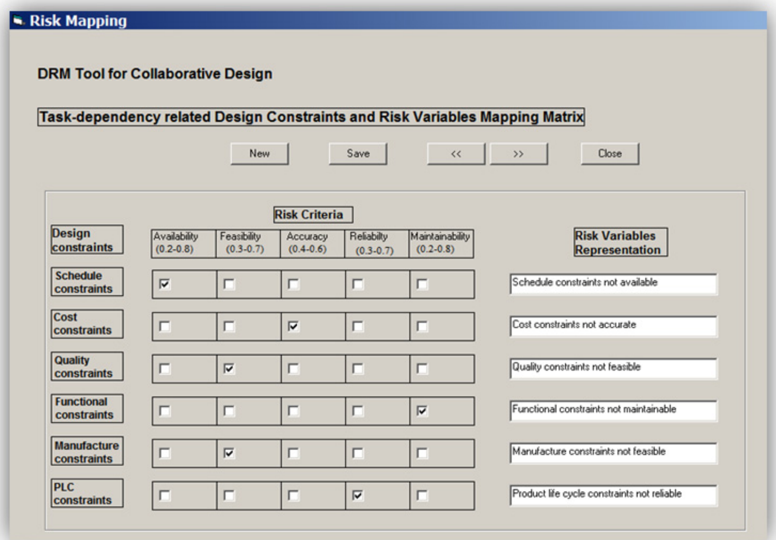
Figure 6.7 The Main Interface of the DRM Tool for Collaborative Design.

Flexible Data Input and Automatic Computation

DRM software prototype provides flexible data input and automatic computation function with the aid of DRM matrix. In risk identification (mapping) stage, participants should represent corresponding design risk variables, which can be captured in accordance with evaluated design constraints and risk criteria. These design risk variables are intended to be demonstrated mainly relating to TOC and encompass a wide range of risk criteria concerns: availability, feasibility, accuracy/safety, reliability and maintainability (see Figure 6.8 to Figure 6.10).

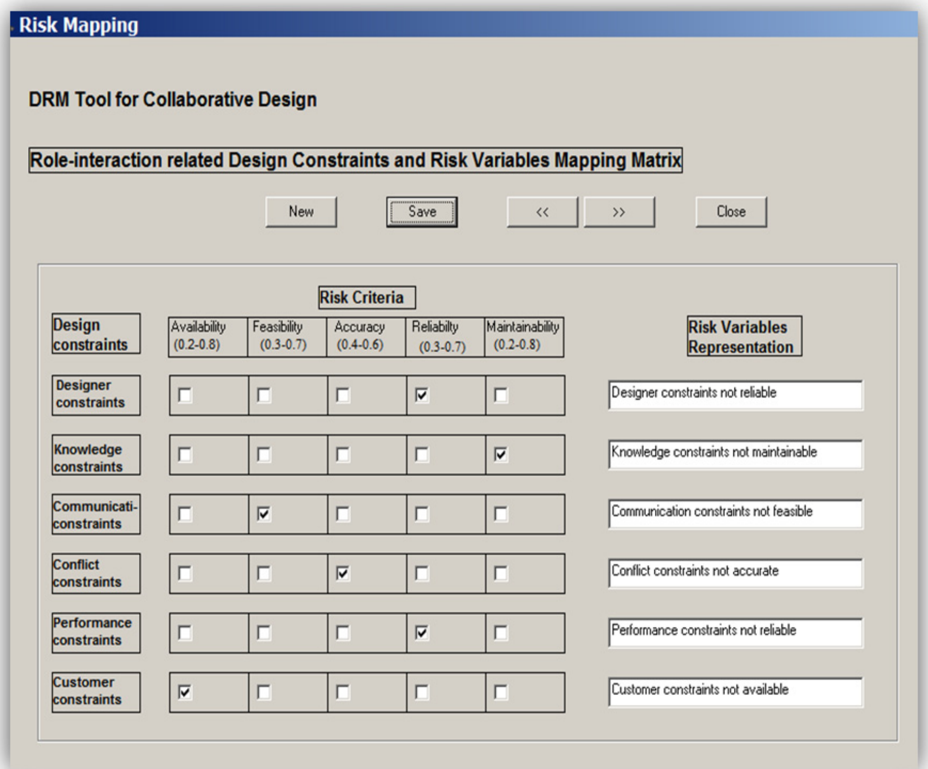
Afterwards, in risk assessment (measuring) stage, participants are required to input assumed probability risk value and to assign estimated probability value for each identified deign risk variables in terms of their experience and knowledge. DRM would produce value of estimated risk, Bayesian probability and Bayesian risk automatically on the basis of input data and Bayesian formulae. Moreover, in light of the value of Bayesian risk of each design risk variables, two categorises of overall risk value can be calculated. One indicated risk magnitude of different collaborative levels in the identical design stage. Another one presents overall collaborative risks of different design stages. These values also show in the main interface of the DRM tool (see Figure 6.11 to Figure 6.13).

In the stage of risk mitigation, users are prompted to provide their own suggestions of risk mitigation with the purpose of providing a solution for future risk analysis and discussion (see Figure 6.14 to Figure 6.16). For instance, in the task-dependency level, if schedule constraints are not available, participants can reschedule or discuss design project planning at a group meeting, or adopt an alternative schedule. If quality constraints are not feasible, a total quality management (TQM) might need to be considered.



Design constraints	Availability (0.2-0.8)	Feasibility (0.3-0.7)	Accuracy (0.4-0.6)	Reliabilty (0.3-0.7)	Maintainability (0.2-0.8)	Risk Variables Representation
Schedule constraints	☑	☐	☐	☐	☐	Schedule constraints not available
Cost constraints	☐	☐	☑	☐	☐	Cost constraints not accurate
Quality constraints	☐	☑	☐	☐	☐	Quality constraints not feasible
Functional constraints	☐	☐	☐	☐	☑	Functional constraints not maintainable
Manufacture constraints	☐	☑	☐	☐	☐	Manufacture constraints not feasible
PLC constraints	☐	☐	☐	☑	☐	Product life cycle constraints not reliable

Figure 6.8 Illustration of the Input of Task-dependency related Risk Variables.

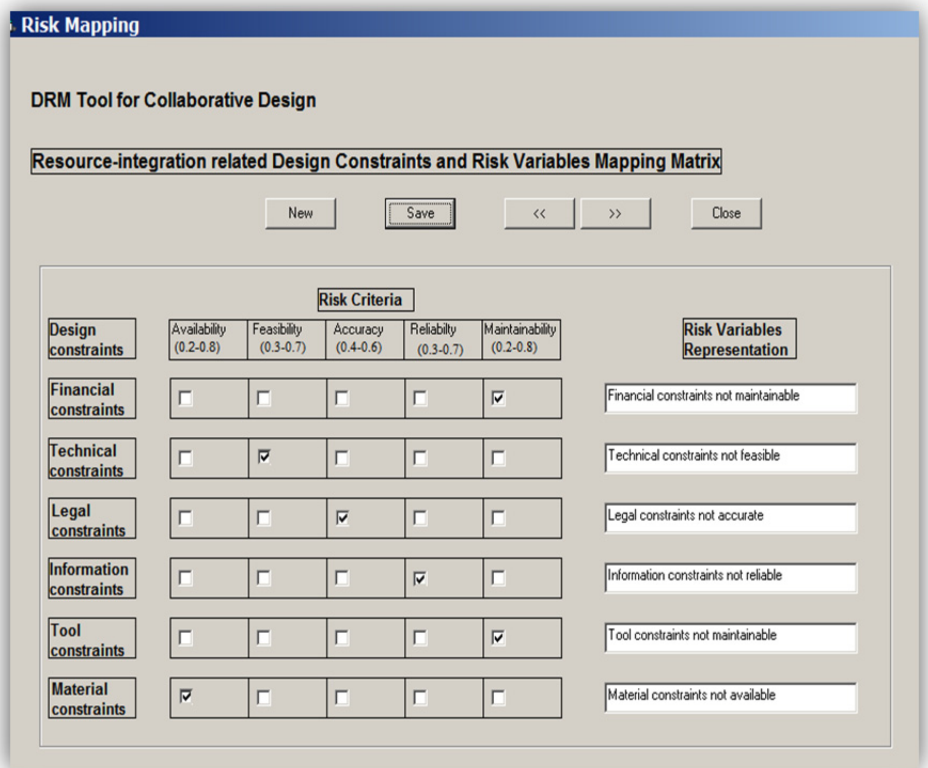


DRM Tool for Collaborative Design

Role-interaction related Design Constraints and Risk Variables Mapping Matrix

	Risk Criteria					
Design constraints	Availability (0.2-0.8)	Feasibility (0.3-0.7)	Accuracy (0.4-0.6)	Reliabilty (0.3-0.7)	Maintainability (0.2-0.8)	Risk Variables Representation
Designer constraints	☐	☐	☐	☑	☐	Designer constraints not reliable
Knowledge constraints	☐	☐	☐	☐	☑	Knowledge constraints not maintainable
Communicati-constraints	☐	☑	☐	☐	☐	Communication constraints not feasible
Conflict constraints	☐	☐	☑	☐	☐	Conflict constraints not accurate
Performance constraints	☐	☐	☐	☑	☐	Performance constraints not reliable
Customer constraints	☑	☐	☐	☐	☐	Customer constraints not available

Figure 6.9 Illustration of the Input of Role-interaction related Risk Variables.

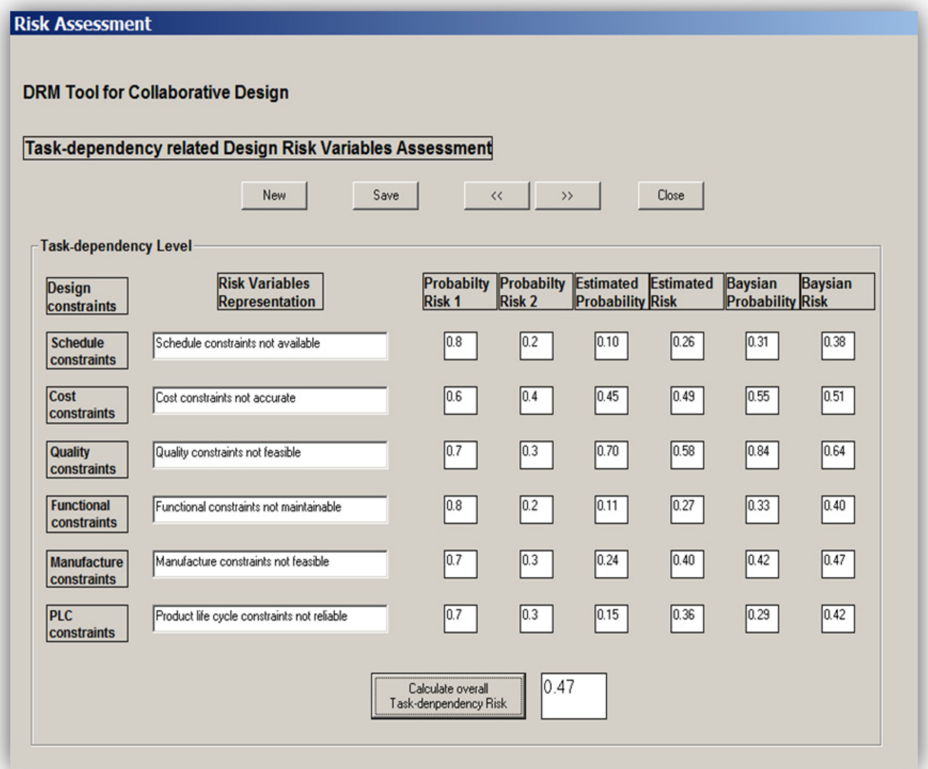


DRM Tool for Collaborative Design

Resource-integration related Design Constraints and Risk Variables Mapping Matrix

	Risk Criteria					
Design constraints	Availability (0.2-0.8)	Feasibility (0.3-0.7)	Accuracy (0.4-0.6)	Reliabilty (0.3-0.7)	Maintainability (0.2-0.8)	Risk Variables Representation
Financial constraints	☐	☐	☐	☐	☑	Financial constraints not maintainable
Technical constraints	☐	☑	☐	☐	☐	Technical constraints not feasible
Legal constraints	☐	☐	☑	☐	☐	Legal constraints not accurate
Information constraints	☐	☐	☐	☑	☐	Information constraints not reliable
Tool constraints	☐	☐	☐	☐	☑	Tool constraints not maintainable
Material constraints	☑	☐	☐	☐	☐	Material constraints not available

Figure 6.10 Illustration of the Input of Resource-integration related Risk Variables.



DRM Tool for Collaborative Design

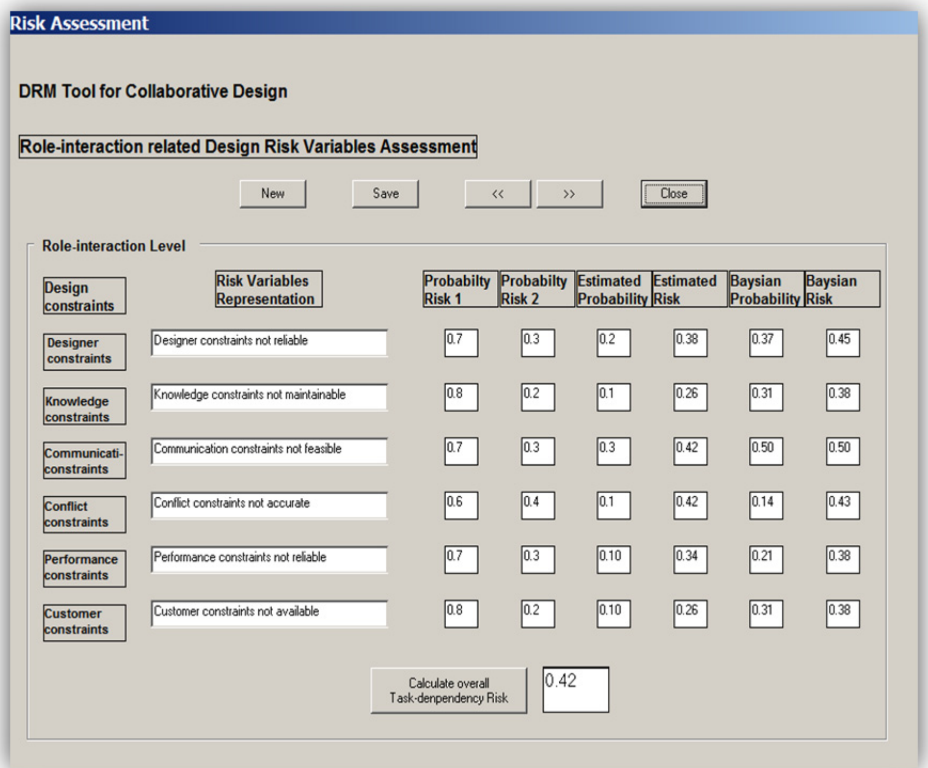
Task-dependency related Design Risk Variables Assessment

Task-dependency Level

Design constraints	Risk Variables Representation	Probabilty Risk 1	Probabilty Risk 2	Estimated Probability	Estimated Risk	Baysian Probability	Baysian Risk
Schedule constraints	Schedule constraints not available	0.8	0.2	0.10	0.26	0.31	0.38
Cost constraints	Cost constraints not accurate	0.6	0.4	0.45	0.49	0.55	0.51
Quality constraints	Quality constraints not feasible	0.7	0.3	0.70	0.58	0.84	0.64
Functional constraints	Functional constraints not maintainable	0.8	0.2	0.11	0.27	0.33	0.40
Manufacture constraints	Manufacture constraints not feasible	0.7	0.3	0.24	0.40	0.42	0.47
PLC constraints	Product life cycle constraints not reliable	0.7	0.3	0.15	0.36	0.29	0.42

Calculate overall Task-denpendency Risk: 0.47

Figure 6.11 Illustration of the Input of Estimated Probability and Risk in Task-dependency Level.



DRM Tool for Collaborative Design

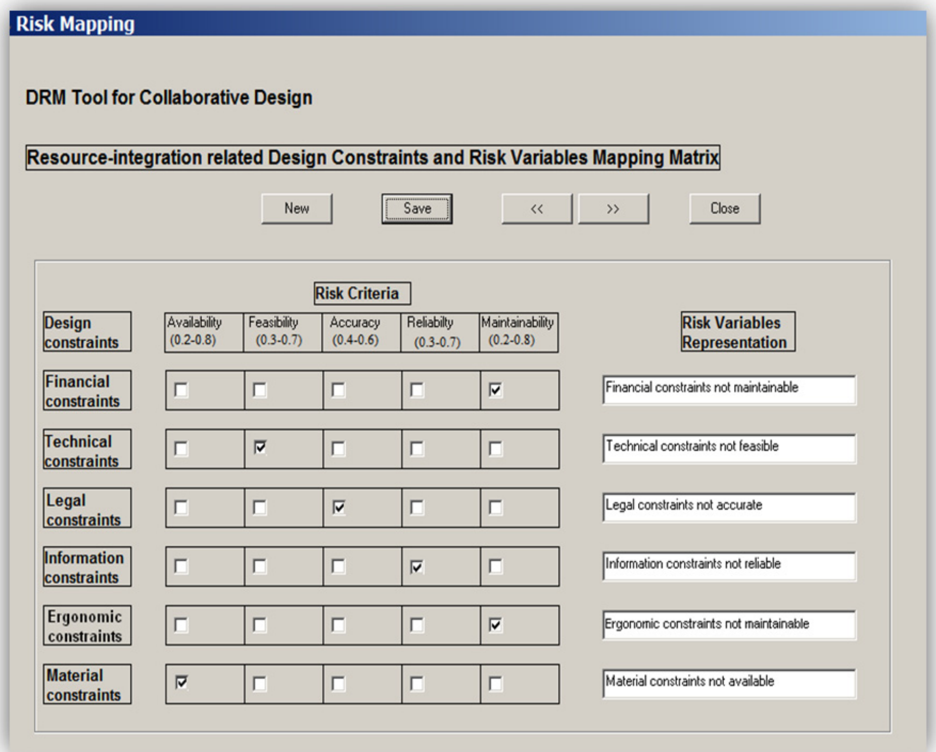
Role-interaction related Design Risk Variables Assessment

Role-interaction Level

Design constraints	Risk Variables Representation	Probabilty Risk 1	Probabilty Risk 2	Estimated Probability	Estimated Risk	Baysian Probability	Baysian Risk
Designer constraints	Designer constraints not reliable	0.7	0.3	0.2	0.38	0.37	0.45
Knowledge constraints	Knowledge constraints not maintainable	0.8	0.2	0.1	0.26	0.31	0.38
Communicati-constraints	Communication constraints not feasible	0.7	0.3	0.3	0.42	0.50	0.50
Conflict constraints	Conflict constraints not accurate	0.6	0.4	0.1	0.42	0.14	0.43
Performance constraints	Performance constraints not reliable	0.7	0.3	0.10	0.34	0.21	0.38
Customer constraints	Customer constraints not available	0.8	0.2	0.10	0.26	0.31	0.38

Calculate overall Task-denpendency Risk: 0.42

Figure 6.12 Illustration of the Input of Estimated Probability and Risk in Role-interaction Level.



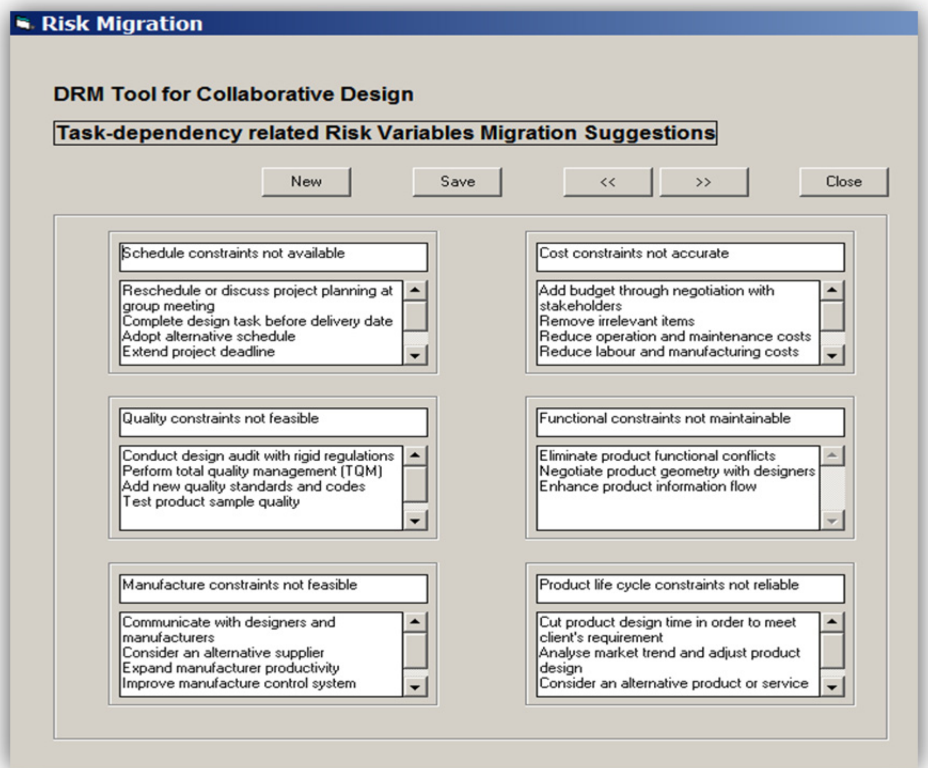
DRM Tool for Collaborative Design

Resource-integration related Design Constraints and Risk Variables Mapping Matrix

Risk Criteria

Design constraints	Availability (0.2-0.8)	Feasibility (0.3-0.7)	Accuracy (0.4-0.6)	Reliabilty (0.3-0.7)	Maintainability (0.2-0.8)	Risk Variables Representation
Financial constraints	☐	☐	☐	☐	☑	Financial constraints not maintainable
Technical constraints	☐	☑	☐	☐	☐	Technical constraints not feasible
Legal constraints	☐	☐	☑	☐	☐	Legal constraints not accurate
Information constraints	☐	☐	☐	☑	☐	Information constraints not reliable
Ergonomic constraints	☐	☐	☐	☐	☑	Ergonomic constraints not maintainable
Material constraints	☑	☐	☐	☐	☐	Material constraints not available

Figure 6.13 Illustration of the Input of Estimated Probability and Risk in Resource-integration Level.



DRM Tool for Collaborative Design

Task-dependency related Risk Variables Migration Suggestions

Schedule constraints not available

Reschedule or discuss project planning at group meeting
Complete design task before delivery date
Adopt alternative schedule
Extend project deadline

Cost constraints not accurate

Add budget through negotiation with stakeholders
Remove irrelevant items
Reduce operation and maintenance costs
Reduce labour and manufacturing costs

Quality constraints not feasible

Conduct design audit with rigid regulations
Perform total quality management (TQM)
Add new quality standards and codes
Test product sample quality

Functional constraints not maintainable

Eliminate product functional conflicts
Negotiate product geometry with designers
Enhance product information flow

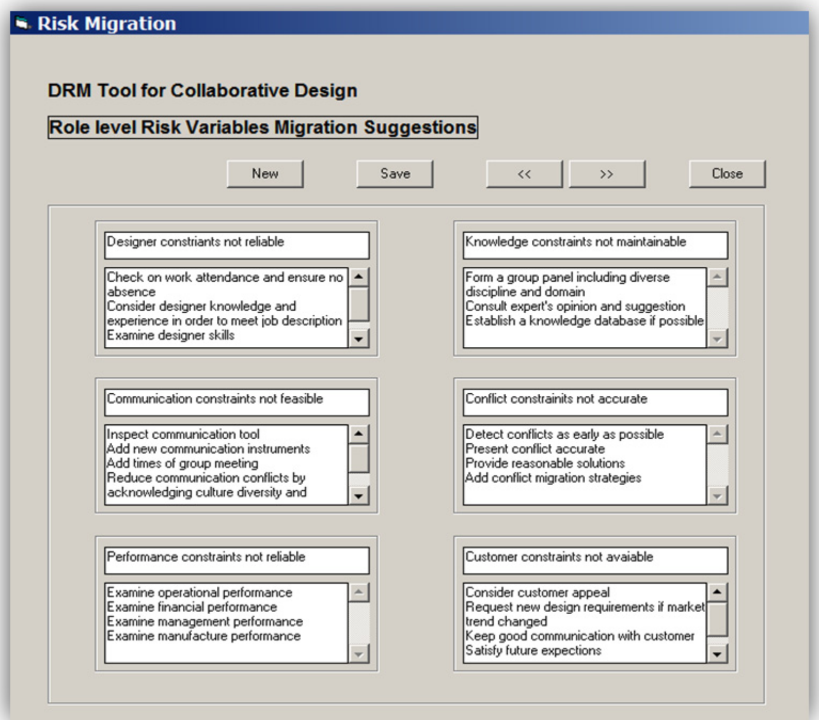
Manufacture constraints not feasible

Communicate with designers and manufacturers
Consider an alternative supplier
Expand manufacturer productivity
Improve manufacture control system

Product life cycle constraints not reliable

Cut product design time in order to meet client's requirement
Analyse market trend and adjust product design
Consider an alternative product or service

Figure 6.14 Illustration of the Input of Suggested Mitigated Risk Variables and Strategies in Task-dependency Level.



Designer constriants not reliable

Check on work attendance and ensure no absence
Consider designer knowledge and experience in order to meet job description
Examine designer skills

Knowledge constraints not maintainable

Form a group panel including diverse discipline and domain
Consult expert's opinion and suggestion
Establish a knowledge database if possible

Communication constraints not feasible

Inspect communication tool
Add new communication instruments
Add times of group meeting
Reduce communication conflicts by acknowledging culture diversity and

Conflict constrainits not accurate

Detect conflicts as early as possible
Present conflict accurate
Provide reasonable solutions
Add conflict migration strategies

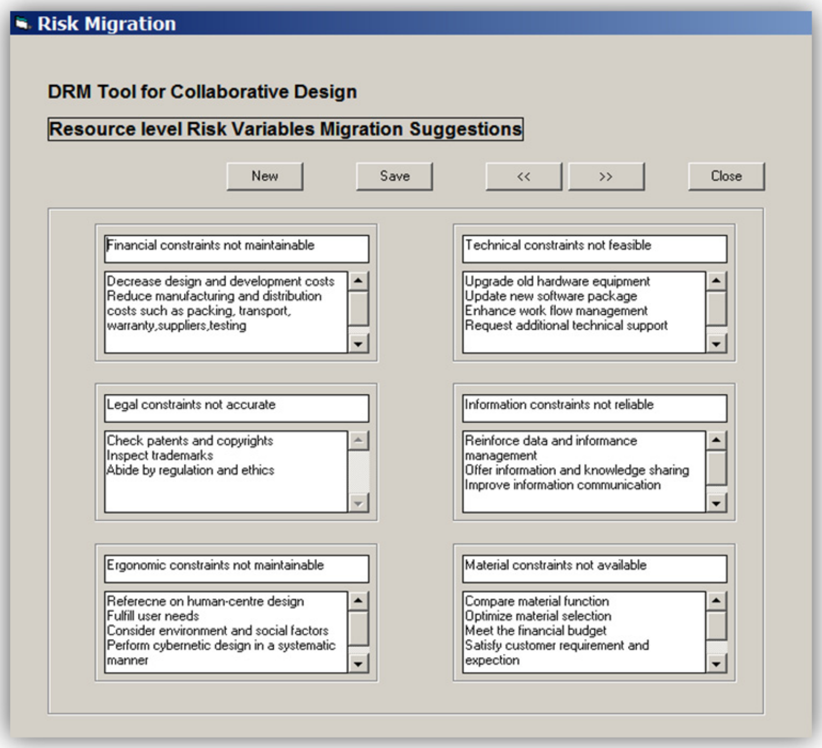
Performance constraints not reliable

Examine operational performance
Examine financial performance
Examine management performance
Examine manufacture performance

Customer constraints not avaiable

Consider customer appeal
Request new design requirements if market trend changed
Keep good communication with customer
Satisfy future expections

Figure 6.15 Illustration of the Input of Suggested Mitigated Risk Variables and Strategies in Role-interaction Level



Financial constraints not maintainable

Decrease design and development costs
Reduce manufacturing and distribution costs such as packing, transport, warranty,suppliers,testing

Technical constraints not feasible

Upgrade old hardware equipment
Update new software package
Enhance work flow management
Request additional technical support

Legal constraints not accurate

Check patents and copyrights
Inspect trademarks
Abide by regulation and ethics

Information constraints not reliable

Reinforce data and informance management
Offer information and knowledge sharing
Improve information communication

Ergonomic constraints not maintainable

Referecne on human-centre design
Fulfill user needs
Consider environment and social factors
Perform cybernetic design in a systematic manner

Material constraints not available

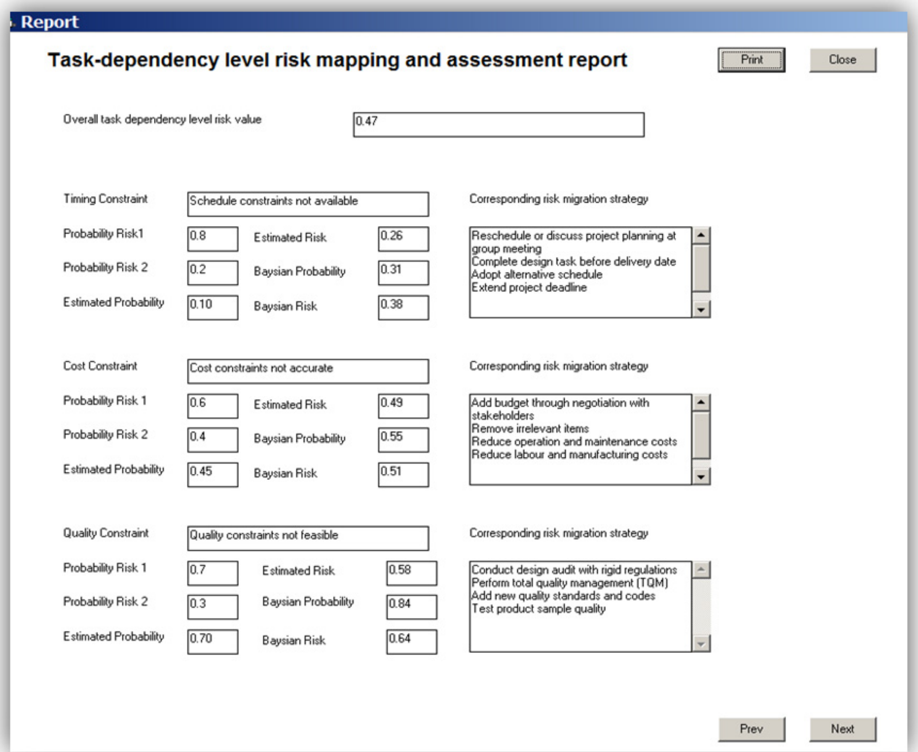
Compare material function
Optimize material selection
Meet the financial budget
Satisfy customer requirement and expection

Figure 6.16 Illustration of the Input of Suggested Mitigated Risk Variables and Strategies in Resource-integration Level.

Multiple Presentations of Results

After the user has completed their DRM data input task, the simulation prototype can compute overall collaborative design risk automatically in three different collaborative levels and calculate overall risk value in four diverse design stages statistically and respectively. As demonstrated in Section 6.4.2, the results of output can be presented in the form of reports and graphics. Reports show all the detailed information conducted in the process of DRM (see Figure 6.17 to Figure 6.21).

On the one hand, given that risk is associated with likelihood and consequence, a ranking method is used to quantify risk variables levels. The risk mitigation strategies are recommended for further analysis and discussion. On the other hand, although a variety of risk variables can be identified and assessed based on DRM matrix and Bayesian theorem, but overall project risk is not merely a sum. Some special design constraints may be concluded in the same decision dimension, which might cause the duplication of all design risk variables.



Task-dependency level risk mapping and assessment report

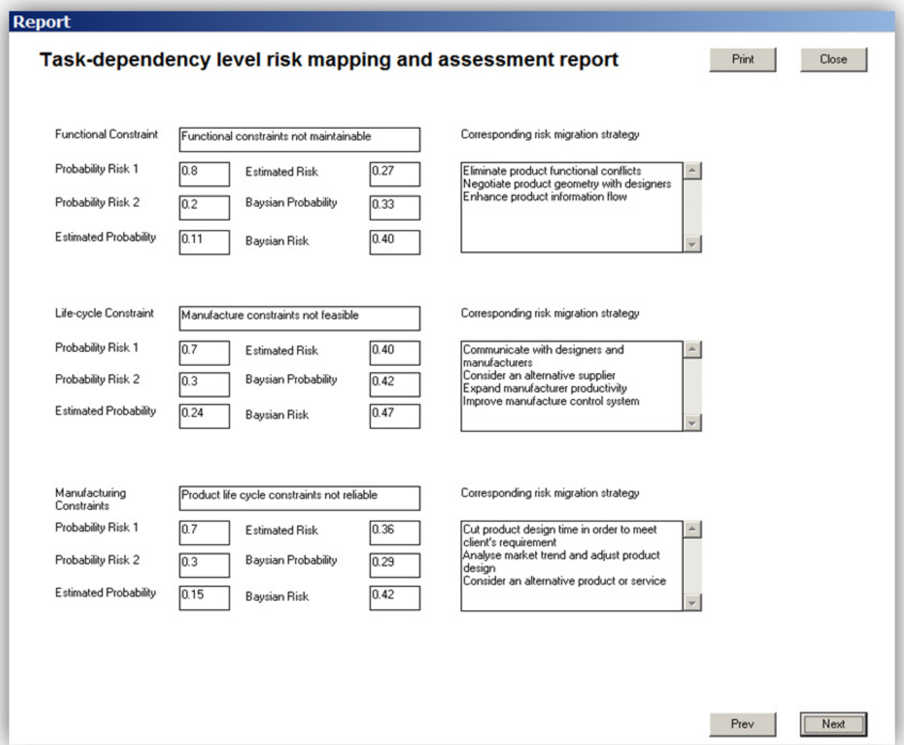
Overall task dependency level risk value: 0.47

Timing Constraint: Schedule constraints not available
Probability Risk1: 0.8
Probability Risk 2: 0.2
Estimated Probability: 0.10
Estimated Risk: 0.26
Baysian Probability: 0.31
Baysian Risk: 0.38
Corresponding risk migration strategy:
Reschedule or discuss project planning at group meeting
Complete design task before delivery date
Adopt alternative schedule
Extend project deadline

Cost Constraint: Cost constraints not accurate
Probability Risk 1: 0.6
Probability Risk 2: 0.4
Estimated Probability: 0.45
Estimated Risk: 0.49
Baysian Probability: 0.55
Baysian Risk: 0.51
Corresponding risk migration strategy:
Add budget through negotiation with stakeholders
Remove irrelevant items
Reduce operation and maintenance costs
Reduce labour and manufacturing costs

Quality Constraint: Quality constraints not feasible
Probability Risk 1: 0.7
Probability Risk 2: 0.3
Estimated Probability: 0.70
Estimated Risk: 0.58
Baysian Probability: 0.84
Baysian Risk: 0.64
Corresponding risk migration strategy:
Conduct design audit with rigid regulations
Perform total quality management (TQM)
Add new quality standards and codes
Test product sample quality

Figure 6.17 Illustration of the Report for Task-dependency Risk Variable.



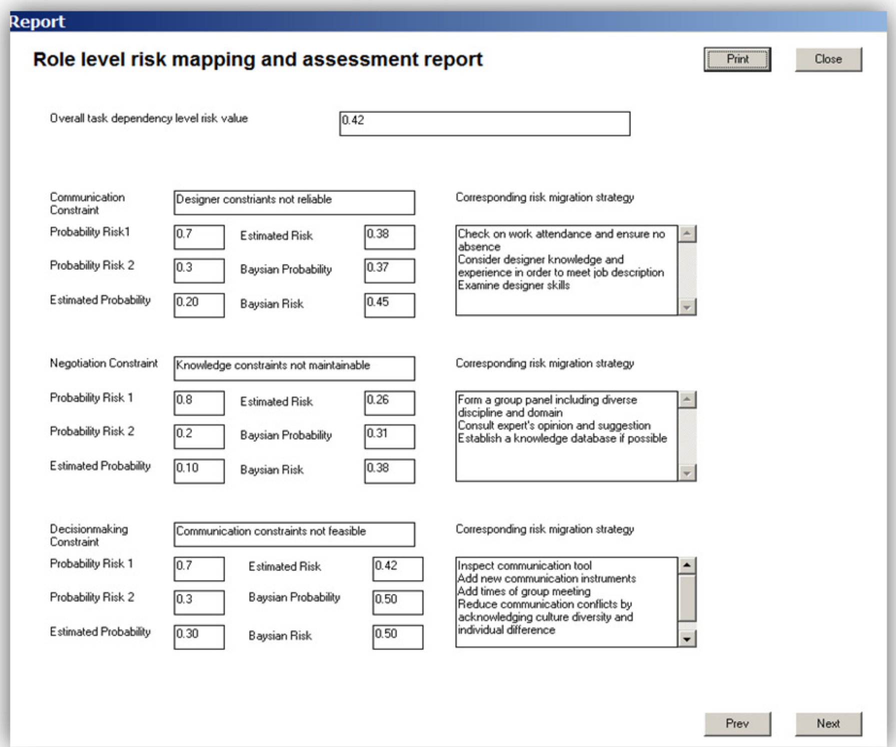
Task-dependency level risk mapping and assessment report

Functional Constraint: Functional constraints not maintainable
Probability Risk 1: 0.8
Probability Risk 2: 0.2
Estimated Probability: 0.11
Estimated Risk: 0.27
Baysian Probability: 0.33
Baysian Risk: 0.40
Corresponding risk migration strategy:
Eliminate product functional conflicts
Negotiate product geometry with designers
Enhance product information flow

Life-cycle Constraint: Manufacture constraints not feasible
Probability Risk 1: 0.7
Probability Risk 2: 0.3
Estimated Probability: 0.24
Estimated Risk: 0.40
Baysian Probability: 0.42
Baysian Risk: 0.47
Corresponding risk migration strategy:
Communicate with designers and manufacturers
Consider an alternative supplier
Expand manufacturer productivity
Improve manufacture control system

Manufacturing Constraints: Product life cycle constraints not reliable
Probability Risk 1: 0.7
Probability Risk 2: 0.3
Estimated Probability: 0.15
Estimated Risk: 0.36
Baysian Probability: 0.29
Baysian Risk: 0.42
Corresponding risk migration strategy:
Cut product design time in order to meet client's requirement
Analyse market trend and adjust product design
Consider an alternative product or service

Figure 6.18 Illustration of the Report for Task-dependency Risk Variables (Continued).



Role level risk mapping and assessment report

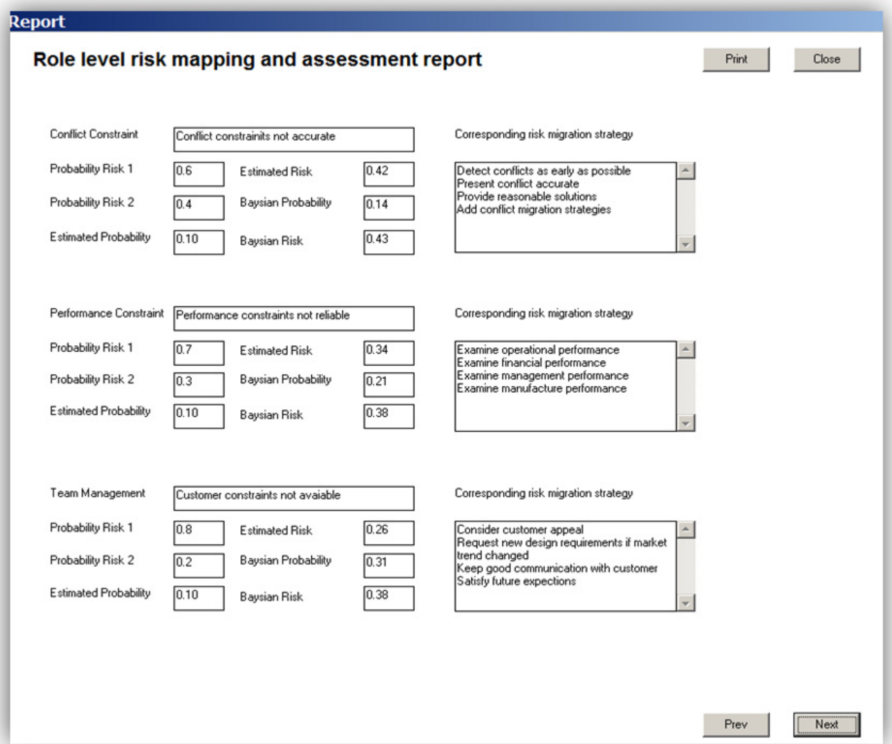
Overall task dependency level risk value: 0.42

Communication Constraint: Designer constriants not reliable
Probability Risk1: 0.7
Probability Risk 2: 0.3
Estimated Probability: 0.20
Estimated Risk: 0.38
Baysian Probability: 0.37
Baysian Risk: 0.45
Corresponding risk migration strategy:
Check on work attendance and ensure no absence
Consider designer knowledge and experience in order to meet job description
Examine designer skills

Negotiation Constraint: Knowledge constraints not maintainable
Probability Risk 1: 0.8
Probability Risk 2: 0.2
Estimated Probability: 0.10
Estimated Risk: 0.26
Baysian Probability: 0.31
Baysian Risk: 0.38
Corresponding risk migration strategy:
Form a group panel including diverse discipline and domain
Consult expert's opinion and suggestion
Establish a knowledge database if possible

Decisionmaking Constraint: Communication constraints not feasible
Probability Risk 1: 0.7
Probability Risk 2: 0.3
Estimated Probability: 0.30
Estimated Risk: 0.42
Baysian Probability: 0.50
Baysian Risk: 0.50
Corresponding risk migration strategy:
Inspect communication tool
Add new communication instruments
Add times of group meeting
Reduce communication conflicts by acknowledging culture diversity and individual difference

Figure 6.19 Illustration of the Report for Role-interaction Risk Variables.



Report

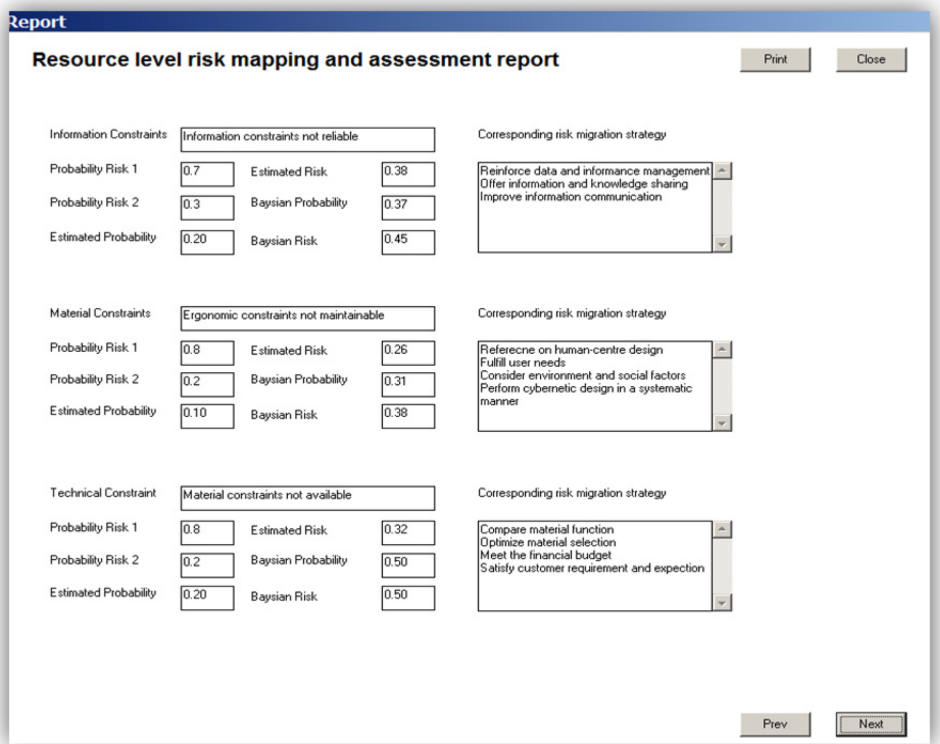
Role level risk mapping and assessment report

Conflict Constraint: Conflict constraints not accurate
Probability Risk 1: 0.6
Probability Risk 2: 0.4
Estimated Probability: 0.10
Estimated Risk: 0.42
Baysian Probability: 0.14
Baysian Risk: 0.43
Corresponding risk migration strategy:
Detect conflicts as early as possible
Present conflict accurate
Provide reasonable solutions
Add conflict migration strategies

Performance Constraint: Performance constraints not reliable
Probability Risk 1: 0.7
Probability Risk 2: 0.3
Estimated Probability: 0.10
Estimated Risk: 0.34
Baysian Probability: 0.21
Baysian Risk: 0.38
Corresponding risk migration strategy:
Examine operational performance
Examine financial performance
Examine management performance
Examine manufacture performance

Team Management: Customer constraints not avaiable
Probability Risk 1: 0.8
Probability Risk 2: 0.2
Estimated Probability: 0.10
Estimated Risk: 0.26
Baysian Probability: 0.31
Baysian Risk: 0.38
Corresponding risk migration strategy:
Consider customer appeal
Request new design requirements if market trend changed
Keep good communication with customer
Satisfy future expections

Figure 6.20 Illustration of the Report for Resources-integration Risk Variables (Continued).



Report

Resource level risk mapping and assessment report

Information Constraints: Information constraints not reliable
Probability Risk 1: 0.7
Probability Risk 2: 0.3
Estimated Probability: 0.20
Estimated Risk: 0.38
Baysian Probability: 0.37
Baysian Risk: 0.45
Corresponding risk migration strategy:
Reinforce data and informance management
Offer information and knowledge sharing
Improve information communication

Material Constraints: Ergonomic constraints not maintainable
Probability Risk 1: 0.8
Probability Risk 2: 0.2
Estimated Probability: 0.10
Estimated Risk: 0.26
Baysian Probability: 0.31
Baysian Risk: 0.38
Corresponding risk migration strategy:
Referecne on human-centre design
Fulfill user needs
Consider environment and social factors
Perform cybernetic design in a systematic manner

Technical Constraint: Material constraints not available
Probability Risk 1: 0.8
Probability Risk 2: 0.2
Estimated Probability: 0.20
Estimated Risk: 0.32
Baysian Probability: 0.50
Baysian Risk: 0.50
Corresponding risk migration strategy:
Compare material function
Optimize material selection
Meet the financial budget
Satisfy customer requirement and expection

Figure 6.21 Illustration of the Report for Resources-integration Risk Variables (Continued).

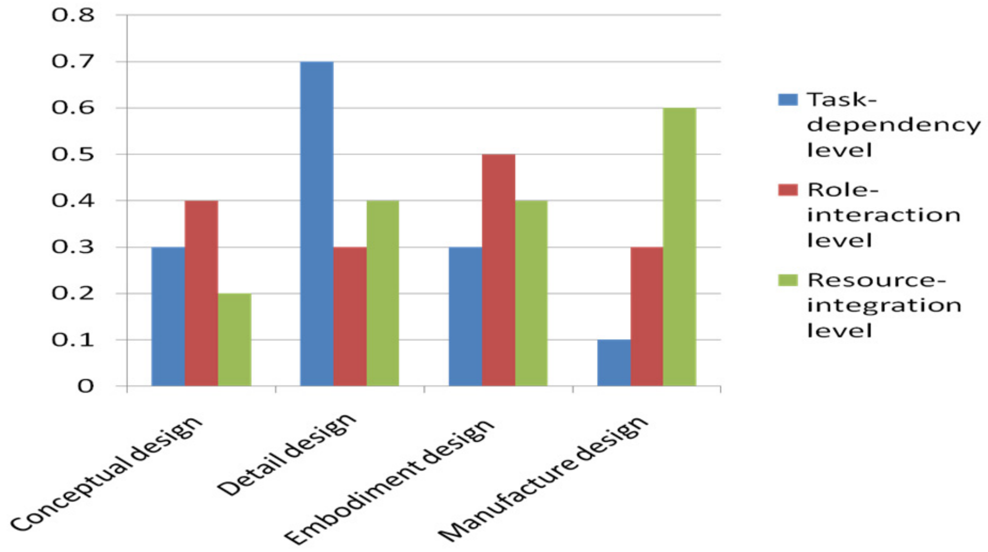


Figure 6.22 Illustration of Comparison of Overall Risk Values of Different Collaborative Levels in each Design Stages for Single User.

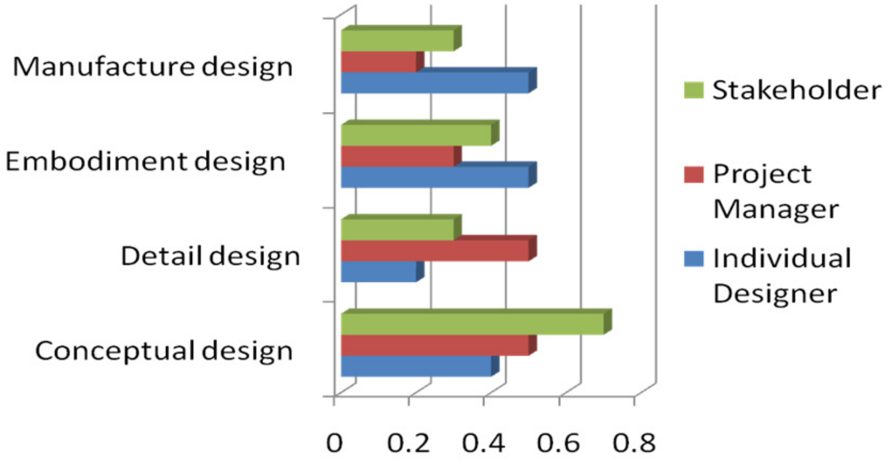


Figure 6.23 Illustration of Contrast of Overall Risk Values of all Users for each Design Stages

Thus, it is necessary to identify and remove the replications, and clarifies all the risk variables by examining reports. Users could analyse risk variables based on the identification of ranking risk magnitude and the elimination of iterative items. Besides, two types of graphic diagrams are also provided in the simulated prototype. One of graphic diagrams presents the comparison of overall risk values of different collaborative levels in each design stages for a single user. Another graphic diagram shows the comparison of overall risk values of all users for each design stages. With the aid of these printout reports and graphic diagrams, users can visualise and contrast the results from different participators straightforwardly. Two illustration graphic diagrams are shown in Figure 6.22 and Figure 6.23.

6.5 Conclusion

This chapter proposes a Bayesian weighting method on the basis of Bayesian theorem. This approach provides a more objective and applicable way for the measurement of design risk variables by comparison with PRA. The modification of this calculation will significantly reduce the subjectivity and increase the accuracy to design risk measurement, while not notably increasing the cost and complexity of process.

Moreover, by incorporating this approach with the DRM conceptual framework and DRM matrix, a DRM simulation prototype is developed in terms of UML and Visual.Basic.NET, which aims at providing a demonstration of the application for further case study evaluation. The prototype tool combines with the constraint-based DRM conceptual framework and matrix based on the specified design collaboration levels and the general risk management process. The tool is developed with a comprehensive risk management setting, flexible data input, automatic risk computation and multi-presentation output. It can be operated on Windows XP systems and be used to determine the design risk at a project level. The results of DRM not only shows risk consequence by a set of simple values, but presents reports that includes a list of detailed risk items with risk sources and possible mitigation solutions. Thus, the DRM tool will be of benefit that supports the demonstration of overall research architectures. By applying the DRM tool, case study evaluations are greatly facilitated.

However, the proposed constraint-based DRM and the simulation prototype are not validated yet. Thus, in the next chapter, case studies with participant observation and semi-structured interviews are conducted in attempt to make a further evaluation.

Chapter 7 Evaluation

7.1 Introduction

The preceding chapters addressed the development of a DRM tool on the basis of Bayesian theory and simulation. This chapter presents the last stage of the research with the case study evaluation for the proposed DRM tool.

Evaluation is one of the most essential stages in the process of a research project development, which to some extent determines the realisation of research objectives. More importantly, evaluation can provide “useful feedback” to increase correspondences between the world of concepts and reality (Grinnell and Unran, 2005). A case study plays a critical role in the domain of the evaluation research. The researchers can explore intensive, in-depth, rich, and full of information and collect detailed data by using a variety of data collection methods to illustrate certain topics within an evaluation (Kothari, 2004; Creswell, 2009; Yin, 2009).

Thus, the investigators can use one or combine more research methods such as questionnaires, in-depth interviews, participant observations that are possible under a case study method. In this chapter, with the intention of evaluating the propose DRM tool, the case study evaluation is conducted in combination with the participant observations and the simulation-based in-depth semi-structured interviews.

7.2 Research Design

7.2.1 Objectives

In association with the case studies, the evaluation research conducts to verify whether the proposed DRM tool can reveal design risks in terms of design constraints and risk criteria within a collaborative design environment. In other words, the case study evaluation intends to make a verification of whether the DRM tool that designers and design managers are able to map, measure and mitigate design risks during the process of collaborative design.

More specifically, participant observations are conducted in an attempt to explore the current status of collaborative design environment with cooperative design team structures and design processes in case studies, and to ensure whether the cases are appropriate for further evaluation. The semi-structured interviews are applied to evaluate whether the DRM tool can be implemented feasibly and effectively to map, measure and mitigate the design risk on the basis of the DRM simulation prototype in the design industry.

7.2.2 Initial Check

An initial check is conducted with the purpose of eliminating potential mistakes and flaws in the first draft of interview survey. More specifically, it provides "a preliminary evaluation and refinement of the measurement in order to create the final version for the main survey" (Zikmund, 1997). The central benefit of performing an initial check is to expose "any potential problems or discrepancies to be highlighted" prior to the execution of the major research (Stanton *et al*, 2005, p.26).

In a research project, a typical initial check generally involves performing interviews to research group or conducting a trial one with few targeted participants. The process of an initial check is "very useful in shaping the interview into its most efficient form and allows any potential problems in the data collection procedure to be highlighted and removed" (Stanton *et al.*, 2005, p.26).

Thus, in order to construct a more appropriate case study evaluation, researcher required feedback from two expert panels. They are requested to make comments on whether the question items are proper or not in order to meet the initial intention. The first group involves two academic staffs and the second group includes four design management research students who conducting relevant research. Each panel member is requested to complete the form of interview survey and make a comment on its clarity, wording, layout, applicability, and whether the interview survey can be used to measure the intended constructs. The interviews were conducted in the interviewees' offices or research centre. Based on the results of the initial check, the interview schedule is improved and the final version of the survey is elicited and presented in Appendix C.

7.2.3 Measurement Validity

Partiality refers to "the inability to generalise from the findings can limit the utility of the case study methods for evaluation" (U.S. General Accounting Office, November, 1990). Thus, it is important to measure the validity of case study evaluation in order to achieve impartiality and generalisability.

In general, case study methods apply two tactics to measure validity: "the multiple sources of the evidence and the use of the chain-of-evidence technique in data reduction" (U.S. General Accounting Office, November, 1990). The former one indicates "the use of several forms of data within a single case study in order to give many reference points for verifying patterns and ruling out alternative explanations in order to eliminate confounding variables and achieve the impartiality that evaluators refers to as internal validity" (U.S. General Accounting Office, November, 1990). Whilst the latter refers to "the combination of the case study methods with other methods, particularly surveys, in order to achieve the generalisability that evaluators called external validity" (U.S. General Accounting Office, November, 1990).

More specifically, the internal validity procedure in this case study evaluation most relies on experimental procedures, treatments and the selection of the experienced and appropriate participants that might seriously intimidate the researcher's capability to make accurate inferences from gathered data.

Thus, although the cases study method essentially demands subjective elements with preference and judgment, the inaccuracy and bias are considerably reduced after internal validity. Moreover, given that “certain case study applications provide a high degree of generalisability with a small number of instances, when both broad generalisations and in-depth understandings are required, designs that cumulate case studies combine other methods in one concurrent effort may meet this dual need” (Stuart *et al*., 2002). Accordingly, in this study, external validity is conducted based on the combination of case study methods with participant observations and interview surveys in order to achieve the generalisability.

7.2.3 Sampling

Sampling is regarded as a process of choosing units such as people, community, organisations from a targeted population. By observing the sample, certain inferences may be made about the population. Bryman and Bell (2007) identified two major sampling methods: “the probability and the non-probability sampling”. The probability sample is “a sample that has been selected using random selection so that each unit in the population has a known chance of being selected” (Bryman and Bell 2007, p.182). The objective of probability sampling is to minimise sampling error. On the contrary, non-probability sample is “a sample that has not been selected using a random selection method. In essential, this implies that some units in the population are more likely to be selected than others.” (Bryman and Bell, 2007, p. 182)

In this study, the case study evaluation is based on probability sample rather than non-probability sample, which means that the sample is representing a known number of population and units. In other words, the sample is “not random, but reflected the selection of specific cases to generalise the theory” (Eisenhardt, 1989). More specifically, the case study evaluation is conducted within three representative design projects, which are carefully selected as sample cases from design industry with the purpose of verifying the proposed DRM tool. Thus, the case projects mostly focus on the field of collaborative product design, and design is considered as prior to other issues in the selected case projects. Besides, the sample case projects offer the researcher an observation opportunity with the intention of collecting an adequate amount of in-depth information.

Case studies usually used by participant observation and semi-structured interview to capture background information and identify critical evaluation opinions from participants. The sample cases encompass three design firms around the world. The sample case A, B, and C were selected from firm A, firm B and firm C separately. Firm A can be categorised into small sized enterprise that has less than 80 people. It is one of the famous artistic and inventive design and innovation consultancy agencies in the UK, which includes a research centre, design studio, and a prototyping workshop. While Firm B specialises in international product design, and it is a top and dominated international industrial design firms in the world, which has more than 700 employees and operates in 10 countries. Firm B works with clients as a trusted partner to design products attempting to open new markets**,** cut costs and increase profits by delivering a development service to create successful and profitable products.

Firm C is one of the biggest personal computer manufacturers in the world, which has its own product research and design team. It has more than 10,000 employees, operates in 130 countries and has more than three corporate headquarters around the world. The firm designs, manufactures and sells products globally. The firm’s product departments contain several different models and target at diverse consumers such as commercial customers and business clients.

More importantly, considering the features of diversities of three distinct organisations, the researcher can assess and examine whether the DRM tool can be applied or not in different types of design organisations. Besides, in each circumstance, “multi-methods and multi-informants were involved to help maintain the internal validity of the data” (Stuart *et al*., 2002). Thus, the data generated from these three companies can be used to analyse the results of the case study evaluation.

7.2.5 Data Processing

Data processing “is essential for a scientific study and for ensuring that all relevant data are collected for making contemplated comparisons and analysis” (Blessing and Chakrabarti, 2009, p.89). In order to make broad generalisations and in-depth understanding and measure the external validation, a combination of participant observation and the simulation-based semi-structured interview is utilised to gather data during the process of case study evaluation. More specifically, participant observation attempts to explore the background of design projects. The background comprises of the design circumstance, the design activities, the design process, the design structure, and the current DRM methods; whilst the simulation-based semi-structured interviews were conducted to investigate the participants’ opinions with the purpose of verifying the proposed DRM tool. As a result, 1 design manager and 3 designers were interviewed in case A, 3 managers and 11 designers were interviewed in case B, and 7 managers and 23 designers were interviewed in case C.

Participant Observation

Participant observation is a method of data collection based on the observer participation in the observed process (Yin, 2009). It is used in the fieldwork when the role of the researcher is not restricted to that of an onlooker but participates in the process. During the process of participant observation, the researcher can gain acceptance and increase familiarity with the field and the problems (Blessing and Chakrabarti, 2009). More importantly, the data collected by participant observation can also be served as one of main source for the case study evaluation.

Thus, the author spent four months on three work placements and participated in each case project group. During the process of the work placement, the author made an observation of the development process of case project A, B and C. These observations combine the document analysis, the surroundings evaluation, the direct participation, and the member consultation. The author took part in weekly meetings, examined correlated documents, and experienced design collaborations for the purpose of evaluate whether the DRM tool can be used to map, measure and mitigate the design risk in the collaborative design project A, B and C.

More specifically, the design objectives, schedules, and organisational structure were revealed in terms of the observation. Moreover, the current design development process and the DRM methods were explored via direct participant and member consultation. As a result, two issues needed to be addressed in the participant observation. The first issue is the validation of whether the DRM tool can be integrated in accordance with three proposed design collaboration levels. The second issue is to assess whether the DRM tool can be implemented during the process of collaborative design project development.

Semi-structured Interviews

Semi-structured interviews provide “a flexible and in-depth way for case study evaluation” (Stanton *et al*., 2005). In this study, the purpose of semi-structured interview is to evaluate whether the DRM tool can be performed based on the DRM simulation software prototype demonstration, and whether the DRM can be operated effectively to map, measure and mitigate design risk under a collaborative design environment. More specifically, the semi-structured interviews are conducted to collect and evaluate the viewpoints from participants about the application of the DRM simulation software prototype.

The semi-structured interview is constructed by three sections: participants’ background information, the DRM presentation and demonstration, and the interview questions. In the first section, the participants are required to provide general background information including their job position, their job responsibility and the company’s information. The second section is concentrated on presenting the research objective, and demonstrating the simulation prototype. In the third section, the participants are required to respond to the interview questions and to comment on the application of DRM simulation prototype.

According to Rossi *et al*. (1999), evaluation questions must be realistic, appropriate and answerable. Realistic means in the light of what the support is attempting to achieve. Appropriate relates to questions should be consistent with the experience in alike supports. In addition, answerable questions indicate that explicit statements should be used. Based on these guide, questions are devised for the exploration of the participants' opinion on the implementation of the proposed DRM tool.

In total, 16 questions were designed for the in-depth semi-structure interview. Based on the results of the initial check from two academics and four research students in the field of design management, the semi-structured interview is improved and the final version of the tool is elicited and presented in Appendix C. 30 participants were selected and interviewed. Each of the interviews was conducted within one hour. The DRM simulation prototype is demonstrated by using a Lenovo laptop with Window XP system.

Besides, a brief is introduced to the participants by the researcher before the implementation of each interview. During the process of brief presentation, the intention of the primary research was provided firstly in order to help the participants to comprehend the purpose and the structure of the industry interview. Three pages of handouts were printed out and handed in participants, which includes Glossary, Theory of Constraints (Section 1.3.6) and detailed information of design constraints (Table 5.2-5.4). These handouts aim to help the participants to understand the major purpose of the survey and to interpret the terms that used in interview questions in order to ensure that the participants could provide more accurate and more valuable answers.

Secondly, the results of the overall research were briefly presented by a prepared PowerPoint presentation, which encompass a conceptual DRM operation framework, a constraint-based DRM matrix, and a DRM weighting method. After the presentation, the interviewer also answered participant's queries during the questioning time. Thirdly, a DRM simulation prototype was presented for demonstrating the application of the proposed DRM tool. The demonstration aims to help participants to be familiar with the interface and the structure of the proposed DRM tool, and to appreciate how to manipulate the tool during the process of industry practice.

7.3 Data Analysis and Interpretation

In the data analysis and interpretation, it is more important to generalise findings as well as exam the effectiveness of simulation prototype. Through case study evaluation, the proposed DRM tool was evaluated in terms of the results from participant observation and in-depth semi-structured interview. Feedback and analysis that generated from original data are explained in the following sections.

7.3.1 Results of Participant Observation

This section explains the outcome of the participant observations of case projects from three companies. Based on four-month industrial placement, the participant observation is conducted separately in the process of case project A, B and C. These sample case observations combined the document analysis, the surroundings evaluation, the direct participation, and the member consultation. In total, 52 design staff participated in the case study observations (see Table 7.1).

Table 7.1 Participants Information.

Case	**Project manager**	**Numbers of Design Manager**	**Numbers of Designer**	**Total**	**Percentage**
A	1	1	4	6	11.53%
B	1	2	11	14	26.92%
C	2	6	24	32	61.55%
Total	4	9	39	52	100%
Percentage	7.69%	17.31%	75%	100%	

1) Case A

Case A is a short-term project from Company A. A small sized design consultant agency that has less than 80 employees and operates in the domestic market. The company offers design innovation, strategy, industrial design, graphic research, new product design and development, 3D structural design and 2 D graphic design.

This project required planning and operation on a large scale in terms of scheduling the process and constituting the design team to conduct the development. It is requested the specifically formulated project team to move from a “blank page” to a full-scale industrial design within four months. A one-month participant observation was conducted at the beginning of the development of case project A. A total of six professionals including one project manager, one design manager, and four designers involved. Moreover, one representative of stakeholders participated during the product design process of at the concept design stage (see Figure 7.1).

More specifically, the project manager was in charge of the overall project management with the responsibility for the communication and reporting to the stakeholders. The designer manager was responsible for fulfilling design task and meeting the design requirements by working closely with the creative team and the project manager.

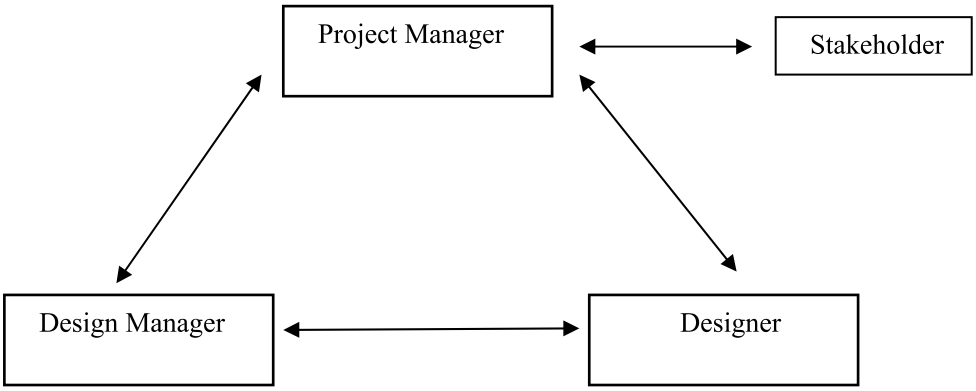


Figure 7.1 Team Structure in Case A.

In addition, the designers had the accountability for ensuring that the maximum standard of innovative output, which is derived from each particular design assignment. Within the project statement, design tasks are dependent on and linked with one another, the design roles are interacted and the design resources can be integrated in order to achieve the design scheme optimisation. Thus, the team structure of case project A is in accordance with the proposed DRM framework. The DRM simulation prototype can be integrated into the case in terms of the levels of design collaboration. Besides, due to small team structure and short-term timescale, this case project has no specific DRM activities, which is similar to the proposed DRM tool. Nevertheless, the observer has discovered that both design managers and designers are inclined to carry out the DRM tool in order to support their design management and improve their collaborative design performance.

2) Case B

Case B is a medium-term project with one-year contract from Company B, a medium scale design enterprise that has more than 700 employees and operates in over 10 countries. It is one of the top and dominated international industrial design firms, which specialises in industrial product design and development. The participant observation was conducted in the middle of the project process and lasted for one month. During the first two weeks, some background information was gathered as much as possible about the case project and the roles of Group Personnel.

In general, case B attempts to conduct R&D and update the existing product to next generation through NPD. A total of 14 professionals consisting of 1 project manager, 2 design managers and 11 designers formed a Group Personnel in support of the overall project in this case. Project managers are responsible for establishing a holistic layout and maintaining corporate identity architecture with an effective project management according to the changing needs of the Group Personnel. The design managers not only provide leadership and direction on the design issues, but also take charge of the strategic design task decomposition, the effective team management and the design resource allocation for new collaborative product design. The designers had the liability for the success of every allocated design assignment. Besides, some stakeholders attended group meeting and reviewed the process of product design.

Additionally, the product design process of case B was divided into four stages explicitly: conceptual design, embodiment design, detail design and manufacturing (see Figure 7.2). This design structure is consistent with the dissection that was proposed by Pahl *et al*. (2007).

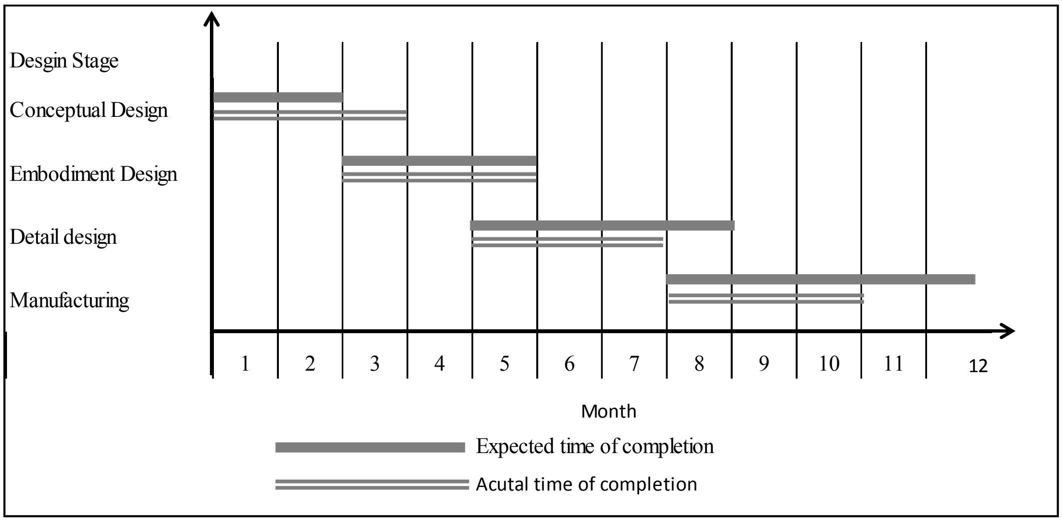


Figure 7.2 Grant Chart for Case B.

More specifically, conceptual design attempts to generate concepts through identifying essential issues, establishing function structures and exploring solution principles. It is outlined the main components and specification with details in order to proceed for a later stage. Embodiment design contains the layouts and configurations of preliminary design. It is crucial to choose the most desirable preliminary configurations and layouts in this design stage.

In the stage of detail design, a well-defined product design is developed based on explicit requirements, and a deliverable documentation is created appropriately for final product manufacture. Moreover, a prototype is produced in order to test ideas at this stage. According to the stage-gate (Cooper, 1993), the progress reviews were conducted in the form of group meetings at the end of each phase during the design process.

In the group meetings, the project manager reviewed the progress in accompaniment with design managers and designers. After the presentation of the fulfilled design task, further design and development assignments were discussed in terms of design requirements and specifications. Sometimes, the stakeholders participated in some project meetings and cooperated with the design team in support of the progress review following the specified stage-gate process. Despite the medium-term project, case B also has no special panel responsible for the design risk management. However, the project manager conducts a risk analysis within his project management. Thus, based on the team structure and the process of case B, the DRM tool can be executed at the beginning of each stage to map, measure, and mitigate design risk. The assessment results can be used during the process of design decision-making for both managers and designers.

3) Case C

Case C is a long-term project and lasts for more than 24 months from Company C, one of the biggest personal computer manufacturers in the world. Considering the global competition, case C is a distributed product development project with decreasing product development lifecycles, and increasing design complexity. Thus, considered the large scale and complexity, the participant observation was incorporated into case C with one of its design teams in the middle of the project process and lasted two months.

In total, four design teams involved in case C, and each team has one project manager, three design managers and twelve engineer designers. Two design teams were located in different research and development (R&D) centres in China, while another two distributed in other R&D centres in North America. The observer participated in the project with one of the former design teams in China. The design teams are responsible for several design functions: user interface design, graphics design, product design, human factor design, and engineering design. In order to deliver high design performance rapidly, project managers, design managers and engineer designers worked closely and reliably to balance risks. Besides, the design managers and the multi-disciplined designers are required to work cooperatively with three other design teams across time zones considering that the case project is operating in a distributed environment.

In addition, owing to the fact that requirements are changed frequently, the incorporation of changes into the design process is also important. However, the overall product development and design process cannot be disclosed because of confidentiality.

In contrast to case A and B, one risk analyst incorporated with the project manager and the design managers formed a special panel in case C (see Table .7.2). The panel is focused on the project risk management, and the collaborative factors are not considered in the process of their analysis and discussion. Furthermore, the communication and collaboration among project manager, design managers and engineer designers were more constant and flexible in case C in comparison with other two cases.

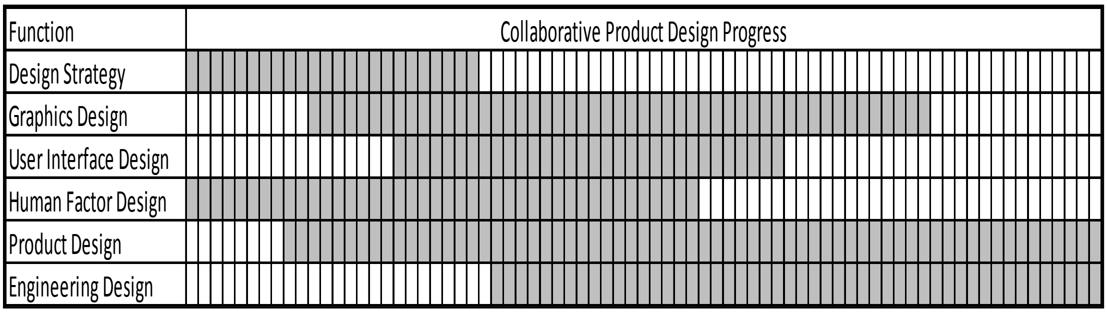
Table 7.2 Case associated with Risk Management (RM) Practice.

	RM practice	**RM panel**	**DRM practice**
Case A	No	No	No
Case B	Yes	No	No
Case C	Yes	Yes	No

In addition, the span of timescale in case C is much longer, while the stage-gate process is not as explicit as operated in case A and B (see Table 7.3). However, the project manager, the design managers and the designers rated highly the significance of the proposed DRM in the interviews. On the one hand, the proposed DRM can be used to facilitate design collaboration based on design constraints under a distributed product development environment. On the other hand, considering design plays a crucial role during the process of product development and design in case C, risk management practices should not only consider design and task issues, but also take into account collaborative factors such as role-interaction with communication and information sharing, resource integration with financial funding and ergonomic thinking.

Thus, with the purpose of assisting design managers and designers to support the collaboration, the DRM simulation prototype tool could also be incorporated into case C with separate design teams according to the collaborative features from a risk perspective.

Table 7.3 Grant Chart for Case C.



To sum up, the status of collaborative design environment with cooperative design team structures and design processes are explored through case study participant observation. The designers and design managers in these cases are inclined to carry out the DRM tool in order to support their design management and improve their collaborative design performance. The DRM tool can be integrated with these cases and be implemented for the case studies evaluation during the process of collaborative design project development. Thus, these cases are qualified for the further case study evaluation interviews.

7.3.2 Results of Case Study Evaluation Interviews

This section explains the outcome of the semi-structured interviews with regard to the implementation of the proposed DRM in three cases. The semi-structured interviews were conducted together with a range of observations during four months, and were applied as the main component for case study evaluation. The main purpose is to explore and demonstrate the feasibility and effectiveness of the DRM simulation prototype according to the interviewees' judgments. Two issues are explored: 1) whether the DRM is applicable and can be incorporated into current case project for collaborative design risk mapping, measurement and mitigation; 2) whether the output of DRM is reliable and can be utilised in support of the design managers and designers with the purpose of facilitating design collaboration.

After data collection, the data were initially input into the SPSS 13.0 in order to present a statistic analysis for the sample. A demographic characteristic is presented. Then, the reliability analysis is conducted for the assessment of sample reliability. This analysis intends to evaluate the scales and assess the constructs of the interview and reduce the statistics bias. The main findings will be concluded by providing results and recommendations as to how the proposed DRM is being evaluated.

Demographic Characteristic

The semi-structured interviewees conducted on 30 industrial practitioners. The data were used to refine the measures and analyse the reliability. The demographic characteristics are provided in Table 7.4-7.5. The results showed that majority of the interviewees are designers (63.33%), the others are managers including design managers (23.33%) and project managers (10%).

Table 7.4 Demographic Profile of Semi-structured Interview Survey Sample.

Sample size (N)	**N**	**%**
Participants		
Project manager	3	10
Design manager	7	23.33
Stakeholder	1	3.33
Designer	19	63.33
Total	30	100
Functions		
Industrial Design	8	26.67
Product Design	11	36.67
Engineering Design	1	3.33
Design Manager	10	33.33
Total	30	100
Working experience		
>1 years	1	3.33
1-3 years	4	13.33
3-5 years	16	53.34
>5 years	9	30
Total	30	100

The results also shows that a high percentage (46.67%) of the respondents come from the manufacturing companies, 30% from the consultancy companies and 13.33% from the design companies. With regard to the size of organisation, the results indicate that only 13.33 %.of the respondents are working in small firms while more than half of the respondents (56.67%) are working in large companies. This great variety of interviewees shows that the semi-structured interviews were performed with the skilled designers and managers based on the multi-background of the design industry. Thus, their opinions and experiences are full of value and more reliable than the casual participants are.

Table 7.5 Demographic Profile of Semi-structured Interview Survey Sample (Continued).

Organization		
Design Company	4	13.33
Consultancy Company	9	30
Engineering Company	3	10
Manufacturing Company	14	46.67
Total	30	100
Organization size		
For-Profit - Small (< 100 employees)	4	13.33
For-Profit - Medium (>100 <1000 employees)	9	30
For-Profit – Large (> 1000 employees)	17	56.67
Total	30	100

All participants are engaged in design industry: 36.67% from product design, 26.67% from industry design, whilst 33.33% of them served as design manager. The majority of participants have more than three years working experience (83.34%), compared with those with one to three years (13.33%); only 3.33% worked less than one years.

Reliability Analysis

The reliability analysis is conducted for "the measures are free from error and therefore yield consistent results" (Peter, 1979, p. 6). In general, reliability could be evaluated by Cronbach's alpha (Cronbach, 1951). Cronbach's alpha is the most commonly acceptable method that used to assess sample reliability in a reseach. It is regarded as "a measure of the degree to which all items are measuring the same thing" (DeVellis, 1991).

Nunnally and Bernstein (1994) indicated that "0.7 should be used as a cut-off point for reliability". In other words, the Cronbach's alpha value between 0.7 to 0.8 is acceptable, while values substantially lower indicate an unreliable scale. de Vaus (2002) and Nunnally and Bernstein (1994) stressed that "the value of alpha equal to 0.70 or above indicates that the items make a reliable set". More specifically, "the Cronbach's alpha value above 0.7 is generally accepted to demonstrate a high level of homogeneity within the scale and to determine whether the item reflects a single dimension" (Nunnally and Bernstein, 1994)

However, Nunnally and Bernstein (1994) also argued that "a coefficient of 0.50 or 0.60 is satisfactory in the early stages of research". If the value of coefficient alpha is great higher than 0.70, which means the samples are highly satisfied for the research purposes (Hair *et al.*, 1995). In this semi-structured interview data, the item is scored as 1= strongly disagree, 2 =tend to disagree, 3=neither to agree or disagree, 4=tend to agree, 5=strong agree. After the complete of the data collection and the statistics input, the reliability analysis is conducted by using SPSS 15.0. The Cronbach's alpha value (0.791) is accepted within the threshold for indicating a good fit for this survey (see Table 7.6)

Table 7.6 The Results of the Reliability Statistics.

Items	Mean	Std. Deviation	Cronbach's Alpha if Item Deleted	Cronbach's Alpha	Sample size (N)
Q6	4.2000	0.71438	0.756	0.791	30
Q7	3.9667	0.76489	0.790		
Q8	3.9667	0.76489	0.756		
Q9	4.2000	0.76112	0.773		
Q10	4.1333	0.68145	0.773		
Q11	3.7000	1.02217	0.748		
Q12	4.1667	0.74664	0.793		
Q13	4.3000	0.59596	0.789		
Q14	4.1000	0.75886	0.760		
Q15	4.3667	0.61495	0.786		
Q16	4.2000	0.71438	0.786		

Results and Recommendations

Case study evaluation interviews aims to assess whether the simulated DRM can be implemented for the measurement collaborative product design risks. More specifically, 11 closed-ended questions (Q6-Q16) are designed to evaluate the DRM tool in diverse aspects, such as the feasibility and applicability of the proposed DRM prototype, the capability of supporting design managers and designers, the reliability of producing desired results, and adaptability of incorporation with various collaborative design projects.

The participants were asked to answer questions in terms of alternative options: strongly disagree (SD); tend to disagree (TD); neither agree nor disagree (NAD); tend to agree (TA); and strongly agree (SA). Table 7.7 summarises the statistics results derived from each question, indicating the overall acceptability of the DRM simulation prototype. The original SPSS results are attached in Appendix D.

Table 7.7 Summary of the Statistics Results

	SD	TD	NAD	TA	SA
Q6	0	0	5	14	11
Q7	0	1	6	16	7
Q8	0	2	3	18	6
Q9	0	1	3	15	6
Q10	0	0	5	16	9
Q11	1	3	6	14	6
Q12	0	1	3	16	10
Q13	0	0	2	17	11
Q14	0	1	4	16	9
Q15	0	0	2	15	13
Q16	0	0	5	14	11

Q6. According to the present design project, to what extent do you agree that the DRM simulation prototype can be implemented and incorporated feasibly?

As presented in Table 7.8, the results show the significant satisfaction of the simulated DRM application from participants. In total, 83.4% (N=25) interviewees suggested that the proposed DRM tool could be implemented and incorporated feasibly in the current design project, while 16.7% (N=5) of them neither agree nor disagree, and there is no negative views on this questions. During the process of the semi-structured interviews, some participants indicated that the DRM tool could be applied mainly because of the specified design collaboration levels and the process of cooperative product design development.

Table 7.8 Results of Q6.

		Frequency (N)	Valid Percent (%)	Cumulative Percent
Valid	NAD(3)	5	16.7	16.7
	TA(4)	14	46.7	63.3
	SA(5)	11	36.7	100.0
	Total	30	100.0	

Moreover, other respondents stressed that the multi-feedback and the DRM risk mapping and measuring could be operated effortlessly. Besides, some of them argued that the proposed DRM tool enabled them foresee the potential design risks, which could support them to avoid design failure by means of exploring the critical design constraints and corresponding risk variables in the process of the design collaboration. This is also in accordance with Lough, Stone and Tumer (2009), who highlighted that "a risk assessment is also necessary to anticipate and prevent accidents from occurring or repeating rather than simply responding to failure events."

Q7. To what extent do you agree that the DRM simulation prototype can be applied in a collaborative design project?

As outlined in Table 7.9, the results show that 76.3% (N=23) of interviewees agreed that the DRM simulation prototype can be applied flexibly in the design industry. Some of them indicated that the DRM conceptual framework allows the DRM tool to be integrated in collaborative design projects. Additionally, the design constraints and the risk criteria in the DRM matrix, and the enhanced Bayesian risk measuring approach are proved to be flexible and applicable in a collaborative design project. In this regard, "the results of combining the effective failure analysis and the risk assessment tools would improve the safety, reliability, and security of products" (Lough, Stone and Tumer, 2009).

Table 7.9 Results of Q7.

		Frequency (N)	Valid Percent (%)	Cumulative Percent
Valid	TD(2)	1	3.3	3.3
	NAD(3)	6	20.0	23.3
	TA(4)	16	53.3	76.7
	SA(5)	7	23.3	100.0
	Total	30	100.0	

As a result, it is ensured the DRM tool could be flexibly employed in a collaborative design project. Nevertheless, other participants (23.3%) hold a negative point of views, 6 neither agree nor disagree and 1 tend to disagree. Some of them explained that, given that the evaluation was performed in terms of theoretical aspect, and the DRM tool had not been incorporated into a commercial design project for realistic application, it is difficult for them to draw a conclusion. In this regard, they strongly recommended that the DRM tool should be applied in other design projects, and the results should be evaluated for further analysis based on the levels of implementation experiment.

Q8. To what extend do you agree that the design constraints can be used incorporated with risk criteria to represent the design risk on the basis of three collaborative levels (Task-dependency, Role-interaction and Resource-integration)?

Table 7.10 Results of Q8

		Frequency (N)	Valid Percent (%)	Cumulative Percent (%)
Valid	TD(2)	2	6.7	6.7
	NAD(3)	3	10.0	16.7
	TA(4)	19	63.3	80.0
	SA(5)	6	20.0	100.0
	Total	30	100.0	

Results in Table 7.10 indicates that 83.3% (N=25) of the participants accepted positively that the design constraints can be used together with the risk criteria to represent the design risk on the basis of three collaborative levels (Task-dependency, Role-interaction and Resource-integration), 10% neither agree or disagree, while 6.7% (N=2) tend to disagree with this conclusion.

Most participants indicated that there is a constructive relation between the design constraints and the risk variables. This result is in consistent with some earlier studies, which suggested that “design is a process of balancing needs and functional requirements against various constraints such as material, technological, economical, physical, functional, operational, environmental, legal, and ergonomical factors” (Voland, 1999; Pahl *et al.*, 2007, p. 395). Thus, Theory of Constraints (TOC) can be as applied the incorporated with risk theory in the analysis of the collaborative design risk.

Q9. To what extent do you agree that the DRM simulation prototype can be used for collaborative design risk mapping during the process of design collaboration?

As states in Table 7.11, the results show that 86.7% (N=26) of the participants agreed that the DRM matrix can be used for mapping design risk accurately and comprehensively in the process of collaborative product design, 10% (N=3) neither agree or disagree, while 3.3% (N=1) tend to disagree with this conclusion.

Table 7.11 Results of Q 9.

		Frequency (N)	Valid Percent (%)	Cumulative Percent (%)
Valid	TD(2)	1	3.3	3.3
	NAD(3)	3	10.0	13.3
	TA(4)	15	50.0	63.3
	SA(5)	11	36.7	100.0
	Total	30	100.0	

Most interviewees indicate that TOC can be applied as a risk means in the process of collaborative design risk management. Some of participants also highlighted that the design constraints and the risk criteria in the DRM matrix are used more effectively and efficient when they are in combination with the design collaboration levels and the risk management process. However, some respondents also stress that despite of the significance of the consideration of the critical design constraints and the related design risks, the influence of some other constraints also cannot be ignored.

Q10. To what extent do you agree that the DRM simulation prototype can measure collaborative design risk during the process of design collaboration?

Table 7.12 Results of Q10.

		Frequency (N)	Valid Percent (%)	Cumulative Percent (%)
Valid	NAD(3)	5	16.7	16.7
	TA(4)	16	53.3	70.0
	SA(5)	9	30.0	100.0
	Total	30	100.0	

As presented in Table 7.12, the results explain that 83.3% (N=25) of the participants believe the DRM simulation prototype can generate accurate and reliable outputs by linking the DRM matrix with the enhanced Bayesian weighting method, 16.7% (N=5) neither agree or disagree, and no disagree on this question. Some participants stressed that the DRM measuring application can represent risk variables more effective and objective with prior assigned values. These values could present an impressive image about the scale of variety of design risks. In addition, other participants indicated that the consideration of the Bayesian weighting method instead of probability analysis could enhance the objectivity and dependability of the DRM results. Thus, it is assure the proposed DRM tool is capable to generate a more objective and accuracy results with no technique bias.

Q11. To what extent do you agree that the DRM simulation prototype can mitigate collaborative design risk during the process of design collaboration?

Table 7.13 Results of Q11.

		Frequency (N)	Valid Percent (%)	Cumulative Percent (%)
Valid	SD(1)	1	3.3	3.3
	TD(2)	3	10.0	13.3
	NAD(3)	6	20.0	33.3
	TA(4)	14	46.7	80.0
	SA(5)	6	20.0	100.0
	Total	30	100.0	

Results in Table 7.13 indicated that 66.7% (N=10) of the interviewees agreed with the DRM simulation prototype can mitigate the collaborative design risk during the process of design collaboration, while 20% neither agree or disagree, 10% tend to disagree with this question. Some interviewees' mention that the DRM mitigate can be feasibly conducted according to experts' reports. Nevertheless, other interviewees also indicate that further improvement should be developed in terms of the case and reason method that is proposed in the DRM framework.

Q12. To what extent do you agree that the proposed DRM tool can generate reliable outputs in terms of the proposed collaborative levels (Task-dependency, Role-interaction and Resource-integration)?

As specified in Table 7.14, 86.6% (N=26) of the participants agreed that the DRM simulation prototype can generate accurate and reliable outputs in terms of the proposed collaborative levels (Task-dependency, Role-interaction and Resource-integration).

Table 7.14 Results of Q12.

		Frequency (N)	Valid Percent (%)	Cumulative Percent (%)
Valid	TD(2)	1	3.3	3.3
	NAD(3)	3	10.0	13.3
	TA(4)	16	53.3	66.7
	SA(5)	10	33.3	100.0
	Total	30	100.0	

However, 13.3% (N=5) neither agree nor disagree, and 3.3% (N=1) participants tend to disagree with this question. Some participants stressed that the setting of three collaborative levels allows the DRM tool to be flexibly utilised in diverse collaborative design projects by integrating with the risk management process. Moreover, other participants indicate that the specified collaborative levels can increase the accuracy of mapping design constraints. The identification of design constraints is crucial for further design risk measurement and mitigation.

Q13. To what extent do you agree that the proposed DRM tool can generate reliable outputs by linking DRM with project manager, design manager, designer and stakeholders?

Table 7.15 Results of Q13.

		Frequency (N)	Valid Percent (%)	Cumulative Percent (%)
Valid	NAD(3)	2	6.7	6.7
	TA(4)	17	56.7	63.3
	SA(5)	11	36.7	100.0
	Total	30	100.0	

As indicated in Table 7.15 , 93.4% (N=28) of the interviewees agreed that the DRM simulation prototype can generate accurate and reliable outputs by linking DRM with project manager, design manager, designer and stakeholders, while 6.7% (N=2) of participants neither agree nor disagree. During the interview, some interviewees indicated that a DRM tool should not only be conducted by managers, but also should be involved designers and stakeholders in terms of collaborative environment. Thus, it can be assumed that most the interviewees recommend that the DRM tool can be more constructive and practical, if it is concerned with not only managers, but also designers and other practitioners involved in an on-going collaborative design project.

Q14. To what extent do you agree that the proposed DRM tool can generate reliable outputs by linking DRM with the stage-based design objectives?

Table 7.16 Results of Q14.

		Frequency (N)	Valid Percent (%)	Cumulative Percent (%)
Valid	TD(2)	1	3.3	3.3
	NAD(3)	4	13.3	16.7
	TA(4)	16	53.3	70.0
	SA(5)	9	30.0	100.0
	Total	30	100.0	

As showed in Table 7.16, the results explain that 83.3% (N=25) of the participants believe the DRM simulation prototype can generated accurate and reliable outputs by linking DRM with the stage-based design objectives, 13.3% (N=5) neither agree or disagree, and 3.3% (N=1) tend to disagree with this question. Some participants indicated that design stages are central to collaborative product design and development, in particular in those small companies with the short-term or the medium-term design project. On the contrary, due to the overlapping design task and the complex design collaboration, the design stages are unambiguous in large companies with long-term design projects.

Q15. To what extent do you agree that the proposed DRM tool can be used in support of both manager and designer to conduct DRM practice during the process of design collaboration?

Table 7.17 Results of Q15.

		Frequency (N)	Valid Percent (%)	Cumulative Percent (%)
Valid	NAD(3)	2	6.7	6.7
	TA(4)	15	50.0	56.7
	SA(5)	13	43.3	100.0
	Total	30	100.0	

Results in Table 7.17 indicate that 93.3% (N=28) of the participants agree that the DRM simulation prototype can be used in support of both managers and designers to conduct the DRM practice during the process of design collaboration. Only 6.7% (N=2) neither agree nor disagree, and no objection on this question. Thus, it can be assumed that most the interviewees recommend that the DRM tool can facilitate the design risk management under a collaborative design environment.

Q16. To what extent do you agree that the DRM simulation prototype can be used in support of both manager and designer to attain design project achievement during the process of design collaboration?

As indicated in the results of Table 7.18, 83.4% (N=25) of the interviewees agree that the DRM simulation prototype can be used in support of both manager and designer to prevent major design risks and achieve design project success during the process of design collaboration, and 16.7% of them neither agree or disagree. Most interviewees believe that the DRM simulation prototype can significantly reduce project design risk by mapping, measuring and mitigating the major constraint-based design risk.

Table 7.18 Results of Q16.

		Frequency (N)	Valid Percent (%)	Cumulative Percent (%)
Valid	NAD(3)	5	16.7	16.7
	TA(4)	14	46.7	63.3
	SA(5)	11	36.7	100.0
	Total	30	100.0	

Some of the participants indicated that the DRM tool provide a conceptual collaborative framework combined with the TOC and the risk management process, that allows the DRM to be integrated into a diverse collaborative environment with varied design projects. More importantly, the design constraint-based DRM matrix and the Bayesian weighting method strongly enhanced the accuracy and the objectivity of risk mapping and measurement in different design projects. However, the other participants also conclude that the commercialism is the key to attain more and more valid feedback practically.

In summary, the proposed DRM tool has been verified with the positive results resulting from case study evaluation, and it can be applied for the collaborative design risk mapping, measuring and mitigating during the process of a new product design development. Besides, some valuable suggestions have also been recommended for future development of the DRM tool.

First, a number of interviewees recommended that the DRM tool might be more valuable if it focuses specifically on the conceptual design stage. Given that “product specification and reliability are affected the most by decisions made during the early design phases” (Lough, Stone and Tumer, 2009), the DRM tool can be performed more predictable and functional with less mature data. The DRM is expecting to anticipate and prevent accidents and failure at the beginning of occurring in the process of design collaboration. Thus, the research focuses on the explicit relationship between design constraints and risk variables can be more valuable in the conceptual design phase.

Second, several participants suggest that in comparison with small sized design projects, the DRM tool might be more suitable for large and long-term items. The former might merely involve a few designers, cooperating in a tight-coupled manner. The design managers may be incapable of dealing with design collaboration without the DRM tool support. In addition, the latter incorporates multidisciplinary designers, which is widely distributed with the complicated design collaboration processes in a global environment. In this sense, the DRM tool might be more needed and fitting for the large and long-term design projects.

Third, a few respondents also indicate that as the risk mitigation strategies can be generated by the iterative processes or the inherited experience, the proposed DRM tool needs more case study evaluation in order to collect more data. The data collected and saved in database will support users to find more appropriate risk mitigation solutions. Therefore, the collaborative design risk mitigation can be flexible performed primary based on prior cases rather than the users' knowledge and experience.

7.4 Conclusion

This chapter provides the results of case study evaluation for the proposed constraint-based DRM tool. Following this, participant observations and semi-structured interviews were undertaken based on four-month industrial placement in three different types of cases. In participant observation, sample case observations combine the document analysis, the surroundings evaluation, the direct participation, and the member consultation. The author took part in weekly meetings, reviewed related documents, and observed group collaborations and a total of 52 design staff participated in this case study observation.

Besides, the semi-structured interviews were executed after a range of observations, and were applied as the main component of case study evaluation for the exploration of the feasibility and effectiveness of the DRM simulation prototype according to the interviewees' judgments. After data collection, the data were input into the SPSS 13.0 for sample statistics analysis. The demographic characteristics of the sample survey have been described. Subsequently, a reliability analysis was performed for the assessment of sample reliability. The main findings and recommendations have been discussed.

The next chapter draws the implications for the overall research with presenting the contributions and limitations of this thesis. The recommendations for future research are also concluded.

Chapter 8 Conclusion

8.1 Introduction

This chapter aims to present a conclusion of the research. The findings and contributions of this thesis are provided, and the limitations incorporated with future research recommendations are presented.

In summary, with increasing global competition, collaborative design becomes the mainstream for product success (Chiu, 2002). Design collaboration represents various stakeholders cooperated for the achievement of a common design purpose in terms of three main features: task-dependency, role-interaction and resource-integration (Wang *et al*., 2002; Yesilbas and Lombard, 2004; Robin *et al*., 2007; Ruan and Qin, 2008). These features are factors that have a significant influence on design collaboration. In this regard, collaborative design is a three-dimensional constructs that constitutes those features in the context of the present research.

The study provided a constraint-based DRM conceptual framework that has been verified as a useful theoretical model for mapping, measuring and mitigating design risk based on the collaborative design features, the risk management process and Theory of Constraints (TOC). Furthermore, a constraint-based design risk management (DRM) matrix combined with evaluated design constraints and risk criteria has been explored in support of mapping, and measuring relevant design risks variables in a more efficient manner. Additionally, a Bayesian weighting method has been developed and applied to improve the objectivity and the accuracy of risk calculation. A visual-based prototype has been created with Visual.Basic.NET for simulation.

In general, the higher the degree of perceived risk, the greater severity consequence for design collaboration will be, and in turn the more hazards to the design project will be. This research has thus answered the original research questions, i.e. “how to conduct design risk management (DRM) under a collaborative product design environment?", "how to map and measure design risk variables in relation to the corresponding design constraints?", "how to measure the design risk magnitude in more appropriate and efficient way" and "how to simulate a DRM tool in terms of preceding integrated research results". Ultimately, the case study evaluations were conducted through participant observations and semi-structured interviews, in order to validate the proposed DRM tool. The theoretical and practical implications of the results are elaborated and recommendations are presented.

8.2 Findings and Contributions

This thesis has developed a novel method for risk management by using TOC for design collaboration. A constraint-based DRM tool combined a conceptual framework with a matrix has been developed for mapping, measuring and mitigating the critical design risks in terms of relevant design constraints. Furthermore, a Bayesian weighting method has been proposed to reinforce risk assessment for DRM tool based on Bayesian theorem. In addition, a smaller, less detailed, less complex DRM simulation prototype has been created in order to conduct a verification of the DRM implementation in design companies in manner of less time consuming, lower cost and no risk. Finally, three industrial case studies evaluation with the participant observations and the semi-structured interview has been performed. Several conference papers and journal papers have been published in terms of research findings and results (see Appendix E). The explicit contributions of this study are as follows:

1. Introduces the concept of using TOC as a complete risk analysis technique for collaborative design projects. Developed a constraint-based DRM conceptual framework to provide a guideline for risk mapping, measuring and mitigating risks during the process of design collaboration.

1.1 Develops a hierarchy constraint network to map design constraints and risk variables in terms of the features of collaborative environment. As collaborative design refers to multidisciplinary staffs spreading widely in a distributed environment, this model can be demonstrated based on three-dimensional levels: task-dependency, role-interaction and resource-integration (Wang *et al.*, 2002; Yesilbas and Lombard, 2004; Robin *et al.*, 2007; Ruan and Qin, 2008).

1.2 Develops a constraint-based DRM conceptual framework that has been proven as a useful theoretical model with the purpose of guiding design risk mapping for mapping, measuring and mitigating design risk incorporated with collaboration features, Theory of Constraints (TOC) and the risk management process.

2 Develops a constraint-based DRM matrix, where risk can be represented by design constraints and risk criteria. The DRM matrix can be implemented in incorporation with the DRM conceptual framework in a different design stages on the basis of risk management process.

2.1 The critical design constraints within three levels of collaboration are identified and be evaluated in a systematic manner. The selected design constraints combined with risk criteria constructed a valuable DRM matrix. This matrix can be applied into DRM framework.

2.2 Tests the DRM matrix with risk mapping and measurement, risk variables are identified and the risk value is assigned and can be calculated by a PRA method. Despite the subjectivity, the PRA method results had good effectiveness and efficiency.

3 Provids a Bayesian weighting method for risk computation in design collaboration. The Bayesian weighting method can be used more objectively and accurately when compared to PRA method. A DRM simulation prototype is developed combined with the constraint-based DRM conceptual framework and matrix aims at providing a demonstration of the application for further case study evaluation. Finally, the case studies evaluation is performed for validation.

3.1 Initiates an improvement of risk measurement. A Bayesian weighting method is developed and incorporated into the DRM matrix. The modification of this calculation will significantly reduce the subjectivity and increase the accuracy to design risk measurement, while not notably increasing the cost and complexity of process.

3.2 Completes the development of DRM simulation prototype. The prototype tool combined DRM framework and matrix based on the specified design collaboration levels and general risk management process. The tool is developed with comprehensive risk management setting, flexible data input, automatic risk computation and multi-presentation output. It can be operated on Windows XP or 7 systems and used to determine the design risk in a project level. The DRM tool will be of benefit that supports the demonstration of overall research architectures. By applying the DRM tool, case study evaluation is greatly facilitated.

3.3 Completes case study evaluations through participant observations and semi-structured interviews in order to validate the proposed DRM tool. These evaluations ensure that whether the establishments of DRM tool can provide assistance for design collaboration by setting an effective way to deal with the industry practice. The findings indicate that the proposed constraint-based DRM tool has a positive influence on the improvement of collaborative performance. The contribution will aid both designers and managers to comprehend the essential role of design constraints and risk management.

8.3 Limitation

The researcher attempts to expand the understanding of how to conduct risk management in a collaborative design environment. More specifically, this research is focused on mapping, measuring and mitigating design risk to facilitate design collaboration. Although the research is valuable, this study also has some limitations.

First, as the risk management research, by its nature, was constrained to the probabilities, which generally result from experts’ knowledge and experience. Nevertheless, risk is measured primarily by the probability and consequence. Thus, the subjectivity and bias in this sense is unavoidable. This may have influence on the overall study results.

Besides, given that this research represents a first attempt to examine TOC and risk management under a collaborative design environment, the findings may be limited to the design collaboration context and may not be appropriate or necessary for all design projects.

In addition, the study used design constraints measurement regarding different collaborative levels and DRM tool is typically focused on the combination of TOC theory and risk management. However, most design constraints were adapted from previous literature, and refined by using results after a small sample questionnaire survey. Even though the proposed DRM tool displayed main design constraints and collaborative features comprehensively, several constraints were eliminated during the process of DRM matrix formulation. Some design constraints are dependent and the relationship between dependent constraints would affect design risk mapping, measurement and mitigation. This research concentrates on the dependent constraints that might limit the generalisability of the findings.

However, these limits do not minimise the main contribution of this research. It provides meaningful implications both theoretically and practically for the current collaborative design risk management.

8.4 Recommendations for Future Research

As the study presented in this thesis makes a progress towards risk management for design collaboration, there exist some relevant areas to explore in the future. Some of them are derived directly from the research limitations, while others are suggested with opportunities for new research directions. Some recommendations for future research include:

- Develop a more efficient web-based software tool.

The current implementation of the DRM tool can be performed by a Windows XP or 7 systems within a couple of hours to finish a single case analysis, which mostly relies on the complexity of collaborative design context. While given that design collaboration represents a dynamical and geographically distributed features (Chua *et al.*, 2003), the proposed DRM cannot be running in that circumstance. Thus, DRM tool can be further developed and operated more efficiently and effectively by means of a web-based software application in a distributed environment. A web-based tool can facilitate DRM through internet access and web communication without geographic restrictions. In this case, developing a web-based software tool based on the results described in this thesis would be more useful.

- Additional case studies to collect more data for design risk mitigation strategy.

Risk mitigation strategy plays a crucial role in preventing design risk occurring that generally generated from participants' knowledge and experiences. However, on the one hand, as not all the participants are experts in the realm of design risk management, they might not be in possession of sufficient knowledge and relevant experience, and their judgments might inherent with subjectivity and bias. This might result in significant influence on the overall study outcome. On the other hand, as risk mitigation strategy can be generated by iterative processes or inherited experience, the data reasoning approach based on previous case studies would help participants to reduce partiality and increase the objectivity.

References

Adler, P. and Mandelbaum, A. (1995), ‘From project to process management: An empirically-based framework for analyzing product development time’. *Management Science 41(3)*, 458– 484.

Ahmed, A., Kayis, B. and Sataporn, A. (2007), ‘A review of techniques for risk management in projects’, *Benchmarking: An International Journal*, 14 (1) pp. 22-36.

Albano, L.D., Suh, N.P., Pecht, M., Slocum, A., Jakiela, M. and Lewis, K. (1999), *“Engineering Design” Mechanical Engineering Handbook*. Boca Raton: CRC Press LLC.

Alexander, C. (2001), *The Bayesian Approach to Measuring Operational Risks’ in Mastering Risk*. London: FT-Prentice Hall.

Ali, A.S., Rahmat, I. and Hassan, H. (2008), ‘Involvement of Key Design Participants in Refurbishment Design Process’, *Facilities*, 26, pp.389-400.

Amornsawadwatana, S. (2002), ‘Risk mitigation investment in concurrent design process’, *Proceedings of the International Conference on Manufacturing Automation – ICMA, Hong Kong, China*. Suffolk: Professional Engineering Publishing Ltd.

Andrew, S. and Halcomb, E. (2009), *Mixed Methods Research for Nursing and the Health Sciences.* USA: John Wiley & Sons, Ltd.

Antonsson, E.K. and Otto, K.N. (1995), ‘Imprecision in engineering design’, *Journal of mechanical design*, 117 (B) pp. 25–32.

Archer, N. and Ghasemzadeh, F. (1999), ‘An integrated framework for project portfolio selection', *International Journal of Project Management*, 17(4), pp. 207-216.

AS/NZ Standard 4360 (1999), Australian/New Zealand Risk Management Standard, AS/NZ Standard 4360.

Aven, T. (1997), 'Alternative Bayesian approaches to risk analysis', Stavanger University College and University of Oslo. Available at: http://www.nr.no/TilfeldigGang/sept97/taven/taven.html. [Accessed 14th June 2007].

Axelrod, R. (1997), 'Advancing the Art of Simulation in the Social Sciences' in Conte R. & Hegselmann R (eds.), Simulating Social Phenomena LNEMS 456, Springer, Berlin.

Baccarini, D. and Archer, R. (2001), 'The risk ranking of projects: a methodology', *International Journal of Project Management*, 19 (3) pp. 139-145.

Balzac, I. (2002), *Time-to-Market Reduction through Collaborative Design.* Available at: http://assets1.csc.com/fashion_and_retail/downloads/9276_2.pdf [Accessed 11th June 2010]

Bauer, M. (2002), *Collaborative Product Design: A Balanced Approach for Enhanced Client Satisfaction and Profitability.* Available at: http://www.csc.com/aerospace_defense/offerings/16309/43118collaborative_product_design. [Accessed 13th June 2009].

Belliveau, P., Griffin, A., and Sommermeyer, S. (2002), *The PDMA Toolbook 2 for New Product Development*. Wiley, New York.

Bernard, H. R. (1995), *Research methods in anthropology: qualitative and quantitative approaches*. CA: AltaMira.

Blessing, L.T.M. and Chakrabarti, A. (2009), *DRM, a Design Research Methodology*, London: Springer Press.

Boehm, B.W. (1991), 'Software risk management: principles and practices', *IEEE Software*, 8, pp. 32-41.

Booch,G., Jacobson, I. and Rumbaugh, J. (2000), OMG Unified Modeling Language Specification, Version 1.3, 1st Edition.

Bouchlaghem, D., Kimmance, A.G. and Anumba, C.J. (2004), 'Integrating product and process information in the construction sector', *Industrial Management & Data Systems,* 104 (3) pp. 218-233.

Brannen, J. (1992), *Mixed methods: qualitative and quantitative research.* England: Avebury.

Brittion, C. and Doake, J. (2005), *A student guide to object-oriented development.* Great Britain: Elsevier.

Bronder, C. and Pritzl, R. (1992), 'Developing strategic alliances: a conceptual framework for successful co-operation', *European Management Journal*, 10(4) pp.412–22.

Bryman, A. (2008), *Social research Methods*. UK: Oxford University Press.

Bryman, A. and Bell, E. (2007), *Business Research Methods.* UK: Oxford University Press.

Bucciarelli, L.L. (2002), 'Between thought and object in engineering design', *Design Studies*, 23 (3) pp. 219-231.

Burgess, R.G. (1982), *Field research: a source book and field manual*. London: Allen and Unwin.

Burns, R.B. (2000), *Introduction to Research Methods*. London: Sage.

Busseri, M.A. and Palmer, J.M. (2000), 'Improving teamwork: the effect of self-assessment on construction design teams', *Design Studies*, 21 (3) pp. 223-238.

Caron, F., Fumagalli, M. and Rigamonti, A. (2007), 'Engineering and contracting projects: a value at risk based approach to portfolio balancing', *International Journal of Project Management,* 25 (6) pp. 569-578.

Carter, B., Hancock, T., Morin, J.M. and Robins, M. (2001), *Introducing Riskman: The European Project Risk Management Methodology*, Oxford: NCC Blackwell Ltd.

Castrup, H. (2007), *Bayesian Risk Analysis,* Available at: http://www.isgmax.com/Articles_Papers/Bayesian%20Risk%20Analysis.pdf [Accessed 23rd May 2009].

Cather,H., Morris, R., Philip, M. and Rose, C. (2001), *Design Engineering*. Great Britain: Elsevier.

Caver, T.V. (1985), 'Risk Management as a Means of Direction and Control', *Fact Sheet Program Managers Notebook*: Defense Systems Management College.

Chapman, C. and Ward, S. (2003), *Project Risk Management: Processes, Techniques and Insights,* Chichester: Wiley.

Chapman, R.J. (1998), ‘The effectiveness of working group risk identification and assessment techniques’, *International Journal of Project Management*, 16(6) pp. 333-343.

Chapman, R.J. (2001), ‘The controlling influences on effective risk identification and assessment for construction design management’, *International Journal of Project Management*, 19, pp.147-160.

Chen,L. and Jin, G.D. (2006), ‘Product modeling for multidisciplinary collaborative design’, *The International Journal of Advanced Manufacturing Technology*, 30(7-8) pp. 589-600.

Cheng, E.W.L., Love, P.E.D., Standing, C. and Gharavi, H. (2006), ‘Intention to e-collaborate: propagation of research propositions’, *Industrial Management & Data Systems*, 106 (1) pp. 139-152.

Chesbrough, H.W. (2003), *Open innovation: the new imperative for creating and profiting from technology*. Boston: Harvard Business School.

Chick, S. E. (2001), ‘Input distribution selection for simulation experiments: accounting for input uncertainty’ .*Operations Research*, 49 (5).pp. 23-35.

Chiu, M.L. (2002), ‘An organisational view of design communication in design collaboration’, *Design Studies*, 23, pp.187-210.

Chu, C., Cheng, C., Wu, C. (2006), ‘Applications of the web-based collaborative visualisation in distributed product development’, *Computers in Industry*, 57, pp. 272-282.

Clarke, C.J. and Varma, S. (1999), ‘Strategic risk management: the new competitive edge’, *Long Range Planning,* 32 (4) pp. 414-424.

Clemen, R.T. (1996), *Making Hard Decisions: An Introduction to Decision Analysis*. New York: Druxbury Press.

Conroy, G. and Soltan, H. (1998), 'CONSERV, a project specific risk management concept', *International Journal of Project Management*, 16(6) pp. 353-366.

Cooper, R.G. and Kleinschmidt, E. J. (1995), 'Benchmarking the firm's critical success factors in new product development', *Journal of Product Innovation Management*, 12, pp.374-391.

Cooper, D. and Schindler,P. (2001), *Business Research Methods*. Boston: McGraw Hill Irwin.

Cooper, R. and Press, M. (1995), *The design agenda: a guide to successful design management*. England: John Wiley & Sons Ltd.

Craig, A., Hart, S. (1993), 'Dimensions of success in new product development', in: Baker, M.J. (ed.) *Perspectives on Marketing Management*. London: John M. Wiley & Sons, Ltd., pp. 207-243.

Creswell, J.W. (2009), *Research design: qualitative, quantitative and mixed methods approaches*, UK: Sage.

Creswell, J.W. and Plano,C.V. (2006), *Designing and Conducting Mixed Methods Research.* California: Sage.

Cross, N. (2000), *Engineering Design Methods: Strategies for Product Design*. England: Wiley & Sons.

Crossland, R., Williams, J.S. and McMahon, C. (2003), 'The practical application of design risk assessment models, Proceeding of IMechE', *Journal of Engineering Manufacture*, 217 (B) pp. 227-234.

Curtis, B., Krasner, B.H. and Iscoe, N. (1988), 'A Field Study of the Software Design Process for Large Teams', *Comm.ACM*, 31 (11) pp. 1268-1287.

Danesi, F., Gardan, N. and Gardan, Y. (2006), 'Collaborative design: from concept to application', *IEEE Proceedings of the Geometric Modeling and Imaging.*

Dawson, C. (2002), *Practical research methods: a user-friendly guide to mastering research.* Oxford: How To Books Ltd.

Defense Systems Management College, (DSMC), (1986), *Risk Management: Concepts and Guidance.* Ft. Belvoir, Va:Defense Systems Management College.

Deck, M. and Strom, M. (2002), 'Model of co-development emerges', *Research Technology Management*, 45 (3) pp. 47–54.

DeMaio, A., Verganti, R. and Corso, M. (1994), 'A multi-project management framework for new product development', *European Journal of Operational Research*, 78 (2) pp.178-191.

De Mozota, B. (2003), *Design management: using design to build brand value and corporate innovation*. New York: Allworth Press.

Denscombe, M.A. (2003), *The good research guide*. 2nd edn. England: Open University Press.

Denzin, N.K. (1978), *The research act: a theoretical introduction to sociological methods*, 2nd edn. New York: McGraw-Hill.

Design Constraints Report. [Online] Available at: http://www.mae.buffalo.edu/courses/mae459/design-info/ConstraintsReport.ppt
[Accessed 17 May 2007]

De´tienne, F. (2006), 'Collaborative design: Managing task interdependencies and multiple perspectives', *Interacting with Computers*, 18, pp. 1–20.
de Vaus, D. A. (2002), *Surveys in Social Research*, 5th edition, Allen &Unwin, Crows Nest, Australia

DeVellis, R.F. (1991), *Scale Development: theory and applications* (Applied Social Research Methods Series, Vol. 26). Newbury Park: Sage.

Dickinson, M.W., Thornton, A.C. and Graves, S. (2001), 'Technology portfolio management: Optimising interdependent projects over multiple time periods', *IEEE Transactions on Engineering Management*, 48 (4) pp. 518-527.

Dolley, k. (2002), *'Simulation Research Methods', Companion to Organisations, Joel Baum (ed.).* London: Blackwell.

Draper, D. (1995), 'Assessment and propagation of model uncertainty', *Journal of the Royal Statistical Society, Series B* 57 (1): 45–97.

Durofee, A.J., Walker, J.A., Alberts, C.J., Higuera, R.P., Murphy, R.L. and Williams, R.J. (1996), *Continuous Risk Management Guidebook*, PA: Carnegie Mellon University.

Dym, C.L. and Little, P. (2003), *Engineering Design: A Project-Based Introduction*. England: Wiley and Sons.

Easterby-Smith, M., Thorpe, R. and Lowe, A. (2002), *Management research: an introduction.* London: Sage.

Elfes, A., Lincoln, W.P., Rodriguez, G., Weisbin, C.R. and Wertz, J.A. (2006),' Risk-based technology portfolio optimisation for early space mission design', *Aerospace and Electronic Systems, IEEE Transactions*, 42(1) pp.22-36.

Emden, Z., Calantone, R.J. and Droge, C. (2006), 'Collaborating for new product development: selecting the partner with maximum potential to create value', *Journal of Product Innovation Management*, 23, pp.330-341.

Eppinger, D.S. (1997), 'Generalized models of design iteration using signal flow graphs'. *Research in Engineering Design 9*, 112–123.

Fairley, R. (1994), 'Risk management for software projects', *IEEE Software,* pp. 57-64.

Ferson,S.(2005), 'Bayesian methods in risk assessment', *Report for Service Environnement & Procédés*, Available at: www.ramas.com/bayes.pdf [Accessed 13 June 2009]

Filippi, S. and Cristofolini, I. (2010), *The Design Guidelines Collaborative Framework: A Design for Multi-X Method for Product Development*. London: Springer.

Flager, F., Welle, B., Bansal, P., Soremekun G., and Haymaker J. (2009), 'Multidisciplinary Process Integration and Design Optimization of a Classroom Building,' ITcon Vol. 14, p. 595-612.

Fowler, M. and Scott, K. (1997), *UML distilled—applying the standard object modelling Language*. Addison-Wesley: Reading.

Frankfort-Nachmias,C., and Nachmias, D. (1996), *Research methods in the social sciences*. 5th edn. London: St. Martin Press.

Fuha, J.Y.H. and Li, W.D. (2005), 'Advances in collaborative CAD: the-state-of-the art', *Computer-Aided Design*, 37, pp. 571–581.

Gandikota, M.S. and Davis, J.F. (1990), 'An expert system framework for the preliminary design of process flow sheets', *Knowledge Based Computer Systems : International Conference KBCS '89,* Bombay, 444, pp.88-104.

Gilbert, N. and Troitzsch, K.G. (2005), *Simulation for the Social Scientist,* 2ndedn, New York: McGraw-Hill House.

Girard, P., Legardeur, J. and Merlo, C. (2007), 'Product innovation through management of collaborative design in concurrent engineering', *International Journal of Technology Management and Sustainable Development*, 6 (2) pp.151-164.

Goldratt, E.M. and Cox, J. (1992), *The Goal: A Process of Ongoing Improvement.* 2ndedn. Great Barrington: North River Press Publishing Corporation.

Gomm, R. (2008), *Social research methodology: a critical introduction*, 2ndedn. London: Palgrave Macmillan.

Gonnet, S., Henning, G. and Leone, H. (2007), 'A model for capturing and representing the engineering design process', *Expert Systems with Applications*, 33, pp. 881–902.

Goonetillake, J.S., Carnduff, T.W. and Gray,W.A.,(2001), 'Integrity constraint management for design object versions in a concurrent engineering design environment', *Database Engineering & Applications, International Symposium.* pp. 255 – 261.

Greasley, A. (2004), *Simulation Modelling for Business*, Aldershot: Ashgate Limited.

Griffin, A. and Hauser, J.R. (1996), 'Integrating R&D and marketing: a review and analysis of the literature', *Journal of Product Innovation Management*, 13, pp. 191-215.

Guikema, S. (2007), ‘A proposal for including technical failure risk in market-based resource reallocation for spacecraft design’, *Engineering and System Safety*, 92, pp. 653 – 659.

Gupta, A., Chen, I. J. and Chiang, D. (1997), *Determining organizational structure choices in advanced manufacturing technology management*. Omega, p. 511-521.

Gupta, M. C. and Boyd, L. H. (2008), ‘Theory of Constraints: A Theory for Operations Management’, *International Journal of Operations and Production Management*, 28(9/10) pp 991-1012.

Hair, J.F.J., Anderson, R.E., Tatham, D.L., Black, W.C. (1995), *Multivariate Data Analysis with Readings*, 4th ed., Prentice-Hall, Upper Saddle River, NJ.

Halcomb, E.J. and Davidson, P.M. (2006), ‘Is verbatim transcription of interview data always necessary?’ *Applied Nursing Research*, 19, pp. 38–42.

Hao, Q., Shen, W., Zhang, Z. and Park, S.W. (2006), ‘Agent-based collaborative product design engineering: An industrial case study’, *Computers in Industry,* 57, pp.26–38.

Harrell, C.R., Ghosh, B.K., Bowden, R. and Bowden, R.O. (2004), *Simulation Using Promodel*, London: McGraw-Hill Higher Education.

He, D.L., Wang, G.Y. and Li, Z.G. (2001), ‘An approach to collaborative design based on distributed constraint-net’, *Journal of Natural Sciences*, 7 (1) pp. 82-86.

HM Treasury (2004), *The orange book.* [Online] Available at: http://www.hm-treasury.gov.uk/media/3/5/FE66035B-BCDC-D4B3-11057A7707D2521F.pdf [Accessed 23 October 2008]

Holzner, S. (2003), Sams teach yourself Microsoft Visual Basic.Net 2003 in 21 Days 2th Edition. US: Sams

Hood, C. and Rothstein, H. (2000), ‘Business risk management in government: pitfalls and possibilities’, *National Audit Office: Supporting Innovation: Managing Risk in Government Departments*, London.

Hu, J.M. (2002), ‘Constraint driven workflow execution for concurrent product development’, *Advances in Concurrent Engineering, Proceedings of the 9th ISPE.*

Huang, C.J, Trappey, A.C. and Yao, Y.H. (2006), ‘Developing an agent-based workflow management system for collaborative product design’, *Industrial Management & Data Systems,* 106 (5) pp. 680-699.

Huang, G.Q., Huang, J. and Mak, K.L. (2000), ‘Agent-based workflow management in collaborative product development on the Internet’, *Computer-Aided Design*, 32 (29) pp. 133– 144.

Hubka, V. and Eder, W.E. (1988), *Theory of technical systems: A total concept theory for engineering design.* 2nd edn. New York: Springer.

Humphreys, P., Huang, G. and Cadden, T. (2005), ‘A web-based supplier evaluation tool for the product development process’, *Industrial Management & Data Systems,* 105 (2) pp. 147-163.

Inman, R.A., Sale,M.L., and Green, K.W. (2009), ‘Analysis of the relationships among TOC use, TOC outcomes, and organisational performance’, *International Journal of Operations & Production Management*, 29 (4) pp. 341-356.

Jaafari, A. (2001), ‘Management of risks, uncertainties and opportunities on projects: time for a fundamental shift’, *International Journal of Project Management,* 19 (2) pp. 89-101.

Jas, A., Chang, Y.S. and Chakravarty, S. (2008), ‘A Methodology for Handling Complex Functional Constraints for Large Industrial Designs’, *Journal of Electronic Testing: Theory and Applications,* 24(1-3) pp. 259-269.

Jeng, T.S. and Eatman, C.M. (1999), ‘Design Process Management’, *Computer-Aided Civil and Infrastructure Engineering,* 14, pp. 55-67.

Jiang, P., Shao, X.Y., Qiu, H.B. and Li, P.G. (2008), ‘Interoperability of Cross-organisational Workflows based on Process-view for Collaborative Product Development’, *Concurrent Engineering: Research and Applications*, 16 (1) pp.73-87.

Joan-Arinyo, R.., Soto-Riera, A. and Vila-Marta, S. (2006), ‘Constraint-Based Techniques to Support Collaborative Design’, *Journal of Computing and Information Science in Engineering,* 6 (2) pp. 139-149.

John, A.S. and Catherine, M. B. (2009), *Principles of Modeling and Simulation: A Multidisciplinary Approahc*. New Jersey: Wiley & Sons, Inc.

Johnson, B. and Turner, L.A. (2003), ‘Data collection strategies in mixed methods research’, in: Jonker, J. and Pennink, B. (2010), T*he Essence of Research Methodology: A Concise Guide for Master and PhD Students in Management Science*. London: Springer Press.

Julien, L.D., Alain, B., Nicolas, P. and Jean-Charles, D. (2009), ‘A Constraints Driven Product Lifecycle Management Framework’, *Proceedings of the 19th CIRP Design Conference – Competitive Design*. Crandfield.

Kayis, B., Arndt, G., Zhou, M., Savci, S., Khoo, Y.B. and Rispler, A. (2006), 'Risk quantification for new product design and development in a concurrent engineering environment', *Annals of the CIRP* 55(1).

Kayis, B., Zhou, M., Savci, S., Khoo, Y.B., Kusumo, R., Ahmed, A. and Rispler, A. (2007), 'IRMAS – development of a risk management tool for collaborative multi-site, multi-partner new product development projects', Journal of Manufacturing Technology Management 18 (4), pp. 387-414.

Kerzner, H. (2009), *Project Management: A Systems Approach to Planning, Scheduling, and Controlling*. England: John Wiley & Sons.

Khan, O., Christopher, M. and Burnes, B. (2008), 'The impact of product design on supply chain risk: a case study', *International Journal of Physical Distribution & Logistics Management*, 38 (5) pp.412 – 432.

Kim, S., Mabin, V.J. and Davies, J. (2008), 'The Theory of Constraints thinking processes: retrospect and prospect', *International Journal of Operations & Production Management*, 28 (2) pp.155-184.

Klein, J.H. and Cork, R.B. (1998), 'An approach to technical risk assessment', *International Journal of Project Management,* 16 (6) pp.345-351.

Kleiner, S., Anderl, R. and Gräb, R. (2003), 'A collaborative design system for product data integration', *J Eng Des,* 14 (4) pp.421-428.

Kleinsmann, M., Valkenburg, R. and Buijs, J. (2007), 'Why do(n't) actors in collaborative design understand each other? An empirical study towards a better understanding of collaborative design', *CoDesign* , 3 (1) pp.59–73.

Kothari, C.R. (2004), *Research Methodology: Methods and Techniques.* New Delhi: New Age International (P) Ltd.

Kuo, J.Y. (2004), 'A document-driven agent-based approach for business process management', *Information and Software Technology*, 46, pp.373-382.

Lai, Y.L. (2009), 'A constraint-based system for product design and manufacturing', *Robotics and Computer-Integrated Manufacturing*, 25 (1) pp.42-58.

Lang,S.Y.T.,Dickinson,J.,and Buchal,R.O.(2002), 'Cognitive factors in distributed design' ,*Computers in Industry*, 48, PP.89–98.

Lee, K. (2008), 'Risk minimisation under budget constraints', *Journal of Risk Finance*, 9 (1) pp.71 – 80.

Lenhard, J. and Küppers, U. (2006), *Simulation: pragmatic construction of reality.* Netherlands: Springer.

Lewis, P.R. (1993), 'Designing with Plastics', *Rapra Review Reports*, 6(4) pp.55-66

Li, W.D., Lu, W.F., Fuh, J.Y.H. and Wong, Y.S. (2005), 'Collaborative computer-aided design-research and development status', *Computer-Aided Design,* 37, pp. 931-940.

Li, W.D., Ong, S.K, Nee, A.Y.C. and McMahon, C.A. (2007), Collaborative Product Design and Manufacturing Methodologies and Applications, Springer, pp. 71–92.

Li, X., Zhao, X.H. and Ruan, X.Y. (2002), 'Conflict management in closely coupled collaborative design system', *International Journal of Computer Integrated Manufacturing,* 15 (4) pp.345–352.

Lin, K., Chen, D., Sun, C. Z. and Dromey, G. (2005), ‘A Constraint Maintenance Strategy and Applications in Real-Time Collaborative Environments’, *Computer Science,* 3675, pp.103-110.

Lin, M.W. and Lai, K.L. (2009), ‘Modeling Collaborative Design via Fuzzy Contraint-Based Agent Negotiation, Fuzzy Systems and Knowledge Discovery, FSKD '09’, *Sixth International Conference*, pp. 560 – 564.

Lincoln,Y.S. and Guba, E. G. (1985), *Naturalistic inquiry*. Beverly Hills, CA: Sage Publications, Inc.

Littler, D., Leverick. F. and Bruce, M. (1995), ‘Factors affecting the process of collaborative product development: a study of UK manufacturers of information and communications technology products’, *Journal of Product Innovation Management,* 12 (1) pp.16–33.

Lottaz, G., Smith, I.F.C., Robert-Nicoud, Y. and Faltings, B.V.(2000), ‘Constraint-based support for negotiation in collaborative design’, *Artificial Intelligence in Engineering*, 14 (3) pp.261-280.

Lougha, K.G., Stonea, R. and Tume, I.R. (2009), ‘The risk in early design method’, *Journal of Engineering Design,* 20 (2) pp. 155–173.

Lu, S.C.Y., and Cai, Y. (2001), ‘A Collaborative design process model in the sociotechnical engineering design framework’, *Artificial Intelligence for Engineering Design, Analysis and Manufacturing,*Vol 15.pp. 3-20.

Lu,S.C.Y., and Jing,N. (2009), ‘A socio-technical negotiation approach for collaborative design in software engineering’, *International Journal of Collaborative Engineering,* 1 (1/2) pp. 185-209.

Lubars,M., Potts, C. and Richter, C. (1993), 'A Review of the State of Practice in Requirements Modeling', *Proc.IEEE Symp. Requirements Eng. (RE'93),* San Diego,CA, IEEE Computer Society Press, pp. 2-14.

Lynch, R.L. and Cross, K.F. (1991), *Measure up – the essential guide to measuring business performance*. London: Mandarin.

Mabin, V.J. and Balderstone, S.J. (2003), 'The performance of the Theory of Constraints methodology: analysis and discussion of successful TOC applications', *International Journal of Operations & Production Management,* 23 (6) pp. 568-595.

Madhusudan, T. (2005), 'An agent-based approach for coordinating product design workflows', *Computers in Industry*, 56(3) pp. 33-41.

Markeset, T. and Kumar, U. (2003), 'Integration of RAMS and risk analysis in product design and development work processes: A case study', *Journal of Quality in Maintenance Engineering*, 9 (4) pp. 393 – 410.

Mervyn F, Senthil Kumar A, Nee AYC. 'A 'plug-and-play' computing environment for collaborative product design and manufacturing across an extended enterprise', *Collaborative product design and manufacturing methodologies and applications*, Springer; p. 71-92.

Meshkat, L., Voss, L., Cornford, S.L. and Feather, M.S. (2005), 'An integrated approach to risk assessment for concurrent design', *Aerospace Conference, IEEE,* 42(1) pp.80-88.

Miles, M.B. and Huberman, A. M. (1994), *Qualitative data analysis: an expanded sourcebook.* Beverly Hills: Sage.

Mizuno, Y., Ninokata, H. and Finnicum, D.J. (2005), 'Risk-informed design of IRIS using a level-1 probabilistic risk assessment from its conceptual design phase', *Engineering and System Safety,* 87, PP. 201–209.

Modarres, M. and Kaminskiy, M. (1999), *Reliability Engineering and Risk Analysis*, New York: Marcel Dekker.

Mohr, J. and Spekman, R. (1994), 'Characteristics of partnership success: partnership attributes, communication behaviour, and conflict resolution techniques', *Strategic Management Journal*, 15 (2) pp. 135–152.

Morrison, J. and Twyford, J. (1994), *Design: Capability and awareness*. Harlow, Essex: Longman.

Murthy, D. N. P., Rausand, M. and Østerås, T. (2008), *Product Reliability: Specification and Performance.* London: Springer.

Neuman, W. L. (2006), *Social research methods: Qualitative and quantitative approaches*, New York: Pearson Education Inc.

Nunnally, J.C., and Bernstein, I.H. (1994), *Psychometric Theory*, 3rd ed. New York: McGraw-Hill.

Olshausen, B.A. (2004), *Bayesian probability theory*, Available at: http://redwood.berkeley.edu/bruno/npb163/bayes.pdf
[Accessed 19th March 2008]

Olson, G. and Olson, J. (2000), 'Distance matters', *Human Computer Interaction,* 15(2) pp.139– 178.

Ouertani, M. Z. and Gzara, L. (2008), ‘Tracking product specification dependencies in collaborative design for conflict management’, *Computer-Aided Design,* 40 (7) pp.828-837.

Pahl, G., Beitz, W., Feldhusen, J. and Grote, H.K. (2007), *Engineering Design: A Systematic Approach*. 3rdedn. London: Springer.

Patterson, F.D. and Neailey, K. (2002), ‘A risk register database system to aid the management of project risk’, *International Journal of Project Management,* 20 (5) pp.365-374.

Patton,M. Q. (1987), *How to Use Qualitative Methods in Evaluation*. California: Sage Publications, Inc.

Patton, M.Q. (2002), *Qualitative research and Evaluation methods.* 3rdedn. CA: Sage Publications Inc.

Paulos, T. (2005), *“Introduction to Probabilistic Risk Assessment Using SAPHIRE,” Jet Propulsion Laboratory Professional Development Course*, CA: Pasadena.

Peter, J.P. (1979), ‘Reliability: A Review of Psychometric Basics and Recent Marketing Practices’, *Journal of Marketing Research*, Vol. 16(Feb), pp. 6-17.

Potts, C. And Catledge, L. (1996), ‘Collaborative Conceptual Design: A Large Software Project Case Study’, *The Journal of Collaborative Computing*, 5, pp. 415-445.

Priest, J.W., Sánchez, J.M. (2001), *Product development and design for manufacturing: a collaborative approach to productbility and reliability*. New York: Headquarters.

Pritchard, C.L. (2001), *Risk Management: Concepts and Guidance*. 2ndedn. Virginia : ESI International.

Project Management Institute (1987), *Project Management Body of Knowledge*. PMI: Drexel Hill, Penn

Project Management Institute (2004), *A Guide to the Project Management Body Of Knowledge*, 3th, PMI: Newtown Square, PA.

Project Management Institute (2008), *A Guide to the Project Management Body Of Knowledge*, 4th, PMI, Newtown Square, PA.

Pugh, S. (1990), *Total Design,* London: Prentice Hall

Puigjaner, R., Benzekri, A. and Ayache, S. (1993), 'Estimation process of performance constraints during the design of Real-Time & Embedded systems, Advanced Information Systems Engineering', *Computer Science,* 685, pp. 629-648.

Pyra, J. and Trask, J. (2002), 'Risk management post analysis: gauging the success of a simple strategy in a complex project', *Project Management Journal*, 33(2) pp. 41-48.

Qin, S.F., Harrison, R., West, A.A., Jordanov, I.N. and Wright, D.K. (2003), 'A framework of web-based conceptual design', *Computers in Industry*, 50, pp.153-164.

Qiu, Y. and Ge, P. (2007), 'A risk-based global coordination system in a distributed product evelopment environment for collaborative design, part 1', *framework,* 15, pp. 357-367.

Qiu, Z.M. and Wong, Y.S. (2007), 'Dynamic workflow change in PDM systems', *Computers in Industry,* 58 (5) pp. 453-463.

Raftery, J. (1994), *Risk Analysis in Project Management,* London: Chapman & Hall.

Raz, T. and Michael, E. (2001), ‘Use and benefits of tools for project risk management’, *International Journal of Project Management,* 19, pp. 9-17.

Roberts, B. (2000), *Risk Management 2000: Lessons for the Millennium*. VA: McLean.

Robin, V., Rose, B. and Girard, P. (2007), ‘Modelling collaborative knowledge to support engineering design project manager’, *Computers in Industry,* 58 (2) pp. 188-198.

Rong, Z.J, Li, P.G, Shao, X.Y. and Chen, K.S. (2006), ‘Constraint-based Collaborative Design’, *IEEE Proceedings of the 10th International Conference on Computer Supported Cooperative Work in Design.*

Royer, P.S. (2000), ‘Risk management: the undiscovered dimension of project management’, *Project Management Journal*, 31 (1) pp. 6-13.

Ruan, J. and Qin, S.F. (2008), ‘A Generic Conceptual Model of Risk Evaluation in Multi-agent Based Collaborative Design’, *Proceedings of the 14th International Conference on Automation & Computing*, Brunel University, West London, UK.

Ruan, J. and Qin, S.F. (2009), ‘A Generic Conceptual Model for Risk Analysis in a Multi-agent Based Collaborative Design Environment’, *Proceedings of the 19th CIRP Design Conference – Competitive Design*. Crandfield University, Crandfield, UK.

Sanchez, H., Robert, B., Bourgault, M., Pellerin, R. (2009), ‘Risk management applied to projects, programs, and portfolios’, *International Journal of Managing Projects in Business,* 2 (1) pp.14 – 35.

Sanjai, A.G.,Gupta, A. and Tiwari. S. (1993), ‘Distributed Constraint Management for Collaborative Engineering Databases’, *CIKM Proceedings of the second international conference on Information and knowledge management,* New York: ACM, pp.55-62.

Sanvido, V.E. & Norton, K.J. (1994), ‘Integrated design-process model’. *Journal of Management in Engineering 10(5)*, 55– 62.

Schragenheim, E., and Dettmer, H.W. (2000), *Manufacturing at Warp Speed*. Boca Raton, FL: St. Lucie Press

Shen, W., Hao, Q. and Li, W. (2008), ‘Computer supported collaborative design: retrospective and perspective’, *Computers in Industry*, 59, pp. 855-862.

Silverman, D. (2000), *Doing Qualitative Research: A Practical Handbook*. London: Sage.

Simatupang, T.M., Wright, A.C. and Sridharan, R. (2004), ‘Applying the Theory of Constraints to supply chain collaboration’, *Supply Chain Management: An International Journal*, 9 (1) pp. 57 – 70.

Skander, A., Roucoules, L., Sébastien, J., Meyer, K. (2008), ‘Design and manufacturing interface modelling for manufacturing processes selection and knowledge synthesis in design’, *The International Journal of Advanced Manufacturing Technology,* 37 (5-6) pp. 443-454.

Smith, P.R. and Eppinger, D.S. (1997), ‘Identifying controlling features of engineering design iteration’. *Management Science 43(3)*, 276–293.

Stanton, N. A., Salmon, P.M., Walker, G.H., Baber, C. and Jenkins, D.P. (2005), *Human factors methods: a practical guide for engineering and design*. England: Ashgate.

Stapelberg, R.F. (2009), *Handbook of Reliability, Availability, Maintainability and Safety in Engineering Design*. London: Springer.

Stewart, M.G. and Melchers, R.E. (1997), *Probabilistic Risk Assessment of Engineering Systems,* London: Chapman & Hall.

Stone, S., Collin, H. (1984), *Crus guide, designing a user study: general research design.* Centre for Research on User Studies, University of Sheffield.

Suh, N.P. (1990), *The Principles of Design*. Oxford: Oxford University Press.

Thurston, D.L. and Carnahan, J.V. (1992), 'Fuzzy Rating and Utility Analysis in Preliminary Design Evaluation of Multiple Attributes', *ASME Journal on Mechanical Design*, 114(4) pp.648-658.

Tichkiewitch, S. and Brissaud, D.(2001), 'Integration of Life-cycle Constraints in Design Activity', *Proceedings of the IFIP TC5 WG5.2 Fourth Workshop on Knowledge Intensive CAD to Knowledge Intensive Engineering,* pp. 84-93.

Tony, P., Kevin, W. and Robert, J.V. (2006), 'Using the Theory of Constraints to improve competitiveness: an airline case study', *Competitiveness Review: An International Business Journal incorporating Journal of Global Competitiveness,* 16 (1) pp. 44 – 50.

Trappey, A.J.C., Trappey, C.V. and Lin, F.T.L. (2006), 'Automated silicon intellectual property trade using mobile agent technology', *Robotics and CIM*, 22, pp.189-202.

Treasury Board of Canada Secretariat (2007), *Integrated Risk Management Implementation Guide.* [Online] Available at: www.tbssct.gc.ca/pubs_pol/dcgpubs/RiskManagement/guide01_e.asp#overviewIRMF [Accessed 19 Oct 2008]

Tseng, M.M., Kyellberg, T. and Lu, S.C.Y. (2003), 'Design in the new e-manufacturing era', *Annals of the CIRP*, 52(2) pp. 43-54.

Turban, E., King, D., Lee, J. and Viehland, D. (2004), *Electronic Commerce: A Managerial Perspective*. London: Pearson Education International.

Ulrich, K.T., Eppinger, S.D. (2004), *Product design and development,* 3rdedn, New York: McGraw- Hill/Irwin.

van Drongelen, C.K., Cook, A. (1997). 'Design principles for the development of measurement systems for research and development processes', *R&D Management,* 27 (4), pp.345-357.

Vanda, L. (2008), 'Take into account knowledge constraints for design of TEL environments in medical education', *Eighth IEEE International Conference on Advanced Learning Technologies.*

Vanegas and Labib, A.W. (2005), 'Fuzzy Approaches to Evaluation in Engineering Design', *ASME Journal of Mechanical Design*, 127 (1) pp. 24-34.

Vergeest, J.S.M. and Horváth, I. (1999), 'Design Model Sharing in Concurrent Engineering:Theory and Practice', *Concurr Eng.* 7 (2) pp. 105-113.

Voland, G. (1999), *Engineering by Design*. MA: Addison-Wesley, Reading.

Walton, M.A. (2002), *Managing Uncertainty in Space Systems Conceptual Design Using Portfolio Theory, Doctoral Thesis, Massachusetts Institute of Technology*, MA : Cambridge.

Wang, L., Shen, W., Xie, H., Neelamkavil, J. and Pardaani, A. (2002), 'Collaborative conceptual design- state of the art and future trends', *Computer-Aided Design*, 34, pp. 981-996.

Wang, W., Hu, J., Yin, J. and Peng, Y. H. (2006), ‘Uncertainty management in the concurrent and collaborative design based on generalised dynamic constraints network (GDCN)’, *Proceeding of the 10th International Conference on Computer Supported Cooperative Work in design*.

Wang, Y., Shen, W. and Ghenniwa, H. (2003), ‘A Web/agent-based multidisciplinary design optimisation environment’, *Computers in Industry*, 52 (1), pp. 17–28.

Ward, S.C. (1999), ‘Assessing and managing important risks’, *International Journal of Project Management*, 17 (6) pp. 331-336.

Webb, A. (1994), *Managing Innovative Projects*. London: Chapman & Hall.

Wertza, J. and Miller, D. (2006), ‘Expected productivity-based risk analysis in conceptual design’, *Acta Astronautica,* 59, pp. 420 – 429.

Whitney, D. (2008), ‘Proper constraint as a design principle for assemblies’, *Assembly Automation*, 28 (2) pp. 120–125.

Williams, T. (1995), ‘A classified bibliography of recent research relating to risk management’, *European Journal of Operational Research,* 85(1) pp. 18-38.

Wilson, J.R. and Corlett, E.N.(1995), *Evaluation of Human Work.* 2ndedn. London: Taylor & Francis.

Wood, K.L. and Antonsson, E.K. (1989),’ Computations with Imprecise Parameters in Engineering Design: Background and Theory’, *ASME Journal of Mechanism, Transmissions, and Automation in Design,* 11(1) pp.616-625.

Wu, Z. and Duffy, A. (2002), *Mutual Knowledge Evolution in Team Design. In: Proceedings of 7th International Conference on Artificial Intelligence in Design (AID '02)*. UK: Cambridge.

Xia, M. and Li, H. (1999), ‘Cooperative software agents for workflow management system, paper presented at APCC/OECC ’99’, *Fifth Asia-Pacific Conference on Communications and Fourth Optoelectronics and Communications*, 2, pp. 1063-1067.

Xu, D. and Wang, H. (2002), ‘Multi-agent collaboration for B2B workflow monitoring’, *Knowledge-Based Systems*, 15, pp. 485-491.

Yan, Y., Maamar, Z. and Shen, W. (2001), ‘Integration of workflow and agent technology for business process management’, *the Sixth International Conference on CSCW in Design*, 7(12-14) pp. 420-426.

Yesilbas, G.L. and Lombard, M. (2004), ‘Towards a knowledge repository for collaborative design process: focus on conflict management’, *Computers in Industry,* 55, pp.335–350.

Yin, R. K. (2009), *Case study research: design and methods*. London: Sage.

Yoshikawa, H. (1981), ‘General design theory and a CAD system’. In *Man- Machine Communication in CAD/CAM*, (Sata, T. and Warman, E.Eds), p. 35. North Holland, Amsterdam.

Yvars, P.A. (2009), ‘A CSP approach for the network of product lifecycle constraints consistency in a collaborative design context’, *Engineering Applications of Artificial Intelligence*, 22 (6) pp. 66-75.

Zha, X. F. and H. D (2006), ‘Knowledge-intensive collaborative design modelling and support part I: Review, distributed models and framework’, *Computers in Industry*, 57, pp.39-55.

Zha, X.F. and Sriram, R.D., Fernandez, M.G. and Mistree, F. (2008), ‘Knowledge-intensive collaborative decision support for design process: a hybrid decision support model and agent’, *Computers in Industry*, 59, pp. 905-922.

Appendix A: Industry Interview

Spring 2007

INDUSTRY INTERVIEW
RESEARCH OF DESIGN RISK MANAGEMENT FOR COLLABORATIVE DESIGN

The intention behind this industry interview is to gather the information from Engineering, Design and Management professionals related to the field of Risk Management. Any data collected from this interview will not be used beyond the scope of this research and in complete confidence. The interview will take about 20 minutes, and covers several topics including your views on collaborative design risk management. Thank you for your participation.

I General Background Information

1. What is your profession?

Please select... ▾	false	false

If you select others, please specify below:

		false	
100	chr		

2. Which functional group you are responsible for in your profession?

- Research ☐
- Design Management ☐
- Engineering Design ☐
- Marketing/Sales ☐
- Industry Design ☐
- Manufacturing ☐
- Product Development ☐
- Other ☐ ____________

2. How long have you been working in this job?

- 0-1 years ☐
- 2-3 years ☐
- 4-5 years ☐

- 6-7 years ☐ • 8 or more years ☐

4. What kind of organisation do you work for?

Please select... ▾ false

false

5. Organisation is:

- For-Profit - Large (> 500 employee) ☐
- For-Profit – Medium (>50 <500 employee) ☐
- For-Profit - Small (< 50 employee) ☐
- Non-Profit / Government ☐

II Related Collaborative Design

6. For current and recent design projects, what percentage of design practice involves collaboration?

•>20% ☐ •20-40% ☐ •40-60% ☐

•60-80% ☐ •80-100% ☐ false

7. During the design project, to what extent has collaboration in the design activities contributed to the new product development for your organisation?

Not Important ☐	Slightly Important ☐	Somewhat Important ☐	Quite Important ☐	Extreme Important ☐

8. According to literature survey, collaborative design can be sum up by three categories (task-dependency, role-interaction and resource-integration), to what extent you agree or disagree with this conclusion?

Strong Disagree ☐	Tend to Disagree ☐	Neither Agree or Disagree ☐	Tend to Agree ☐	Strong Agree ☐

III Current Design Risk Practice

9. For current and recent design projects, are there any DRM tool or method used to support design management?

If yes, what is it? If no, do you conduct any design risk assessment activities in your design project?

10. Do you find it is important to bring DRM tool or practice into Collaborative Product Design?

Why?

11. Who are in charge or responsible for DRM practice? Why?

12. What kinds of process are took in your DRM practice?

13. What kinds of risk items are considered in your DRM practice? Why?

14. What methods are usually used to measure risk items in your DRM practice? Why?

15. What methods are used to evaluate risk items after measurement? Why?

16. Any solutions are generated to avoid these identified risk items?

17. During the NPD, how satisfied were you with the results of DRM administrative operations?

Not Satisfied	Slightly Satisfied	Somewhat Satisfied	Quite Satisfied	Extreme Satisfied
☐	☐	☐	☐	☐

18. Any recommendation for improving current DRM practice?

IV DRM Development Suggestion

19. Who should be involved in the operation of collaborative design risk management? Why?

- Design manager ☐
- Designer ☐
- Customer ☐
- Design stakeholder ☐
- Others ☐

20. Do you agree or disagree with three risk management process (risk identification, risk assessment and risk mitigation), which are specified by PMBOK（Project Management Body of Knowledge）?

Strong Disagree ☐	Tend to Disagree ☐	Neither Agree or Disagree ☐	Tend to Agree ☐	Strong Agree ☐

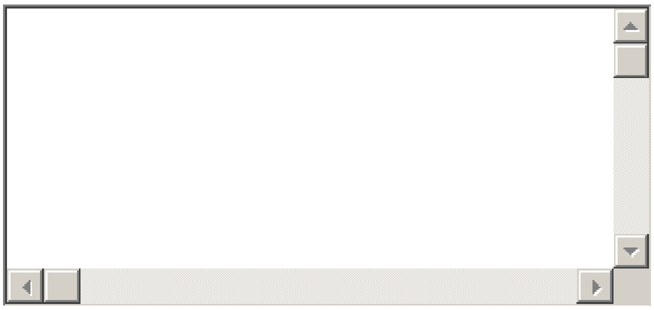
21. To what extent do you agree that a constraint theory related to design practice should be introduced into design risk management field?

Not Satisfied ☐	Slightly Satisfied ☐	Somewhat Satisfied ☐	Quite Satisfied ☐	Extreme Satisfied ☐

22. What kinds of risk items do you think are important and should be included while conducting DRM practice? Why?

- Downstream Design activities ☐
- Designer ☐
- Product ☐
- Supply chain ☐
- Design process ☐
- End user ☐
- Designer ☐
- Upstream industry chain ☐
- Others ☐

23. Any more recommendation for development of DRM?



THANK YOU FOR YOUR COOPERATION!

Appendix B: Questionnaire Survey

Design Constraints and Risk Criteria Evaluation
For Collaborative Design

Spring 2008

Introduction

Thank you for your participation. This questionnaire survey should take you no more than 10 minutes.

The research is focused on developing a Design Risk Management (DRM) tool which can be used to support collaborative design in the process of new product development. This questionnaire aims at evaluate main design constraints and risk criteria, in order to support mapping and measuring corresponding collaborative design risk variables through a constraint-based variables matrix. These constraints and criteria have been clarified from the literature survey in the area of design management, NPD and risk management. Thirty design constraints are concluded into three collaborative categories, and five risk criteria are selected as a risk standard.

You will be asked to select the six most important design constraints from the list and rank priority after your evaluation. We will also ask your opinion about risk criteria which can be used as a foundation as well as design constraints for the development of DRM mapping and measuring matrix. Please look through the following questions cautiously and give an appropriate answer.

I would like to assure you that all the information we collect will be kept in the strictest confidence, and used for research purposes only. It will not be possible to identify any particular individual or address in the results. If you have any query about this questionnaire or research, please contact: Jian.Ruan@brunel.ac.uk.

Participant Information

Organisation:

- Research Organisation ☐ • Design Company ☐
- Engineering Company ☐

Profession:

- Designer ☐ • Engineer ☐ • Design Manager ☐
- Other ☐

Working Experience:

- 0-1 years ☐ • 2-3 years ☐ • 4-5 years ☐ • 6-7 years ☐
- 8 or more years ☐

Organisation is:

- For-Profit - Large (> 500 employee) ☐
- For-Profit – Medium (>50 <500 employee) ☐
- For-Profit - Small (< 50 employee) ☐
- Non-Profit / Government ☐

Job Responsibility:

- Research ☐ • Industry Design ☐
- Design Management ☐ • Engineering Design ☐
- Product Development ☐ • Other ☐

Part One Task-dependency level Design Constraints

Q1 Which of the following design constraints have the most influence on collaborative design in <u>Task-dependency</u> level? Please tick SIX of them in the corresponding box.

❒	a)	**Cost constraints**	☐
	b)	**Quality constraints**	☐
❒	c)	**Maintenance constraints**	☐
	d)	**Schedule constraints**	☐
❒	e)	**Function constraints**	☐
	f)	**Product life cycle constraints**	☐
❒	g)	**Process Constraints**	☐
	h)	**Operation constraints**	☐
❒	I)	**Safety constraints**	☐
	j)	**Manufacture constraints**	☐

Q2 **From those design constraints you have chosen, which do you think would play more important roles than others in the process of collaborative design? Please prioritize them by ranking significance (1-6).**

6-Extremely important	
5-Fairly important	
4-Really important	
3-Important	
2-Relatively important	
1- Slightly important	

Q3 **If there are any other constraints you think that should be included into <u>Task-dependency</u> level, Please list below.**

Part Two Role-interaction level Design Constraints

Q4 **Which of the following design constraints have the most influence on collaborative design in <u>Role-interaction</u> level? Please tick SIX of them in the corresponding box.**

❒	a)	**Communication constraints**	☐
	b)	**Customer constraints**	☐
❒	c)	**Designer constraints**	☐
	d)	**Performance constraints**	☐
❒	e)	**Decision constraints**	☐
	f)	**Knowledge constraints**	☐
❒	g)	**Stakeholder Constraints**	☐
	h)	**Supplier constraints**	☐
❒	I)	**Conflict constraints**	☐
	j)	**Negotiation constraints**	☐

Q5 **From those design constraints you have chosen, which do you think would play more important roles than others in the process of collaborative design? Please prioritize them by ranking significance (1-6).**

6-Extremely important	
5-Fairly important	
4-Really important	
3-Important	
2-Relatively important	
1- Slightly important	

Q6 **If there is any other constraints you are concerned that should be included into <u>Role-interaction</u> level, Please list below.**

Part Three Resource-integration level Design Constraints

Q7 **Which of the following design constraints have the most influence on collaborative design in <u>Resource-integration</u> level? Please tick SIX of them in the corresponding box.**

❐	a)	**Legal constraints**	☐
	b)	**Technical constraints**	☐
❐	c)	**Information constraints**	☐
	d)	**Ergonomic constraints**	☐
❐	e)	**Market constraints**	☐
	f)	**System constraints**	☐
❐	g)	**Material Constraints**	☐
	h)	**Ecological constraints**	☐
❐	I)	**Tool constraints**	☐
	j)	**Ecological constraints**	☐

Q8 **From those design constraints you have chosen, which do you think would play more important roles than others in the process of collaborative design? Please prioritize them by ranking significance (1-6).**

6-Extremely important	
5-Fairly important	
4-Really important	
3-Important	
2-Relatively important	
1- Slightly important	

Q9 **If there is any other constraints you are concerned that should be involved into <u>Resource-integration</u> level, Please list below.**

____

____

____

____

Part Four Risk Criteria Evaluation

Q10 **To what extent do you agree or disagree with ‘Availability’ is a risk criterion of design constraints?** SINGLE CLICK ONLY

A	Strongly agree	☐
B	Tend to agree	☐
C	Neither agree nor disagree	☐
D	Tend to disagree	☐
E	Strongly disagree	☐

Q11 **To what extent do you agree or disagree with ‘Feasibility’ is a risk criterion of design constraints?** SINGLE CLICK ONLY

A	Strongly agree	☐
B	Tend to agree	☐
C	Neither agree nor disagree	☐
D	Tend to disagree	☐
E	Strongly disagree	☐

Q12 **To what extent do you agree or disagree with ‘Accuracy or Safety’ is a risk criterion of design constraints?** SINGLE CLICK ONLY

A	Strongly agree	☐
B	Tend to agree	☐
C	Neither agree nor disagree	☐
D	Tend to disagree	☐
E	Strongly disagree	☐

Q13 **To what extent do you agree or disagree with ‘Reliability’ is a risk criterion of design constraints?** SINGLE CLICK ONLY

A	Strongly agree	☐
B	Tend to agree	☐
C	Neither agree nor disagree	☐
D	Tend to disagree	☐
E	Strongly disagree	☐

Q14 **To what extent do you agree or disagree with ‘Maintainability’ is a risk criterion of design constraints?** SINGLE CLICK ONLY

A	Strongly agree	☐

B	Tend to agree	☐
C	Neither agree nor disagree	☐
D	Tend to disagree	☐
E	Strongly disagree	☐

Q15 **To what extent are you satisfied or dissatisfied with the way of selection of risk criteria?** SINGLE CLICK ONLY

A	Very satisfied	☐
B	Fairly satisfied	☐
C	Neither satisfied nor dissatisfied	☐
D	Fairly dissatisfied	☐
E	Very dissatisfied	☐

THANK YOU FOR YOUR COOPERATION!

Appendix C: Industry Interview for Case Study Evaluation

The intention behind this industry interview is to conduct an evaluation for the results of a PhD research by a constraint-based Design Risk Management (DRM) simulation software prototype. This prototype is incorporated with a DRM conceptual framework, a DRM matrix and a DRM weighting application method. More details of the functions of DRM is presented and demonstrated in Section II. Subsequently, the interviewees will be asked to participant in a simulated DRM process under a virtual design project environment. Ultimately, in Section III, the participants are required to answer ten evaluation questions on the basis of their knowledge and experience. Any data collected from this interview will not be used beyond the scope of this research and in complete confidence. Thank you for your participation.

Section I General Background Information

1. What is your profession?

- Designer ☐
- Design Manager ☐
- Project Manager ☐
- Stakeholder ☐

2. Which functional group you are responsible for in your profession?

- Research ☐
- Industry Design ☐
- Design Management ☐
- Engineering Design ☐
- Product Design ☐
- Other ☐

3. How long have you been working in this job?

- >1 years ☐
- 1-3 years ☐
- 3-5 years ☐
- >5 years ☐

4. What kind of organisation do you work for?

- Design Company ☐
- Consultancy Company ☐
- Engineering Company ☐
- Manufacturing Company ☐

5. Organisation is:

- For-Profit - Large (> 1000 employees) ☐
- For-Profit - Medium (>100 <1000 employees) ☐
- For-Profit - Small (< 100 employees) ☐
- Non-Profit / Government ☐

Section II Presentation and Demonstration

In Section II, interviewer will briefly describe the results of this PhD research. This includes a DRM operation framework, a DRM matrix, and a DRM weighting application model. Subsequently, a DRM simulation software prototype will be demonstrated in order to present a holistic view of implementation of the proposed DRM tool.

Section III Evaluation Questions

6. According to the present design project, to what extent *do you agree that the simulated DRM instrument can be implemented and incorporated feasibly?*

Strong Disagree ☐	Tend to Disagree ☐	Neither Agree or Disagree ☐	Tend to Agree ☐	Strong Agree ☐

7. To what extent *do you agree that the simulated DRM instrument can be applied flexibly in design industry*?

Strong Disagree ☐	Tend to Disagree ☐	Neither Agree or Disagree ☐	Tend to Agree ☐	Strong Agree ☐

8. To what extend *do you agree that the design constraints can be incorporated into risk criteria to represent design risk on the basis of three collaborative levels?* (Task-dependency, Role-interaction and Resource-integration)

Strong Disagree ☐	Tend to Disagree ☐	Neither Agree or Disagree ☐	Tend to Agree ☐	Strong Agree ☐

9. To what extent *do you agree that the simulated DRM instrument can be used for collaborative design risk mapping during the process of design collaboration?*

Strong Disagree ☐	Tend to Disagree ☐	Neither Agree or Disagree ☐	Tend to Agree ☐	Strong Agree ☐

10. To what extent *do you agree that the simulated DRM instrument can measure collaborative design risk during the process of design collaboration?*

Strong Disagree ☐	Tend to Disagree ☐	Neither Agree or Disagree ☐	Tend to Agree ☐	Strong Agree ☐

11. To what extent *do you agree that the simulated DRM instrument can mitigate collaborative design risk during the process of design collaboration?*

Strong Disagree ☐	Tend to Disagree ☐	Neither Agree or Disagree ☐	Tend to Agree ☐	Strong Agree ☐

12. To what extent *do you agree that the proposed DRM instrument can generate reliable outputs in terms of the proposed collaborative levels?* (Task-dependency, Role-interaction and Resource-integration)

Strong Disagree ☐	Tend to Disagree ☐	Neither Agree or Disagree ☐	Tend to Agree ☐	Strong Agree ☐

13. To what extent *do you agree that the proposed DRM instrument can generate reliable outputs by linking DRM with project manager, design manager, designer and stakeholders?*

Strong Disagree ☐	Tend to Disagree ☐	Neither Agree or Disagree ☐	Tend to Agree ☐	Strong Agree ☐

14. To what extent *do you agree that the proposed DRM instrument can generate reliable outputs by linking DRM with the stage-based design objectives?*

Strong Disagree ☐	Tend to Disagree ☐	Neither Agree or Disagree ☐	Tend to Agree ☐	Strong Agree ☐

15. To what extent *do you agree that the proposed DRM instrument can be used in support of both manager and designer to conduct DRM practice during the process of design collaboration?*

Strong Disagree ☐	Tend to Disagree ☐	Neither Agree or Disagree ☐	Tend to Agree ☐	Strong Agree ☐

16. To what extent *do you agree that the proposed DRM instrument can be used in support of both manager and designer to attain design project achievement during the process of design collaboration?*

Strong Disagree ☐	Tend to Disagree ☐	Neither Agree or Disagree ☐	Tend to Agree ☐	Strong Agree ☐

17. Any more recommendation for development of DRM?

THANK YOU FOR YOUR COOPERATION!

Appendix D: The Original SPSS Results of Case Study Evaluation Interviews

Q6	Q7	Q8	Q9	Q10	Q11	Q12	Q13	Q14	Q15	Q16
5	5	4	4	5	3	4	5	4	5	5
3	3	2	3	3	1	2	3	2	3	3
4	4	4	5	4	5	3	4	4	5	4
4	4	4	5	3	4	5	5	5	4	5
4	4	3	4	4	3	5	4	3	4	3
4	4	4	5	4	5	3	4	5	5	5
3	3	4	4	3	4	4	4	5	5	4
5	4	5	4	4	5	4	3	4	5	5
3	2	4	3	3	2	5	4	3	5	5
5	4	4	5	4	3	4	5	4	4	5
4	5	5	4	4	3	4	4	4	5	4
5	5	4	4	4	4	4	4	5	4	3
5	5	5	4	4	4	5	5	5	4	3
4	3	2	5	4	4	4	5	5	5	4
4	4	4	5	5	5	3	4	4	5	4
3	3	4	5	5	4	4	4	4	5	4
4	4	4	5	4	4	4	5	4	4	4
3	4	3	2	3	2	4	4	3	3	3
5	4	5	4	5	4	5	4	4	4	4
5	4	4	5	4	4	5	4	5	4	4
4	3	4	5	5	3	4	5	4	4	5
5	5	4	4	4	4	5	5	3	5	4
5	5	5	4	5	4	5	5	4	4	4
4	4	4	3	4	4	4	5	4	5	5
4	4	3	4	4	2	4	5	4	4	4
5	4	4	4	5	4	4	4	4	4	5
5	4	5	4	4	5	5	4	5	4	5
4	3	4	5	5	5	4	4	5	4	4
4	4	4	4	5	4	4	4	4	5	5
4	5	4	4	4	3	5	4	4	4	4

Appendix E: Publication List

Journal Articles
Currently being submitted …

1. “A Constraint-based DRM tool for Collaborative Design: An Empirical Study of Design Risk Management” , target journal, International Journal of Operations and Production Management.

2. “Exploring Design Constraints and Risk Criteria of Collaborative Design: A DRM matrix for Risk Mapping and Measuring” , submitted to, Design Studies.

Contributions to Conference Proceedings…refereed

3. “A Generic Conceptual Model for Risk Analysis in a Multi-agent Based Collaborative Design Environment” , Proceedings of the 19th CIRP Design Conference: Competitive Design, Cranfield University, March 2009

4. “Modelling a Constraint-based Design Risk Management Tool: An Empirical Study for Collaborative Product Design”, Proceedings of the IEEE International Conference on Industrial Engineering and Engineering Management (IEEM), Singapore, December 2011

5. “A Constraint-based DRM Matrix for Global Collaborative Product Design”, submitted to Proceedings of Tsinghua-DMI International Design Management Symposium, Hong Kong, December 20