AN ABSTRACT OF THE DISSERTATION OF

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Risk is a crucial decision factor besides traditional cost and performance during collaborative decision making in a distributed environment. Three main challenges exist: 1) stakeholders' different perspectives and/or diverse cultures can lead to inconsistent risk probability evaluations; 2) risk consequence is hard to be quantified in concrete unit; 3) risk evaluations uncertainties exist during collaborations. In this work, a risk-based global negotiation (RBN) methodology is developed to support integrative risk negotiation among distributed stakeholders. Two main aspects are covered to manage the challenges: risk content preparation and risk negotiation. Three steps are included in risk preparation: 1) a

uniform risk structure is constructed to capture and synthesize heterogeneous risk evaluations at both intra- and inter- stakeholders; 2) risk hierarchy is introduced to quantify risk consequence in notional monetary unit; 3) a consistency scheme is proposed to achieve consistent risk probability evaluations across stakeholders. In risk negotiation aspect, two models are proposed: 1) a static model is constructed to evaluate expected risk values and associated risk preferences systematically; 2) a dynamic uncertainty model is built to address risk uncertainty, and assist collaborative decision making problems such as resource allocation.

Two engineering examples are chosen to demonstrate the methodology. The first hypothetical example illustrates risk consequence notional quantification and corresponding resource allocation decision making. The second application focuses on local risk analysis and risk probability global consistency. The results show effectiveness and efficiency of the RBN. Innovations can be summarized: 1) risk probability consistency and risk consequence notional quantification are first introduced in distributed collaborative design; 2) varying weights method is first developed to aggregate multiple stakeholders' preference utilities; 3) static and dynamic uncertainty models are constructed to evaluate risk conditions and assist risk negotiation.

Contribution of the work exists in both design research and practice domains. For design research, risk is notionally quantified, and then it can directly combine with traditional cost and performance analysis, and provide more effective and comprehensive negotiation support; for design practice, the methodology in a mathematical form is ready to be embedded into existing commercial Product Data Management tools, which can help stakeholders achieve maximum market profits with acceptable cost-effective risk in the global economy.

Risk-based Negotiation for Collaborative System Design in a Distributed Environment

by
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Dean of the Graduate School

I understand that my dissertation will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my dissertation to any reader upon request.

Yuming Qiu, Author

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1. INTRODUCTION

1.1 COLLABORATIVE SYSTEM DESIGN

1.1.1 OVERVIEW

Collaboration exists everywhere in the modern society. “Collaboration is a process through which parties who see different aspects of a problem can constructively explore their differences and search for solutions that go beyond their own limited vision of what is possible" [Gray, 1989]. More than one parties are involved in a collaboration to achieve the same goal, and their joint activities can gain a better result than that from single party because of extensive perspectives and visions. Current society advancement demands collaborations within states or across nations. Many branches of science and technology have emerged and advanced such as Mechanical Engineering, Electrical Engineering and Computer Science. A single person can not possibly grasp all knowledge during his lifetime. However, design and manufacture of commercial goods is complicated and requires multi-discipline expertise, then a single person can not solely complete commercial goods independently. This requirement calls for multi-discipline collaboration. Besides specialization can allow people to conduct what they do best and increase their productivity [Mankiw, 2006], thus current social divisions of labor have been classified specifically based on specializations such as design engineers, process engineers and manufacturers. This fact also requires multi-discipline collaboration.

Besides collaboration in local domain, global collaboration occurs to obtain the maximum collaboration benefits, because more labor specializations and lower cost can be realized during global collaboration. New technology achievements have provided necessary and convenient tools for global collaboration such as long-range transportation and global communication technologies. Large commercial planes can easily transport people across the whole earth, and wireless cell-phones can immediately connect two persons anywhere.

"Trade can make everyone better off" [Mankiw, 2006]. Similarly, global collaboration can make involved collaborators or even their society better off. First, global collaborations can benefit collaborators. Many product development companies collaborate with domestic or international partners to achieve their maximum profits [Ganguly, 2005]. For instance, a US company conducts its product research and design in domestic areas, which provides job positions at high labor rates. Then it sends design drawings and requirements to Chinese plants, which can build and manufacture those products at very low cost. Finally the US company can distribute its salesmen and sell final products across the world. Product prices are greatly reduced, and the US company can obtain its maximum profits. In the meantime, Chinese plants can achieve proper profits and create more job positions. Second, global collaborations can benefit people. If goods can be distributed and sold across nations freely, then people can buy and use a large number and variety of imported goods with better quality and lower prices than local goods. Thus global collaboration is usually a win-win situation: everyone can be happy.

An important characteristic of global collaboration is that collaborators are distributed across the world. These collaborators form a distributed environment. A distributed environment can be viewed as several stakeholders, distributed at different geographical locations, collaborate and form a connected network to achieve certain common objectives [Chanron, 2005]. A stakeholder represents an organization or group which includes a number of members. Then members compose a stakeholder, and stakeholders form a distributed environment. Figure 1 shows a traditional distributed environment with n stakeholders. Three stakeholders are included in stakeholder 1, and n stakeholders are contained in a distributed environment. These two-level structures of a distributed environment are called intra- and inter- levels [Qiu, 2007a]. Intra- level means multiple members within a stakeholder, and inter- level indicates multiple stakeholders within a distributed environment. The two-level structure will be deliberated in this paper.

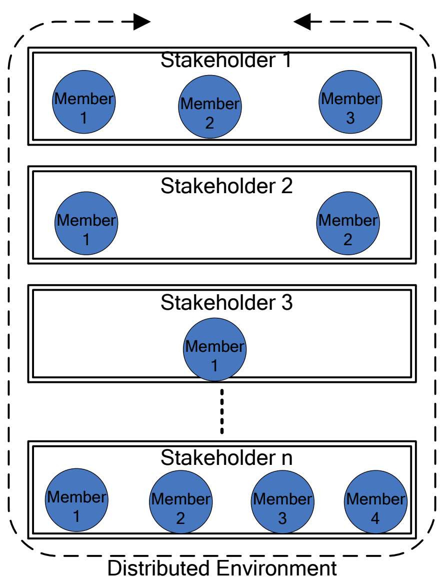


Figure 1 Distributed Environment

1.1.2 BARRIERS

Global collaboration can make every collaborator better off, but it is not always true, since good collaboration is not spontaneous and automatic. If collaborators are not well coordinated, their collaboration may adversely hurt collaborators. Some unsuccessful collaborations can be found in the history. There are several barriers for an effective collaboration. First, stakeholders' human social dynamics [Cross, 2002] can become collaboration barrier. When several collaborators with multi-discipline backgrounds work together, they need to learn scientific languages from other disciplines as basic communication tools. During this period, they may become uncomfortable, and misunderstanding can occur and push their collaboration in a difficult position. Other human social dynamics, such as dishonesty, selfishness and ignorance of others' goals [Cross, 2002], can also greatly affect involved stakeholders' motivations, and further deteriorate or ruin their collaboration. Some uniform structures and quantitative measures are proposed in this paper to mitigate the effect from this type of barrier.

Second inconsistency can occur and become collaboration barrier. In a local centralized environment, collaborators with different disciplines can have different perceptions on the same components, and then cause local inconsistency. In a global distributed environment, collaborators with diverse cultures can have different evaluations on the same components, and then lead to global inconsistency. Both inconsistencies can result in conflicts, and further prevent collaboration running smoothly. "Conflict is an expression of dissatisfaction or disagreement with an interaction, process, product, or service" [Costantino, 1995]. It is important to make all stakeholders' evaluations consistent. A consistency scheme is constructed in this paper to deal with this barrier.

1.1.3 NEGOTIATION AND RISK

Barriers exist in a distributed environment and prevent smooth collaboration. A collaboration challenge is how to enable all distributed stakeholders to work effectively and efficiently. Based on an extensive literature investigation, negotiation emerges as a solution. “Negotiation is an interpersonal decision-making process by which two or more people agree how to allocate scarce resources” [Thompson, 2001]. It “focuses on gaining the favor of people from whom we want things” [Scott, 1996]. Many social factors affect negotiation results. Respect, affection, trust, friendship, and graciousness can help put negotiations to the good side. Intimidation, disrespect and discomfort can push negotiations to the bad side [Scott, 1996; Jin, 2007]. In engineering domain, negotiation nature is to find win-win alternatives: all stakeholders are happy and no stakeholders experience a net loss.

Many factors can be employed as negotiation contents. Schedule, cost and performance are three important negotiation factors [Mankiw, 2006]. Risk is the forth factor. Risk is defined as “the combination of the probability and consequences that an undesired event may occur” [Bedford, 2001]. The famous Murphy’s Law says: “whatever can go wrong will go wrong” [Bloch, 2003]. It indicates popularity of risk in daily life and emphasizes risk effect. Risk is an important factor in a collaborative system design and should be emphasized. For example, National Aeronautics and Space Administration (NASA) designed and built the Mars Climate Orbiter spacecraft in 1999. Because of unit conversion errors between two collaborative groups, the spacecraft finally crashed resulting in $125,000,000 loss [NASA, 1999]. The error seems small, but its consequence is tremendous. If this type of risk can be analyzed and emphasized in advance, significant resources can be saved.

Schedule, cost and performance can lead to complicated trade-offs [Otto, 1991], while risk can exist within each aspect in a collaborative environment. First risk associated with schedule is common. Collaboration success depends on all stakeholders, and a key stakeholder's delay can affect whole project's schedule; second, risk can be associated with cost. A collaborative project's cost estimation is hard to be accurate during proposal stage, and then there is certain risk that final collaboration cost can be far above original budget proposal; third, risk can be associated with performance. Small risk can lead to big performance loss during collaboration. Collaboration increases intermediate steps, and further raises overall risk concerning performance of final products. Suppose completion of a commercial product includes 200 steps, and each step has 0.1% failure rate. 0.1% indicates small risk, but it turns out that final product success rate is only 81.9%. If steps increase to 300, then the success rate drops to 74.1%!

1.2 MOTIVATIONS AND OBJECTIVES

Existing work has examined risk-based design and shown promise for supporting distributed negotiations [Mehr, 2006; Stone, 2005; Tumer, 2003 & 2005]. Risk, combined with cost, can be a crucial factor in examining feasible alternatives in real engineering problems [Tumer, 2005; Chen, 2002; Loch, 2003; Jin, 1998]. However, risk evaluations are usually subjective and inaccurate, which renders risk-based system design highly challenging. This has provided us the motivation to study risk as an underpinning criteria of collaborative decision support. Many risk analysis tools have been developed and widely used in industry, such as Failure Mode and Effects Analysis (FMEA), HAZOP, Fault Tree Analysis and Event Tree Analysis [Barbour, 1977; Kmenta, 1999; Haimes, 1998]. These tools provide good guidelines for single stakeholder's risk analysis, but they cannot solve the inconsistency problem from multiple stakeholders [Qiu, 2007a]. More importantly, most existing risk tools are qualitative, and do not provide uniform quantifiable measures in distributed problems. There is a knowledge gap of integrating risk analysis in collaborative system design for effective and efficient negotiation support. The main motivation of this paper is to analyze and quantify risk in a distributed environment, and then mitigate collaboration barriers to achieve robust collaborative system design support. Three objectives are determined. The first is to understand fundamental risk mechanism; the second is to use a notional measure to quantify risk and incorporate it into existing collaborative system design; the third is to develop a risk-based negotiation methodology to help negotiation across distributed stakeholders based on the notional risk quantification. The ultimate goal is that the proposed mathematical methodology can be incorporated into commercial Product Data Management (PDM) software tools, so that it can support more real world engineering problems.

1.3 DISSERTATION ORGANIZATION

Six main chapters are included in this paper, and their structures are illustrated in Figure 2. First research background is briefly introduced; second existing relevant literatures are reviewed; third research problem is formed, and the problem is dissected step by step; forth a risk-based negotiation methodology is presented based on the problem dissection; fifth case studies are demonstrated to show and validate the presented methodology; and sixth conclusions and future work are discussed. The major part is the Risk-based Negotiation Methodology (RBN), which constructs mathematic static and dynamic uncertainty models to support risk-based negotiation in a distributed environment. The RBN includes three main steps: 1) local risk analysis; 2) collaborative system design; 3) Collaborative Negotiation.

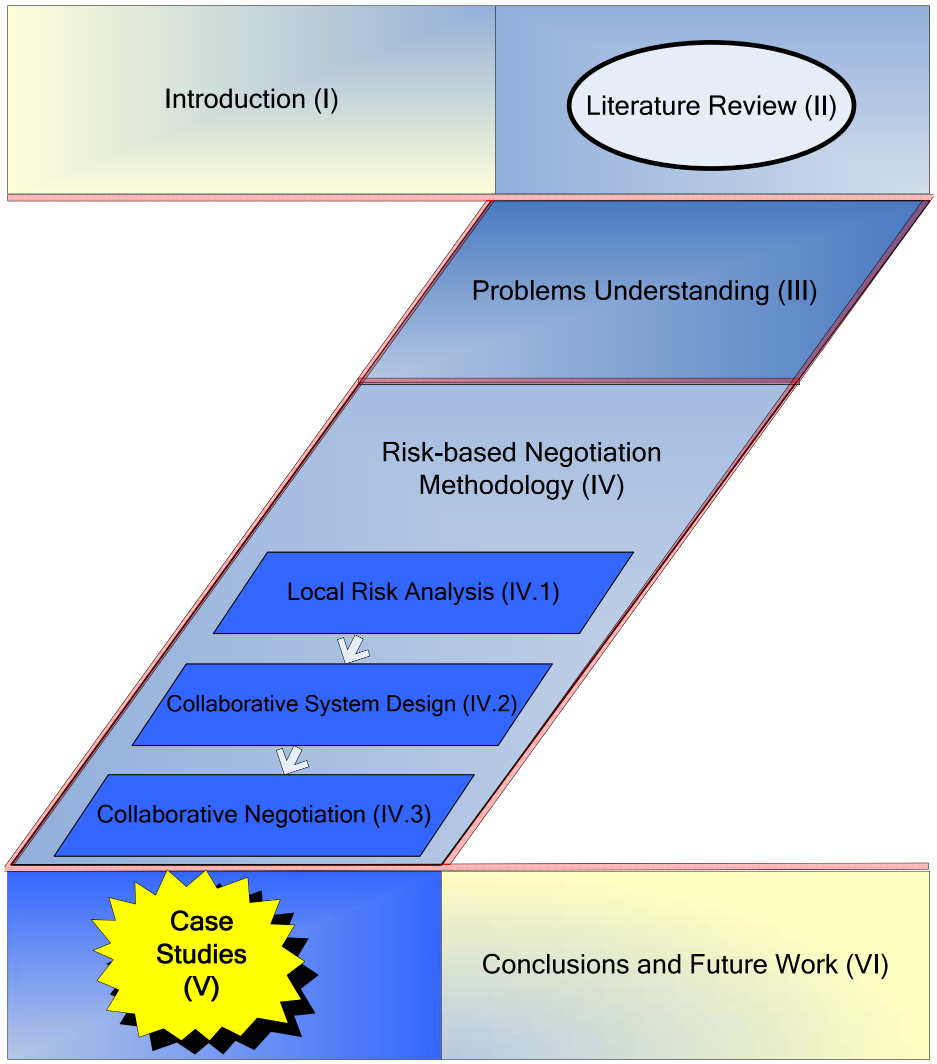


Figure 2 Dissertation Organization

2. LITERATURE REVIEW

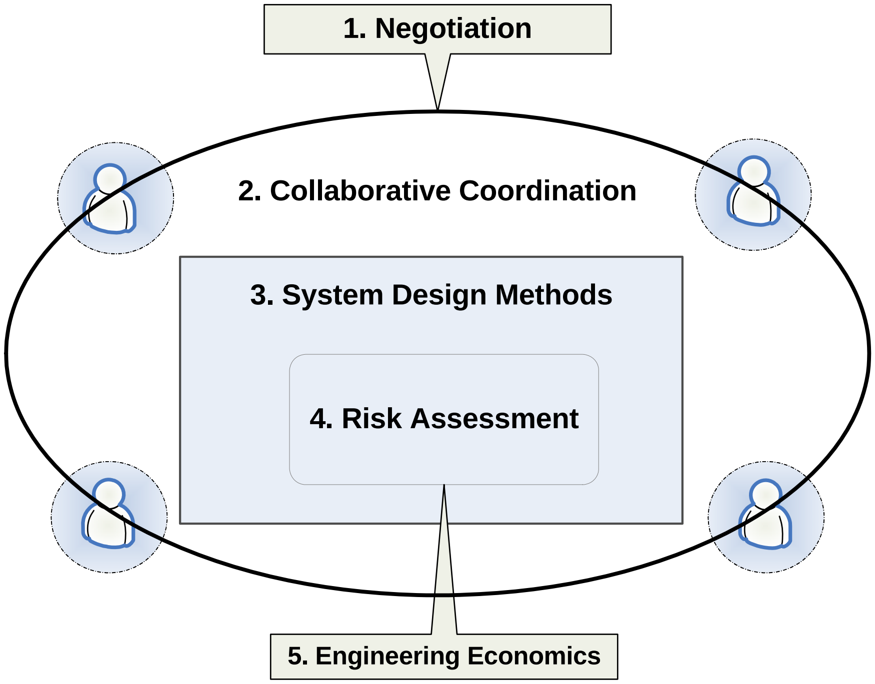


Figure 3 Relevant Literatures

The research goal is to support collaborative system design based on risk analysis in a distributed environment. Cross-discipline research areas are involved, and five relevant areas are reviewed as summarized in Figure 3. First, "Negotiation" reviews fundamental negotiation theories from a social science viewpoint, which provides a good foundation for this research; second, "Collaborative Coordination" reviews some general methodologies concerning effective coordination and collaboration in a collaborative environment; third, "System Design Methods" discuss some popular theories specifically in engineering design; forth, "Risk Assessment" reviews common risk analysis tools for risk identification and evaluation; fifth "Engineering Economics" shows basic engineering methods from an economic point of view, which provide good guidelines for risk quantification in a distributed environment.

2.1 NEGOTIATION

Originated from social science [Cross, 2002], negotiation has been studied for many years as a method for “facilitating information exchange, mutual understanding and joint decision making” [Jin, 1998]. In engineering design research community, theoretical and experimental investigations also show that negotiation outcomes can be positively affected by a negotiation support system [Lu, 2003; Ge, 2005]. This has led to the initial research idea of developing a negotiation support system in a distributed environment. There are five general negotiation styles and strategies: avoidance, competition, accommodation, collaboration and compromise [Thomas, 1976]. Avoidance style is try to avoid negotiation; competition style aims at getting the most; accommodation style is willing to give up; collaboration style is to find the most benefits for all; compromise style is try to solve competitive conflicts based on certain criterions; collaboration style is to make best use of limited resource based on collaborators’ different interests [Thomas, 1976]. Engineering negotiation prefers collaboration style. For instance, both A and B own a single book with CD. A only wants the hard copy, and B only needs the CD, then both A and B can get what they want. A win-win alternative is achieved! The key is to find out all collaborators’ real interests.

Besides negotiation styles, human social dynamics are the other important factors for effective negotiation. Human social dynamics are in the field of social science, and they are the factors related to humans and organizations when more than one human being is involved in a decision making [Cross, 2002]. Human social dynamics can include power, affect, production, politics, culture, trust and etc. [Cross, 2002; Waldstroem, 2001]. Existing literatures have revealed their impacts on negotiation performance, and provided guidelines for efficient negotiation. Power is one of the most important factors for collaborative negotiation. Negotiation power can be defined as "the ability of the negotiator to influence the behavior of another" [Cross, 2002]. Several types of power can have significant effect on negotiation results, and they can be from various resources such as positional power, rewards, sanctions, force, information and etc. Part of power effects on collaborative negotiation is incorporated in the proposed methodology.

Negotiation in decentralized environment can be performed easily, because negotiators can meet and communicate directly and regularly, while in a distributed environment, communication is usually indirect, and cultural difference can exist. These make distributed negotiation more complicated. For instance, trust can help negotiation, but it is harder to be obtained in a distributed environment than in a non-distributed environment. Some of these fundamental research outcomes are used for reference in this paper, but because of the author's engineering background, social factors are simplified in this paper.

2.2 COORDINATION AND COLLABORATION

"Coordination is the act of coordinating to making different people or things work together for a goal or effect" [Chambers, 1919]. In order to increase collaboration efficiency and achieve huge economic profits, various theories and methodologies have been developed to coordinate collaboration. Several representative methods are reviewed.

Group decision and negotiation approach aims at improving system performance via optimizing group structures. Loch [2003] built a mathematical model to theoretically show that overall system performance deteriorates with system size, and cooperation can improve system performance. Barczak [1991] demonstrated that teams are more efficient and successful if they are fully communicated. A proper team size of 2 to 6 has more communication effectiveness [Chung, 1994]. Then Chen [2002] developed a project task coordination model that identifies sequence and structure of all tasks, and decomposes large interdependent task groups into smaller task groups. These studies lead to the proposed method of decomposing large groups in 4.2.3.

Agent-based Approach utilizes agent to support design activities. Jin [1998] developed a framework of ASCAD to facilitate conflict and streamline work flows, which provides ways to support knowledge representation, sharing and exchange. Ganguly [2005] developed a principle-agent model with penalty induced negotiation (PIN) mechanism, and decomposed collaborative design into a sequence of decision making stages. Sun [2000] utilized service agents to model different product development phases, and provided an effective way to allow geographically dispersed entities to work co-operatively.

Set-based Approach uses set theory in engineering design. A solution is treated as union of a number of feasible parts rather than an individual “point-based” solution [Sobek, 1996]. Ge [2005] developed a set-based approach to support negotiations among engineering design teams. Multiple stakeholders perform risk analysis individually, and finally their aggregation set converges on a solution.

Engineering as Collaborative Negotiation (ECN) aims to capture all important collaboration knowledge. Engineering is formulated as a min-max problem that satisfies minimum functional requirements from the sciences of nature, and maximizes a human profit from the sciences of artificial [Kimura, 2002; Lu, 2003]. Kimura [2002] proposes fuzzy analysis to model uncertainty of design at the early phases.

These existing literatures provide theoretical foundations for negotiation support focusing on cost and physics-based constraints. However, such cost-driven negotiation mechanisms are not sufficient for in a distributed environment. Risk is introduced in this paper to assist comprehensive collaborative negotiation.

2.3 SYSTEM DESIGN METHODS

In engineering field, a large number of methodologies have been developed to help engineers design their product efficiently. Some relevant representatives are reviewed.

Decision-based Design (DBD) is a process that enables engineers to identify the best trade-off and focus on the greatest payoff positions [Callaghan, 2000; Choi, 2003; Fernandez, 2001 & 2002]. Decision-based design aims at negotiated solutions among different participants from non-cooperative or cooperative environment [Lewis, 1998 & 1999]. Its embodiment, Decision Support Problem (DSP), aims at finding "Satisficing" ("good enough, but not the best") solutions [Hernandez, 2002].

Function-based Design (FBD) focuses on conceptual system functions instead of physical forms. It enables designers to design system from functions, which can be independent of physical form of product [Roberts, 2005; Hirtz, 2002]. Matrix techniques and standardized terminology [Stone, 2005; Collins, 1976] have been developed to store historical solutions and retrieve knowledge [Strawbridge, 2002]. Design Repository is one of the representative function-based design methodologies. It is designed to represent, archive and search product design knowledge in support of conceptual design activities [Bryant, 2006; Bohm, 2005; Haimes, 1998]. It can transform a disparate set of product design knowledge into single knowledge base. Design Repository also provides a necessary foundation to link generic risk analysis methods/tools to system design.

Risk-based Design (RBD) is to combine generic risk analysis and system design methods for decision making. Risk knowledge is used to guide design process to yield more reliable products at acceptable costs [Roberts, 2002]. Stone [2005] and Tumer [2003] developed a functional basis for functional modeling in product design and yielded a Failure Function Design method (FFDM). FFDM can be used for decision making in aerospace system design. FFDM helps designers improve designs by predicting failure modes based on product functionality [Stone, 2005]. Failure modes are stored in a function-failure knowledge base, and then potential failures are derived through a series of matrix multiplications that relate functions to failures [Roberts, 2005]. FFDM is extended to combine with a concept generator approach [Strawbridge, 2002] to develop new designs with fewer failures. Lough [2006] developed Risk in Early Design (RED) to manipulate the matrices and then support risk decision making. It is assumed that additive relationship exists among undesirable events associated with components, and then the summation of all component risk is used to indicate the system risk level. Mehr [2006] developed a consistent risk-based decision making framework, Risk and Uncertainty Based Integrated Concurrent Design Methodology (RUBIC), for complex aerospace system. RUBIC quantifies risk consequence in monetary unit, and helps final decision making.

The relationship between function-based design and risk-based design can be briefly illustrated in Figure 4. Four concepts: function, failure, component and system, are involved and inter-connected in both types of design. Several matrices are utilized to represent such relationships. Focusing on product functions, design repository considers the relationship between system and component, and uses matrices to store the design knowledge. While Failure Function Design method mainly represents the relationship among function, failure, and component using a set of matrices.

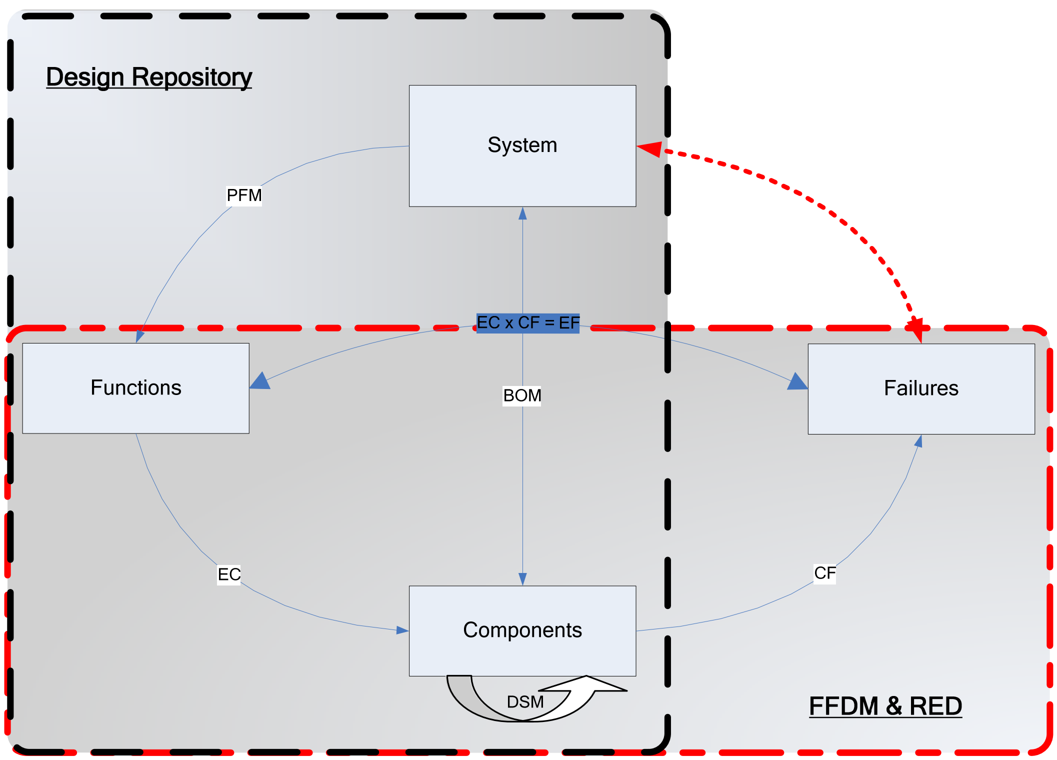


Figure 4 Relationship among Function, Failure, Component and System

"Product Function Matrix" (PFM) is used to represent the relationship between product and function; "Bill of Material" (BoM) to relate a system and its components; "Function Component Matrix" (EC) to show the connection between functions and components; "Component Failure Matrix" (CF) to relate a component with associated failures; and "Design Structure Matrix" (DSM) to indicate the correlation among the components [Alizon, 2006]. By multiplying matrix "EC" and "CF" [Stone

2005; Tumer, 2003], "Function Failure Matrix" (EF) can be obtained to illustrate the relationship between function and failure.

Existing methods have limitations in dealing with risk hierarchical relationship and corresponding influence on system design. They are feasible if independence exists among undesirable events, but such independence condition is usually violated in a collaborative environment due to functional/physical inter-dependence among components or interconnected nature of distributed stakeholders. In such cases, the inter-relationship among undesirable events and their impact on the system is important. This inter-relationship is specially considered in the proposed methodology.

2.4 RISK ASSESSMENT

Traditional Risk Analysis is "the process of quantitatively or qualitatively assessing risks" [Galway, 2004]. Various risk definitions are given in different literatures [Bedford, 2001; Haimes, 1998], which apply for different applications and situations. Many qualitative risk modeling methods have been developed such as Hazard and Operability Study (HAZOP), Failure Mode and Effects Analysis (FEMA), Fault Tree Analysis, Event Tree Analysis and so on [Bedford, 2001]. FMEA is first developed for system engineering to examine potential failures and evaluate management priorities for risk mitigation [Hari, 1999], and has been the industry standard failure analysis method for many years, but its operation is laborious and time-consuming [Wirth, 1996]. HAZOP uses a set of guidewords to identify the scenario that may result in a hazard or an operational problem [Ian, 1992; Suokas, 1993]. Risk Assessment Matrix [Haimes, 1998; Melchers, 1995] is also used to provide qualitative risk evaluations with limited capability of quantitative analysis. Fault tree analysis is widely used in failure analysis and risk-based system design method. A fault tree is “a logical graph which shows the relation between system failures” [Haimes, 1998]. Its construction process is: first define an undesirable event, then identify its causal relationships of failures, and numerical probabilities of occurrence can be entered to evaluate the probability of the events [Haimes, 1998]. Event tree analysis can illustrate sequence of outcomes arising after the occurrence of a selected initial event, and is mainly used in consequence analysis for pre-incident and post-incident application [Haimes, 1998]. These tools can help single stakeholder analyze potential risk, but have limitations when applied in a distributed collaborative environment.

Risk quantification is an important part of risk assessment. Risk quantification is to measure subjective risk in a quantified way. Risk is an abstract concept, and thus few literatures provide ways to quantify risk comprehensively. Risk consequence and probability is usually ranked into several levels [Bedford, 2001], and then an expected risk function is used to quantify the overall risk [Kumamoto, 1996; Haimes, 1998]. Risk is usually perceived in terms of utility to decision makers, but physical scales are universally used when discussing project risk [DeGroot, 1970]. Then uniform risk quantification methods are needed. In economics and finance, Value-at-Risk and Conditional Value-at-Risk [Artzner, 1997; Pflug, 2000] measure the market risk of asset portfolios. Linear approximation [Duffie, 1997; Pritsker, 1997] or Monte Carlo simulation [Bucay, 1999] is used to estimate them. In engineering, Mehr [2006] quantified risk in momentary unit to help resource allocation, but risk hierarchy affects in a distributed environment are not considered.

2.5 ENGINEERING ECONOMICS

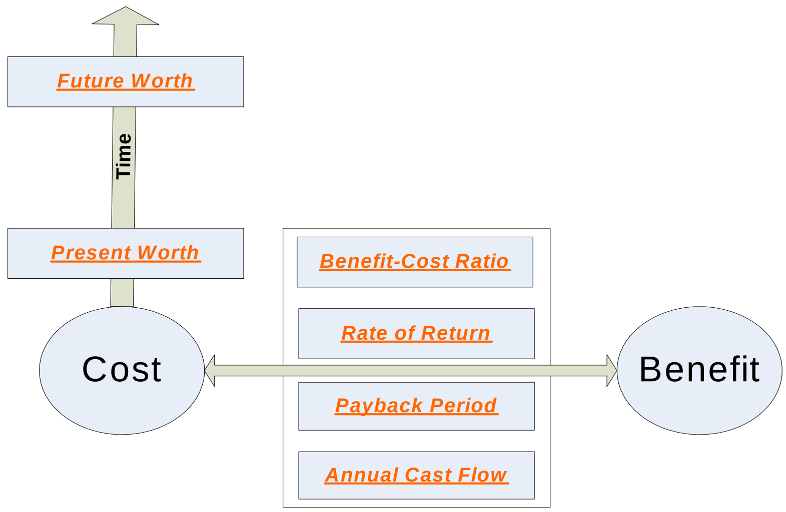


Figure 5 Classic Methods in Engineering Economics

“Economics is the study of how society manages its scarce resources” [Mankiw, 2006]. In engineering, economic is usually used to help engineering decision making: selecting the most competitive alternative from a set of alternatives based on appropriate criteria [Blaug, 2007]. A large number of economics methods have been developed. The representative methods can be presented in Figure 5. Two axes indicate two different points of views: horizontal axis deals with the most classical economics factors: cost and benefit, and the vertical axis indicates the effect of the other important factor: time.

First, the vertical axis is associated with time issue. Bank interest rate or inflation rate is familiar in the daily life. Both rates can indicate that monetary money is directly associated with specific time. For instance, $100 today is much less than the $100 value ten years ago. Then timing issue is a necessary factor of economic analysis. Two concepts are developed to compare monetary value at different time periods: present worth and future worth. Present worth is “the equivalent current value on a given date of a future payment or series of future payments, discounted to reflect the time value of money and other factors such as investment risk" [Gregory, 2006]. Present value provides a means to compare cash flows at different time periods. Future worth is similar as present worth. All benefits or costs are converted to values at certain future point. Both present worth and future worth can be converted to each other.

Second, the horizontal axis is considered. Cost is "the value of money that has been used up to produce something, and hence is not available for use anymore" [Mankiw, 2006]. Economic benefit is "the positive contribution to gross national product (or other measure of value) from an economic activity or project" [Mankiw, 2006]. In engineering decision making, comparing total costs with total benefits can be used to choose the most profitable alternative. Focusing on cost and benefit, four main economic analysis methods have been developed. Benefit-cost analysis is to directly calculate ratio of benefit and cost. If multiple alternatives are involved, benefit-cost analysis must be performed incrementally [Mankiw, 2006]. To account for time effect, the ratio for an alternative is calculated as equivalent benefits divided by equivalent costs. Rate of return (ROR) is "the ratio of money gained or lost on an investment relative to the amount of the money invested" [Mankiw, 2006]. It is usually expressed as a percentage rather than decimal value. Payback period is an approximate analysis method. The payback period of a project is the time required for cumulative benefits to equal the investment [Mankiw, 2006]. This analysis criterion is to choose the alternative with the lowest payback period. Cash flow analysis is the method to deal with cash flow in whole process of a project. "Cash flow is the balance of the amounts of cash being received and paid by a business during a defined period of time for a specific project" [Mankiw, 2006].

Cash flows are usually classified into three types: operational, investment and financing cash flows. All three types together can determine the net cash flow, and then indicates the beginning cash balance and the ending cash balance [Mankiw, 2006]. All analysis methods are used in engineering economic decision making. Most of time they generate the same result from a set of alternatives, but sometimes additional criteria are needed to choose the best method [Mankiw, 2006]. In this paper, present worth value is suggested to consider time issues concerning risk.

2.6 SUMMARY

Five relevant fields are reviewed, which provide basic foundations of this research. However, all of them have certain constraints for comprehensive risk-based negotiation support. First existing negotiation literatures mainly focus on negotiation factors from social science perspective, and specific negotiation from engineering point view is seldom touched; second, most of collaboration coordination methods focus on performance, and this research add two additional factors: risk and cost; third, majority of present engineering system design methods focus on real engineering system and performance, but ignore the importance of negotiation. Negotiation is introduced in this dissertation to fill this gap; forth, current risk assessment methods mainly deal with single stakeholder, and few risk quantification methods exist from a global perspective. This research provides a quantification way from a global perspective; fifth, engineering economics analysis involves a large number of estimations, and correspondingly uncertainty is an important issue for engineering economics. Uncertainty issue is a weak part in existing engineering economics methods. A dynamic uncertainty model is introduced to address the uncertainty economics issue.

3. PROBLEM UNDERSTANDING

3.1 PROBLEM DISSECTION

3.1.1 NEGOTIATION MECHANISM IN A DISTRIBUTED ENVIRONMENT

Definitions of several core concepts are provided in the following to clarify their meanings in subsequent sections [Qiu, 2007a].

Design space: The set of all design alternatives, which may be uncertain at the early design stage.

Decision space: The set of a stakeholder's interested decision factors that are utilized to generate, evaluate, and select design alternatives.

Decision dimension: The fundamental measure of a certain decision factor in the decision space.

Risk: "Combination of the probability and consequences that an undesired event may occur" [Bedford, 2001].

Risk space: A space set composed of risk items associated with a member or a stakeholder group.

Negotiation space: Combination of overlapped risk items for multiple stakeholders' negotiation.

A distributed environment includes inter- and intra-level organizations, and correspondingly its coordination and negotiation process occurs at two levels: intra-stakeholder and inter-stakeholder. Intra-stakeholder represents interactive activities among members within a stakeholder, while inter-stakeholder portrays the interactive activities among stakeholders. To achieve good collaboration results, the participating stakeholders and their associated members need to communicate and negotiate effectively.

Decision space information exchange is the key of a successful collaboration and negotiation, and the communication process is the main and effective strategy to achieve such information exchange. Members within a stakeholder are usually familiar with each other, and thus intra-level communication is usually effective. Communication process at inter-level is complicated. Take three stakeholders as an example: S1, S2 and S3. Their communication process and decision space (D.S) evolution during global coordination process can be demonstrated in Figure 6.

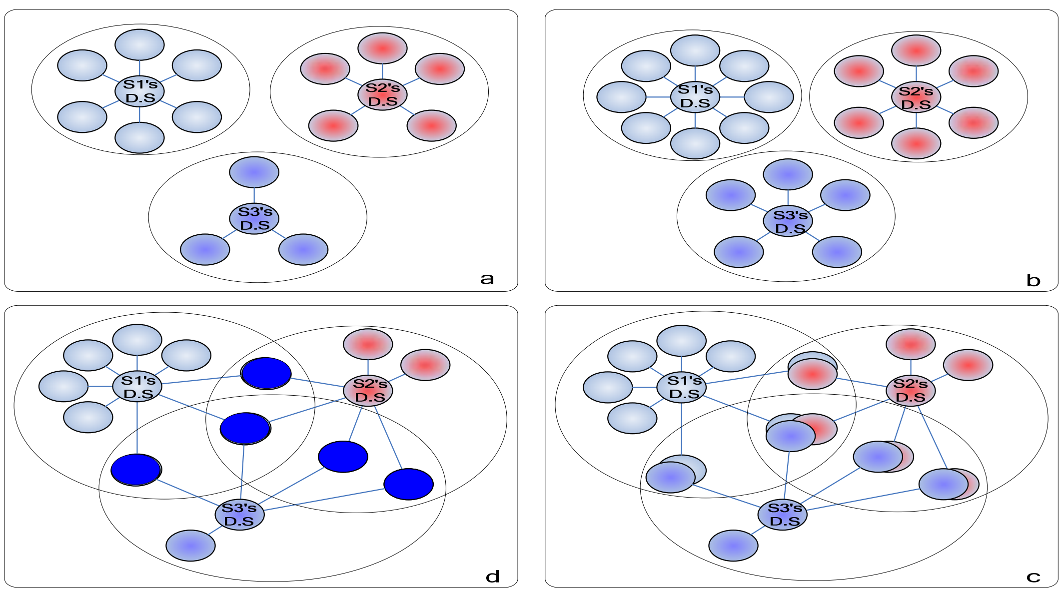


Figure 6 D.S Evolution via Communication and Negotiation

1. Initial Decision Space (Figure 6a)

Initially, each stakeholder desires a particular objective from the collaboration which forms their decision space. Belonging to different organizations with various expertise, stakeholders can have distinct decision dimensions. Their shared collaboration objective will overlap with some of their decision dimensions, and their heterogeneities will lead to other non-overlapped dimensions. At early design stage, when stakeholders are not yet familiar with each other, both types of decision dimensions may not be clearly determined.

2. Communication (Figure 6b)

When the stakeholders have a strong desire to collaborate, they need communicate to ensure a successful collaboration. Each stakeholder will present some of its expertise and decision space so that other stakeholders can understand and accept it. Via communication, each stakeholder can better understand others' decision space, and then correspondingly modify or expand its initial decision space for better cooperation. Because of shared decision space and overlapped decision dimensions, a potential negotiation space can be determined at this stage.

3. Negotiation (Figure 6c)

After communication, stakeholders understand each other's decision space, but usually some decision dimensions are not universally acceptable. Thus, negotiation is needed to facilitate compromise about the conflicts and achieve an acceptable alternative for all participants. Non-overlapped items have no impact on other stakeholders, eliminating any need for negotiation. Overlapped dimensions influence at least two stakeholders, and negotiation may be needed. With limited knowledge and different preferences, stakeholders may have inaccurate and misleading evaluations for the overlapped dimensions, which can lead to poor decision making, and render the collaboration into a stalemate. After understanding the differences between evaluations, involved stakeholders can negotiate to achieve consistent and reasonable evaluations for better collaboration.

4. Consistent Global Decision Space (Figure 6d)

After several rounds of negotiations, if no consistent and acceptable results for everyone can be obtained, then the collaboration may fail. However, stakeholders may have gained a better understand about the cause of the collapse, and future collaboration may be possible if some conditions are changed. If the collaboration is able to proceed, then consistent and more reasonable evaluations for overlapped items can be formed, and all involved stakeholders would then modify their decision space to adapt the changes.

Communication process at intra-stakeholder level is similar, but easier and more effective. Members of a stakeholder are usually close to each other in a certain geographical location, and they can get to know each other over time. They may be able to anticipate other member's expectations, and thus the influence from intra-stakeholders on a member's decision space is relatively more predictable than that from inter-stakeholders.

3.1.2 DECISION, RISK, AND NEGOTIATION SPACE

Decision space is generally a key of effective collaboration. However, decision space is too specific to be employed directly for effective and efficient global negotiation. This paper focuses on risk and corresponding collaborative negotiation support, and thus generic decision space is narrowed down to risk space and negotiation space. The relationship between decision space, risk space and negotiation is illustrated in Figure 7. A key intermediate layer, risk space, is used to link decision space and the shared coordination and negotiation space. A risk space is used as a middle layer between decision space and global negotiation space. Risk space is derived from decision space, and in turn affects and serves decision space. Risk space can be determined by decision space. Decision space is composed of decision dimensions, and a decision dimension is associated with several potential risk items. Thus risk items can be derived from each stakeholder's decision space. This leads to a mapping between decision space and its associated risk space.

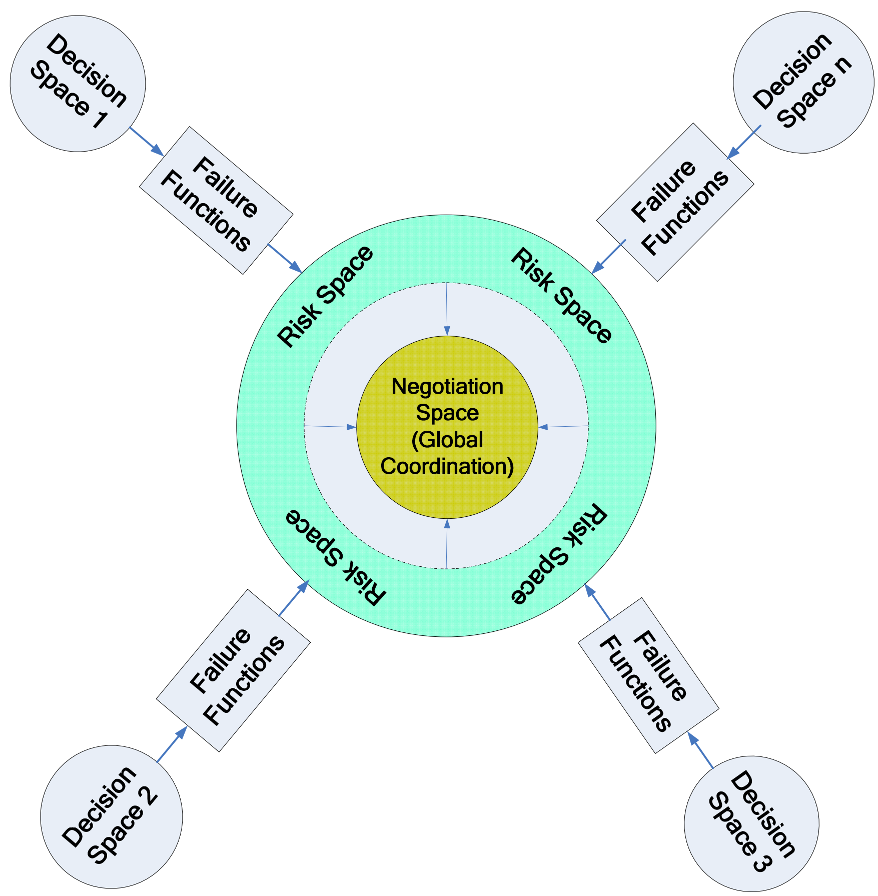


Figure 7 Decision Space, Risk Space and Negotiation Space

Based on the inter-relationship of different stakeholders' risk items, stakeholders' risk items can be categorized as: overlapped or non-overlapped. Non-overlapped risk items only affect one stakeholder, and other stakeholders do not care about it, and thus they will only be evaluated within single stakeholder, and will not be included in global communication and negotiation among stakeholders. Then only overlapped risk items are considered in negotiation, and all the overlapped risk items form the negotiation space. But non-overlapped risk items can still affect each stakeholder's evaluations on its potential risk level, and communication and negotiation across stakeholders can lead to transformation of overlapped and non-overlapped items, and further reshape the negotiation space.

The ultra objective of risk analysis is to help decision making, i.e., to serve the real decision space. From this point of view, risk items can be classified into two classes: changeable and non-changeable items. If a risk dimension can be modified through changing decision space, then it is called a changeable risk item. For instance, the probability of data collection failure can be reduced by adding more sensors during an experiment, and in return, the negotiation on such risk items can lead to a change in sensor quantity. If a risk dimension exists objectively and cannot be altered according to a particular stakeholders' decision space, then it is a non-changeable risk item. For example, the failure rate of a sensor does not change according to stakeholders' will.

The research goal is to analyze risk evaluations from a global perspective, and then obtain consistent and acceptable risk evaluations among all involved stakeholders, which means that for changeable risk items, stakeholders can adjust their decision space to achieve acceptable risk levels. For non-changeable items, the stakeholders can achieve more comprehensive and reasonable evaluations, and avoid making wrong decisions.

3.1.3 DECISION PREFERENCE ON EXTREME CASES

Decision space contains interest contents during multi-stakeholder's negotiation. However, actual perception of real values for each decision dimension is directly associated with the other important concept: decision preference. For instance, a coat is blue. One stakeholder may like it, but the other one may dislike it. The coat and its color are the same objectively, but they are of different preferences to different stakeholders. Decision preference is an important subjective factor for collaborative negotiation. Different scenarios can lead to different preferences. Three zones are summarized according to stakeholders' preference perceptions. A normal case means that its decision preference is within a certain expectation range for a specific stakeholder [Qiu, 2008a]. It occurs most of the time, and many existing methods have been developed to support its decision making [Watson, 1982; Thurston, 1991; Keeney, 1993]. However in the real world, unusual scenarios may happen occasionally. Such scenarios are called extreme cases, which contain either extremely high or pretty low preference attribute(s) for a specific stakeholder [Qiu, 2008a]. These extreme cases are investigated to support general multi-attribute decision making problems.

Multi-attribute decision making is a common human activity, and widely encountered in engineering design. Suppose a decision maker (DM) aims at finding the most desirable alternative(s) from a set of alternatives. Some decision information is then constructed. For example, when a man buys a car, he usually compares different cars' cost, appearance and performance from various vendors, and then selects the most desirable model. A large amount of tools or methodologies have been developed to help make such multi-attribute decisions, such as ranking and rating methods, weighted sum approaches, strength of preference and

Hypothetical Equivalents and Inequivalents [Watson, 1982; Thurston, 1991; Keeney, 1993; See, 2002 & 2004]. These methods provide ways to quantify and compare various alternatives, and determine rankings of the alternatives. But all these methods assume decision scenarios are normal cases, and ignore potential dynamic and fuzzy human thinking process in extreme cases. There are usually two factors for decision making: attribute values and weights [See, 2004]. A human's thinking pattern is complicated for both factors, and his/her decision criteria are usually hard to be exactly quantified mathematically [Keeney, 1996] in extreme cases.

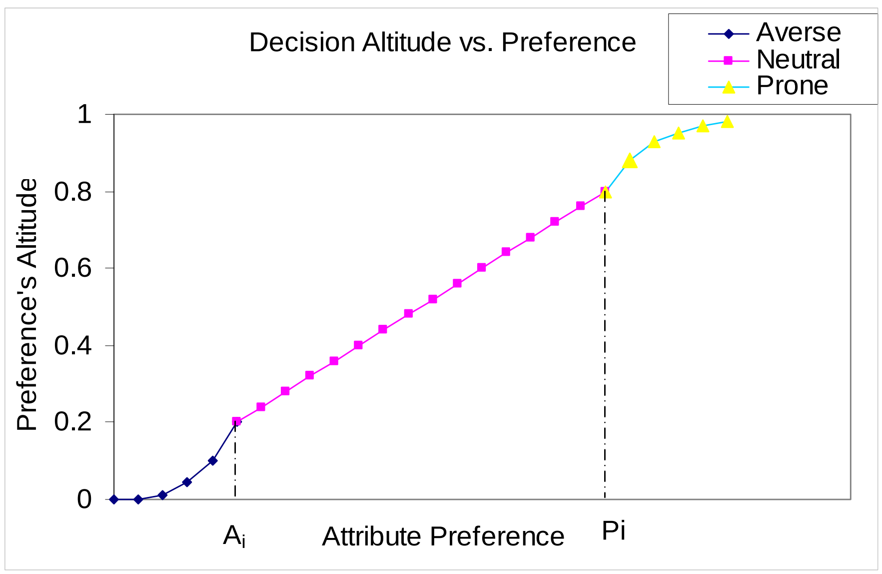


Figure 8 Three Zones with Different Decision Altitudes

First for attribute values, setting exact constraint numbers for decision making is usually challenging. For example, the cost budget of a project is a decision constraint, which can be roughly set in the product planning stage, but such constraint number is usually flexible. For instance the alternative can be still feasible if excellent performance can be achieved even though the budget constraint is violated slightly. Strength of preference [Keeney, 1993] is used to reflect a DM's preference concerning an attribute value, and there are a number of ways to assess the strength of preferences including utility theory methods [Thurston, 1991; Keeney, 1993]. The actual attribute values vary much depending on specific problems, but they can be mapped to certain preferences, which are consistently in the range of 0 and 1. Thus preference from a DM is chosen as a uniform measure of various attribute values, and it is employed as the X axis in Figure 8. Figure 8 shows a DM's potential thinking pattern when evaluating attribute preferences. The decision altitude with respect to attribute preference is chosen as the Y axis. The DM can have different altitudes for various problem scenarios, but usually the attribute preferences can be categorized into three zones: averse, neutral and prone zones, and each zone has specific decision altitude. The neutral zone represents a normal scenario, which is the most common in real applications. In this zone (from A_i to P_i in Figure 8), a DM has a linear decision strategy concerning the preference: the more preference leads to a more tendency to this alternative linearly. The decision making in this zone is straightforward and directly determined by the attribute preference. There may exist two other extreme cases away from both ends the neutral zone. Suppose the attribute preference is decreased toward 0, and thus the DM is averse to this attribute more and more. At a specific point A_i, he/she is almost reluctant to accept such alternative. The point is usually set as a decision constraint for this specific attribute. But multiple attributes are involved in the decision making, the alternative with such attribute preference lower than A_i may be still overall feasible when considering all other decision attributes, and thus this constraint is usually a fuzzy criterion in multi-attribute decision making problem. But from the perspective of this single attribute only, the DM is averse. The range with preference lower than A_i is called averse zone, which represents the bad scenario with respect to this single attribute. For aversion, the DM usually has a non-linear decision altitude with respect to the attribute preference as illustrated in Figure 8. On the other hand, if the attribute preference is increased toward 1 resulting in more and more fondness from the DM. It is possible that the DM has an initial expectation Pi, which is already good enough, and then further increase over P_i is beyond the DM's normal expectation. Overall the DM prefers such attribute more and more, but he/she may not maintain the linear decision altitude on this attribute. He/she can be quite prone or indifferent to the additional preference increase. The nonlinear altitude (from P_i to 1) is illustrated in Figure 8. The range with preference bigger than P_i is called prone zone, which represents the good scenario with respect to this single attribute. The problems with attributes in the averse or prone zones are called extreme cases, where a DM has nonlinear altitude on the attribute preference. Then attribute preferences are not enough for decision making, and decision altitude should also be considered for more comprehensive decision.

Second, for attribute weights, determining them is usually an arbitrary process, which can directly affect decision precision. Some methods have been proposed to estimate them in a more stable way [See, 2002 & 2004]. The achieved constant weights are consistent with human's thinking pattern for most normal cases. But weights are constant, then they can not truly capture a DM's dynamic preference change for extreme cases: a DM may give more attentions on the attributes in extreme zones, and then adjust their weights after comprehensively considering all attributes' values, i.e., actual weights may not be constant, and depend on all attributes' preferences.

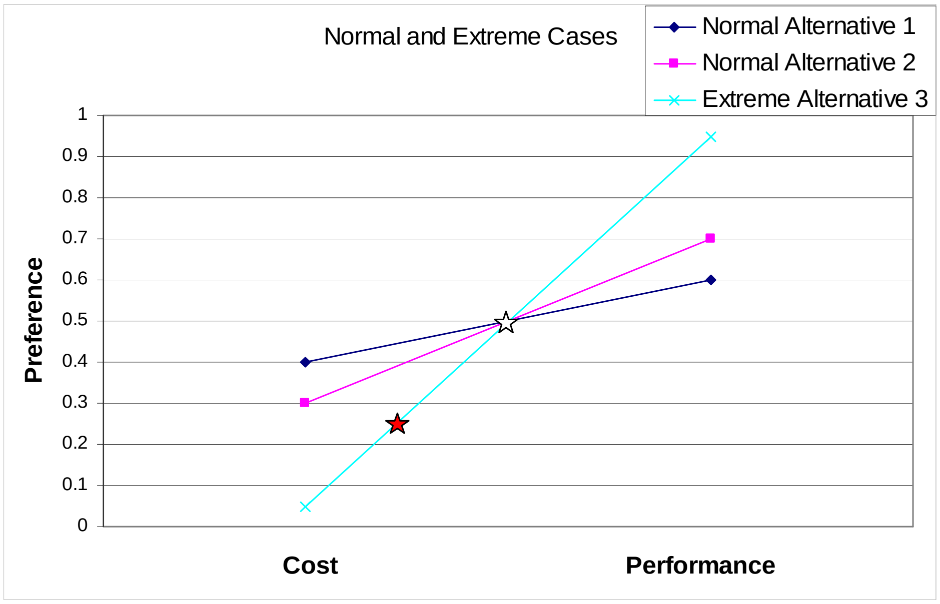


Figure 9 Weight Sum Method in the Presence of Extreme Cases

Varying weights are introduced to simulate the change pattern concerning relative importance of attributes, and a uniform framework has been developed to support the decision making mathematically for extreme case as in the following chapter 4.3.1. Figure 9 illustrates a simple multi-attribute decision making problem about car selecting. Two attributes, cost and performance, are involved. Suppose for normal cases, a DM assigns equal weight 0.5 for both attributes, and then he/she picks up the alternatives based on their attribute preferences. Suppose three alternatives are considered, and their preference sets for Alternative 1, 2, 3 are (0.4, 0.6), (0.3, 0.7) and (0.05, 0.95) respectively. Existing weighted sum methods would achieve the same aggregation preference for all three alternatives, i.e., all alternatives have the same value to the DM. But this may not truly affect a DM's preference. Since alternative 1 and 2 have fairly similar preferences for both attributes, but Alternative 3 has a very low preference on the cost with a high preference on the performance. Alternative 3 may not have the same aggregation preference as the other two. It can be an extreme case: its cost is beyond the DM's initial budget slightly and in the averse zone, while its performance is also beyond initial expectation in the prone zone, then his/her final decision depends on the most dominant attribute. For instance, if the DM can not accept such high cost even though much good performance can be achieved, then the other two is preferred to Alternative 3. Or if the DM is excited about the performance of alternative 3, and the cost is still acceptable, then Alternative 3 is preferred to the other two. Thus the final decision depends on the DM's altitudes with respect to attributes in extreme zones.

3.2 RISK IN NATURE

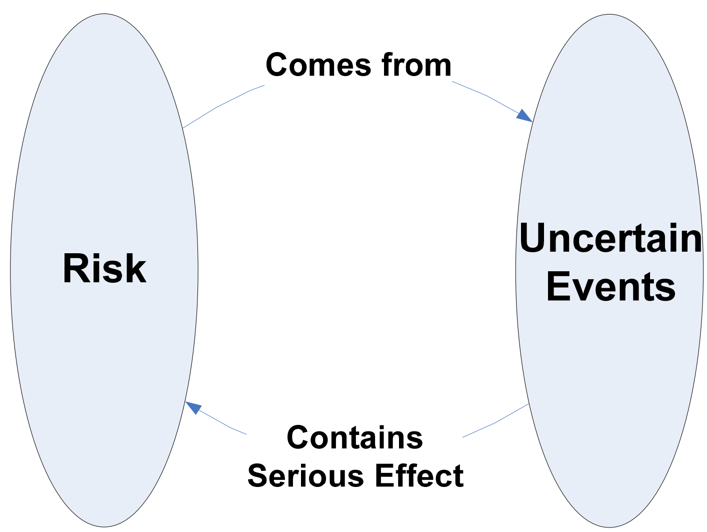


Figure 10 Risk and Uncertain Events

Risk can be perceived in daily life, but it is an abstract concept. Uncertain events are more familiar and popular in real engineering problems, and risk is in nature closely associated with uncertain events. Variability and unpredictability are two key properties of uncertain events. Both properties are internally connected. Variability indicates that the problem has a range of final outputs instead of a fixed value, while unpredictability shows that humans cannot accurately pre-determine the exact final output, i.e. a fixed value, but usually humans can estimate the final output in a certain range, which is exactly what the variability indicates. The event with variability and unpredictability are called uncertain event. Probability is an important measure of an uncertain event, which means how often the uncertain event occur, while risk is defined as the product of its probability and consequence, and thus risk and an uncertain event are similar from the probability point of view. Specifically the relationship between risk and uncertain event can be represented as Figure 10.

Uncertain event is a broader concept, while risk is a more important concept requiring more considerations. From the perspective of probability, risk in nature comes from uncertain event, but not all uncertain events are classified as risk. Risk has the other important property of consequence. Only an uncertain event containing serious effects is treated as risk.

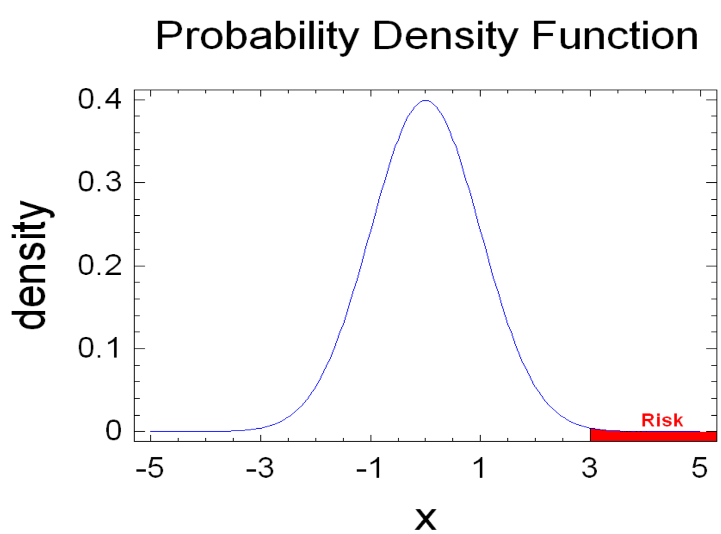


Figure 11 Risk Relevant Fields

Though not explicitly addressed, risk concept exists in multi-discipline fields, which in turn provide strong theoretical foundations for risk study. Figure 11 shows a visualized picture of risk concepts in several fields. In mathematics, probability density function provides a good way to express probability of uncertain events mathematically. An uncertain event has variability property, and thus such uncertain event has a range of final output. The horizontal axis of Figure 11 indicates such variability characteristics. For instance, the uncertain event, X, can have a final output from -5 to 5. The vertical axis of Figure 11 then shows the probability density of each specific output. For example, "0" has the biggest probability density, and during 40% of time, the uncertain event X would have an output of 0. If when X outputs are above 3, the event is considered as having serious effects by certain evaluators, then X in this scenario is called risk, which is illustrated by the red bar in Figure 11; in statistics, p-value is the most important statistical concept, which is "the probability of obtaining a result at least as extreme as the one that was actually observed given that the null hypothesis is true" [Fred Ramsey, 2001]. If the null hypothesis is viewed as that the system/component is successful, i.e., does not fail, then the p-value can be considered as the risk tolerance level, so statistical p-value can be associated with risk; in economics, risk is directly considered in real portfolios. Value at Risk (VaR) is proposed to indicate the potential economic loss. Value at Risk is "the maximum loss not exceeded with a given probability defined as the confidence level over a given period of time" [Pritsker, 1997]. It is a general concept, but commonly used by banks to measure the market risk of their asset portfolios. Thus risk is quantitatively analyzed in many financial applications, and such methods can be used for reference in engineering risk analysis. In industrial engineering field, Six Sigma is also proposed as an efficient strategy to deal with the variability issues, and improve manufacturing processes and eliminate defects in industrial processes. It "seeks to identify and remove the causes of defects and errors in manufacturing processes" [Adams, 2003]. Thus Six Sigma method is also closely associated with risk. These multidiscipline fields provide strong foundations for risk research. Some of them are partially used in the proposed risk-based negotiation methodology. A wide range of considerations of risk in multidiscipline fields imply abroad applications concerning risk: from theoretical research, financial economics, to industrial process.

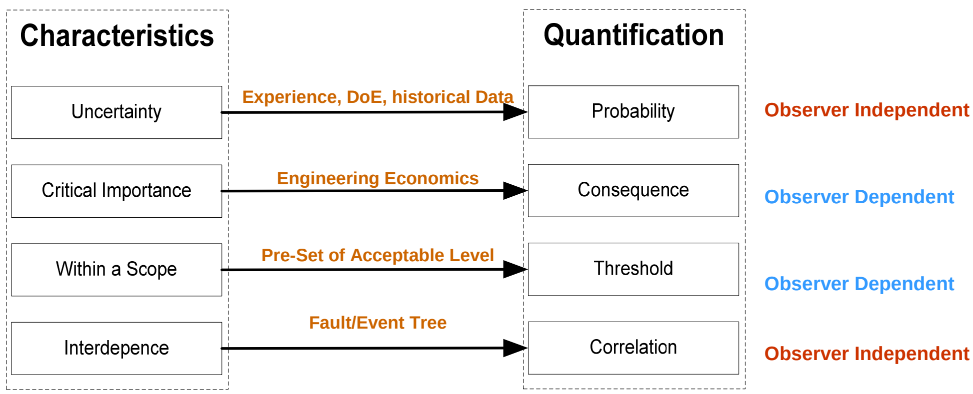


Figure 12 Risk Characteristics and Their Quantification

Figure 12 shows four important risk characteristics and their corresponding quantification in risk existing risk analysis field. From "common sense" perspective, risk characteristics can be revealed. First, risk is associated with uncertainty such as the unpredictable stock market. Second risk can be critical importance to human life, environment or society. For example, millions dollars were lost in the Mars Climate Orbiter spacecraft [NASA, 1999], and thousands of people's life were taken away in the 2004 Indian Ocean Tsunami. These disastrous events deserve most concerns. Third, risk is usually a small probability event within a certain scope such as the car accidents. If probability of car accidents is large enough such as 60%, then no people would dare to drive even though it is a convenient transportation tool. So risk objectively exists, but it can only be accepted within a certain scope. Forth, interdependence usually exists in several risk items, and a single risk item can cause a chain effect: the occurrence of one risk item can induce other relevant risk items. For example, if a timing belt of a car was broken during driving, the car engine would usually have crashed. Such chain effect comes directly from interdependence of several risk items.

Such four characteristics can be revealed or felt during the daily life, but it is not enough only to know these characteristics. Property quantification is necessary for risk analysis research. Some quantification methods have been developed to quantify each characteristic. Their relationship between each characteristics and its quantification can be illustrated as the arrow line in Figure 12.

First, mathematical probability can be used to represent uncertainty. Experience, historical data, and further design of experiments can be used to estimate or calculate such uncertainty probability. Risk probability estimation is usually the most mature factor in real engineering risk analysis, and engineers usually have the least difficulties to estimate risk probabilities than other factors, and thus risk probability estimation is not discussed in detail in the following chapters. It is assumed that risk probability can be estimated from a member or a stakeholder, no matter it can be very subjective depending on the stakeholder’s judgment.

Second, risk consequence is utilized to indicate the risk critical importance. Though risk consequence is important, there are still no satisfactory tools to objectively and comprehensively quantify risk consequence. Usually experts use their experiences to judge the risk consequence for each risk item, but such judgments are subjective and too rough to assist accurate engineering decision making. Some engineering economics methods have been used to calculate the risk consequence, but they usually ignore interdependence and hierarchy of several risk items, and then their results are not comprehensive. Considering the consequence importance and its least consideration, risk consequence quantification is deliberated in Chapter 4.2.2 from an overall system perspective.

Third, risk with a scope can be noted by a risk threshold, which indicates the pre-set acceptable level for each risk item. Such threshold is a subjective measure of evaluators' risk tolerance, and different evaluators can have various thresholds or the same evaluator may have different thresholds over time.

Forth, risk interdependence can be indicated by risk correlation and hierarchy. Existing fault or event tree methods can be used to help the translation. Both trees can reveal internal relationships of risk items, and the chain effect can be retrieved from logic paths in the trees.

All four characteristics can be quantified by four quantitative measures theoretically. This paper is to quantify risk in monetary unit, and then calculate simple risk measures to help negotiation. Risk objectively exists in the daily life, but it is the human that makes the risk assessment, and thus human's subjectivity will be added to the revaluation. Four risk properties can be categorized into two groups: observer dependence and observer independence. Observer dependence means that the risk evaluation depends on specific risk evaluator, and observer independence shows that the risk evaluation does not depend on specific evaluator theoretically. Risk probability and correlation are observer independence, because both properties have already existed objectively before evaluators evaluate them. Risk consequence and threshold are observer dependence, since these properties would depend on specified scenarios. Different strategies are used to deal with both types of risk. For observer independent properties, objective evaluations theoretically exist, and their consistency issue becomes important and forms a part of this paper. For observer dependence properties, only subjective evaluations exist, and thus no further considerations are needed. However their quantification becomes a part of this dissertation.

3.3 CHALLENGES AND RESEARCH QUESTIONS

3.3.1 NEGOTIATION CHALLENGES

Negotiation helps stakeholders to communicate and exchange their objectives and preferences. It serves as a facilitator for involved stakeholders to achieve win-win agreements. The key research challenges include two aspects: negotiation preparation and pareto-frontier determination [Young, 1991; Lewicki, 1999].

Negotiators need to satisfy each party's most important needs while sacrificing less important requirements, because it is usually impossible to satisfy all stakeholders' needs at the same time. One of the most powerful things for efficient negotiation is to help negotiators prepare more effectively. It is hard to obtain comprehensive preparation before negotiation. In engineering negotiation, this challenge is how to determine all stakeholders' objectives and preferences, and then quantify and model them. Risk is systematically deliberated in this paper to help stakeholders prepare their risk information for negotiation. The second challenge is to achieve the pareto-frontier [Lewicki, 1999] even with enough preparations. Pareto-frontier is "an outcome that cannot be improved for any party without making another party worse off"

[Metcalfe, 2007]. It is reported that less than 25% of executives in negotiation simulations reach the pareto-frontier, and 50% of them are obtained by chance [Metcalfe, 2007]. In this paper, a uniform risk structure is constructed to help stakeholders' risk negotiation preparation, and a mathematical model is constructed to simulate risk preference of each stakeholder, and then pareto-frontier are calculated numerically to assist stakeholders' negotiation

3.3.2 RISK EVALUATION CHALLENGES

Besides generic negotiation challenges, risk evaluations also confronts challenges because of risk heterogeneity in a distributed environment. In a distributed environment, heterogeneity and implicitness across multiple stakeholders in terms of concerned tasks, risk perception and interpretation exist. Each stakeholder may: 1) have interest in their own specific tasks; 2) perceive and interpret the risk associated with these tasks based on local available information and knowledge; 3) evaluate the risk based on their available approaches/tools; 4) know little about other stakeholders' risk evaluations [Qiu, 2007a]. The heterogeneity and the implicitness could prevent transparency across stakeholders, and worse, lead to over- or under-estimation of risk severity that negatively influences the decisions and corrupts the collaboration. Each evaluator can perform risk modeling and evaluation from its local perspective, but the whole system collaboration must consider all participated stakeholders simultaneously from global systematic point of view. These different perspectives render risk modeling and evaluation intricate in three aspects, which are closely connected with four risk characteristics.

First, inconsistent risk probability and confusing consequence quantification may exist. Stakeholders may have various organization cultures, which can lead to different interpretations and evaluations on the same overlapped risk items, resulting in inconsistent probability evaluations. These inconsistent probability evaluations can result in unfavorable collaboration. On the other hand of consequence evaluation, conventional risk analysis methods usually quantify consequence by subjective ranks, which are meaningful to the evaluator itself, but may not be comprehensible to or agreed by others, thus such stakeholder's risk consequence evaluation can be confusing for others. For instance, stakeholder A estimates risk consequence at Level 1 with $1,000 potential loss, but stakeholder B may have an estimation of $2,000 loss when reviewing this level of risk consequence. A clear definition of a consequence scale agreed upon is sometime useful to help clarify the confusion on what a certain consequence level means among members within a stakeholder group, but such an agreement is usually hard to be achieved in a distributed environment because of diverse social and cultural environments. Both the probability inconsistency and consequence confusion across stakeholders can cause potential barriers and prevent stakeholders from working smoothly, which in turn demands the stakeholders' involvement in resolving the conflicts.

Second, system risk items can come in two ways: internal or external source [Bedford, 2001]. The latter leads to overlapped risk items, which exert certain risk consequences on all involved stakeholders simultaneously. Thus overlapped risk items have additive consequence effect to the system, which should be considered when a system manager allocates resource for global system risk reduction. In Figure 13, a distributed environment (the largest circle) includes Stakeholder A – X. From the perspective of X (the center circle), a fault tree (within the center circle) can be constructed to indicate the inter-relationship among risk items of the system. In the fault tree, besides the risk items solely from Stakeholder X, there exist some overlapped risk items from external stakeholders. For example, the risk item E1 exists in X's local fault tree, and it is actually an external risk item from A. Arrows are used to indicate the original owners. Some risk items may be dependent on each other, and have different weights on the global system, so the relationship among risk items and the system is important for comprehensive risk-based decision making.

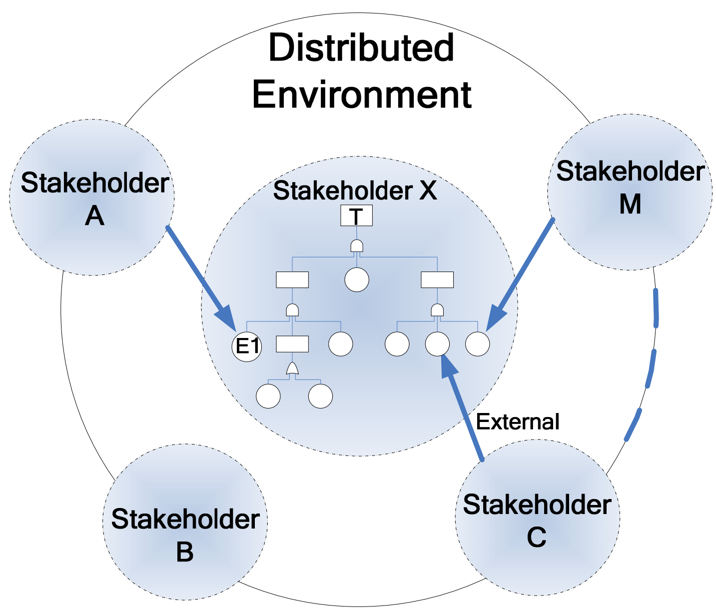


Figure 13 Internal and External Risk Sources

Third, usually only risk probability and consequence evaluation are considered in risk-based system design. They may not be sufficient in a distributed environment. For instance, risk exists anywhere objectively. Its probability can only be mitigated or decreased to certain extent, and can not be eliminated absolutely, thus stakeholders usually assume certain risk tolerance when making risk-based decision. “Without tolerance criteria, you can't make rational risk decisions” [Bendixen, 1987]. It is good enough to reduce risk probability to the set tolerance rather than pushing for further unrealistic low risk level during resource allocation.

To solve the challenges, risk is considered from four aspects: probability, consequence, causal relationship, and tolerance. Specifically a consistent optimization process is conducted to make overlapped risk probability evaluations consistent, and economic monetary unit is used to quantify risk consequence and avoid possible negotiation confuses, also risk hierarchy and stakeholders' risk tolerance are both considered in the risk model for a more comprehensive negotiation.

3.3.3 RESEARCH QUESTIONS

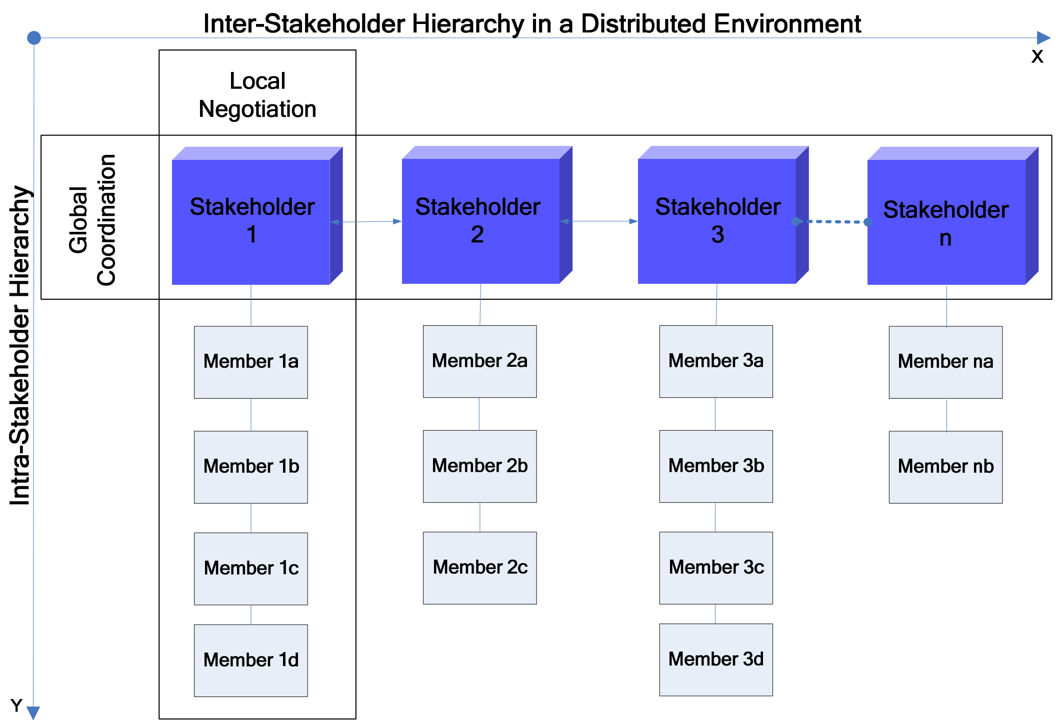


Figure 14 2-level Structure in a Distributed Environment

Based on research challenges, a systematic approach is urgently needed to provide strategic support for coordination and negotiations in a distributed environment. In order to achieve that, the following research questions highlight focus of this dissertation and some research questions can be illustrated in Figure 14.

1. In the intra- level, how does a stakeholder identify, represent, and synthesize its individual members' risk evaluations?

Because of the structure complexity in a distributed environment, there exist two levels as shows in Figure 14. The intra- level risk information makes preparation for inter- level negotiation. The vertical direction illustrates the intra-stakeholder hierarchy within each stakeholder group. Within a single stakeholder group, the risk evaluation originally comes from individual members. The members exchange risk information and work with other members to come up with a uniform risk assessment for this stakeholder as a group representation to be used in the global level coordination. This is called a local level communication. The focus is to enable local assessment to be usable in global coordination.

2. In the inter- level, how do stakeholders capture heterogeneous risk evaluations, and then achieve consistent overall risk evaluations?

The horizontal direction in Figure 14 illustrates the inter-stakeholder relationships among different stakeholders. All stakeholders co-exist in a distributed environment, and they are connected through their interactive flow of material and information. They cooperate and negotiate with each other based on certain criteria. This is called a global level negotiation. Both risk probability consistency and consequence quantification are addressed in this research question.

3. How to construct a collaborative mathematical model including all four risk characteristics?

To achieve comprehensive risk evaluations, four risk characteristics are considered. This question is concerning a uniform mathematical way to deal with those four characteristics simultaneously and construct possible simple measures to indicate each stakeholder's risk.

3.4 A THEORETICAL MODEL FOR NEGOTIATION

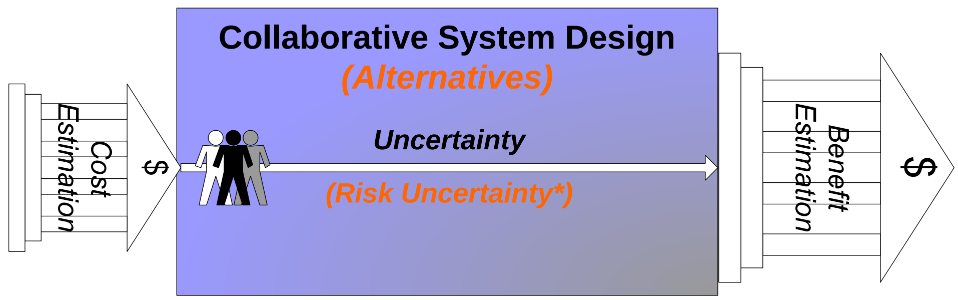


Figure 15 Theoretical Negotiation Model

To answer the research questions, a theoretical negotiation model is proposed as Figure 15. Generic economics model and principles are utilized. The basic principles include: 1 People face trade-off; 2 Trade can make everyone better-off; 3 Rational people think of margin [Mankiw, 2006]. The first principle tells that some benefits need to be sacrificed to achieve other benefits; the second principle indicates the best benefits of collaboration: everyone can get happy; the third principle shows the rational decision criteria for negotiation decision making. These principles originally come from economics field, but they are also well suited in engineering field. First, engineers face the dilemma of choosing alternatives such as choosing better material with higher cost or inferior material with lower cost. There is no universal criterion for all scenarios. Second, engineer collaboration desires win-win solution during negotiation, where anyone can get whatever he/she can accept and be satisfied, i.e., everyone can be better-off. Third, the margin is also one of the most important objectives for engineering decision making. Many economics principles can be used in this dissertation.

Figure 15 shows a basic theoretical model for negotiation. Cost is the model input, and benefit is the output. Collaborative system design is in the middle to help collaboration and choose the best alternative for every stakeholder. Cost and benefit are dominant factors for many real decision making problems. In the real world, with existence of interest and inflation rate, both cost and benefit can have various instead of fixed values over time. Thus time issue should be considered. Existing engineering economics literature as in 2.5 has provided methods to deal with the time issue. Cost or benefit with time variation can be quantified by equivalent cost or benefit measure.

The focus of this dissertation is the middle part: risk uncertainty. Uncertainty issues exist in every part of the model. In conceptual design stage, both cost and benefit can not be accurately estimated, and then uncertainty occurs. In collaborative system design, stakeholders collaborate with each other, and many unforeseeable or uncontrollable factors can affect the collaboration resulting in uncertainty. As discussed in 3.2, risk is a type of uncertain event. When uncertainty in the model brings undesirable or disastrous consequences, risk becomes an important decision factor of collaboration.

The objective of risk analysis is to assist negotiation. A negotiation model is a quantification mechanism which helps analyze, model, predict, and manage effectiveness of negotiation process. Because of existence of uncertainty, negotiation model is a dynamic and stochastic model. From the abstract theoretical model in Figure 15, a negotiation model can be developed as Figure 16. First a static engineering economic model is constructed based on scenario information, and then risk factors are incorporated into this static model, and a stochastic engineering economic model can be formed; finally all uncertainty (risk) factors are quantified, and a negotiation model can be constructed.

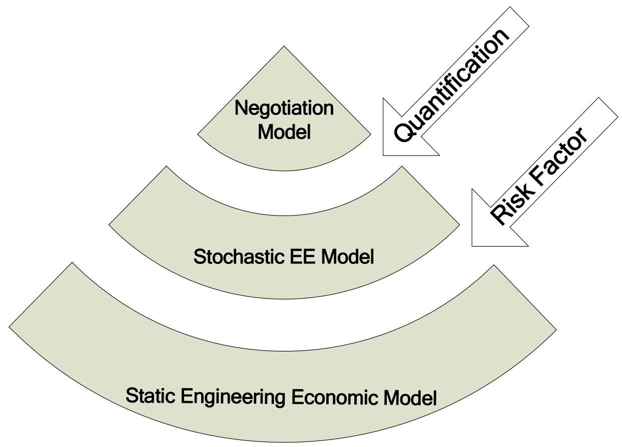


Figure 16 Stochastic Negotiation Model

4. A RISK-BASED NEGOTIATION MODEL

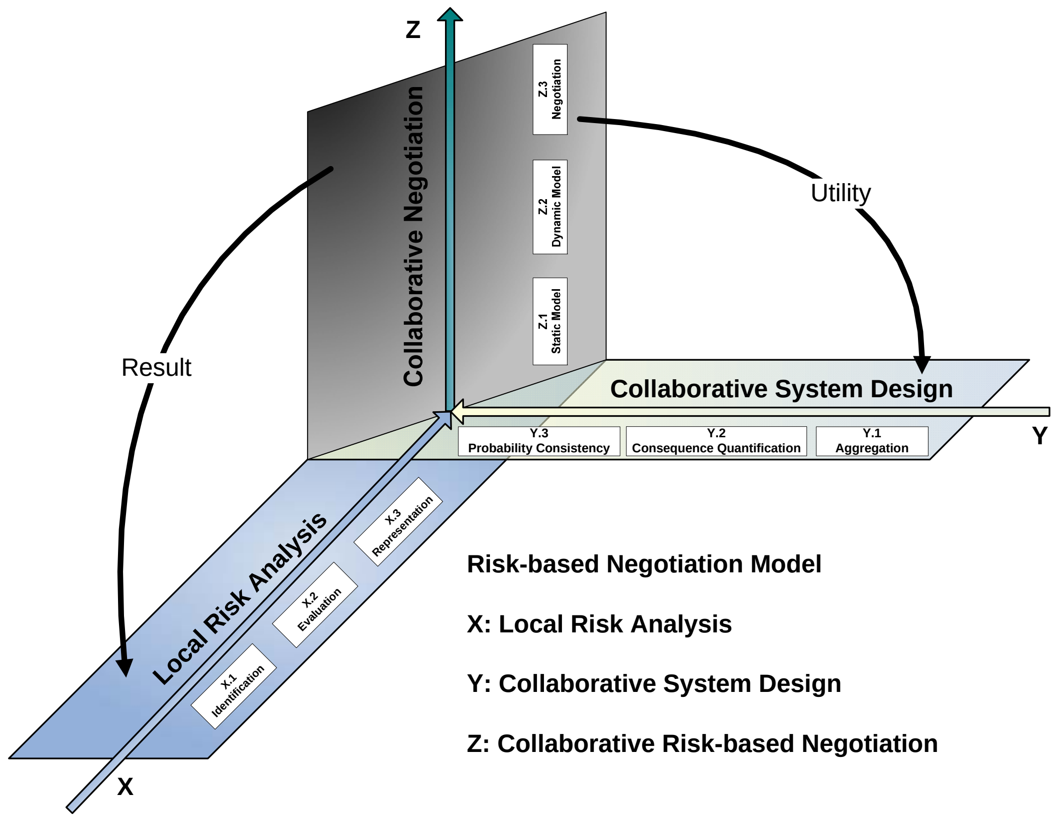


Figure 17 Risk-based Negotiation Model

Based on the theoretical models in Figure 15 and 16, a risk-based Negotiation Model (RBN) framework is developed and illustrated as in Figure 17. The framework is divided into three steps with close internal connections with others.

Step 1: Local Risk Analysis determines and prepares local risk information. Traditional risk analysis tools can be used to help each stakeholder or their members identify risk items, clarify causal relationships and evaluate expected risk in its or their local domain [Qiu, 2007a]. This step is to answer the research question 1 in chapter 3.3.3. Three sub steps are included: risk identification, risk evaluation, and risk representation. Risk identification is to determine possible risk items; risk evaluation is to evaluate severity and probability of each risk item; and risk representation is to illustrate interrelationships of a group of risk items. Local risk analysis focuses on local domain, and provides necessary risk information for global collaboration, and serves as the input of Step 2.

Step 2: Collaborative System Design deals with all stakeholders. This step is mainly to answer the research question 2 in chapter 3.3.3 [Qiu, 2007b]. Three sub steps are included: risk aggregation, risk consequence quantification, and risk probability consistency. First based on the input of Step 1, all local risk information can be aggregated to represent initial risk condition in a collaborative environment; second each risk item's consequence is quantified by a newly developed quantification method, which can mitigate the confusing consequence problem and help stakeholders make decision directly; third a probability consistency scheme is proposed to deal with the inconsistent risk probability problem and make all risk probabilities consistent. After this step, consistent risk information within a stakeholder and cross stakeholders is achieved and ready for the next collaborative risk-based negotiation.

Step 3: Collaborative Risk-based Negotiation includes three sub-steps: static model construction, dynamic uncertainty model construction and collaborative negotiation support. This step aims at answering the research question 3 and 4 in chapter 3.3.3 [Qiu, 2008b]. First a static model is built to evaluate expected risk values and risk preference functions for both individual stakeholders and their composed environment; second a dynamic model is constructed to evaluate risk uncertainty and help decrease expected risk values with limited resource, and further directly assist resource allocation decision problems; third both models' outputs are used to support risk-based collaborative negotiation. The expected risk value results return as updated input of Step 1 for stakeholder's re-evaluation, and the risk utility information flows back to Step 2 for collaborative stakeholders' confirmation.

These three steps internally form an iterative process. One step result can affect the others, and an iterative process continues until all stakeholders are satisfied or quits when some design constraints are met.

4.1 LOCAL RISK ANALYSIS

To achieve effective risk-based collaborative negotiation, negotiation information preparation is the first step and serves as an important foundation. Local risk analysis is a key process to obtain such information preparation. Local risk analysis is deliberated from three steps: risk identification, risk evaluation, and risk representation.

4.1.1 RISK IDENTIFICATION

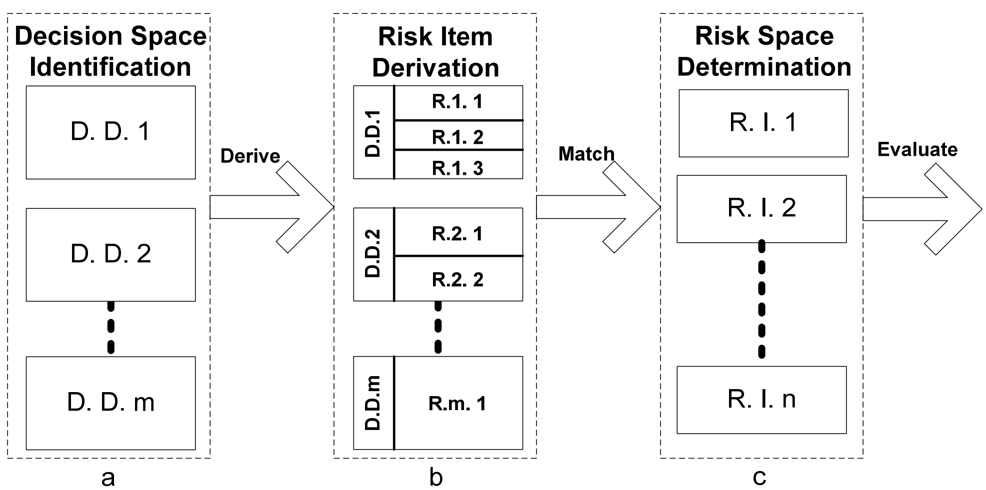


Figure 18 Decision Dimensions and Risk Items Identification

As discussed in 3.1.2, risk space is served as a key intermediate layer to link the decision space and the negotiation space, and then risk space is closely associated with decision space, and can be derived from decision space. The derivation of local risk items from decision dimensions can be illustrated as Figure 18. Three sub steps are included.

1. Decision Space Identification. (Figure 18.a)

This step is to determine local decision space, i.e., a member's decision space. Each stakeholder has its own role and concerns about the collaboration, and this forms the stakeholder's decision space. Each member's decision space can be unique and quite different from others, and it can contain several decision dimensions, such as D.D.1 to D.D.m in Figure 18.a. These decision dimensions indicate objects and interests of each member, and they are used to derive risk space. Some of the decision dimensions are negotiable, and provide initial negotiation contents for global risk-based coordination. The initially non-negotiable dimensions and stakeholders' specific requirements form constraints for later global coordination and negotiation.

Suppose each stakeholder can clarify its own decision space, and then a decision space set associated with the distributed environment is expressed as **DS**:

$$\mathbf{DS} = \{DS^{(i)}, i=1..n\} \qquad (1)$$

where $DS^{(i)}$ is a table representing the i^{th} stakeholder's decision space.

$$DS^{(i)} = \{DSD_j^{(i)}, j = 1..KK^{(i)}\}$$

where $KK^{(i)}$ is total number of decision dimensions in the i^{th} stakeholder's decision space, and $DSD_j^{(i)}$ is the i^{th} decision dimension defined as:

$$DSD_j^{(i)} = [function, range]$$

where “function” is the task that the stakeholder cares about, and “range” is how flexible the function can be. For example, the function could be finished at a specific time, or within a specified duration. A stakeholder’s decision space can be dynamically updated whenever the stakeholder desires change. For example, after stakeholders are familiar with their collaboration environment, they are more willing to update their initial decision spaces. The “range” property can also affect the negotiation results of corresponding risk items.

2. Risk Items Derivation. (Figure 18.b)

Each decision dimension is associated with several risk items. For example decision dimension D.D.1 can be broken into three risk items: R.1.1 to R.1.3. Risk item(s) can be derived from a decision dimension in several ways. One approach is heuristics-based, which derives risk items from each decision dimension based on experience and historical records. The other possible approach is a failure functions design method. Stone [2005] developed a functional basis for functional modeling in product design and used this basis to further yield a Failure Function Design, and some database can be constructed and be used to assist risk derivation from functions. Some research has been conducted, and computer programs can be coded to assist the derivation process. Another common method of risk derivation can be directly from risk experts, who can list risk items based on their experiences. In this way, no decision space is needed, but the risk information quality depends much on experts’ experiences, and then the risk results are not stable.

3. Risk Space Determination. (Figure 18.c)

Each local member can identify his/her risk items from each decision dimension, and then all the derived risk items form the member’s risk space. However risk space is not a simple sum of all the derived risk items, since several different decision dimensions may generate the same risk item causing duplication in the union set of all risk items. Then one step is needed to identify the replicated risk items, remove the duplications, and then clarify a simple risk space. The core of this process is actually to compare the risk items in the aggregated union of all risk items, and delete the duplications. This can also be conducted with the help of computer programs. In other words, current computer technology can greatly assist and simplify the risk space determination, and the framework of the proposed model is ready to be embedded into some commercial software programs.

4.1.2 RISK EVALUATION

After determining risk space, each member in a stakeholder can estimate risk properties. Existing literature suggests expected risk value to indicate risk severity. Denote $P_j^{(i)}$ and $C_j^{(i)}$ as risk probability and consequence of the i^{th} stakeholder's j^{th} risk item, and then the expected risk value $EV_j^{(i)}$ for this risk item are the product of probability and consequence, which is represented as [Bedford, 2001]:

$$EV_j^{(i)} = P_j^{(i)} \times C_j^{(i)} \qquad (2)$$

Risk probability and risk consequence are two dominant properties of risk. If both can be quantitatively measured, then a quantitative risk measure, expected risk value, can be yielded. However, qualitative measures of both probability and consequence are more common in existing literatures of engineering fields.

Risk probability is usually evaluated subjectively from evaluators' experiences. Some literatures suggest ranking risk probability into several discrete levels [Bedford, 2001]. Five levels, from A to E, are demonstrated and shown in Table 1 [Qiu, 2007a]. Level "A" indicates that this level of risk is likely to occur frequently in the experimental period, while other remaining levels show less risk probabilities. The five probability levels and their descriptions are illustrated in Table 1.

Table 1 Risk Probability Quantification

Description	**Specific Item**	**Level**	**Quantitative Rank (*a priori*)**
Frequent	Likely to occur frequently in the experimental period	A	80%
Probable	Will occur several times in whole experimental period	B	50%
Occasional	Likely to occur some times	C	30%
Remote	Unlikely but possible to occur	D	10%
Improbable	So unlikely, assumed occurrence may not be experienced	E	~0%

These five levels can be used to represent risk probability, but they are qualitative. As discussed in Chapter 3.3.2, possible confusing problems concerning this type of discrete level can occur during negotiation. A quantitative method is better for collaborative risk-based negotiation. Experts can assign a specific percentage number for each level. For example, "80%" can be assigned to indicate risk probability of level A. Similarly other levels and their quantifications are summarized in the last column of Table 1. This method is the most direct way for risk probability quantification, but is not accurate. Instead of fixed percentage number for each risk level, fuzzy logics can be used to quantity probability levels, and the results can satisfy human's risk expectations better. Some fuzzy research areas [Zadeh, 1962 & 1965; Roychowdhury, 1994; Scott, 1995] focus on this specific topics. Probability evaluation in local domain is not the focus of this paper. It is assumed that easy quantification methods in local domain can be adopted.

Experts' experiences are used resulting in subjective risk evaluations. To achieve more objective results, historical data and design of experiments can be used to estimate, calculate or measure risk probability. If historical risk data such as occurrences of failures exists, then risk probabilities can be either counted or calculated directly, or modeled by certain statistical regression models. When no historical risk data is available, but accurate and objective risk probability information is required, design of experiment can be used to effectively design risk failure experiments, and then estimate risk probabilities. For example, design of experiment is widely used in Material Science to test new materials' yielding strength, and predict their failure rates [Collins, 1986].

Similarly as probability, risk consequence is usually estimated by evaluators' experiences, and a discrete ranking method is used. Such consequence categories and their quantifications are summarized in Table 2, where risk is ranked into four levels: I, II, III and IV. Level I shows this type of risk is catastrophic, and many concerns are required. Similar percentage number can be assigned for each level of risk consequence. Table 2 summarizes such risk consequence levels and their quantification.

Table 2 Risk Consequence Quantification

Description	**Category**	**Quantitative rank (*a priori*)**
Catastrophic	I	10
Critical	II	7
Marginal	III	4
Negligible	IV	0

This type of consequence method is still subjective. Four discrete levels are not precise and accurate enough to present risk consequence. More objective and accurate risk consequence quantification is crucial for a comprehensive risk analysis. A new consequence quantification method is developed and illustrated in 4.2.2.

4.1.3 RISK REPRESENTATION

Besides risk probability and consequence, risk tolerance is the third important risk property. Risk tolerance indicates the pre-set acceptable level of risk item. A member's or stakeholder's risk tolerance varies according to financial condition, expectation, culture and etc. For example, an old retired engineer generally has a lower risk tolerance than a single young engineer, who has long time to make up for risk loss. Thus risk tolerance is a subjective term depending on specific stakeholder and specific time. For risk-based negotiation support, risk tolerance is an important decision factor, and needs to be included in risk analysis.

Risk tolerance is usually directly determined by specific stakeholders, and can be represented in several ways. In economics, a direct way is to set a monetary threshold, which indicates the maximum acceptable loss. In engineering fields, risk tolerance is usually a qualitative level, which is a combination of risk probability and risk consequence [Lough, 2006]. In other cases, risk tolerance can be applied to only risk probability or risk consequence individually. No matter tolerance formats are, risk tolerance itself is always a maximum threshold that a stakeholder can accept for certain risk properties.

A single stakeholder can contain a large number of risk items, and they are not necessary to be independent. To indicate dependent relationships of a set of risk items, risk hierarchy is introduced. Risk hierarchy shows internal risk items' correlations and their relationships with the system. Two existing methods have been developed to represent it: fault tree analysis and event tree analysis. Fault tree analysis is a failure analysis, and Boolean logics are used to illustrate the relationship between an undesired state of a system and other basic risk items. A fault tree is a simple pictorial representation of causal relationships among items using a Boolean expression [Haimes, 1998; Bedford, 2001]. Fault tree analysis is widely used in all major fields of engineering, and can be utilized as a visualized tool to track down or predict the most likely system failure. Engineer experts are responsible for development of fault trees in a collaborative environment. Since it is usually costly and cumbersome to consider failure of a whole and complex system, decomposition and integration strategy is utilized. Each complex system is divided into small sub-systems, and then fault tree analysis is designed to deal with sub-system failures. When all fault trees are determined, these trees are integrated to form and analyze the whole system [Haimes, 1998; Bedford, 2001]. Fewer errors can be achieved with fewer efforts.

The top (root) of a fault tree is called "top event", which is an undesired effect. This undesired effect is usually a set of combinations of certain basic risk items, and the combinations themselves indicate risk items' hierarchy. Only one top event is allowed in a fault tree. When the top event is determined, all other conditions which cause this top event are added below the root according to certain logic expressions [Haimes, 1998]. Conventional logic gate symbols such as "AND" and "OR" gates are used to represent such logic expressions. "The route through a tree between an event and an initiator in the tree" is called a cut set [Bedford, 2001]. "The shortest credible way through the tree from fault to initiating event" is called a minimal cut set [Bedford, 2001]. Computer commercial programs, such as Relex Fault/Event Tree Analysis and RiskSpectrum, can assist tree construction and other basic calculations. A fault tree example is illustrated in Figure 19. This “top event” includes three combinations of basic risk items, or three cut sets. At the bottom of the tree, three basic risk items and their combinations make the top event happen. Risk failure logic of the top event T in Figure 19 is:

$$T = A \bullet B + A \bullet \overline{B} \bullet C + \overline{A} \bullet B \bullet C$$

where “+” represents logic “OR”, and “•” indicates “AND”.

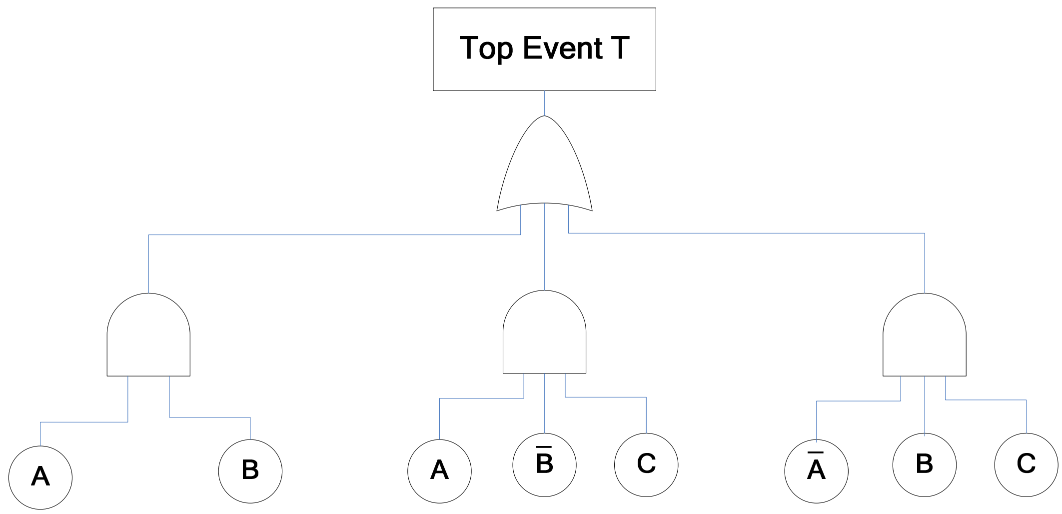


Figure 19 Risk Fault Tree Example

Event tree analysis is the other common method to represent risk hierarchy. Event tree is “a representation of all possible events in a system, which shows the sequences of events involving success or failure of system components” [Bedford, 2001]. An event tree begins from an undesired initiator such as component failure, and then follows possible system events or flows to reach a set of final consequences. When a new event is considered, a new node is added to the tree with both branches: success and failure. Finally a set of “top events” (outcomes) can be identified. Their probabilities can be evaluated from probabilities of the initial events, and their consequences can be evaluated [Bedford, 2001].

With better understanding of four important risk properties, risk can be represented in a more uniform way. Within a stakeholder, consistent risk definitions and evaluations across members can help members understand each other, and improve their collaboration effectiveness. As discussed in 1.1.2, members in a stakeholder can have their specific risk evaluations or even risk definitions, and then their implicitness and heterogeneity can form barriers for effective communication and collaboration. To help members within a stakeholder understand each other better, a standard uniform risk property table is constructed to capture risk information across members as shown in Table 3.

Table 3 Individual Member’s Risk Property Table

Risk Item	**Probability**	**Consequence**	**Tolerance**	**Desire**	**Confidence**
XXXX	%	$	$	Strong / weak	%

In the table, “Risk Item” is risk description of an item. A risk item is usually measured by its “Probability”, “Consequence” and “Tolerance”, and then those three columns follow after “Risk Item”. “Desire” column indicates degree of an evaluator’s willingness to negotiate this risk item. It can be assigned either strong or weak rating. “Strong” means the evaluator requires that probability or consequence of the risk item must be satisfied, and these types of risk items become constraints and boundaries for later local or global negotiation. “Weak” means property of this risk item can be changed, which leaves negotiation room. “Confidence” indicates how much assurance the evaluator has about his/her evaluation. For example, 100% shows full confidence, and 10% indicates little confidence in the evaluation.

Each risk item of a stakeholder can be represented as a row in the property table 3. With this uniform risk property table, members within a stakeholder can have a more efficient way to understand, communicate and negotiate with others concerning risk. After all risk items are filled in the table, their risk hierarchy can be indicated or represented by corresponding fault trees or event trees. In this way, risk items and their properties within a single stakeholder can be completely represented.

4.2 COLLABORATIVE SYSTEM DESIGN

4.2.1 RISK AGGREGATION

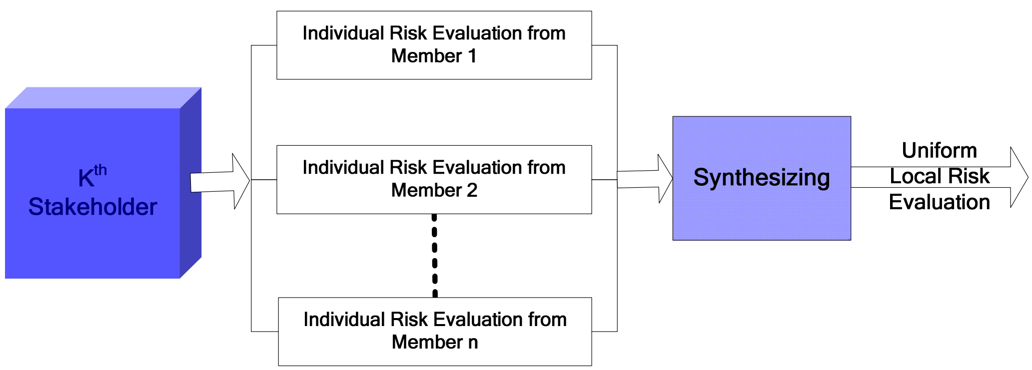


Figure 20 A Stakeholder's Risk Space Aggregation

Members in a stakeholder have their own risk space and conduct corresponding evaluations, but during global negotiation, it is a stakeholder group that interacts with other stakeholders instead of individual members. This condition requires each stakeholder group to have uniform evaluations for all its members' risk items. A stakeholder consists of members, and thus its risk space should aggregate all its members' risk space. . A uniform stakeholder group's risk assessment needs to be constructed based on its members' evaluations, but such aggregation process is usually not just simple adding because of the existence of overlapped risk items. Figure 20 shows a stakeholder's risk space aggregation process. First all members (from 1 to n) within the k^{th} stakeholder conduct their own risk assessment, and then all their evaluations are gathered, and a synthesizing process is conducted to achieve a final uniform risk assessment for the stakeholder group.

1. Collect all stakeholder members' risk property tables.
2. Compare the tables, and determine the overlapped risk items.
3. Negotiate risk properties of the overlapped risk items.
4. Fill the stakeholder's risk property table.

A compiling process is used to partially reconcile disparate risk definitions among different members during risk assessment. First, each member defines all his/her own risk items and fills in risk property table in Table 3 according to belief and experience; second, the table is shared with other members within the same stakeholder. Once all shared risk tables are available, members can determine overlapped risk items, and negotiate on specifics of their definitions and evaluations. Finally, a property table for a stakeholder group can be constructed as in Table 4.

Table 4 Risk Property Table for Stakeholder Group's Risk Evaluation

Risk Item	**Probability**	**Consequence**	**Tolerance**	**Requirement**	**Related Stakeholders**
Name	Level or %	Level or %	Level or %	XXXX	XXXX

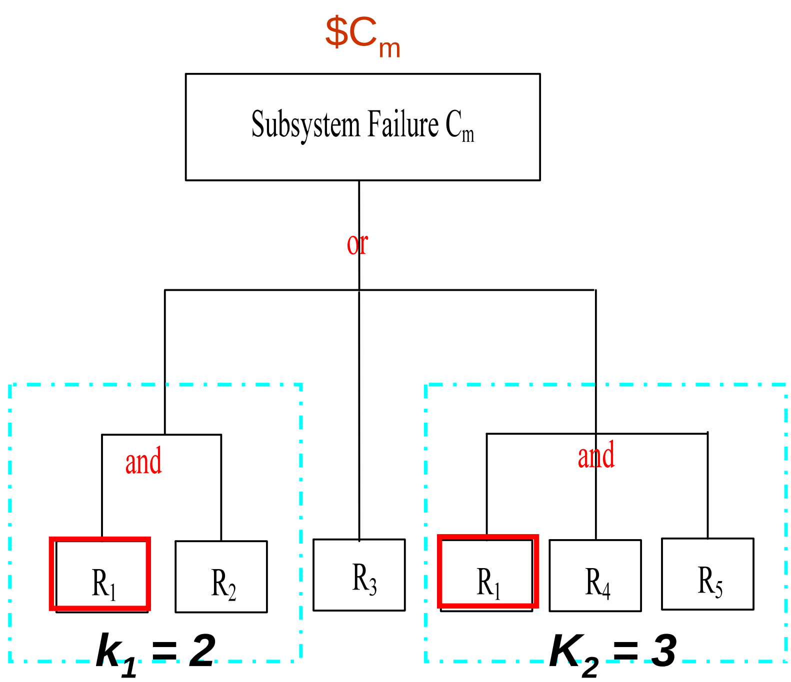
Compared with individual member's property table in Table 3, "confidence" property is removed, while "requirement" and "related stakeholders" are added. "Confident" factor exists when members make their risk evaluations, and it is useful to achieve a uniform group evaluation with a high assurance via local negotiation, since a stakeholder's risk assessment is synthesis of its members' individual assessments. After a stakeholder's group evaluation is determined, there is no need of "Confidence" in a stakeholder's risk table, and then such individual assurance property disappears. "Requirement" in Table 4 is optional, which can indicate stakeholder's special requirements for certain risk items, and then can be used as constraints of further collaborative negotiations. "Related stakeholders" is added and used to form a linking table so that relationships among all stakeholders can be retrieved. The "related stakeholders" information can also be utilized to construct a linking table, which can indicate overlapped risk items and their locations, and then form the negotiation space.

4.2.2 CONSEQUENCE QUANTIFICATION

Risk probability and consequence are two most important properties of risk. Risk probability is a solid concept, and can be quantified from stakeholders' (or their members') experiences or from historical data. While consequence is an abstract concept, and is usually hard to be quantified directly and accurately especially when multiple stakeholders with complicated risk hierarchies are involved. Little research has been conducted concerning comprehensive consequence quantification in a collaborative environment. Risk consequence itself is a subjective term, which depends much on specific stakeholders. For example, a sensor failure is serious for stakeholder "A", but stakeholder "B" may not care about it. Negotiating risk consequences among different stakeholders in a distributed environment is usually not helpful, and thus negotiation is not a good way for risk consequence quantification. As discussed in 4.1.2, risk consequence can be quantified by several discrete levels in Table 2, and then a certain monetary unit can be assigned for each severity level under a specific scenario. For example, level 5 of risk consequence can be assumed to $10,000 during an automobile's risk analysis. Experiences and many subjective evaluations are involved in this type of consequence quantification resulting in unstable or even misleading results. Further because of existence of overlapped risk items, a stakeholder may care for external risk items from other collaborative stakeholders. However a stakeholder generally has little experiences about external risk items, and can have hard time estimating external risk items' consequences. Existing discrete level quantification methods do not satisfy precision requirement in a distributed environment, and then a new risk consequence method is proposed to quantify risk consequence. Monetary unit is a standard measure, and can be understood across all stakeholders, and then it is chosen to measure risk consequence in this paper. A comprehensive monetary quantification method is presented based on risk fault/event trees.

In a distributed environment, basic risk items themselves can be independent, but a union of them can lead to occurrence of top events. Risk hierarchy is introduced to represent such relationships. Considering these dependent relationships, an individual risk item's consequence depends on a set of related risk items. Since fault tree is a common way to represent risk hierarchy, it is chosen to quantify single risk item's consequence. Considering nature of fault tree, only one top event can exist in a fault tree, and a stakeholder can have multiple fault trees. The proposed strategy is to quantify risk consequences in a single fault tree first, and then combine quantification results from all fault trees to obtain a final result. An arbitrary stakeholder, $S^{(i)}$, is chosen from a distributed environment, and consequence of $S^{(i)}$'s risk item, $R_j^{(i)}$, is being quantified, then the following six steps are conducted for each fault tree in stakeholder $S^{(i)}$ as in Figure 21.

$$T_m = R_1 \bullet R_2 + R_3 + R_1 \bullet R_4 \bullet R_5$$



$$P(CSN_1) = P(R_2) \qquad P(CSN_2) = P(R_4) \times P(R_5)$$

$$C_m(R_{11}) = \frac{\$C_m \times P(CSN_1)}{2} \qquad C_m(R_{12}) = \frac{\$C_m \times P(CSN_2)}{3}$$

Figure 21 Risk Consequence Quantification based on Fault Tree

1. *Quantify consequence of top event in a fault tree*

The first step for stakeholder $S^{(i)}$ is to construct and determine all its cared fault trees, which form a fault tree set:

$$FT^{(i)} = \{FT_j^{(i)}, j = 1 \ldots MM^{(i)}\} \qquad (3)$$

where $FT_j^{(i)}$ is the i^{th} stakeholder's j^{th} fault tree, and $MM^{(i)}$ is total number of fault trees in the i^{th} stakeholder.

Top event of a fault tree is usually a sub-system failure. In engineering, this sub-system failure consequence can be directly associated with economic loss. Risk analysis experts who build the fault tree can have good understanding of this sub-system failure, and can estimate its corresponding consequence. This assumption is made:

Assumption I: Consequence of the top event in a fault tree can be estimated and quantified in monetary unit.

Risk consequence depends on specific stakeholders, and there is no need for consistent risk consequence evaluations across collaborative stakeholders. A stakeholder can assign consequence estimations for its own fault trees by itself. $S^{(i)}$ can examine all trees in $FT^{(i)}$, and then estimate economic loss if each top event occurs. Its estimations then form a consequence quantification set:

$$CQ^{(i)} = \{\$C_j^{(i)},\ j = 1...MM^{(i)}\} \qquad (4)$$

where $\$C_j^{(i)}$ is the i^{th} stakeholder's consequence estimation on top event of its j^{th} fault tree. Taking Figure 21 as an example, a stakeholder selects one fault tree from its fault tree set, and after deep consideration and evaluation of this sub-system failure, the stakeholder assign $\$C_m$ as consequence of this top event.

2. Search cut sets $CSS_j^{(i)}$ including $R_j^{(i)}$

A fault tree indicates a set of risk items' hierarchy, and a logic expression can also represent a set of risk items' hierarchy. A fault tree and a logic expression can be equally converted to each other. A logic expression can determined directly from a fault tree to indicate risk hierarchy of a top event. A simple logic expression is a union of several cut sets, and a cut set is an intersection of several basic risk items [Bedford, 2001]. A logic expression set can be determined based on stakeholder $S^{(i)}$'s fault tree set:

$T^{(i)} = \{T_j^{(i)}\ \ j = 1...MM^{(i)}\}$ (5)

where $T_j^{(i)}$ is a logic expression for the j^{th} fault tree. Denote cut sets of stakeholder $S^{(i)}$'s j^{th} fault tree as $CS_j^{(i)}$. $T_j^{(i)}$ is a union of several cut sets in the form of $\bigcup CS_{jk}^{(i)}$. Suppose stakeholder $S^{(i)}$'s j^{th} fault tree includes $N^{(j)}$ cut sets, then

$$T_j^{(i)} = \bigcup_{k=1}^{k=N^{(j)}} CS_{jk}^{(i)}$$

For example in Figure 21, the top event has a logic expression:

$$T_m = R_1 \bullet R_2 + R_3 + R_1 \bullet R_4 \bullet R_5$$

where "+" represents logic "OR", and "•" indicates "AND".

With logic equation set, a stakeholder can determine all cut sets for each of its fault tree. For instance, three cut sets exist in Figure 21:

$CS_1 = \{(R_1, R_2), (R_3), (R_1, R_4, R_5)\}$.

With the determined cut sets $CS_j^{(i)}$, the next step is to search and find those cut sets which include the interested risk item $R_j^{(i)}$. Denote it as $CSS_j^{(i)}$. Taking R_1 as an example in Figure 21, two related cut sets can be found: $CSS_1 = \{ (R_1, R_2), (R_1, R_4, R_5)\}$

3. Count numbers of risk items in $CSS_j^{(i)}$: $K_j^{(i)}$

This step is to count number of risk items in the obtained cut sets $CSS_j^{(i)}$ from Step 2, and gain a corresponding number set $K_j^{(i)}$. For instance in Figure 21,

$K_1 = \{ 2, 3 \}$

4. Calculate risk probability of $CSS_j^{(i)}$ ignoring the risk item $R_j^{(i)}$

All cut sets in $CSS_j^{(i)}$ include the specific risk item $R_j^{(i)}$, and they may include other risk items, which can affect risk consequence of $R_j^{(i)}$. The step is to remove $R_j^{(i)}$ from the cut sets in $CSS_j^{(i)}$ and obtain new cuts $CSN_j^{(i)}$,and then consider the effect of all remaining risk items in $CSN_j^{(i)}$. In this way, all relevant risk items about $R_j^{(i)}$ can be considered simultaneously. Risk probabilities of the cut sets $CSN_j^{(i)}$ are used as an effect measure: $P(CSN_{jk}{}^{(i)})$

where P is probability function of a combination of risk items.

For example, two cut sets, (R_1, R_2) and (R_1, R_4, R_5), exist in CSS_1 in Figure 21, and if R_1 is removed, then the remained cut sets are

$CSN_1 = \{(R_2), (R_4, R_5)\}$

Then their risk probabilities are:

$P(CSN_1) = \{ P(R_2),\ P(R_4) \times P(R_5) \}$

5. Calculate risk consequence of $R_j^{(i)}$ in each fault tree

Based on the information obtained, risk item's consequence in each fault tree can be calculated. Traditional risk consequence is defined as the loss when a risk item fails, and it does not depend on other risk items. However, when risk hierarchy is involved, it is possible that only when several risk items happen simultaneously, a loss can occur, i.e., when a single risk item fails and others do not, a sub-system can still run well with no consequence loss on the system. In this case, traditional consequence of this risk item yields zero. However this risk item does have certain harm effect on the system, and then traditional risk consequence definition is not satisfying any more. A new conditional risk consequence is given to extend current consequence meaning:

A risk item's consequence in a fault tree is the conditional expected risk value divided by a certain factor if this risk item happens.

In this definition, a risk item's consequence depends on other related risk items and their hierarchy. The objective of this definition is to consider connection of several risk items, but can quantify consequence of each risk item separately. Otherwise, all risk items in a cut set have to be considered simultaneously all the time, which is not convenient during collaborative risk-based negotiation. If single risk item can be separately quantified, a large number of post risk analysis can be conducted easily.

The top event can be triggered by a set of cut sets. A cut set is a union of certain basic risk items, then a cut set's risk consequence is sum of its risk items' consequences. This step is to distribute the quantified top event consequence to relevant basic risk items, and then form their consequence values. For example, both R_1 and R_2 can lead to occurrence of the top event in Figure 21, then the consequence $\$C_m$ should be distributed to R_1 and R_2 based on some weights. All basic risk items in bottom of a fault tree exist objectively, and do not depend on others. It can be assumed that they are independent. For each cut set, a top event will not happen without any one risk item within a cut set. Considering such equal effect, all risk items within a fault can have the same weights. Then the following assumption concerning distribution weights is made:

Assumption II: from consequence effect perspective, every risk item in a cut set of a fault tree has the same contribution weight as the others within the same cut set.

With this assumption, consequence of the top event can be distributed to basic risk items. With both assumption I and II, every risk item's consequence in a fault tree can be calculated. Step 3 calculates the distribution weights, and then risk item $R_j^{(i)}$ within Stakeholder $S^{(i)}$'s j^{th} fault tree can be calculated as:

$$C_j^{(i)}(R_j^{(i)}) = \sum_{k=1}^{N^{(j)}} \frac{\$C_j^{(i)} \times P(CSN_{jk}^{(i)})}{K_{jk}^{(i)}} \quad (6)$$

Take R_1 in Figure 21 as an example, its consequence is:

$$C_m(R_1) = \frac{\$C_m \times P(CSN_1)}{2} + \frac{\$C_m \times P(CSN_2)}{3}$$

All risk items receive certain portion of risk consequence of their top event. When all risk items in a cut set are combined, their total expected risk value should be the same as the expected value of the top event of this cut set. The consequence calculated from Eq.(6) can satisfy this fact, which also corroborates the assumption II.

A stakeholder can include many fault trees. Risk consequence is additive, i.e., if a risk item exists in multiple fault trees, then total consequence of this risk item is sum of consequences in all involved fault trees. Then all fault trees of a stakeholder can be integrated to achieve total risk consequence, which is the Step 6.

6. Sum up all risk consequences from all fault trees.

Each stakeholder can have many fault trees, and for each event tree, the same algorithm can be applied to calculate consequence of each risk item. Finally all the event trees are combined. The total consequence of arbitrary risk item $R_j^{(i)}$ can be calculated as:

$$C(R_j^{(i)}) = \sum_{j=1}^{MM^{(i)}} C_j^{(i)}(R_j^{(i)}) \quad (7)$$

Then a notional risk consequence can be quantified in the formula (7). It also incorporates additive effect of overlapped risk items. All calculations in the six steps can be conducted automatically, and this calculation algorithm can be embed into commercial computer programs to quantify risk consequence.

Similarly, risk consequence can be quantified from event trees if final outcome consequence of each event tree can be quantified in monetary unit. Each risk item in an event tree has two statuses: "Success" or "Failure". "Success" means that this risk item does not happen resulting in no consequence. "Failure" means that this risk item does happen. When calculating risk consequence, only "Failure" branches are of the interest. Similar quantification algorithm is applied:

For each event tree:

1. Quantify each final outcome event consequence: $\$C_j^{(i)}$

2. Search tree branches ($TB_{jk}^{(i)}$) including interested risk item $R_j^{(i)}$

3. Count risk items in $TB_{jk}^{(i)}$: $K_{jk}^{(i)}$

4. Calculate risk probability ($P(TBN_{jk}^{(i)})$) of each branch in $TB_{jk}^{(i)}$ ignoring $R_j^{(i)}$

5. Calculate risk consequence of $R_j^{(i)}$ in this event tree:

$$C_j^{(i)}(R_j^{(i)}) = \sum_{k=1}^{N(j)} \frac{\$C_j^{(i)} \times P(TBN_{jk}^{(i)})}{K_{jk}^{(i)}}$$

For all event trees:

6. Sum up risk consequence in all event trees including $R_j^{(i)}$

4.2.3 PROBABILITY CONSISTENCY

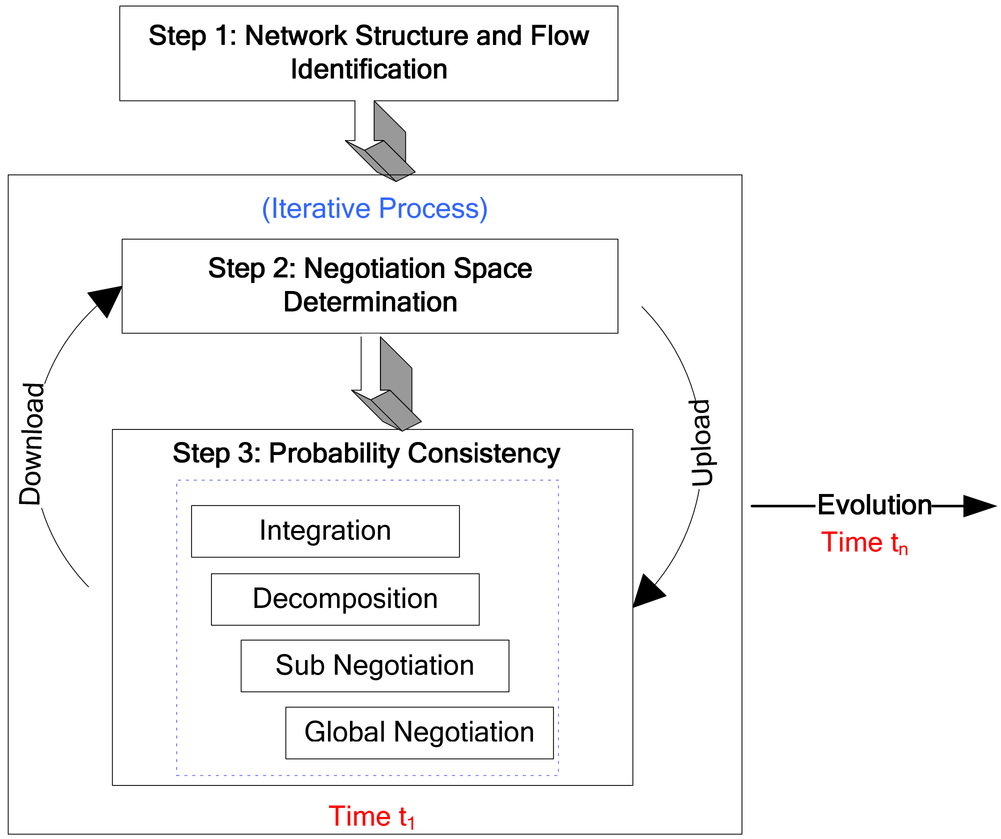


Figure 22 Risk Probability Consistency for Overlapped Risk Items

In a distributed environment, risk consequence quantification is a necessary condition, but not a sufficient condition for effective collaborative negotiation. As discussed in 3.3.2, risk probability consistency is the other necessary condition. To achieve consistent probability evaluation for overlapped risk items, a risk probability consistency scheme is developed as in Figure 22. Three main steps are involved. Step 1 is to identify the collaborative distributed environment structure and its working flow, so that networked stakeholders can better understand each other and their collaborative environment, and further can negotiate on specifics when necessary. Step 2 is to identify negotiation space based on local risk analysis information and evaluate overlapped risk items. Step 3 is to coordinate stakeholders based on their risk evaluations from Step 2, and then aim to achieve consistent probability evaluations for overlapped risk items. Step 2 and 3 are iterative until an acceptable negotiation result (consistent risk probabilities) is achieved. In Step 3, “decomposition” and “sub negotiation” are two optional sub-steps, which are identified as strategies for large-scale distributed environment (increased complexity) to improve negotiation efficiency. In a distributed environment with many stakeholders, it will be more effective to achieve a global satisfactory result if small groups’ requirements can be met first. Decomposition and sub negotiation are identified as strategies when such conditions exist. The stakeholders can be decomposed into several sub groups based on their relationships, and then each sub group can viewed as a smaller size distributed environment. The proposed methodology can be applied to this smaller environment in order to achieve a satisfactory negotiation result. Finally, integration of all the sub negotiation results can form the global negotiation result. When time issue is considered, evolution step occurs, which considers evolution along a time line to achieve sustainable collaboration environment. Decomposition and evolution issue are not focus of this paper, and they are roughly mentioned.

1. <u>Network Structure and Flow Identification</u>

It is important for networked stakeholders to know each other and their internal possible work flow, so that they can negotiate on specifics with appropriate stakeholders when necessary. This step provides good preparation towards effective collaboration, and it is similar as the process of cognition among strange persons. At the inter-stakeholder level, each stakeholder communicates with those who have direct relationship, clarifies each other's responsibilities and tasks, and then becomes familiar with the process flow. This step can also be applied to the intra-stakeholder level, where each stakeholder clarifies its internal hierarchy, and then distributes its tasks to proper members. Suppose there are n stakeholders in the environment, then a stakeholder set S can be defined:

$$\mathbf{S} = \{S^{(i)}, i=1..n\} \quad (8)$$

where $S^{(i)}$ represents the i^{th} stakeholder.

Then the "sociometric notation" [Wasserman, 1994] can be used to represent the relationship among all the stakeholders. A Sociomatrix M can be defined to represent the environment structure as:

$$\mathbf{M} = \{M_{ij}, i=1..n; j=1..n\}$$

where M_{ij} is the value of the tie from the stakeholder S_i to S_j, and is defined as:

$$M_{ij} = \begin{cases} 0\text{: Having no interactive activities} \\ 1\text{: Having direct interactive activities} \\ 2\text{: having the same stakeholders} \end{cases}$$

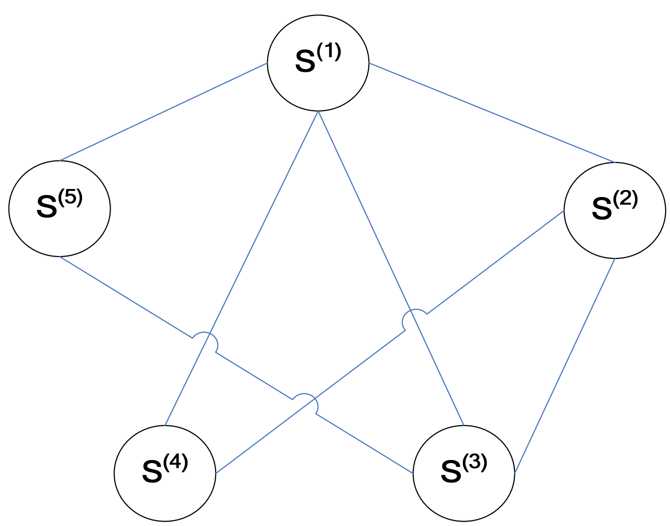


Figure 23 A Networked Environment

Figure 23 shows an example of collaborative environment. Five stakeholders are involved in the environment.

S = $\{S^{(1)}, S^{(2)}, S^{(3)}, S^{(4)}, S^{(5)}\}$

Their relationships **M** can be represented as:

Table 5 Sociomatrix M

2	1	1	1	1
1	2	1	1	0
1	1	2	0	1
1	1	0	2	0
1	0	1	0	2

Each stakeholder has a specific work flow from its perspective. A flow Set **FL** is defined to include all flows in the environment structure:

FL = $\{FL^{(k)}, k=1..n.\}$

where $FL^{(k)}$ represents the k^{th} stakeholder's work flow, and it is a flow table that can be expressed as a collection of $m^{(k)}$ flow items FLI:

$FL^{(k)} = \{ FLI_j^{(k)}, j = 1..m^{(k)}\}$

where $m^{(k)}$ is the number of total steps of the k^{th} stakeholder's work flow, and $FLI_j^{(k)}$ is depends on specific negotiation scenario, which is:

$FLI_j^{(k)}$ = [Step No., Task, Associated Stakeholder, Schedule]

More environment structure and work flow backgrounds are discussed in the previous work [Qiu, 2007a & 2007b].

2. Negotiation Space Determination

When each stakeholder has formed its own subjective risk space, and then each stakeholder can upload its risk evaluations to the collaborative environment and share with others. Thus each stakeholder can understand others' risk evaluations, find out overlapped risk items, identify their evaluation differences, and determine negotiation contents.

Suppose stakeholder $\mathbf{S}^{(\mathbf{k})}$ as its risk space $\mathbf{F}^{(k)}$ derived from its decision space $\mathbf{DS}^{(k)}$. Then all stakeholders' risk space can be integrated and then form a global risk set:

$$\mathbf{F} = \{F^{(k)}, k=1..n.\} \quad (9)$$

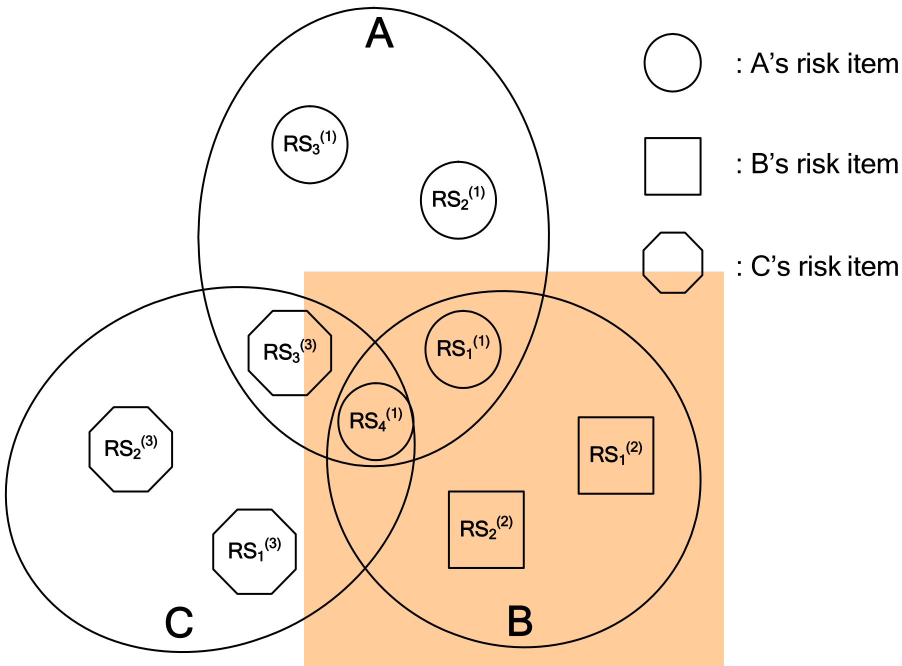


Figure 24 Overlapped Risk Items

Simple comparison algorithms can be applied to **F** to find overlapped risk items. Figure 24 shows an example of overlapped risk items. Three stakeholders A, B and C form a distributed environment, and all their risk items construct a global risk space as shown in Figure 24. Stakeholder A contains four risk items $RS_1^{(1)}$, $RS_2^{(1)}$, $RS_3^{(1)}$, and $RS_4^{(1)}$. One of them, $RS_1^{(1)}$, will affect stakeholder B, and the other one $RS_4^{(1)}$ will affect both stakeholder B and C, so $RS_1^{(1)}$ and $RS_4^{(1)}$ are considered as overlapped risk items. Similarly $RS_3^{(3)}$ can also be determined as overlapped risk items. After this comparison process, all the overlapped risk items can be determined, and then all of them form Overlapped Risk Space (**ORS**), i.e., negotiation space**:**

$$\mathbf{ORS} = \{ORS_j, j=1...p\} \quad (10)$$

where ORS_j is the j^{th} overlapped risk item, and p is the total number of overlapped items. In the example of Figure 24:

$p=3$;

$ORS_1 = RS_1^{(1)}$, $ORS_2 = RS_4^{(1)}$, $ORS_3 = RS_3^{(3)}$

For single risk item, ORS_j can be evaluated by [P-probability, C-consequence]. Consequence is quantified in 4.2.2. Risk probability exist objective and does not depend on specific stakeholders. No matter whom the stakeholder is, the probability of a risk item has essentially a fixed value, though stakeholders may not know this true value. Stakeholders usually have to use their experiences to estimate risk probabilities, and then risk probability evaluations is subjective, and different stakeholders can have different evaluations on the same risk items. Then inconsistent probability evaluations across stakeholders in a distributed environment exist, and further can lead to inefficient collaboration or erroneous decision making. Thus risk probability consistency is important.

3. Risk Probability Consistency

This step aims at providing quantitative values and reasonable criteria to help stakeholders negotiate and collaborate effectively. It is designed to achieve consistent values based on all stakeholders' subjective evaluations. Since true values of risk probability may never be discovered, risk probability is always a subjective term ever for consistent risk probability after negotiation. However consistent aggregated evaluations are usually more close to true values, and more importantly, all stakeholders in a collaborative environment can accept such consistent evaluations (though may not be right), and then corresponding human social factors would make good to the collaboration. So risk probability consistency is necessary for effective collaboration.

Denote xx_j as the Objective Risk Probability Assessment (negotiated result) of overlapped risk item ORS_j, and $xx_j^{(k)}$ as the k^{th} stakeholder's Subjective Risk Probability Assessment for ORS_j. Then a set of all variables xx_j can be represented as vector **XX**:

$$\mathbf{XX} = \{xx_j\ ,\ j = 1 \ldots p\}$$

where xx_j is denoted as $ORA(ORS_j)$, and p is total number of overlapped risk items. Since multiple stakeholders have evaluations on risk items in **XX,** the expected risk function xx_j should include all its involved stakeholders' effects. For each stakeholder $S^{(k)}$ in a distributed environment, it can have its specific evaluations on all the overlapped risk items in **XX**, and then the expected risk function for the k^{th} stakeholder associated with overlapped risk items is:

$$F^{(k)} = \sum_{j=1}^{P} xx_j \times C_j^{(k)}$$

All overlapped risk items are included in the expected risk function, but a specific stakeholder may only care about certain risk items, and then the following assumption is made to satisfy the uniform equation above.

Assumption III: If stakeholder $S^{(k)}$ has no evaluation for ORS_j, then it is assumed $S^{(k)}$ does not care about this risk item, and its associated consequence $C_j^{(k)}$ is set to zero.

Stakeholder $S^{(k)}$ may have some special requirements in its decision dimension, then these requirements will be transformed into constrains of negotiation in the forms:

$G_i^{(k)}(XX) \leq 0$, i = 1 ... n_G

$H_l^{(k)}(XX) = 0$, l = 1 ... n_H

With all negotiation contents identified, the next problem is how to conduct effective negotiation concerning risk probability consistency. Several negotiation methods exist in game theory such as fair division, mediation of disputes, arbitration procedure and etc. [Thomas, 1976; Young, 1991]. “Arbitration procedure” is the most popular one, and is chosen in this method.

Specific objective criteria (such as fastness, accuracy, reliability) are the key to achieve effective arbitration decision [Keeney, 1976]. These criteria should fairly represent all significant stakeholders’ perspectives in a real collaborative environment, and can be used to search for reasonable solutions. Human social dynamics can greatly affect negotiation process. Different trust networks, power structures etc. may achieve different negotiation results. To simplify such human social dynamics, only negotiation power is chosen considering its importance in engineering. In a distributed environment, three possible criteria are summarized as: “the quickest convergence (least iteration)”, “key stakeholders”, “equal stakeholders”. These three criteria represent three most popular scenarios in the real negotiation world. When time is the biggest negotiation concern, “the quickest convergence” can be employed to achieve fastest negotiation results. If no major decision power difference exists in the collaboration environment, “equal stakeholders” criterion can be used to indicate that all involved stakeholders are equal. But if a stakeholder holds the greatest decision power, then "key stakeholders" criterion needs to be utilized to favor this key stakeholder. A function **W** is used to represent the arbitration criterion, which is a composite function created from all stakeholders' expected risk values, and is based on the selected arbitration criterion. Based on the definitions and formulas, the consistency negotiation problem can be summarized as a multi-objective optimization problem:

$$\begin{cases} XX = \{xx_j,\ j = 1 \ldots p\} \\ \text{Min. } \mathbf{W}(F(XX)^{(1)}, F(XX)^{(2)}, \ldots, F(XX)^{(k)}, \ldots, F(XX)^{(n)}) \\ \text{s.t.} \\ G_i^{(k)}(XX) \leq 0,\ i = 1 \ldots n_G,\ k = 1 \ldots n \\ H_l^{(k)}(XX) = 0,\ l = 1 \ldots n_H,\ k = 1 \ldots n \end{cases} \qquad (11)$$

Existing algorithms can be used to calculate the optimum risk probability evaluation set **XX** from the model. All stakeholders can then negotiate based on this calculated results, and achieve a global coordination result (XX*). When one cycle of negotiation is completed, XX* can be distributed to all stakeholders who then forward the result to their members. Each stakeholder then compares its (local) result value against the corresponding global result. If all stakeholders are satisfied, then a temporary globally consistent result is achieved. If any stakeholder is not satisfied, the stakeholder will provide an explanation and can request another negotiation run. This process can be repeated until all participants are satisfied, or the collaboration breaks down. Thus, the end negotiation result may lead to either an agreement or a well-informed disagreement among stakeholders.

Evolution and Update may be needed for long term collaboration. Stakeholders may change their decision space and associated risk evaluations over time, even though a consistent collaboration environment was once achieved. Therefore, an evolutionary factor needs to be considered in such cases and a new cycle of negotiation is needed. Another possible case is that the collaboration requires updating when new information arrives. The authors put forth that collaboration must be treated as a learning process. For example, a previous successful collaboration and the associated information can be saved in a knowledge base for future use. This knowledge base can be reused to guide similar new negotiations and improve negotiation efficiency. For example, if some experiments requiring collaboration between multiple stakeholders were successful, and their risk data was stored in a database, then a new similar proposed experiment may not require a re-evaluation of every risk item. The same risk items as in the database can be re-used to reduce the number of iterations required for successful negotiation. This could be done by assigning a “strong” desire in their risk property table. In general, unless conditions are changed dramatically, existing risk evaluations can usually be directly reused. More details concerning this consistency method can be found in the previous work [Qiu, 2007a & 2007b].

4.3 COLLABORATIVE NEGOTIATION

Each risk item contains two properties of risk probability and consequence. Risk consequence is comprehensively quantified in monetary unit in 4.2.2, and risk probability evaluations across different stakeholders are made consistent in 4.2.3. Thus each risk item and its expected risk value can be theoretically determined. Such determination is only applicable in local risk domain. A further global collaborative negotiation model is necessary based on local quantification risk results.

The question is how to aggregate local risk item information to present stakeholder and entire environment's expected risk values and corresponding risk preference.

When integrating a set of risk items during collaborative negotiation, risk threshold and stakeholders' risk altitude are also important factors besides risk probability and consequence. During global collaborative negotiation, all stakeholders' evaluations and their decision altitudes should be considered simultaneously. Also even in a single stakeholder, there are still many risk items, which needs simultaneous consideration. All these simultaneous operations increase negotiation complexity and affect negotiation efficiency. Weight methods are used to aggregate multiple attributes and objectives and help decision making, and those weights are usually constant. But real world and applications are complicated, and such const weight methods are not sufficient to reflect decision makers' true preference in the presence of extreme cases [Qiu, 2008a], especially for risk decision making. A varying weights method is proposed in the following to capture the dynamics of weights. Uniform mathematical equations are presented.

Extreme cases that contain either extremely high or pretty low preference attribute(s) are investigated for multi-attribute decision making problems. Based on observation of human's actual thinking process, a three-zone pattern (averse, neutral, and prone) is presented, and efforts are made to capture this pattern mathematically. Besides traditional preference function, a threshold and coefficient for both averse and prone zones are introduced to present more comprehensive decision making patterns.

4.3.1 VARYING WEIGHTS METHOD

This adjustable method is based on existing weighted sum approach with constant weights. The process is to first transform attribute values to preference utilities, and then use existing methods to estimate their weights for neutral cases, and finally make adjustment on these weights based on all attributes' utilities and decision altitudes. Six steps are involved in the proposed varying weights method as in Figure 25. Since this method can also be applied in other generic multi-attribute decision making problems, generic mathematic form is used.

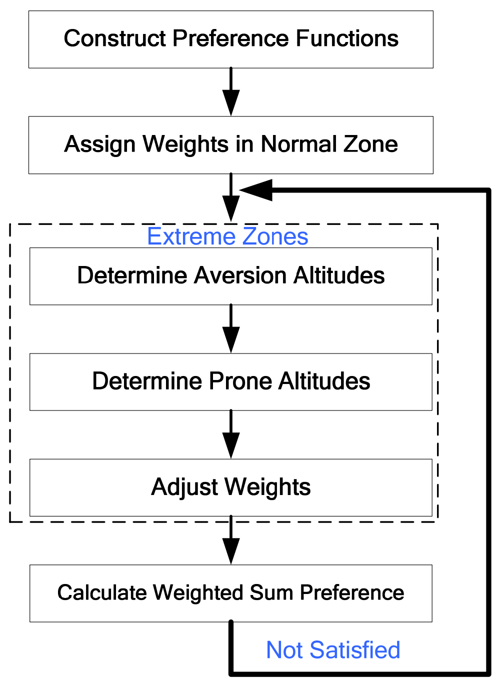


Figure 25 Varying Weights Decision Making Process

Step 1: Construct Preference Functions

This step is to determine the mapping between attribute values and a decision maker's preference. Many existing methods have been developed [Keeney, 1993], and can be directly used to construct the appropriate functions for each attribute. Suppose h decision attributes are included in the decision making. An attribute list X can be defined as:

X = [x_i, i=1... h]

where x_i represents the i^{th} decision attribute.

For each x_i, a preference function is constructed based on decision maker's intuition or experience. All those functions can be written in a list:

U = [$u_i(x_i)$, i=1... h]

where u_i represents the preference function concerning the i^{th} decision attribute x_i.

Step 2: Assign Attribute Weights

Under normal cases, A decision maker (DM) usually has stable opinions on attributes' weights. This step is to determine or assign normal attribute weight for each attribute. Existing methods can be used to help the DM [Watson, 1982; See, 2002 & 2004]. An attribute weight list can be formed as:

W = [w_i, i=1... h]

where w_i represents constant weight of the i^{th} decision attribute for normal cases.

Step 3: Determine Averse Altitudes

This step is to consider and quantify averse altitudes in the averse zone. A DM usually has a rough aversion threshold for each attribute value, and then with the obtained preference functions, the DM can determine a fuzzy averse threshold for each attribute. The threshold (illustrated as point A_i in Figure 8) is the preference number that the DM is extremely averse to. Then an averse threshold list A can be formed as:

A = [A_i, i=1... h]

where A_i represents the averse threshold for the i^{th} attribute.

A DM has nonlinear decision altitude with respect to the attribute preference in this averse zone. This altitude can be quantified by some functions such as polynomial functions. For simplicity, a polynomial function such as $z = c * u^n$ is employed in this work. "u" is the attribute preference, and then the averse altitude can be only measured by the order "n", which is called averse coefficient.

All these coefficients form an averse altitude list A:

N = [n_i, i=1... h]

where n_i represents the averse coefficient for the i^{th} attribute. n_i represents the DM's averse magnitude: a bigger value corresponds to stronger aversion. n_i is usually larger than 1.

Considering the continuity of the altitude curve (Figure 8), the altitude curve in the aversion zone always passes the point (A_i, A_i), and thus the altitude function z_i in the averse zone can be uniformly constructed as:

$$z_i = A_i * (\frac{u_i}{A_i})^{n_i} = u_i * (\frac{u_i}{A_i})^{n_i - 1} = u_i * k_{ai}$$

An averse scale, k_i, is introduced to indicate the nonlinear degree, which is defined as:

$$k_{ai} = (\frac{u_i}{A_i})^{n_i - 1} \qquad (12)$$

k_{ai} is determined by the preference u_i, aversion threshold A_i and coefficient n_i. Since u_i is always less than A_i in the averse zone, and n_i is larger than 1, then k_{ai} is always less than 1. This attribute requires more attentions and weight in the decision making. If n_i is reduced to 1, then k_{ai} is always 1, which indicates a linear normal case.

Step 4: Determine Prone Altitudes

Similarly as Step 3, this step focuses on the prone zone. The DM can assign a fuzzy prone threshold (illustrated as point P_i in Figure 8) for each decision attribute: he/she is extremely prone to the preference above this number. Then a prone threshold list P is formed:

P = [P_i, i=1... h]

where P_i represents the prone threshold for the i^{th} attribute.

The DM has non-linear altitude in this prone zone. Still suppose polynomial functions such as $z = c * u^m$ are employed to quantify this decision altitude. Then the prone altitude can be measured by the polynomial order m, which is called prone coefficient. All those coefficients form a prone altitude list M as:

M = [m_i, i=1... h]

where m_i represents the prone coefficient for the i^{th} attribute. m_i represents the DM's prone magnitude: a bigger value corresponds to better tendency. More attentions are required for this attribute during decision making. Considering the continuity of the altitude curve (Figure 8), the altitude curve in the prone zone always passes the point (P_i, P_i), and thus the altitude function z_i in the prone zone is constructed as:

$$z_i = P_i * (\frac{u_i}{P_i})^{m_i} = u_i * (\frac{u_i}{P_i})^{m_i - 1} = u_i / k_{pi}$$

The prone scale, k_{pi}, is also introduced to indicate the nonlinear degree defined as:

$$k_{pi} = (\frac{P_i}{u_i})^{m_i - 1} \qquad (13)$$

k_{pi} is determined by the preference u_i, prone threshold P_i and coefficient m_i. u_i is always greater than P_i in the prone zone, but m_i can be any positive number in real applications, and then k_i falls into the following three categories:

1. if $m_i > 1$, then $k_{pi} < 1$, which indicates that the DM is prone to this attribute preference resulting in more weight on the i^{th} attribute.
2. if $m_i = 1$, then $k_{pi} = 1$, which indicates that the DM is neutral to the attribute preference resulting in unadjusted weight on the i^{th} attribute.
3. if $m_i < 1$, then $k_{pi} > 1$, which indicates that the DM is averse to the attribute preference resulting in less weight on the i^{th} attribute.

Magnitude of k_{pi} determines more or less weight on the i^{th} attribute. Since k_{ai} is less than 1, and corresponds to more weight on the i^{th} attribute in the averse zone, then both k_{ai} and k_{pi} are consistent in the tendency of weight adjustment. A uniform preference scale k_i is defined:

$$k_i = \begin{cases} k_{ai}, & \text{the } i^{th} \text{ attribute in the averse zone} \\ k_{pi}, & \text{the } i^{th} \text{ attribute in the prone zone} \end{cases} \qquad (14)$$

Thus the scales in both averse and prone zones can be represented by a single parameter k_i, which is a good measure to represent a DM's nonlinear altitude.

Step 5: Adjust Weights

Thinking pattern suggests comprehensive consideration of all attributes' preferences when assigning attribute weight, and also the sum of all weights is always equal to 1, thus one weight change can affect all other weights. All weights adjustment is considered simultaneously in this work. The adjustment strategy depends on the following assumption:

***Assumption**:* The ratio of any two attributes' adjusted weights is equal to the ratio of their initial weights over their preference scales, i.e., the ratio of the new weights for the ith and jth attributes i:

$$w_i' : w_j' = \frac{w_i}{k_i} : \frac{w_j}{k_j}$$

Considering the sum of all weights is equal to 1, the new weight for the ith attribute is calculated as:

$$w_i' = \frac{w_i}{k_i} \Big/ \sum_{j=1}^{H} \frac{w_j}{k_j} \qquad (15)$$

Step 6: Calculate Weighted Sum Preference

Existing weighted sum approach is used to calculate the aggregation utility for multi-attribute decision, but weights are replaced with the new weights other than the initial constant weights. The aggregation preference is calculated as:

$$P = \sum_{i=1}^{H} w_i' * u_i \qquad (16)$$

With the calculated aggregation preference, the DM can rank all the alternatives, and make appropriate decisions. If the DM is not satisfied with the final aggregation results, he/she can adjust his/her extreme altitudes, and perform varying weighted calculation again. This iterative process is conducted until he/she is satisfied with the final result.

The advantages of this method include: 1) it is consistent with a decision maker's changeable altitudes over time, and can dynamically represent more decision altitudes besides attributes' preferences comparing to constant weight methods; 2) it considers fuzzy constraints, and provides equations to adjust weights automatically. This method will be directly used in the following to evaluate risk preferences of both single stakeholder and the overall collaborative environment.

4.3.2 STATIC MODEL

Risk information gathering is completed: 1) 4.2.1 uses a uniform risk structure to capture and synthesize heterogeneous risk evaluations; 2) 4.2.2 mainly deals with quantified risk consequence with risk hierarchy incorporated; 3) 4.2.3 focuses on probability aspect, and provides a consistency scheme to achieve consistent risk probability evaluations. Both risk probability and consequence have been adjusted from local stakeholder domain to global environment domain. After risk hierarchy is incorporated to quantify risk consequence, single risk item can be evaluated by a simple measure. The varying weights method provides a way to manipulate multiple properties and stakeholders' decision preferences simultaneously. Then a static model is constructed to systematically evaluate expected risk values for both individual stakeholders and their collaborative environment. Further an overall preference utility is calculated to indicate stakeholders and their environment's overall risk preferences with the help of varying weights method. This static model can be applied at two levels: individual stakeholders and their group of distributed environment. The static model in each level is separately deliberated in the following.

4.3.2.1 Individual Stakeholder

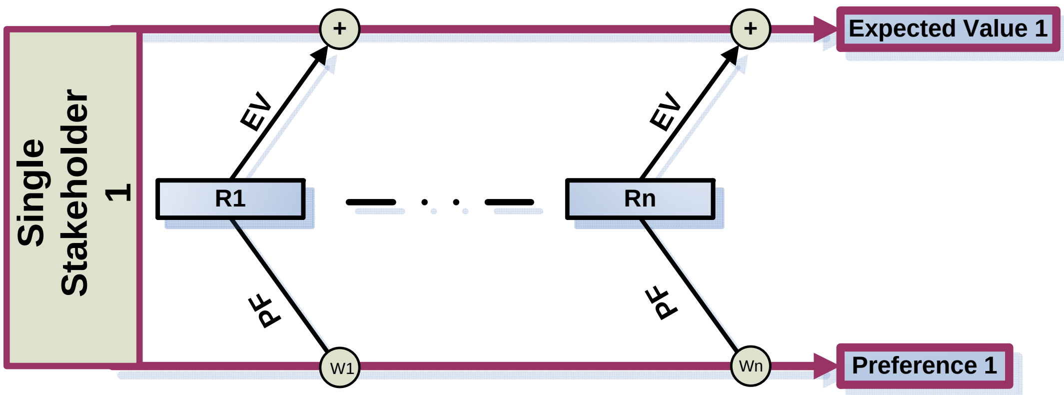


Figure 26 Single Stakeholder's Static Model

Figure 26 illustrates basic process of a static model for a single stakeholder. Every stakeholder within a distributed environment can include a set of risk items such as those from R1 to Rn. For each single risk item, two measures, expected risk value (EV) and risk preference (PF), can be calculated. All risk items are then integrated to measure risk condition of that stakeholder. EVs from all risk items are simply added together to achieve expected risk value of the stakeholder, and PFs from all risk items are aggregated via a weighted sum method to form risk preference of the stakeholder. Both expected risk value and risk preference can be calculated based on existing literatures [Bedford, 2001]. For the j^{th} risk item in the i^{th} stakeholder, its expected risk value is:

$$EV_j^{(i)} = P_j^{(i)} \times C_j^{(i)} \quad (17)$$

where $P_j^{(i)}$, $C_j^{(i)}$ is probability and consequence of $R_j^{(i)}$. All risk items within $S^{(i)}$ can be calculated, and all these risk items' expected values can be added to form the expected risk value of that stakeholder.

The other measure, risk preference, indicates a stakeholder's desire on each risk item. A preference depends on not only expected risk value of a risk item, but also its stakeholder's threshold on that risk item. For instance, the same risk of $1,000 loss means different preferences between a millionaire and a college student, because their loss threshold is quite different even though the expected risk value is the same. a tolerance list **TR** can be expressed as:

$$TR = \{TR_j^{(i)}, i = 1...n, j = 1...L^{(i)}\}$$

where $TR_j^{(i)}$ represents the i^{th} stakeholder's risk tolerance on its j^{th} risk item. In engineering applications, a stakeholder may have only tolerances for its cared risk items, but ignore tolerances on other risk items. Those unassigned risk items' tolerances can be set high enough to indicate that that stakeholder is not averse to those risk items. Risk preference of an arbitrary risk item $R_j^{(i)}$ is a function of both EV and TR. Various forms of functions can be assigned to represent a stakeholder's preference utility on its risk perception. An easy form of such preference is a linear function such as:

$$PF_j^{(i)} = f(EV_j^{(i)}, TR_j^{(i)}) = \max(1 - EV_j^{(i)} / TR_j^{(i)}, 0) \qquad (18)$$

Risk preference function indicates a relationship between expected risk value and risk threshold. When expected risk value is greater than threshold, then the preference function from (18) would yield 0, which is consistent with the fact that a stakeholder will not accept a risk item if its expected risk value is out of the stakeholder's tolerance.

After single risk item's measures are determined, a stakeholder risk measures can be calculated. For expected risk value measure, simple adding operation is utilized because of the additive property. Then the expected risk value for the i^{th} stakeholder is:

$$EV^{(i)} = \sum_{j=1}^{L^{(i)}} EV_j^{(i)} \tag{19}$$

To achieve a stakeholder's risk preference from multiple risk items' preferences, simple adding is not appropriate. If all risk items are in normal ranges [Qiu, 2008a], then constant weights can be assigned for each risk item to achieve an integrated overall risk preference. Suppose constant weights in the i^th^ stakeholder are:

$$w^{(i)} = \{w_j^{(i)},\ j = 1...L^{(i)}\}$$

Under normal cases [Qiu, 2008a], these constant weights can be directly used to calculate the i^{th} stakeholder's overall risk preference:

$$PF^{(i)} = \sum w_j^{(i)} \times PF_j^{(i)} \tag{20}$$

But extreme cases [Qiu, 2008a] occur most of time in a risk-based design, and then the constant weights need to be adjusted. A stakeholder would have additional averse or prone thresholds concerning its risk preference. Since for risk, extreme preference is always in the averse zone, it is assumed that a stakeholder has an averse threshold for its risk preference. If a risk item's preference is above this threshold, it is treated as normal case, otherwise the stakeholder is averse to this risk item, and additional concerns are needed. Varying weights method can be utilized to calculate the adjusted weights. Suppose an averse threshold list A is formed to represent all stakeholders' averse thresholds:

A = [$A^{(i)}$, i=1... n]

where $A^{(i)}$ represents the averse threshold for the i^{th} stakeholder.

Stakeholders' corresponding coefficients of averse altitudes are:

N = [$n^{(i)}$, i=1... n]

where $n^{(i)}$ represents the averse coefficient of the i^{th} stakeholder. A bigger value corresponds to stronger aversion. Varying weights are calculated as the method in 4.3.1. For the j^{th} risk item in the i^{th} stakeholder, its adjusted weight is:

$$w_j^{(i)}{}' = \frac{\dfrac{w_j^{(i)}}{k_j^{(i)}}}{\displaystyle\sum_{j=1}^{L^{(i)}} \frac{w_j^{(i)}}{k_j^{(i)}}}$$

where:

$$k_j^{(i)} = \left(\frac{PF_j^{(i)}}{A^{(i)}}\right)^{n^{(i)}-1}$$

Then the i^{th} stakeholder's overall risk preference is:

$$PF^{(i)} = \sum w_j^{(i)'} \times PF_j^{(i)} \qquad (21)$$

4.3.2.2 Distributed Environment

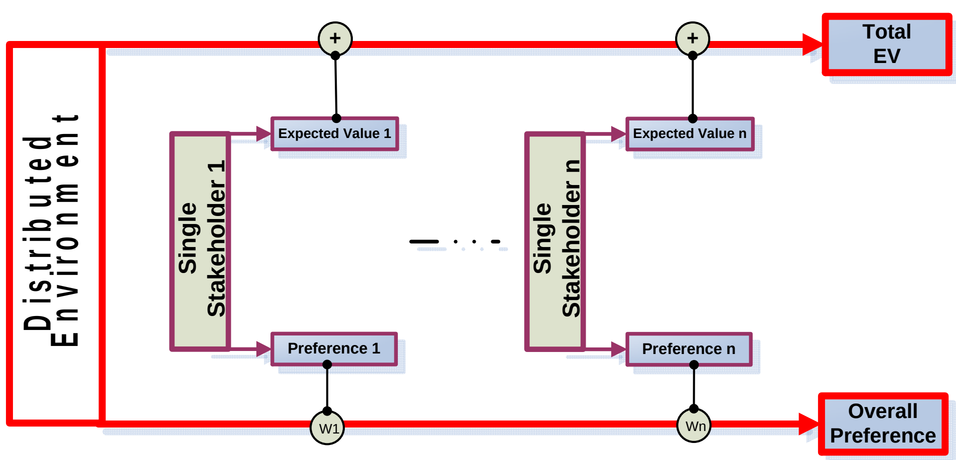


Figure 27 Distributed Environment's Static Model

After stakeholders evaluate their expected risk values and risk preferences, all the evaluations can be aggregated to form risk measures of their collaborative environment. Figure 27 shows aggregation process of both measures. All expected values are added together to achieve total expected value of the distributed environment, and all risk preferences are summed by certain weights to achieve overall risk preference.

The expected risk value of a distributed environment is sum of expected risk values from all its stakeholders, i.e.,

$$EV = \sum_{i=1}^{n} EV^{(i)} \qquad (22)$$

This total expected risk value can indicate total potential risk loss in a collaborative environment. From Eq.(22), each stakeholder can compare its expected risk value with the environment's total expected risk value, and then identify its risk contribution to the whole environment.

All stakeholders' risk preferences are integrated to achieve the environment's overall risk preference with weight method. Each stakeholder can be assigned a weight factor w, and then overall risk preference of the environment is calculated as:

$$PF = \sum_{i=1}^{n} w^{(i)} \times PF^{(i)} \qquad (23)$$

where $w^{(i)}$ is weight of the i^{th} stakeholder in its distributed environment. Varying weight methods can also be used to adjust weight factors if extreme cases occur. Usually stakeholders' power distributions in the distributed environment determine stakeholders' weights, which are relatively constant during collaborative negotiation.

This static model provides good measures of risk for a stakeholder and a distributed collaborative environment. With expected risk values, a stakeholder can estimate how much potential loss due to all its risk items, and further a collaborative environment can evaluate overall economic loss from all stakeholders. Risk preference value can directly indicate a stakeholder's risk utility and an environment's risk utility, which can be directly used to assist stakeholders' negotiation concerning risk. With this static risk information, the next step is to make decisions how to improve current risk conditions in a distributed environment. A dynamic model is developed to model dynamic and uncertain properties of risk measures.

4.3.3 DYNAMIC MODEL

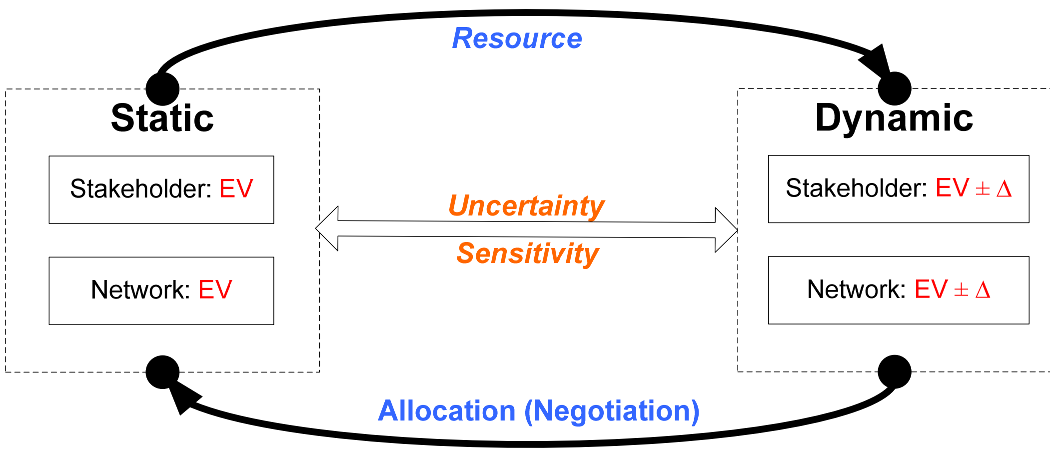


Figure 28 Static Model and Dynamic Model

Uncertainty [Thornton, 2001] always exists in the real world. A static model is based on stakeholders' or their members' subjective evaluations, which are associated with uncertainties. In engineering field, the objective of risk analysis is not only to evaluate risk conditions, but also to improve risk conditions. Static risk model is not enough. A dynamic model is built to handles uncertainty during collaborative negotiation and assist real collaborative decision makings such as resource allocation to effectively improve current risk situation. The relationship between a static model and a dynamic model is illustrated in Figure 28. A static model estimates expected values for both stakeholder and collaborative environment. When uncertainty issue involves, those expected values vary within a range instead of keeping fixed numbers. On the other hand, if certain resource is available, some improvements can be conducted to improve current environment's risk condition. Expected values of both a stakeholder and environment can be theoretically decreased. Since sensitivities of different risk items to total environment's expected risk change are different, resource allocation strategies on different risk items can have decrease different expected risk values. The objective of the proposed dynamic uncertainty model is to allocate resource effectively so that total expected values can be decreased to the maximum extent.

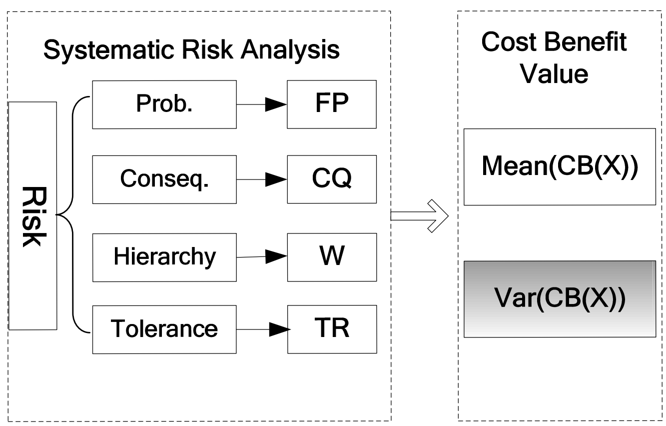


Figure 29 Cost Benefit Measure

Resource can be used to decrease expected risk value. There is a relationship between resource cost and expected risk value change. A cost benefit measure is then constructed to represent the relationship of resource cost and obtained risk benefit. Its objective is to search an optimal strategy which can maximize system risk reduction within given constraints. Then the result can assist stakeholders to collaborate effectively within acceptable system risk and affordable cost in a distributed environment. Figure 29 illustrates basic process of a cost benefit measure. First four basic risk properties are obtained from systematic risk analysis, and then these properties are used to calculate mean value and variance of cost benefit value.

When resource is allocated, it can be distributed to solid components or abstract functions of stakeholders' systems. In engineering applications, solid component is more common, and then it is assumed in this paper that resource is allocated to different components of stakeholders. There can be a large number of components in a distributed environment. Only key components associated with important risk items are considered to reduce computation complexity.

An arbitrary stakeholder, $S^{(i)}$, can identify its key local components, and a global component list can be integrated as:

$\mathbf{C} = [C_j^{(i)}, i=1...n, j = 1...M^{(i)}]$

where $C_j^{(i)}$ represents the i^{th} stakeholder's j^{th} key components, and $M^{(i)}$ is the number of the i^{th} stakeholder's key components. The total number of key components in the distributed environment is: $M=\sum_{l=1}^{n} M^{(l)}$.

A risk space is defined as a set of risk items [Qiu, 2007a]. In a distributed environment, each stakeholder can form a risk space based on its local perspective and available information, and the global risk space list **F** can be expressed as:

$\mathbf{F} = [F_j^{(i)}, i=1...n, j=1...K^{(i)}]$

where $F_j^{(i)}$ represents the i^{th} stakeholder's j^{th} risk item, and $K^{(i)}$ is the number of the i^{th} stakeholder's risk items. The total number of risk items in the distributed environment is: $K=\sum_{l=1}^{n} K^{(l)}$. Each stakeholder can determine a component-failure matrix $CF^{(i)}$ to indicate the relationship between each component and risk item using Design Repository or related methods. A global component-failure list can then be expressed as:

$$\mathbf{CF} = [CF^{(i)}, i=1...n]$$

where $CF^{(i)}$ represents the i^{th} stakeholder's component-failure matrix including $M^{(i)}$ rows and $K^{(i)}$ columns:

$$CF^{(i)} = [\, CF_{jk}^{(i)}, j = 1...M^{(i)}, k = 1...K^{(i)}]$$

where $CF_{jk}^{(i)}$ indicates the relationship between the j^{th} component and the k^{th} risk item of the i^{th} stakeholder.

$$CF_{jk}^{(i)} = \begin{cases} 1\text{: the } k^{th} \text{ risk item is from the } j^{th} \text{ component} \\ 0\text{: otherwise.} \end{cases}$$

Given the information, a resource allocation strategy can be determined to distribute certain resources to each stakeholder, and further onto specific key components. Then a resource allocation list **X** can be written as:

$$\mathbf{X} = [x_j^{(i)}, i=1...n, j = 1...M^{(i)}] \qquad (24)$$

where $x_j^{(i)}$ is the unknown resource allocated for the i^{th} stakeholder's j^{th} component. To avoid unnecessary superscript and subscript complexity, the resource strategy **X** is mapped to M variables so that for each $x_j^{(i)}$, a corresponding "z_m" (resource allocation variable for component) is constructed:

$$z_m = x_j^{(i)}, \text{ where } m = j + \sum_{l=1}^{i-1} M^{(l)}$$

The expected system risk can be reduced by allocating resources in two ways: reducing risk probability and/or risk consequence. Risk probability reduction is more common, and considered in this paper with the assumption of unchanged risk hierarchy. More resources can decrease risk probability, but the reduction rate depends on specific components and risk items. The true rate is hard or impossible to be obtained, but stakeholders can usually estimate a rough relationship between resources and risk probability reduction at a certain confidence interval. For example, a specific component in a stakeholder may have various alternative components with different cost and associated risk probabilities, and then the stakeholder can compare the difference and achieve a mean risk reduction function for each risk item. A probability reduction function list **PR** can be defined as:

$$\mathbf{PR} = [f_j^{(i)}(x),\ i=1...n,\ j=1...K^{(i)}] \quad (25)$$

where $f_j^{(i)}$ is the i^{th} stakeholder's mean risk probability reduction function for the j^{th} risk item. In real world applications, this function is usually non-decreasing: more resources can not yield less risk probability reduction. Also the independent variable of the function $f_j^{(i)}$, i.e., the resource allocated on the j^{th} risk item is $\sum_{k=1}^{M^{(i)}} (CF_{kj}^{(i)} * X_k^{(i)})$, which can be written in terms of z. Then a new set of function g including independent variable z is constructed for superscript and subscript simplicity:

$$g_m(z) = f_j^{(i)}(z), \text{ where } m = j + \sum_{l=1}^{i-1} K^{(l)} \quad (26)$$

g_m is non-decreasing, and represents a stakeholder' mean risk reduction function. Usually a stakeholder may have a range of evaluations, which can be denoted by an upper bond g_m^+ and lower bound g_m^- as illustrated in Figure 30. The lower bound corresponds to the worst case scenario. The real probability reduction function lies between the upper and lower bound statistically, and has a certain distribution. The source of stakeholders' evaluations usually comes from previous historical data, experience, manufacturer's specifications and etc. Existing literature shows that a triangular distribution is a good model in the absence of other information [Taylor, 1994]. A triangular distribution is assumed and corresponding standard uncertainty function is [Taylor, 1994]:

$$u_m(z) = (g_m(z)^+ - g_m(z)^-) / (2\sqrt{6})$$

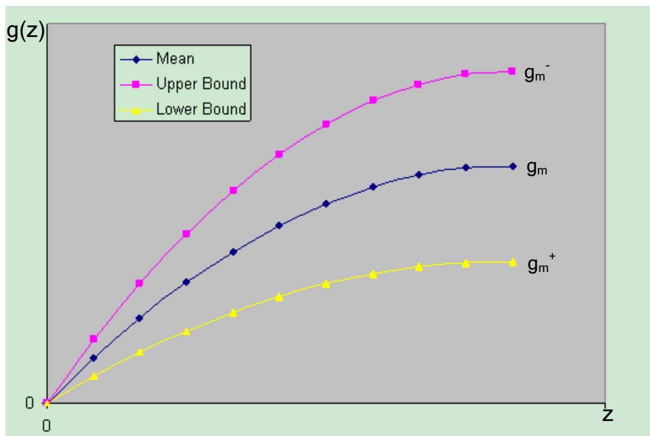


Figure 30 Probability Reduction Function and Its Uncertainty

Each stakeholder can use existing probabilistic risk analysis methods to construct its local risk space **F**, and estimate initial risk probabilities. All stakeholders' probability estimations form a global initial probability list **IFP.** For the overlapped risk items, inconsistency may exist across participating stakeholders. To resolve the inconsistence issue of risk probabilities, a global coordination scheme has been developed in the author's previous work [Qiu, 2007a & 2007b]. Globally consistent evaluations among various stakeholders promote mutual understanding, consensus building, and thus lead to better decision making. Suppose a consistent risk probability list **FP** is reached via 4.2.3:

$$\mathbf{FP} = [FP_j^{(i)}, i=1...n; j = 1...K^{(i)}]$$

where $FP_j^{(i)}$ is the i^{th} stakeholder's probability evaluation on the j^{th} risk item, i.e. the probability of $F_j^{(i)}$.

A cost benefit measure of risk is defined as the product of effective global probability reduction and its risk consequence in monetary unit [Qiu, 2008b]. In Figure 29, risk is considered in four aspects to achieve this measure: risk probability, consequence, hierarchy and tolerance.

Probability reduction function list **PR** and an initial consistent risk probability list **FP** are obtained, and then an updated risk probability list **FP'** can then be expressed in terms of risk reduction function:

FP' = $[FP'^{(i)}_j, i=1...n; j = 1...K^{(i)}]$

where, $FP_j'^{(i)}(g_m) = FP_j^{(i)} - PR_j^{(i)} = FP_j^{(i)} - g_m$

As discussed before, consequences of all fault trees of stakeholders in the distributed environment can be quantified, and the quantified consequence set **CQ** is:

CQ = $[\$C_j^{(i)}, i=1...n, j=1... MM^{(i)}]$

where $\$C_j^{(i)}$ is the i^{th} stakeholder's consequence estimation on the top event of its j^{th} fault tree.

For the i^{th} stakeholder, the probability of the top event of its j^{th} fault tree can be denoted as a risk probability function $w_j^{(i)}$:

$w_j^{(i)}(FP) = Probability(FT_j^{(i)})$

Risk tolerance (TR) refers to a threshold for the system risk reduction, then any further reduction would lead to no additional benefit (i.e., unnecessary reduction). Each stakeholder can set tolerances for its fault trees. Then an overall tolerance list **TR** is expressed as:

TR = $[TR_j^{(i)}, i=1...n, j=1...MM^{(i)}]$

where $TR_j^{(i)}$ represents the i^{th} stakeholder's risk tolerance on its j^{th} fault tree. Effective global probability reduction is associated with risk tolerance since addition reduction beyond tolerance is unnecessary. However, risk tolerance imposes many difficulties in calculating the cost benefit, especially for uncertainty calculation. The author first introduces a basic definition, and later considers tolerance with a revised form.

1) A Basic Definition without Tolerance Consideration

An effective probability reduction for the i^{th} stakeholder is:

$h_j^{(i)}(g) = w_j^{(i)}(FP) - w_j^{(i)}(FP')$

The initial risk probabilities FP are constant, and FP' are functions in terms of g, thus the function $h_j^{(i)'}(g)$ is also a function concerning g. Then the i^{th} stakeholder's mean cost benefit is defined as:

$$\mathrm{CB}^{(i)}(g) = \sum_{j=1}^{\mathrm{MM}^{(i)}} \mathrm{CQ}_j^{(i)} \times h_j^{(i)}(g) \qquad (27)$$

The summation of all stakeholders' mean cost benefit yields the total mean cost benefit for the distributed environment:

$$F(g) = \sum_{i=1}^{n} \mathrm{CB}^{(i)}(g) \qquad (28)$$

With the existence of a range of estimations for functions g (see Figure 30), the uncertainty associated with cost benefit is also an important decision factor. Mehr [2006] chose variance to model uncertainty, and used correlation matrix to calculate the variance. However, the matrix and necessary expert knowledge may not be available in many distributed environment applications for using this model. In the author's work, the resource allocation variable z is determined with theoretical zero uncertainty, and g(z) is associated with uncertainty (Eq.(26)); this has rendered the total cost benefit function

F(g) with uncertainty consideration. A “Root-Sum-of-Squares” (RSS) method [Taylor, 1994] can be utilized to yield the uncertainty associated with the overall cost benefit F(g), and its combined standard uncertainty $u_c(F)$ is then expressed as:

$$u_c^{\,2}(F) = \sum_{i=1}^{N}\left(\frac{\partial F}{\partial g_i}\right)^2 u^2(g_i) + 2\sum_{i=1}^{N}\sum_{j=i+1}^{N}\left(\frac{\partial F}{\partial g_i}\right)\left(\frac{\partial F}{\partial g_j}\right)u(g_i, g_j) \qquad (29)$$

where $u(g_i)$ is the standard uncertainty associated with the probability reduction function g_i, which is estimated by Eq.(26); $u(g_i, g_j)$ is the covariance associated with g_i and g_j. Since one resource item z_m may affect several risk items simultaneously, thus g_i and g_j can be correlated. Considering the mathematical probability reduction function, the correlation factor between any two g_i and g_j is either 1 or 0: for each stakeholder, if two risk items are from the same component, then their probability reduction functions contain the same resource variable resulting in a correlation factor of 1, otherwise the correlation factor is 0. In this way, correlation factor ρ_{ij} between g_i and g_j can be determined, and the covariance associated with g_i and g_j can be calculated as:

$$u(g_i, g_j) = \rho_{ij} * u(g_i) * u(g_j)$$

2) A Revised Definition with Tolerance Consideration

The effective probability reduction may not be always the same as Eq.(25). If the overall probability is decreased below the set tolerance, then extra probability reduction is unnecessary. It is assumed that the initial $w_j^{(i)}$ (FP) is always greater than $TR_j^{(i)}$, otherwise the ith stakeholder’s initial risk probability is already below the tolerance, and there is no need for further reduction. Then this fault tree can be ignored during resource allocation. With the tolerance consideration, the new effective probability reduction is:

$h_j^{(i)}(g)' = \min(w_j^{(i)}(FP) - w_j^{(i)}(FP'), w_j^{(i)}(FP) - TR_j^{(i)}) = \min(h^{(i)}(g), const))$

And then the total mean cost benefit for the distributed environment can be calculated as:

$$F(g)' = \sum_{i=1}^{n} \sum_{j=1}^{MM^{(i)}} CQ_j^{(i)} \times h_j^{(i)}(g)' \qquad (30)$$

The associated uncertainty is hard to calculate because of the existence of "minimum" function. Since only the optimum solutions are of interest and the resource allocation primary objective is to achieve the maximum mean cost benefit, an important conclusion is inferred: given limited resources (total available resource is less than what is needed), no stakeholders' risk can be decreased below the tolerance in the Pareto frontier of the solution domain, i.e., no one can reach its risk tolerance if the strategy is optimum. Because if one stakeholder A or more reaches its tolerance, then the additional resource beyond its tolerance can be taken away and redistributed to other stakeholder B who has not reached its tolerance, and this will lead to the increase of total cost benefit. Thus the original resource allocation strategy is not optimum. So in the Pareto frontier, the mean cost benefit and its uncertainty are the same as Eqs.(28) and (29) because no one reaches its tolerance. For non-optimum solutions, the mean cost benefit is calculated by Eq.(30). Considering the less importance of non-optimum solutions, the induction process for calculating their standard uncertainties is not presented here. The standard uncertainty is estimated by:

$$u_c(F)' = \max\left(u_c(F) + \frac{F(g)' - F(g)}{k}, 0\right) \qquad (31)$$

where "k" is the coverage factor chosen on the basis of desired level of confidence [Taylor, 1994]. There is certain distribution associated with the calculated cost benefit, and the worst scenario attracts much attention, and is also an important decision factor. A 5^{th}-percentile cost benefit is chosen to measure the worst scenario, denoted by lower benefit L(g), i.e., the cumulative probability of cost benefit less than L(g) is 5%. L(g) is estimated by:

$$L(g) = F(g)' - k^* \, u_c(F)'$$

Typically k is in the range of 2 to 3. Considering the triangular distribution of all functions g, k is recommended as 2 in this paper.

Based on the mean cost benefit and its lower benefit, a resource allocation can be carried out using multi-objective optimization techniques. The objectives are to obtain the maximum mean cost benefit with maximum lower benefit given limited resource $T. Based on the definition and formulas, the risk-based resource allocation problem is formulated as:

$$\begin{cases} \text{Maximize:} \quad F(g)' \\ \text{Maximize:} \quad L(g) \\ \text{s.t.} \\ \sum_{i=1}^{n} \sum_{j=1}^{m^i} x_j^{(i)} = \$T \end{cases} \qquad (32)$$

The mathematic problem of the model is a risk-efficient resource allocation problem. The involved functions can be highly complicated, and currently numerical methods are used to achieve optimal solutions. The dynamic model can be represented in Eq. (32). The other way to present this dynamic model is to use Monte-Carlo simulation process, which can simulate uncertainty risk probability distribution and then estimate mean and variance of cost benefits. Due to time and paper length constraints, it is not covered in details in this paper. The following case study will provide an example of a Monte-Carlo simulation, and then compare its result with the calculated results from Eq.(32). Both results agree.

Time issue is another important factor in risk-based design and negotiation. It is assumed that in the model (32), when resource is applied to certain components, their risk probabilities can be reduced quickly, and then there is no need to consider monetary benefit values change concerning time. If this assumption is invalid, suppose a stakeholder's resource implementation needs long time to decrease risk probabilities of its fault/event trees, then present worth analysis needs to be employed to consider the time issue. Theoretically all other steps are the same as the above except that present worth analysis is applied to final cost benefit value in Eq. (28) and (30). More efforts are needed to present this dynamic uncertainty model in a uniform mathematical way, which is one area of the future work.

4.3.4 COLLABORATIVE NEGOTIATION

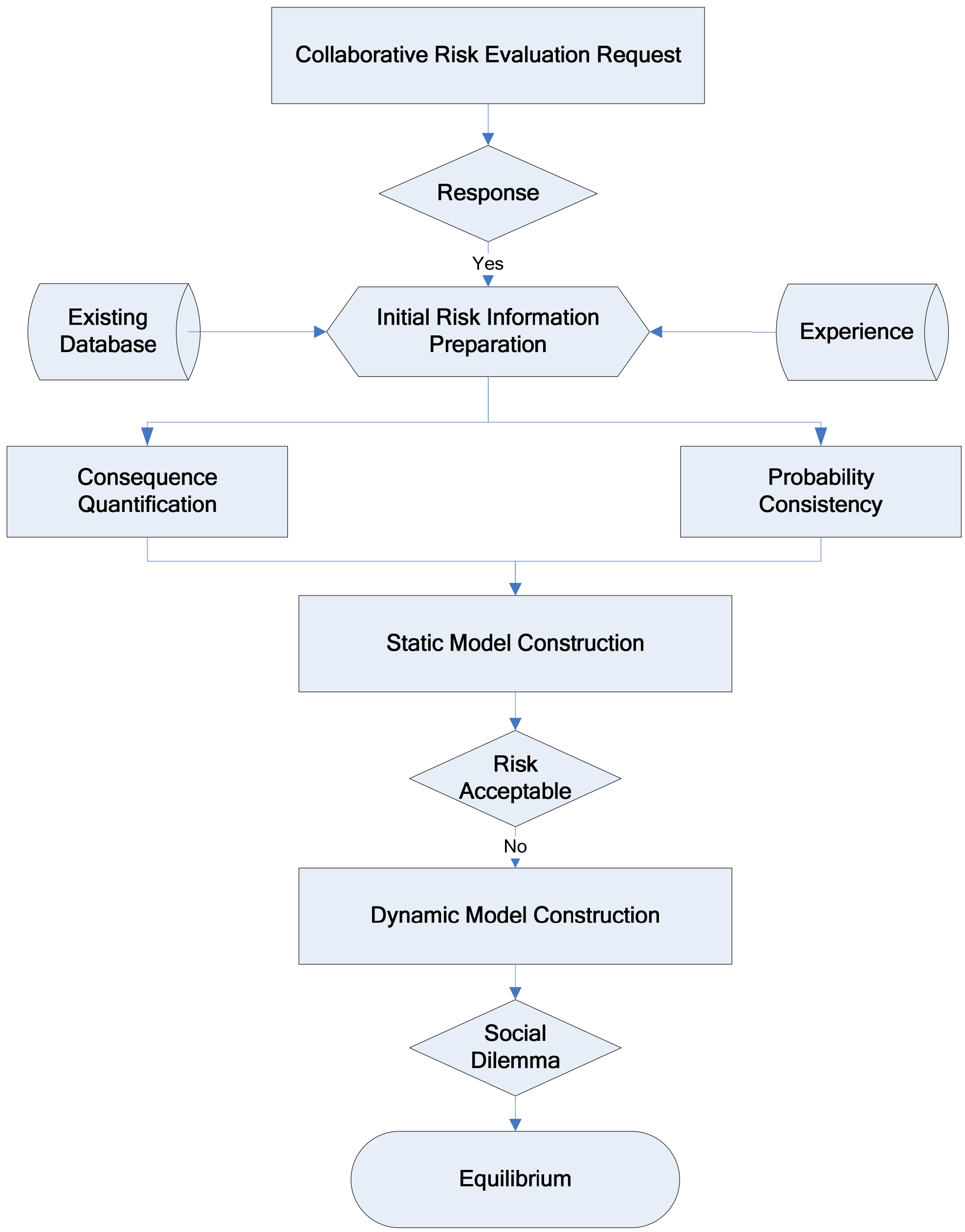


Figure 31 Collaborative Negotiation Process

Static and dynamic uncertainty models can calculate risk measures to help stakeholders or environment evaluate their risk conditions. The generic collaborative negotiation process from information preparation to final negotiation is illustrated in Figure 31. First certain stakeholders in a distributed environment have concerns about potential risk in their collaboration, then they request collaborative risk evaluations. Second the request is reviewed by other stakeholders. If most stakeholders have the same desire on overall risk evaluation, the collaborative evaluation and negotiation process begins. All stakeholders then start preparing their initial risk information. Existing risk database can be used to collect such risk information, or members' experiences are used to evaluate initial risk information. Third with obtained initial risk information, risk consequence quantification is completed to quantify risk items in monetary unit, and risk probability consistency is achieved for better risk understanding. Forth, a static model is constructed to evaluate total expected risk values and risk preferences for both stakeholders and the environment. If total expected values are acceptable for all, then risk based negotiation is completed, and stakeholders achieve better understanding on risk conditions of their collaborative environment. Otherwise certain operations such as resource allocation are necessary to improve current risk conditions. Then fifth a dynamic uncertainty model is constructed to evaluate uncertainty and sensitivity of risk items, and then calculate a cost benefit measure to assist collaborative decision making of resource allocation. A set of optimum strategies can be calculated from the dynamic model theoretically, and then stakeholders can negotiate and choose the best one from the set. Human social dynamics factors from stakeholders will affect stakeholder's selection. The optimum set result can help stakeholders negotiate effectively instead of negotiating all possible strategies aimlessly. Also the proposed models separate objective risk information and stakeholders' social dynamics to the maximum extent, so that this risk-based research can depend less on human social factors from social science, which is not the author' expertise.

5. CASE STUDY

The proposed risk-based negotiation methodology or its parts can be applied in various application scenarios such as better understanding of risk conditions or allocating resource to improve risk situations in collaboration environments. Several projects have been conducted to validate the proposed methodology. In the following, the first example is hypothetical focusing on static and dynamic models, and the second project is illustrating local risk analysis and risk probability consistency.

5.1 HYDROPOWER COLLABORATIVE ENVIRONMENT

Suppose a water company dumps a large amount of water into a river nearby every day. Much energy can be recovered from the dumped water, and thus a 50 kW hydropower generator is suggested to recover the waste power and generate electricity. Considering various generators' prices on the market, the water company chooses a Chinese machinery plant, which can design, manufacture and ship a desired generator at competitive price. Generation installation is complicated, and then another group, a US engineering contractor, is involved. These three stakeholders collaborate and form a distributed collaborative environment. Denote:

A: Chinese Machinery Plant

B: US Water Company

C: US Engineer Contractor

These three stakeholders form a stakeholders' set:

$S = \{ S^{(1)}, S^{(2)}, S^{(3)}\} = \{A, B, C\}$

Their rough interaction flows are: B requests a hydropower generator for A, and then A designs a specific generator based on B's requirements, manufactures it, and ships it to A. After that, C will discuss with B about requirements and contact A concerning generator's specification during installation. After carefully reviewing internal and interaction flows, each stakeholder conducts an initial risk analysis based on its experiences. It is assumed that initial risk information is obtained. The following demonstration will focus on collaborative negotiation models in 4.3 with a simplified scenario.

A rotor is the most important part of a hydropower generator, and all stakeholders are concerned with it. Several basic risk items can lead to failure of the rotor. Stakeholders chose risk items, considered their risk hierarchy, and constructed fault trees. Suppose each stakeholder has a fault tree concerning this rotor failure, and top event of the fault tree is:

$FT^{(1)}$: Rotor can not work

$FT^{(2)}$: Rotor does not function well during operation

$FT^{(3)}$: Rotor can not be installed on time

Relevant basic risk items concerning these top events are:

$F = \{F^{(1)}, F^{(2)}, F^{(3)}\}$

where,

$F^{(1)} = [F_1^{(1)}, F_2^{(1)}, F_3^{(1)}]$

= [Design error, Manufacture error, Shipment error]

$F^{(2)} = [F_1^{(2)}, F_2^{(2)}]$

= [Design Requirement error, Design Review error]

$F^{(3)} = [F_1^{(3)}, F_2^{(3)}, F_3^{(3)}]$

= [Key Electrician unavailable, Electrical installation error, Mechanical installation error]

Boolean expressions of the fault trees are:

$$\begin{cases} T^{(1)} = F_1^{(1)} + F_2^{(1)} \bullet F_3^{(3)} + F_3^{(1)} \bullet F_3^{(3)} \\ T^{(2)} = F_1^{(2)} + F_2^{(2)} \bullet F_1^{(1)} \\ T^{(3)} = F_1^{(3)} + F_2^{(3)} \bullet F_3^{(3)} \end{cases}$$

Consequences of top events are estimated as:

$$CQ = \{CQ^{(1)}, CQ^{(2)}, CQ^{(3)}\}$$

$$= \{\$1M, \$2M, \$4M\}$$

Initial risk probability evaluations are estimated as:

$$\mathbf{FP} = \{[FP_1^{(1)}, FP_2^{(1)}, FP_3^{(1)}], [FP_1^{(2)}, FP_2^{(2)}], [FP_1^{(3)}, FP_2^{(3)}, FP_3^{(3)}]\}$$

$$= \{[5\%, 4\%, 3\%], [6\%, 6\%], [5\%, 6\%, 7\%]\}$$

Risk item’s consequence is quantified with the steps in 4.2.2.1.

Risk items in Stakeholder A:

$$C_1^{(1)a} = \$1M$$

$$C_2^{(1)a} = \$1M \times FP_3^{(3)} / 2 = \$1M \times 7\% / 2 = \$.035M$$

$$C_3^{(1)a} = \$1M \times FP_3^{(3)} / 2 = \$1M \times 7\% / 2 = \$.035M$$

$$C_3^{(3)a} = \$1M \times FP_2^{(1)}/2 + \$1M \times FP_3^{(1)} / 2$$

$$= \$1M \times (4\% / 2 + 3\% / 2) = \$.035M$$

Risk items in Stakeholder B:

$$C_1^{(2)b} = \$2M$$

$$C_2^{(2)b} = \$2M \times FP_1^{(1)} / 2 = \$2M \times 5\% / 2 = \$.05M$$

$$C_1^{(1)b} = \$2M \times FP_2^{(2)} / 2 = \$2M \times 6\% / 2 = \$.06M$$

Risk items in Stakeholder C:

$$C_1^{(3)c} = \$4M$$

$C_2^{(3)c}$ = $4M x $FP_3^{(3)}$ /2 = $4M x 7% / 2 = $.14M

$C_3^{(3)c}$ = $4M x $FP_2^{(3)}$ /2 = $4M x 6% / 2 = $.12M

Thus each risk item's consequence can be calculated as:

$C_1^{(1)}$ = $C_1^{(1)a} + C_1^{(1)b}$ = $1M + $.06M = $1.06M

$C_2^{(1)}$ = $C_2^{(1)a}$ = $.035M

$C_3^{(1)}$ = $C_3^{(1)a}$ = $.035M

$C_1^{(2)}$ = $C_1^{(2)b}$ = $2M

$C_2^{(2)}$ = $C_2^{(2)b}$ = $.05M

$C_1^{(3)}$ = $C_1^{(3)c}$ = $4M

$C_2^{(3)}$ = $C_2^{(3)c}$ = $.14M

$C_3^{(3)}$ = $C_3^{(3)c} + C_3^{(3)a}$ = $.12M + $.035M = $.155M

Then each risk item's consequence can be quantified separately.

Static Model:

Expected Risk Value for Stakeholder A:

$EV^{(1)}$ = $FP_1^{(1)} \times C_1^{(1)} + FP_2^{(1)} \times C_2^{(1)} + FP_3^{(1)} \times C_3^{(1)}$

= 5% x $1.06M + 4% x $.035M + 3% x $.035M

= $.05545M

Expected Risk Value for Stakeholder B:

$EV^{(2)}$ = $FP_1^{(2)} \times C_1^{(2)} + FP_2^{(2)} \times C_2^{(2)}$

= 6% x $2M + 6% x $.05M

= $.123M

Expected Risk Value for Stakeholder C:

$EV^{(3)}$ = $FP_1^{(3)} \times C_1^{(3)} + FP_2^{(3)} \times C_2^{(3)} + FP_3^{(3)} \times C_3^{(3)}$

= 5% x $4M + 6% x $.14M + 7% x $.155M

= $.21925M

Expected Risk Value for the distributed environment:

$$EV = EV^{(1)} + EV^{(2)} + EV^{(3)}$$

$$= \$.05545M + \$.123M + \$.21925$$

$$= \$.3977M$$

Dynamic Model:

Suppose stakeholders are not satisfied with current expected system risk, and a certain amount of resource is available for mitigating the risk. The resource is not sufficient to decrease all risk items, and then a good strategy is needed to utilize the limited resource. Suppose ten-unit resource is available for allocation among A, B, and C. The resource allocation strategy list can be expressed as:

$$\mathbf{X} = [[x_1^{(1)}, x_2^{(1)}], [x_1^{(2)}, x_2^{(2)}], [x_1^{(3)}, x_2^{(3)}]]$$

A resource allocation variable for component z is defined so that:

$z_1 = x_1^{(1)}$, $z_2 = x_2^{(1)}$, $z_3 = x_1^{(2)}$, $z_4 = x_2^{(2)}$, $z_5 = x_1^{(3)}$, $z_6 = x_2^{(3)}$

Several members exist in each stakeholder. If each member is treated as a component of a stakeholder, then a component list is formed:

$$C = [C^{(1)}, C^{(2)}, C^{(3)}]$$

where,

$C^{(1)} = [C_1^{(1)}, C_2^{(1)}]$ = [Designer, Manufacturer]

$C^{(2)} = [C_1^{(2)}, C_2^{(2)}]$ = [Designer, Reviewer]

$C^{(3)} = [C_1^{(3)}, C_2^{(3)}]$ = [Electrician, Mechanician]

Component-failure matrices are determined:

$$\mathbf{CF} = [CF^{(1)}, CF^{(2)}, CF^{(3)}]$$

where,

$CF^{(1)}$ = [[1,0,1],[0,1,0]]

$CF^{(2)}$ = [[1,0],[0,1]]

$CF^{(3)}$ = [[1,1,0],[0,0,1]]

Three types of risk altitudes are used to simulate stakeholders' evaluations on risk probability reduction: risk prone, risk neutral and risk aversion. Correspondingly their risk reduction functions with boundaries are summarized in Table 6. Suppose all the functions are in the same form: $a*z^2+b*z$.

Table 6 Risk Reduction Functions

	[$g_1(z_1)$]	**[$g_2(z_2)$]**	**[$g_3(z_1)$]**	**[$g_4(z_3)$]**	**[$g_5(z_4)$]**	**[$g_6(z_5)$]**	**[$g_7(z_5)$]**	**[$g_8(z_6)$]**
Altitude	Prone	Neutral	Aversion	Prone	Neutral	Aversion	Prone	Neutral
A	-0.00036	0	0.00016	-0.00048	0	0.00016	-0.00024	0
B	0.0072	0.002	0	0.0096	0.003	0	0.0048	0.002
g^+	1.3 g_1	1.2 g_2	1.1 g_3	1.3 g_4	1.2 g_5	1.1 g_6	1.3 g_7	1.2 g_8
g^-	0.7 g_1	0.8 g_2	0.9 g_3	0.7 g_4	0.8 g_5	0.9 g_6	0.7 g_7	0.8 g_8
u_m	0.1225 g_1	0.0815 g_2	0.041 g_3	0.1225 g_4	0.0815 g_5	0.041 g_6	0.1225 g_7	0.0815 g_8

Thus new failure probability list is:

FP' = {[5%- g_1, 4%- g_2, 3%- g_3], [6%- g_4, 6%- g_5], [5%- g_6, 6%- g_7, 7%- g_8]}

The failure probability function of fault tree for each stakeholder can be obtained:

$w^{(1)}(FP) = Pr(T^{(1)})$

$w^{(2)}(FP) = Pr(T^{(2)})$

$w^{(3)}(FP) = \quad Pr(T^{(3)})$

Suppose all three stakeholders have the same risk tolerance of 3% concerning risk probability, i.e.

TR = [3%, 3%, 3%]

The initial overall probability can be calculated as:

$$\begin{cases} w^{(1)}(FP) = 1-(1-FP_1^{(1)})(1-FP_2^{(1)} \times FP_3^{(3)})(1-FP_3^{(1)} \times FP_3^{(3)}) = 5.46\% \\ w^{(2)}(FP) = 1-(1-FP_1^{(2)})(1-FP_2^{(2)} \times FP_1^{(1)}) = 6.28\% \\ w^{(3)}(FP) = 1-(1-FP_1^{(3)})(1-FP_2^{(3)} \times FP_3^{(3)}) = 5.40\% \end{cases}$$

Given the resource vector, the final overall probability is:

$$\begin{cases} w^{(1)}(FP') = 1-(0.95+ g_1)(1-(0.04- g_2)(0.07- g_8))(1-(0.03- g_3)(0.07- g_8)) \\ w^{(2)}(FP') = 1-(0.94+ g_4)(1-(0.06- g_5)(0.05- g_1)) \\ w^{(3)}(FP') = 1-(0.95+ g_6)(1-(0.06- g_7)(0.07- g_8)) \end{cases}$$

Without tolerance consideration, effective probability reduction is:

$$\begin{cases} h^{(1)}(g) = w^{(1)}(FP) - w^{(1)}(FP') \\ \quad = -0.9454+ \\ \quad (0.95+g_1)(1-(0.04-g_2)(0.07-g_8))(1-(0.03- g_3)(0.07- g_8)) \\ h^{(2)}(g) = w^{(2)}(FP) - w^{(2)}(FP') \\ \quad = -0.9372+(0.94+ g_4)(1-(0.06- g_5)(0.05- g_1)) \\ h^{(3)}(g) = w^{(3)}(FP) - w^{(3)}(FP') \\ \quad = -0.9460+(0.95+ g_6)(1-(0.06- g_7)(0.07- g_8)) \end{cases}$$

So the mean of the total cost benefit is calculated as:

$$F(g) = CB(g)$$

$$= \$1M \times h^{(1)}(g) + \$2M \times h^{(2)}(g) + \$4M \times h^{(3)}(g)$$

The standard uncertainty is calculated as:

$$u_c(F) = \sqrt{\sum_{i=1}^{8}\left(\frac{\partial F}{\partial g_i}\right)^2 u^2(g_i) + 2\sum_{i=1}^{8}\sum_{j=i+1}^{8}\left(\frac{\partial F}{\partial g_i}\right)\left(\frac{\partial F}{\partial g_j}\right)\rho_{ij} u(g_i) u(g_j)}$$

From the component-failure matrices, for stakeholder A, $F_1^{(1)}$ and $F_3^{(1)}$ are correlated; for stakeholder C, $F_1^{(3)}$ and $F_2^{(3)}$ are correlated. Thus only two corresponding correlation factors are 1 ($\rho_{13} = \rho_{67} = 1$), and all the other factors are 0. With the standard uncertainty of each g_i given in Table 6, the cost benefit and its uncertainty can be.

With tolerance consideration, the effective probability reduction is:

$$\begin{cases} h^{(1)}(g)' = \min(h^{(1)}(g), 5.46\% - 3\%) \\ h^{(2)}(g)' = \min(h^{(2)}(g), 6.28\% - 3\%) \\ h^{(3)}(g)' = \min(h^{(3)}(g), 5.40\% - 3\%) \end{cases}$$

So the mean of the total cost benefit is calculated as:

$F'(g) = \$1M * h^{(1)'}(g) + \$2M * h^{(2)'}(g) + \$4M * h^{(3)'}(g)$

The standard uncertainty is calculated as:

$$u_c(F)' = \max(u_c(F) + \frac{F(g)' - F(g)}{k}, 0)$$

The lower benefit can be calculated as:

$L(g) = F(g)' - 2 * u_c(F)'$

Finally, a multi-objective optimization design model can be constructed as the following:

$$\begin{cases} \text{Maximize:} \quad F(g)' \\ \text{Maximize:} \quad L(g) \\ \text{s.t.} \\ \sum_{i=1}^{3}\sum_{j=1}^{2} X_j^i = 10 \end{cases}$$

Both F(g)’ and L(g) are complicated functions in terms of g, and numerical methods are used to solve this multi-objective model. An enumeration of all strategies X is possible with the assumption of integer $X_j^{(i)}$. The solution process is implemented in Excel. Each strategy corresponds to a specific mean, lower benefit and associated uncertainty of cost benefit measure. Figure 32 shows the trade-off between mean and standard uncertainty, also a Pareto frontier is determined. Based on the frontier, the lower benefit is calculated and drawn in Figure 32. For this simple case, the point marked in the circle represents the maximum mean with biggest lower benefit value, i.e. the most optimum strategy with the mean and lower benefit of \$91,900 and \$75,600 respectively. The resource allocation list X is:

$$x^{(1)} = [\ 4\ ,\ 0\ ];\ x^{(2)} = [\ 4\ ,\ 0\ ];\ x^{(3)} = [\ 2\ ,\ 0\ ].$$

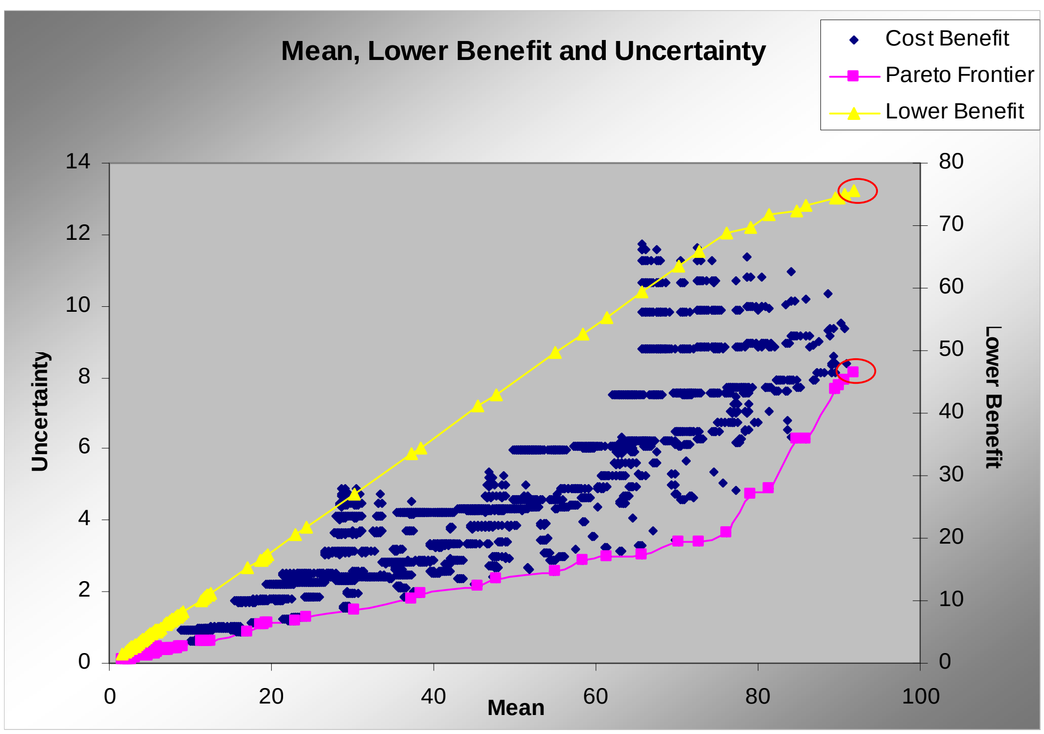


Figure 32 Mean Cost Benefit and Its Uncertainty

The maximum mean cost benefit does not always accompany with the biggest lower benefit. For different cases, there may be trade-off between mean and lower benefit of the cost benefit. Stakeholders may need to choose the appropriate point in the Pareto frontier.

To verify the standard uncertainty and lower benefit calculation, a Monte-Carlo simulation is used, and both results agree well. For example, for the optimum strategy chosen above, 1,000 simulations are used to simulate the triangular distribution of each probability reduction function g_i, and then for each simulation, the corresponding cost benefit is calculated based on Eq.(28) without tolerance consideration and Eq.(30) with tolerance consideration. Thus the mean cost benefit for both scenarios can be calculated, and a distribution for the cost benefit measure can be obtained as shown in Figure 33. Note that, "PDF" represents probability density function.

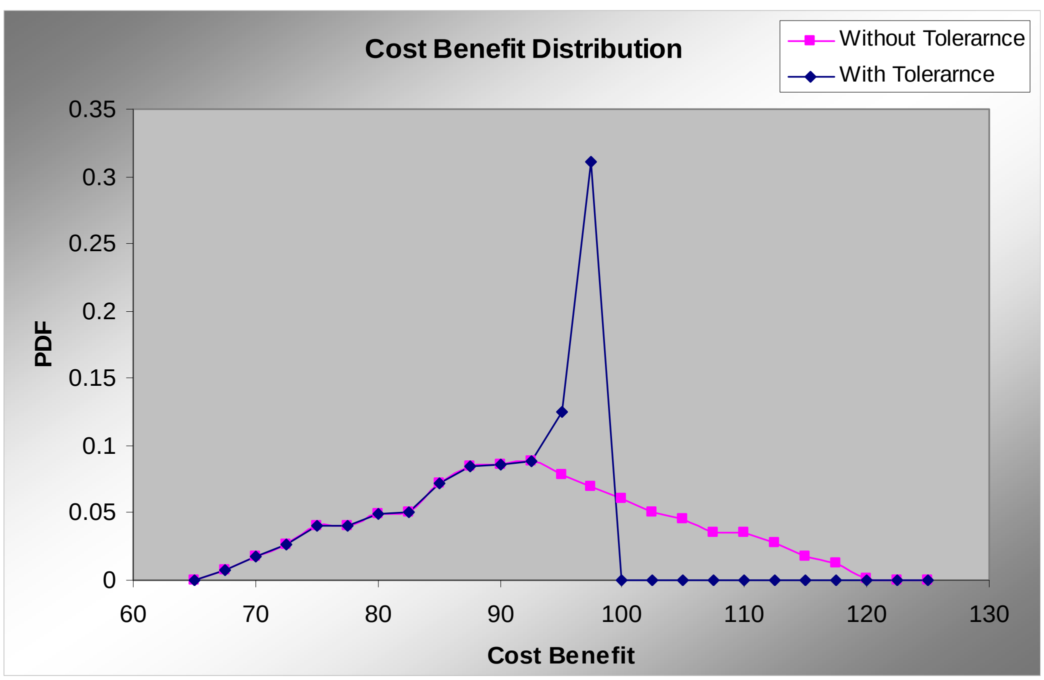


Figure 33 Distribution Sample of Cost Benefit (1,000 Monte-Carlo Simulations)

As shown in Figure 33, without tolerance consideration, the cost benefit applies to a rough triangular distribution. The mean, lower and upper bound are approximately $92,000, $66,000 and $118,000 respectively, also the 5^{th}-percentile lower benefit is $75,000. When considering tolerance, the minimum function in Eq.(30) leads to a maximum mean value, and thus the probability density over this value is zero. Its mean, lower and upper bound are approximately $89,000, $66,000 and $96,000 respectively, also the 5^{th}-percentile lower benefit is $75,000. The important finding is that in the lower range of cost benefit, the probability densities for both cases are the same, and their lower benefits are also the same, which leads to the formation of Eq.(31). It can be verified that the calculated mean cost benefit and its lower benefit from these Equations are within 5% variation of those from Monte-Carlo simulation. The small variation of mean cost benefit between equation calculation and Monte-Carlo simulation comes from some correlation between functions g, and a more complicated and accurate method may be needed to calculate the expected value of Eq.(30). Considering the calculation complexity and the small variation, no correlation factors are considered when calculating mean value in this example. It is noted that the cost benefit above is only notional, which can represent a benefit measure in a relative scale instead of an absolute scale. Different cost benefits calculated can be compared directly, but they may not reflect true meanings in absolute monetary unit.

5.2 NEES Collaborative Environment

Earthquake Engineering Simulation (NEES) is a network of 15 large-scale experimental sites distributed at universities across US, featuring advanced tools including permanent and mobile shake tables, centrifuges that simulate earthquake effects, and a tsunami research facility [NEES, 2008]. NEES Consortium, Inc. (NEESinc), together with its board of directors, governs the entire NEES site operations. The National Science Foundation (NSF) is usually the sponsor of NEES. Clients request and conduct experiments in NEES equipment sites, and all these stakeholders form a distributed environment. Figure 34 shows a 3-dimensional representation of the relationships and interaction flow in the distributed environment. The X axis represents intra-relationships among groups (elliptical areas) within similar categories (square areas). The Y axis describes the organizational hierarchy of a stakeholder; the Z axis shows inter-relationships among stakeholders within different categories. The XY plane shows members' intra- interactions within a stakeholder (intra-stakeholder), and the Z direction represents inter- interaction among multiple stakeholders (inter-stakeholder).

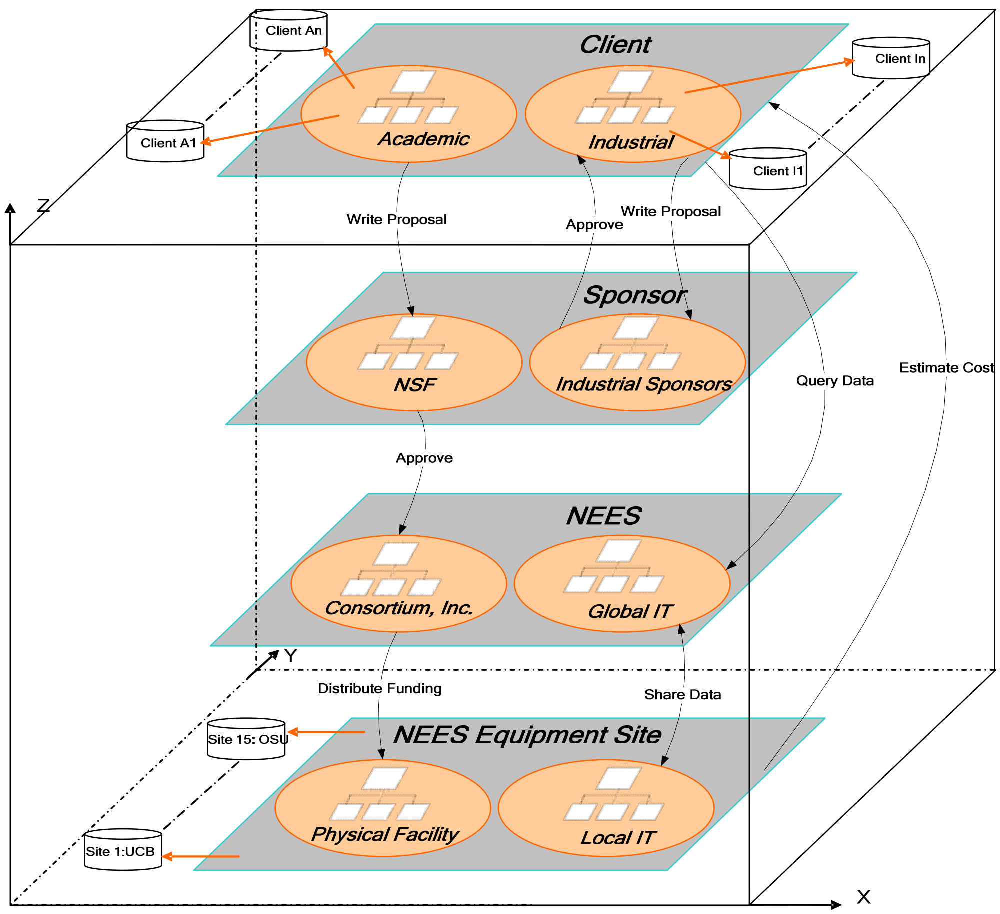


Figure 34 Interaction Flow in a NEES-sponsored Research Network

The inter-level interactions among stakeholders usually start with a client's new research topic, which needs experimental testing and verification. The client consults with experts at the experimental sites for cost and other estimates, and then writes a proposal to NSF for funding support. If the proposal is approved, NEESinc notifies the client and gives "credits" to the experimental sites to support the client's research. The client can then schedule and conduct the work at the experimental sites. When the experiment is being conducted, site staff will count on Local IT support for tasks such as querying and sharing data with the Global IT stakeholder. After the experiment is completed, the Local IT group will upload the experimental data into the Global IT (NEEScentral) database, where it can then be used by other researchers. This project is conducted in one of the 15 experimental sites: The O.H. Hinsdale Wave Research Laboratory at Oregon State University (OSU-HWRL) [O.H., 2008], which specializes in tsunami related physical experiments. OSU-HWRL houses Tsunami Wave Basins, and supports state-of-the-art information technology (IT) as part of the NEES vision, which allows researchers at remote locations to collaborate, coordinate, and participate in experiments. Planning, design, and implementation of an experiment at the OSU-HWRL usually involve a group of decision stakeholders. They work together to come up with an "experimental design alternative" (decision alternative), whereby the cost and risk is acceptable to everyone involved.

At the preliminary design phase, risk is a crucial criterion for stakeholders to make decisions. NSF (and most sponsors) is interested in achieving the best scientific results within a limited budget. Thus, if a client's proposal is high risk, a sponsor like NSF is usually unwilling to fund the proposed research. From the client's perspective, high risk experimental design may lead to new scientific insights, his/her preferences may vary based on the research objectives and available resources. OSU-HWRL's concern is to attract a steady number of clients interested in conducting experiments at the facility in order to maintain sufficient funds to support normal operation and maintenance. OSU-HWRL also has a vested interested in the researcher achieving their desired experimental goals so that researchers return and new clients apply. Thus a reasonable risk assessment of the situation is very important for all involved stakeholders. Unfortunately, risk evaluations are often not optimally accurate and consistent due to limited knowledge and differing preferences resulting in strong needs for global negotiation.

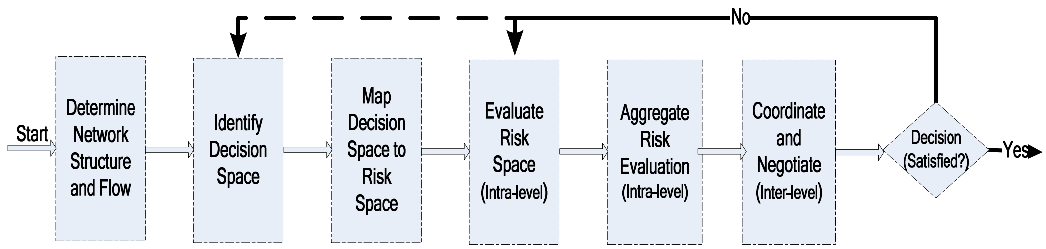


Figure 35 Risk-based Negotiation

The steps to achieve better understanding of risk are illustrated in Figure 35. Three representative stakeholders (an academic client, the OSU-HWRL and NEESinc) are chosen from the collaborative environment. The process is initiated when the client submits a proposal. All three stakeholders evaluate this proposal in terms of risk, obtain their initial subjective risk assessments, and then negotiate overlapped risk items.

Step 1: Determine Network Structure and Flow

Three stakeholders form a stakeholders' set:

S = {OSU-HWRL, NEESinc, Client}

Each stakeholder has an interactive relationship with the other two. Their network structure can be represented by a Sociomatrix M in Table 7.

Table 7 Sociomatrix M

Stakeholder	OSU-HWRL	NEESinc	Client
OSU-HWRL	2	1	1
NEESinc	1	2	1
Client	1	1	2

Their interactive flow set is summarized in Table 8.

Table 8 Stakeholders' Interactive Flow Set

Stakeholder	Step No.	Task	Associated Stakeholder	Schedule
Client	1	Feasibility and cost estimation	OSU-HWRL	
	2	Write proposal for funding	NEESinc	Before deadline of applying budget
	3	Negotiate experimental schedule if budget approval	OSU-HWRL	Consider available time
	4	Confirmation of schedule	OSU-HWRL	
	5	Perform experiment	OSU-HWRL	In allotted time
	6	Analyze experimental results	OSU-HWRL	
	7	Dissertation publication	NEESinc	Before final evaluation
OSU-HWRL	1	Feasibility and cost estimation	Client	
	1	Funded from NEESinc if experiment approved	NEESinc	
	2	Negotiate and confirm experimental schedule	Client	Consider other experiments
	3	Resource preparation and execution of experiment	Client	In allotted time
	4	Debrief outcome with client	Client	
	5	Dissertation publication	NEESinc	Before final evaluation
NEES	1	Review proposal	Client	
	2	Fund OSU-HWRL if approved	OSU-HWRL	Before performing experiment
	3	Review experimental results	Client & OSU-HWRL	
	4	Evaluate	Client & OSU-HWRL	

Step 2: Identify Decision Space

Both stakeholder and members should identify their decision space. For stakeholders, the specific decision space is shown in Table 9. For example, OSU-HWRL needs financing and a schedule to keep the entire facility running properly. All of these requirements are aggregated and form OSU-HWRL's decision space. Stakeholders then share decision space. OSU-HWRL is the most knowledgeable about its availability and resources and also the client's experimental requirements, and they may modify their decision space based on updated information.

Table 9 Stakeholders' Decision Space

<table>
<tr><th>Stakeholders</th><th colspan="2">Function</th><th>Range</th></tr>
<tr><td rowspan="8">OSU-HWRL</td><td rowspan="2">Finance</td><td>Source of Funds</td><td>Moderate</td></tr>
<tr><td>Allocation of expenditures</td><td>Moderate</td></tr>
<tr><td rowspan="2">Human Resource</td><td>Salary</td><td>Moderate</td></tr>
<tr><td>Responsibilities</td><td>Narrow</td></tr>
<tr><td rowspan="2">Schedule</td><td>Equipment</td><td>Narrow</td></tr>
<tr><td>Human</td><td>Moderate</td></tr>
<tr><td rowspan="2">Equipment/Facility</td><td>Staging area</td><td>Narrow</td></tr>
<tr><td>Sensors</td><td>Narrow</td></tr>
<tr><td rowspan="3">NEESinc</td><td colspan="2">Finance</td><td>Narrow</td></tr>
<tr><td colspan="2">Human Resource</td><td>Moderate</td></tr>
<tr><td colspan="2">Outcome</td><td>Moderate</td></tr>
<tr><td rowspan="3">Client</td><td colspan="2">Finance</td><td>Narrow</td></tr>
<tr><td colspan="2">Schedule</td><td>Moderate</td></tr>
<tr><td colspan="2">Outcome</td><td>Moderate</td></tr>
</table>

Stakeholder members have specific roles and different initial decision space. To illustrate this, the OSU-HWRL decision space identification is described as follows. For simplicity, only the laboratory director (denoted as “A”) and data collection technician (denoted as “B”) are examined, and their decision space is described in Table 10.

Table 10 Decision Space for Members “A” and “B”

Member	**Function**		**Range**
A	Finance	Source of funding	Moderate
		Allocation of expenditures	Moderate
	Human Resource	Salary	Moderate
		Responsibilities	Narrow
	Schedule	Equipment	Narrow
		Human	Moderate
	Equipment/Facility	Staging area	Narrow
		Sensors	Narrow
B	Human factors	Salary	Narrow
		Responsibilities	Narrow
		Physical problems	Narrow
	Responsibilities	Data collection	Moderate
		Data transfer	Moderate
		Data storage	Moderate

Step 3: Map Decision Space to Risk Space

Each member can derive potential risk items from his/her decision dimensions which constitute his/her risk space. For example from the OSU-HWRL’s finance decision dimension, the risk items of “shortage of funding” and “cost overrun” can be derived; from the human resources decision dimension, the risk items of “technician sickness” and “unavailability of key personnel” are derived. These derivations form the risk space as shown in Table 11.

Table 11 Risk Space and Decision Space

Member	Decision Dimension (Function)	Risk Item
A	Finance	shortage of funding
		cost overrun
	Human Resource	technician B sick
		key personnel unavailable
	Schedule	time schedule conflicts
	Equipment	power/water out
		model delayed
		data storing failure
		data transfer failure
		data collection failure
B	Human factors	sickness
	Responsibilities	data storage failure
		data transfer failure
		data collection failure

Step 4: Evaluate Risk Space (Intra- Level)

Risk likelihood and consequences are usually ranked by several levels, and their quantification has been summarized in 4.1.2. “A” and “B” can then assign risk evaluations for all risk items, and fill the property tables summarized in Table 12.

Table 12 Members' Risk Property Table

Member	Risk Item	Probability	Consequence	Desire	Confidence	Category
A	shortage of funding	D	I	Weak	90%	Human
	cost overrun	C	III	Weak	90%	Human
	Technician B sick	D	III	Weak	50%	Human
	key personnel unavailable	C	III	Strong	60%	Human
	time schedule conflicts	B	III	Weak	80%	Human
	power/water out	D	II	Weak	90%	Hardware
	model delayed	D	IV	Weak	80%	Human
	data storage failure	B	II	Weak	50%	Software
	data transfer failure	C	II	Weak	50%	Hardware
	data collection failure	B	II	Weak	50%	Hardware
B	sickness	C	II	Strong	90%	Human
	data storage failure	C	I	Weak	90%	Software
	data transfer failure	C	II	Weak	90%	Hardware
	data collection failure	C	II	Weak	90%	Hardware

Step 5: Aggregate Risk Evaluations (Intra-Level)

After members have evaluated their risk items respectively, they need to synthesize a uniform risk space for their group as a whole. In this case, four risk items for "B" are included in "A's" risk space, which means these four overlapped risk items need to be negotiated locally between "A" and "B". For example, (see underlined sections in Table 13), for the risk item: “technician B sick”, “B’s” desire property is “Strong”, and “B” is 90% confident in his evaluation. “A’s” desire property for “technician B sick” is “Weak”, and “A” is only 50% confident. Thus the negotiated property for this item is mostly in favor of “B’s” evaluation and preference. For “data storage failure”, both “A” and “B” have “weak” desire, but B is 90% confident while “A” is only 50% confident. In this case, the final negotiated property can be a confidence-weighted average. By conducting a local negotiation, each overlapped risk item can achieve a uniform evaluation in the stakeholder group. A final risk property table for the OSU-HWRL is shown in Table 14.

Table 13 OSU-HWRL’s Risk Property Table

Risk Item	**Probability**	**Consequence**	**Desire**	**Category**	**Related Stakeholders**
Shortage of funding	D	I	Weak	Human	NEESinc, OSU-HWRL
Cost overrun	C	III	Weak	Human	Client, OSU-HWRL
Technician B sickness	C	II	Strong	Human	OSU-HWRL
Key personnel unavailable	C	III	Strong	Human	OSU-HWRL
Time schedule conflicts	B	III	Weak	Human	Client, OSU-HWRL
Power/Water out	D	II	Weak	Hardware	OSU-HWRL
Model delayed	D	IV	Weak	Human	Client, OSU-HWRL
Data storing failure	C	I	Weak	Software	OSU-HWRL
Data transferring failure	C	II	Weak	Hardware	OSU-HWRL
Data collection failure	C	II	Weak	Hardware	OSU-HWRL

Table 14 OSU-HWRL's Risk Property Table

Risk Item	Probability	Consequence	Desire	Category	Related Stakeholders
Shortage of funding	D	I	Weak	Human	NEESinc, OSU-HWRL
Cost overrun	C	III	Weak	Human	Client, OSU-HWRL
Technician B sickness	C	II	Strong	Human	OSU-HWRL
Key personnel unavailable	C	III	Strong	Human	OSU-HWRL
Time schedule conflicts	B	III	Weak	Human	Client, OSU-HWRL
Power/Water out	D	II	Weak	Hardware	OSU-HWRL
Model delayed	D	IV	Weak	Human	Client, OSU-HWRL
Data storing failure	C	I	Weak	Software	OSU-HWRL
Data transferring failure	C	II	Weak	Hardware	OSU-HWRL
Data collection failure	C	II	Weak	Hardware	OSU-HWRL

Stakeholders' risk space with subjective risk assessment is summarized in Table 15.

Table 15 Risk Space and Subjective Risk Assessment

stakeholders	Risk Item	Related Stakeholder	Likelihood	Consequence
OSU-HWRL	shortage of funding	NEESinc, OSU-HWRL	D	I
	cost overrun	Client, OSU-HWRL	C	III
	technician sickness	OSU-HWRL	D	III
	key personnel unavailable	OSU-HWRL	C	III
	time schedule conflicts	Client, OSU-HWRL	B	III
	power/water out	OSU-HWRL	D	II
	model delayed	Client, OSU-HWRL	D	IV
	facility out of work	OSU-HWRL	C	II
	sensor quantity	Client, OSU-HWRL	C	II
Client	cost overrun	OSU-HWRL	B	II
	facility out of work	OSU-HWRL	B	II
	key personnel unavailable	OSU-HWRL	B	II
	model delayed	Client	D	II
	shortage of future funding	Client	D	I
	proposals denied	NEESinc	B	I
	shortage of funding	NEESinc	C	I
	sensor quantity	Client, OSU-HWRL	D	I
NEESinc	shortage of funding	NEESinc	E	I
	conflicts between management and staff	NEESinc	D	II
	proposals denied	Client	D	II

Step 6: Coordinate and Negotiate Globally (Inter-Level)

Once risk space is determined, negotiation is needed to achieve a consistent and satisfactory result for all stakeholders. Overlapped risk items can be identified by comparing all stakeholders' risk items, and then categorizing them as "changeable" or "non-changeable" items. Currently, these procedures are conducted manually. As an example to illustrate this item, only the availability of sensors and the schedule in the application are categorized into changeable risk items. All other risk items are classified as non-changeable.

a) Changeable Risk Items

"Sensor quantity" can directly result in data failure. Increasing the sensor inventory can reduce the probability of failure, but also increases the cost. For example, assume there are ten sensors at the OSU-HWRL facility, and based on experience, have a 30% failure rate. The client requires the data failure probability is below 10%. Thus the facility cannot satisfy the client's requirements, and a conflict occurs. The OSU_HWRL can purchase more sensors to guarantee the failure probability, but additional costs may be beyond the facilities budget. If the client's budget also cannot support the increased cost of purchasing more sensors, both OSU_HWRL and client should negotiate a reasonable failure probability and assess the costs. For example, the client increases the allowable expected failure probability to 15%, and the facility guarantees this probability by adding only two sensors at a cost that their budget can support. The negotiation on this risk item can affect both stakeholders' decision space: quantity of sensors, expected failure probability and cost. The same negotiation process can be applied to "Time and schedule conflicts".

b) Non-Changeable Risk Items

Table 16 Overlapped Risk Space and Their Subjective Evaluation

Overlapped Risk Items	**Description**	**Related Stakeholders' SRA(ORS_j)**		
		OSU-HWRL	**Client**	**NEESinc**
ORS_1	shortage of funding	10%	30%	0%
ORS_2	cost overrun	30%	50%	
ORS_3	facilities out of work	30%	50%	
ORS_4	key personnel unavailable	30%	50%	
ORS_5	specimens delayed	10%	10%	
ORS_6	proposals denied		50%	10%

To determine overlapped risk items (ORS_j), a matching table including corresponding risk evaluations of ORS_j is summarized in Table 16. Each stakeholder can form a risk function F related to ORS_j, and then negotiate the overlapped risk items from a global perspective to achieve their Objective Risk Assessment (ORA). An overall objective function can be constructed, and a multi-objective optimization problem can be formulated as follows:

$$\begin{cases} X = \{X_1, X_2, X_3, X_4, X_5, X_6\}, \text{ where } X_j = ORA\,(ORS_j) \\ \text{Min. } \quad W\,\{\mathbf{F}\text{-OSU-HWRL}(X), \mathbf{F}\text{-NEESinc}(X), \mathbf{F}\text{-Client}(X)\} \\ \mathbf{F}\text{-OSU-HWRL}(X) = X_1 * 10 + X_2 * 4 + X_3 * 7 + X_4 * 4 + X_5 * 0 \\ \mathbf{F}\text{-NEESinc}(X) = X_1 * 10 + X_6 * 7 \\ \mathbf{F}\text{-Client}(X) = X_1 * 10 + X_2 * 7 + X_3 * 7 + X_4 * 7 + X_5 * 7 + X_6 * 10 \\ \text{s. t.} \\ X_3 <= 30\% \text{ (the OSU-HWRL has a “strong” desire of below 30\%)} \end{cases}$$

where,

X: negotiation variable vector.

W: global negotiation function (objective function).

F-OSU-HWRL(X): risk function for OSU-HWRL.

F-NEESinc(X): risk function for NEESinc.

F-Client(X): risk function for Client.

The goal of the optimization is to find a globally consistent X, which can minimize the objective function W. Different distributed environments lead to different negotiation function W. Two example criteria, "local convergence" and "global convergence" are examined.

(a) "Local convergence" criterion

"Local Convergence" means negotiation processes are performed locally. All risk functions are linear, and variable X_j can be decomposed. Assume that each stakeholder's decision power is equal, which means all stakeholders can negotiate single risk items X_j one by one, and achieve a good negotiation result by combining all overlapped risk items. The idea for the global negotiation function "W" comes from the probability weighted average, which can guarantee convergence of all opinions. For example, using this criterion to negotiate X_2, a sub multi-objective optimization problem including only X_2 is formed as:

$$\begin{cases} \text{MIN. W } \{\mathbf{F}\text{-OSU-HWRL}(X_2), \mathbf{F}\text{-Client }(X_2)\} \\ \mathbf{F}\text{-OSU-HWRL }(X) = X_2 * 4 \\ \mathbf{F}\text{-Client }(X) = X_2 * 7 \end{cases}$$

Given the values for X_2 from individual stakeholders:

From OSU-HWRL: $X_2^{(1)}$ = SRA (ORS_2) = 30 %

From Client: $X_2^{(2)}$ = SRA (ORS_2) = 50%

The "center of gravity" of X2 for both stakeholders is calculated as:

X_2-centerofgravity = $(X_2^{(1)} * W_1 + X_2^{(2)} * W_2) / (W_1+W_2)$

where W_1 and W_2 are weight factors, which are assigned with corresponding risk consequences. Thus the negotiated risk assessment value for X_2 is:

X_2 = (30% * 4 + 50% * 7) / (4 + 7) = 42.7 %

Similarly other variables can be negotiated in this way. The final negotiated results are summarized in Table 17 (Note: X_3 is required to be lower than 30% in the constraint). This method is simple and converges quickly. However, it can only be applied when all risk functions are linear, and the result is very sensitive to every stakeholder's evaluation.

(b) "Global Convergence" Criterion

"Global Convergence" means negotiation processes should consider all risk items X simultaneously. A global negotiation function is selected as the displacement between negotiated risk assessments and multi stakeholders' subjective risk assessments. Detailed process is as follows:

1. stakeholders construct risk function **F** for overlapped risk items.

2. an "arbitrator" determines all stakeholders' rankings based on their reliabilities and roles, and assigns each stakeholder a weight factor.

3. **W** is constructed using the weight factors and risk functions.

4. a multi-objective optimization problem is formulated and calculated.

For this example, the following symbols are defined:

V-OSU-HWRL = **F**-OSU-HWRL (X) evaluated by OSU-HWRL

= 10%*10 + 30%*4 + 30%*7 + 30%*4 + 10%*0

V-NEESinc = **F**-NEESinc (X) evaluated by NEESinc

= 0% * 10 + 10% * 7

V-Client = F-Client (X) evaluated by Client

= 30%*10 + 50%*7 + 50%*7 + 50%*7 + 10%*7 + 50% * 10

Then the overall objective function W can be:

$$\mathbf{W} = K_1 * (\mathbf{F}\text{-OSU-HWRL (X)} - \text{V-OSU-HWRL})^2 + K_2 * (\mathbf{F}\text{-NEESinc (X)} - \text{V-NEESinc})^2 + K_3 * (\mathbf{F}\text{-Client (X)} - \text{V-Client})^2$$

$$= K_1*[(X_1\text{-}10\%)*10+(X_2\text{-}30\%)*4+(X_3\text{-}30\%)*7+(X_4-30\%)*4+(X_5\text{-}10\%)*0]^2 + K_2*[(X_1\text{-}0\%)*10+(X_6\text{-}10\%)*7]^2 + K_3*[(X_1\text{-}30\%)*10+(X_2\text{-}50\%)*7+(X_3\text{-}50\%)*7+(X_4-50\%)*7+(X_5\text{-}10\%)*7+(X_6\text{-}50\%)*10]^2$$

Then the global coordination problem can be expressed as:

Minimize: **W**

S.T.

$X_3 <= 30\%$. (The final value is less than 30%)

where K_1, K_2 and K_3 are weight factors assigned by the arbitrator. MAPLE was used to perform this optimization calculation. The optimization results are summarized in Table 17 for the situation $K_1 = K_2 = K_3 = 1$.

This criterion has good physical and mathematical meaning. It is more stable than local convergence criteria, and can be applied to any network structure and any nonlinear risk functions. Drawbacks are that it is more complex and computationally expensive, and the weight factors in this criterion need to be assigned manually by the arbitrator who must have necessary expertise and experience. Further convergence may not be obtained if weight factors are not set up properly.

Table 17 Negotiated Values based on Different Convergence Criteria

Negotiable variables	Negotiated value (*X**) based on local convergence	Negotiated value (*X**) based on global convergence	difference
X_1	13.3%	3.3%	-10%
X_2	42.7%	50%	7.3%
X_3	30%	30%	0
X_4	42.7%	50%	7.3%
X_5	10%	10%	0
X_6	33.5%	50%	16.5%

After one cycle of negotiation, the global coordination result (X*) can be formed and "downloaded" to all stakeholders. all stakeholders can then re-evaluate it. If all are satisfied, then a temporary globally consistent result is achieved, and the experimental set up proposed at the very beginning can be determined. If any stakeholder is not satisfied with some of the results, another negotiation run can be requested. This iterative process usually goes back to step 4, and possibly to step 2 if decision space needs to be updated. If that is the case then:

the process goes back to step 2 - individual decision space is modified;

jump to step 4 - subjective risk assessment or negotiation criteria is modified.

The negotiation process will continue until either all stakeholders are satisfied with the risk evaluation, or individual stakeholders stop participating in the environment, resulting in breakdown of the collaboration.

6. CONCLUSIONS AND FUTURE WORK

Collaboration becomes popular with rapid society advancement. Its interaction domain can be within states or across nations. This type of distributed collaboration can make every involved stakeholder better-off. However effective negotiation is crucial to overcome collaboration barriers and achieve good collaboration results for all. Performance, cost, and schedule are usually the most dominant decision factors when trading off different alternatives in a collaborative environment. In addition, risk is less considered but crucial in many engineering applications. Risk is an abstract concept, and is seldom systematically and quantitatively considered in engineering domain. If risk can be quantified in a solid way, then it can combine with traditional cost benefit analysis, and provide more comprehensive design support for complex engineering problems, which is a research gap of engineering decision support. This dissertation is a cross-discipline research, and a large number of existing literatures exist. After comprehensively reviewing some of them and dissecting basic problems in a distributed environment, a risk-based global negotiation (RBN) methodology is constructed step by step. The methodology considers whole collaborative environment simultaneously: it quantifies risk consequence in a monetary unit, makes risk probability consistent cross stakeholders, considers additional risk hierarchy and risk tolerance properties, builds a risk static model to evaluate risk conditions of collaboration, constructs a dynamic uncertainty model to directly support risk-based resource allocation engineering problems, and finally provides supports for integrative risk negotiations. It is important to note that this quantified method is notional risk analysis, which can indicate risk value in relative scales instead of absolute scales.

Two main aspects are covered in this approach: risk content preparation and risk negotiation. Risk content preparation helps involved stakeholders gather necessary risk information efficiently, and risk negotiation provides risk measures and strategies to support stakeholders' negotiation. Three steps are included in risk preparation: 1) a uniform risk structure is used to capture and synthesize heterogeneous and implicit risk evaluations at both intra- and inter- stakeholder levels for better information exchange and understanding; 2) risk hierarchy is introduced to quantify risk consequence in monetary unit; 3) a risk-based consistency scheme is proposed to achieve consistent risk probability evaluations. In risk negotiation aspect, two models are proposed: 1) a static model is constructed to systematically evaluate expected risk value and risk preference utility for both individual stakeholders and their collaborative environment; 2) a dynamic uncertainty model is built to consider uncertainty risk issues, and assist collaboration decision making problems such as resource allocation. Two engineering applications are then chosen to demonstrate implementation steps of RBN. The first NEES application aims at comprehensive analysis of collaboration risk condition, then it mainly shows local risk analysis and risk probability consistency within a collaborative environment (4.1, 4.2.1 & 4.2.3). The result shows effectiveness and efficiency of the proposed method. The second hydropower project tries to not only evaluate collaboration risk condition, but also improve risk condition. The demonstration focuses on risk consequence quantification (4.2.2) and collaborative risk-based negotiation (4.3). Considering complicated scenarios in real applications, presented risk items are simplified, and only key parts are addressed. The investigation shows promise of the methodology in evaluating overall environment risk condition and facilitating optimum resource allocation for a distributed collaborative system design. The approach presented is intended to be applicable to a wide range of scenarios. The appropriate scenarios for applying this approach can be summarized as: 1) stakeholders intend to collaborate, and quantified risk is an important concern; 2) each stakeholder is capable of risk assessment independently; 3) stakeholders are willing to collaborate and desire collaboration negotiation.

Comparing with traditional risk analysis methods, innovations of the RBN can be summarized in four aspects: 1) two additional risk properties, risk threshold and risk hierarchy, are included for more comprehensive risk evaluations; 2) risk probability consistency and risk consequence quantification are first introduced for more accurate and direct quantitative risk evaluations; 3) varying weights method is first developed to aggregate multiple stakeholders' preferences dynamically; 4) Both static and dynamic models are constructed to evaluate environment's static and dynamic risk conditions, and Pareto frontier can be calculated to assist stakeholders' risk negotiation effectively. The contributions of the proposed work include two aspects. For design knowledge aspect, 1) complicated negotiation process is divided into three interdependent steps, which are easier to be implemented during real engineering applications. Also the work extends local to global risk analysis, and provides systematic risk measures of overall environment. 2) Risk is quantified in monetary unit from a system perspective, and it can combine with traditional cost and performance mechanism to achieve more comprehensive results. For design practice aspect, the whole work utilizes uniform mathematical equations, and then it is ready for computer program implementation, and can be incorporated into existing collaborative software tools to enhance their risk functions and help distributed companies achieve the maximum market profits with acceptable risk. Currently most engineering decision making concerning risk is human-based, which depends much on humans and their expertise and is not stable. The proposed systematic model can be a type of machine design. It still requires human's expertise in the first preparation stage, but decreases human dependency to the least extent. After a model is built, optimization and other post processes can be conducted to help engineering negotiation and decision making. This systematic design is stable and more preferable.

Four areas are under future consideration: 1) more applications are better to validate the robustness and effectiveness of the model, which is a key direction of future work; 2) the methodology is mathematically represented, and the authors' objective is to implement the methodology with computer programs and incorporate it with existing collaborative software tools; 3) currently the methodology separates objective risk information and stakeholders' subject social dynamics to the maximum extent. An optimum set can be obtained from the methodology, and then more social dynamics factors should involved during negotiation. More research is needed to help stakeholders choose the best one from the optimum set; 4) considering subjective issues concerning risk probability and consequence evaluations, a quantified measure with confidence interval is more appropriate than a point-based value. Essentially, the mean and variance of cost benefit measure (CB) in the dynamic model are utilized to manipulate the confidence interval factor. However, they are from an overall system perspective without specific consideration of single risk item. Besides, several assumptions concerning variance formulation are made in this paper to simplify the calculation. More precision work concerning confidence interval can be conducted in the future.

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