CONCURRENT ENGINEERING: Research and Applications

A Risk-based Global Coordination System in a Distributed Product Development Environment for Collaborative Design, Part I, Framework

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Abstract: This is the first of a two-part paper introducing a risk-based global coordination system in a distributed environment for collaborative design. Part I presents the basic concepts and a theoretical framework, and Part II describes the implementation and practical application to a National Science Foundation supported collaborative network. In a distributed environment, local negotiations within a stakeholder group (intra-stakeholder) and global negotiations among stakeholders (inter-stakeholder) co-exist. Strategic support is necessary to facilitate the integrative negotiation at the both intra- and inter- levels for effective distributed decision making. The challenge is that the distributed stakeholders have different subjective risk perceptions, interpretations and evaluations, which can be inconsistent and incoherent from a global perspective, and thus create considerable barriers for effective negotiation and coordination. Our approach is to (1) understand and capture heterogeneous risk evaluations at intra- and inter-levels, (2) represent and quantify all participants' subjective risk evaluations using a uniform structure, and (3) facilitate the negotiations through a risk-based coordination mechanism designed to achieve a globally consistent risk assessment (building consensus). The long-term goal of this work is to achieve a more fundamental understanding and develop useful tools for effective collaborative design.

Key Words: collaborative product development, distributed decision making, risk, negotiation, global coordination.

1. Introduction

With widespread use of a distributed product development environment designed to achieve desirable effectiveness and efficiency, collaborative design is becoming more complex. A typical distributed environment [1] can be viewed as several stakeholders, distributed at different geographical locations, collaborate and form a connected network to achieve some common objectives. A stakeholder represents an organization or group that includes a number of members (a two-level structure): members compose a stakeholder, and stakeholders form a distributed network.

Risk is an important factor which affects stakeholders to effectively coordinate and is widely considered in designing engineering systems, such as nuclear power plants, aerospace systems, and tsunami experimental facilities. Existing work has examined risk-based design [2–5] and shown promise for supporting distributed coordination and negotiations. Risk, combined with cost, is a crucial factor in examining feasible alternatives in many real world decision making situations [5–8]. However, risk evaluations are usually subjective, and sometimes, no obvious objective evaluations are available, which renders risk-based system design highly challenging. This has provided us the motivation to study risk as an underpinning criteria needed to support collaborative decision making.

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. 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. This situation calls for a globally consistent and coherent risk assessment, which more likely yields a win-win outcome.

A risk-based global coordination methodology is presented in this work to deal with the above heterogeneity and implicitness issues. The proposed approach strives for a consistent and less subjective risk assessment across stakeholders so as to achieve a 'win-win' situation for all. A coordination and negotiation process

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is involved in achieving agreements on various risk evaluations across stakeholders on overlapping risk items and also acknowledging the existence of nonoverlapping risk items. A shared risk standard across stakeholders is helpful for the process, but it is not required here since in many cases, it may not be feasible. Stakeholders' communication and negotiation strategies play an important role in the process. General negotiation strategies and styles include accommodation, avoidance, competition, compromise, etc. [9]. In a collaborative environment, 'compromise' negotiation is usually preferred in order to achieve a 'win-win' situation, which usually means that all stakeholders can benefit (i.e., have a net gain) in some way, and no partner experiences a net loss. Under the assumption of 'compromise' negotiation and 'win-win' situations, stakeholders tend to accept alternatives unless the proposal is too risky for some stakeholders.

In this paper, we focus on the basic concepts and a theoretical framework of the risk-based global coordination methodology. Section 2 reviews related literature. Section 3 highlights the fundamental issues, and formulates the research problems. Section 4 presents a risk-based global coordination model. Section 5 concludes and discusses potential for future work.

2. Background Review

2.1 Global Coordination and Distributed Environment

Global coordination is an important theme in existing work on collaborative design. Agent-based approach plays an important role in supporting design activities in a distributed, collaborative environment. Jin et al. [8] developed an agent-supported framework ASCAD to facilitate conflict management and streamline work flows. It provides knowledge infrastructure to support knowledge representation, sharing and exchange. However, additional mechanisms besides communication are needed to drive the negotiation toward the desired goal. Ganguly and Wu [10] developed a Principle-Agent Model for decision support in a distributed environment. This Model addresses the need for a shared criteria as a common basis to facilitate negotiations among distributed stakeholders, by using cost as a stakeholder utility (not including customers), and trades-off these individual utilities against the cost that the customers desire. In this work, risk is used as the major basis to facilitate the negotiations among stakeholders rather than cost utility, and real cost is considered as a contributing factor when evaluating risk.. It would be better to consider risk and cost simultaneously, and more integration work on cost needs to be considered in the current methodology framework. Ge et al. [11] developed a set-based approach to support negotiations among engineering design teams, which are arranged in a hierarchical manner from system, subsystem, to component product design teams. The major application domain is the parametric design of large-scale systems. This approach only deals with intra-level negotiation support, and does not address the inter-level issues.

For complex concurrent design, Loch et al. [7] built a mathematical meta-model, which uses local component decisions and their interactions to determine system performance. It shows that the network structure and interactions among local components have great impact on the overall network performance. This supports our findings that negotiations can exist at both intra- and inter-level among distributed, multiple stakeholders. But when complicated networks with large team sizes are present, negotiation and coordination efficiency occurs as a collaboration barrier. Barczak and Wilemon [12] showed that teams are more efficient and successful if communicating fully and effectively, and a team size of 2–6 has more communication effectiveness. In the case of a complicated network, some methods [10,13,14] were developed to decompose large complex design problems for efficiency improvement. Chen and Lin [6] investigated task coordination and team organization from a global coordination perspective, and developed a project task coordination model that identifies the sequence and structure of all project tasks, and decomposes large interdependent task groups into smaller task groups. Prasad [15,16] addressed the negotiation efficiency problem with large team size in concurrent engineering. He proposed decomposition and sub negotiation techniques. The study provides the foundation for team arrangement and global coordination, and provides a useful guideline to decompose complex network structure into smaller groups for effective coordination. Both decomposition and sub-negotiation are included in our methodology. Their implementations are not the focus of this paper, so are only briefly mentioned.

2.2 Risk Assessment and Risk-based Design

Many risk assessment methods have been developed. Hazard and Operability uses a set of guidewords to identify the scenario that may result in a hazardous or an operational problem [17]. Failure Mode and Effects Analysis was developed in the 1950s. In this family of methods, each potential failure mode in the system is analyzed to determine its effect on the system, and then classified by its severity [17]. These methods provide qualitative risk evaluations, but have limited capability to render quantitative risk analysis which is important for effective negotiation in a distributed network. Probabilistic risk analysis is another reliable method for analytical approach of risk assessment. Fault- and event-tree analysis is widely used in failure analysis and risk-based design methodology. A fault tree is a logical graph which shows the relationship between system failures. Event-tree analysis can illustrate the sequence of outcomes arising after the occurrence of a selected initial event, and it is mainly used in consequence analysis for preincident and postincident application. For intra-level risk assessment, members can choose these existing methods to identify and quantify their risk evaluations. For example, event-tree method is used in case studies [18] to determine the risk source and quantify the probabilities of accidents [17,19]. A good deal of research has been conducted for local domain risk assessment, but the possible influence and variations of the distributed network (inter-level) have seldom been considered in support of the global collaboration and coordination.

Risk-based design is attracting significant attention in designing products used daily to large-scale products, such as aircraft and aerospace systems. It combines risk assessment and systematic design methods. Risk information and knowledge is obtained and used to guide the design process to yield more reliable products at acceptable costs. Stone and Tumer [2] and Tumer and Stone [3] developed a functional basis for functional modeling in product design and used this basis to further yield a Failure Function Design (FFD) method. Mehr and Tumer [4] and Tumer et al. [5] used risk as quantitative values and utilities for design decision making in aerospace system design with the support of a knowledge base in a concurrent design environment. In this work, risk is associated with decision space, and viewed as an intermediate parameter used to support decision making.

Negotiation and coordination in a collaborative network is a complicated process, especially in a distributed environment. To better understand the concept, this type of distributed collaborative problem is dissected and two associated research questions are raised.

3. Problem Dissection and Research Questions

Definitions of core concepts are provided to clarify their meanings in subsequent sections.

3.1 Defining Core Concepts

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 [20].

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

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

3.2 Problem Dissection

A distributed network includes inter- and intra-level hierarchies, and correspondingly the 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 occurring among stakeholders.

To achieve effective collaboration, the participating stakeholders and their associated members need to communicate and negotiate through a process, as shown in Figure 1. The communication process at the inter-stakeholder level is usually complicated. Take three stakeholders as an example: *S*1, *S*2, and *S*3. Their communication process and decision space evolution during the global coordination process can be demonstrated in Figure 1.

(a) Initial Decision Space (Figure 1(a))

Initially, each stakeholder desires a particular objective from the collaboration which forms their decision space. Belonging to different organizations with various expertises, stakeholders usually have distinct decision dimensions. Their shared collaboration objective will overlap with some of their decision dimensions, and their heterogeneities will lead to other nonoverlapping dimensions. At the early design stage, when the stakeholders are not yet familiar with each other, these two types of decision dimensions may not be clear.

(b) Communication (Figure 1(b))

When the stakeholders have a strong desire to collaborate, they will communicate effectively 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 other stakeholders' decision space, and then modify or expand its initial decision space for better cooperation based on the new information. Because of shared decision space and overlapping decision dimensions, a potential negotiation space can be determined at this stage.

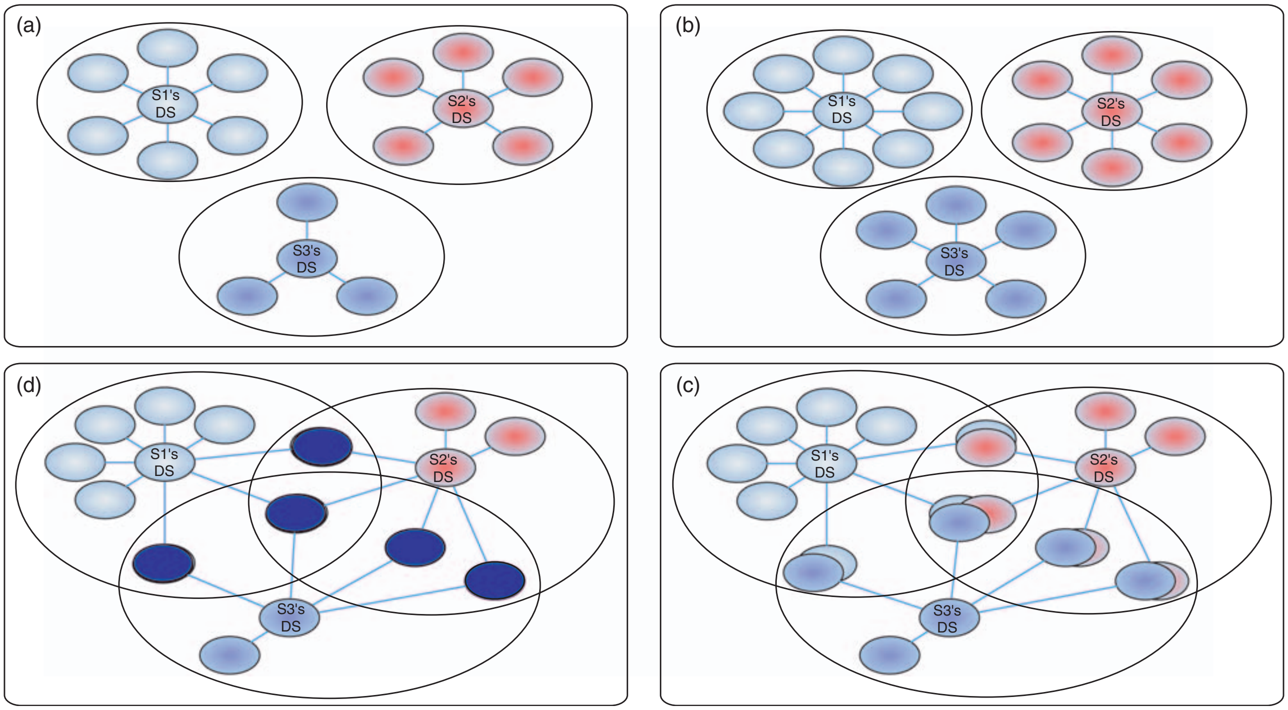

Figure 1. Decision Space (DS) evolution via communication and negotiation: (a) Initial DS; (b) Communication; (c) Negotiation; (d) Consistent Global DS.

(c) Negotiation (Figure 1(c))

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. Nonoverlapping items have no impact on other stakeholders, eliminating any need for negotiation. Overlapping 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 overlapping 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.

(d) Consistent Global Decision Space (Figure 1(d))

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 overlapping 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. As the stakeholder members get to know each other over time, they may be able to anticipate each other's expectations. Thus the influence from intra-stakeholders on a member's decision space is relatively more predictable than that from inter-stakeholders.

3.3 Decision Space, Risk Space, and Negotiation Space

Besides the decision space, risk and negotiation space are introduced here. The objective of this approach is to help stakeholders coordinate and negotiate effectively based on their decision space. However, decision space may be too specific to be employed directly for effective and efficient global negotiation, thus a key intermediate layer, risk space, is used to link the decision space and the shared coordination and negotiation space. Their relationships are illustrated in Figure 2.

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.

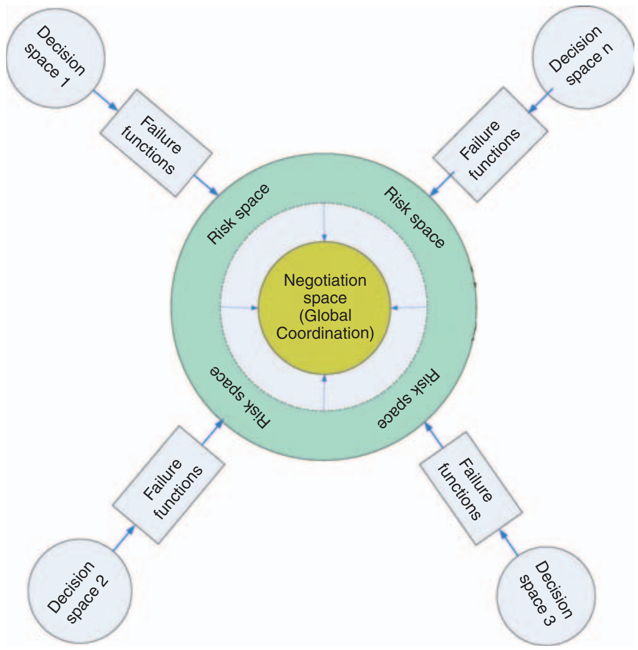

Figure 2. A risk-based approach to support global coordination in distributed environment.

Stakeholders' risk items can be overlapping or nonoverlapping. Only overlapping risk items are considered in negotiation, and all the overlapping risk items form the negotiation space. Communication and negotiation across stakeholders can lead to transformation of overlapping and nonoverlapping items, and further reshape the negotiation space.

A risk space can also serve as a decision space. If the risk dimension can be modified through changing decision space, then it is categorized as 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 the 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. Our global coordination goal is to 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 results. For nonchangeable items, the stakeholders can achieve more comprehensive and reasonable evaluations, and avoid making wrong decisions.

3.4 Summary of Research Questions

Coordination and negotiation represent two levels. At the inter-stakeholder level, stakeholders are connected through interactive flow of material and information in the distributed environment. They cooperate and negotiate based on certain criteria with our focus on risk. At the intra-stakeholder level, the members within a stakeholder need to exchange risk information and work with other members to come up with a uniform risk assessment that represents the group. This can then be used in the inter-stakeholder level coordination and negotiation. A systematic approach is urgently needed to provide strategic support for coordination and negotiations at both levels. In order to achieve that, the following research questions need to be addressed:

1. How does a stakeholder identify, represent, and synthesize its individual members' risk evaluations?
2. How do stakeholders coordinate and achieve consistent risk assessments with other stakeholders?

The first question is specifically addressed in section 4.3 and the second in 4.4.

4. A Risk-based Global Coordination to Support Collaborative Decision Making

The focus of this paper is to present a theoretical framework for modeling the risk-based global coordination process within and across stakeholders. An overall theoretical framework is shown in Figure 3. The following five steps are involved in this global coordination process.

4.1 Network Structure and Flow Identification

It is important for the networked stakeholders to get to know each other and possible work flow, so that they can negotiate on specifics when necessary. This step provides an important move towards further collaboration. At the inter-stakeholder level, each stakeholder communicates with those who have direct relationship, clarifies every stakeholder's responsibilities and tasks, which determine the process flow. At the intra-stakeholder level, each stakeholder clarifies their internal hierarchy, and how it distributes tasks to members.

Suppose there are n stakeholders in the network, then the sociometric notation [21] can be used to represent the relationship among all the stakeholders. The stakeholder set **S** is defined as:

$$\mathbf{S} = \{S_i, \quad i = 1, \ldots, n\} \tag{1}$$

where S_i represents the ith stakeholder.

A Sociomatrix **M** can be defined to represent the network structure as:

$$\mathbf{M} = \{M_{ij}, \quad i = 1, \ldots, n; \quad j = 1, \ldots, n\} \tag{2}$$

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

$$M_{ij} = \begin{cases} 0: \text{Having no interactive activites.} \\ 1: \text{Having interactive activites.} \\ 2: \text{Having the same stackholders.} \end{cases} \quad (3)$$

Each stakeholder has a specific work flow from their perspective, so a flow Set **FL** is defined to represent all the flows in the network structure **M**:

$$\mathbf{FL} = \{\mathrm{FL}^{(k)}, \quad k = 1, \ldots, n.\} \quad (4)$$

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

$$FL^{(k)} = \{\mathrm{FLI}_j^{(k)}, \quad j = 1, \ldots, m^{(k)}\} \quad (5)$$

where $m^{(k)}$ is the number of total steps of the kth stakeholder's work flow, and $\mathrm{FLI}_j^{(k)}$ is:

$$\mathrm{FLI}_j^{(k)} = [\text{Step No., Task, Associated Stakeholder, Schedule}] \quad (6)$$

4.2 Decision Space Identification

Each stakeholder has its own role and concerns about the collaboration, and this forms the stakeholder's decision space. Some of the decision dimensions are negotiable, and provide initial negotiation contents for global risk-based coordination. The initially nonnegotiable dimensions and stakeholders' specific requirements form constraints for later global coordination.

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

$$\mathbf{DS} = \{\mathrm{DS}^{(k)}, \quad k = 1, \ldots, n\} \quad (7)$$

where $\mathrm{DS}^{(k)}$ is a table, which represents the kth stakeholder's decision space.

$$\mathrm{DS}^{(k)} = \{\mathrm{DSD}_j^{(k)}, \quad j = 1 \ldots K^{(k)}\} \quad (8)$$

where $K^{(k)}$ is total number of decision dimensions in the kth stakeholder's decision space, and $\mathrm{DSD}_j^{(k)}$ is the jth decision dimension defined as:

$$\mathrm{DSD}_j^{(k)} = [\text{function, range}] \quad (9)$$

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 understands more and also desires change. For example, after stakeholders are more familiar with their collaboration environment, they usually are more willing to update their initial decision spaces.

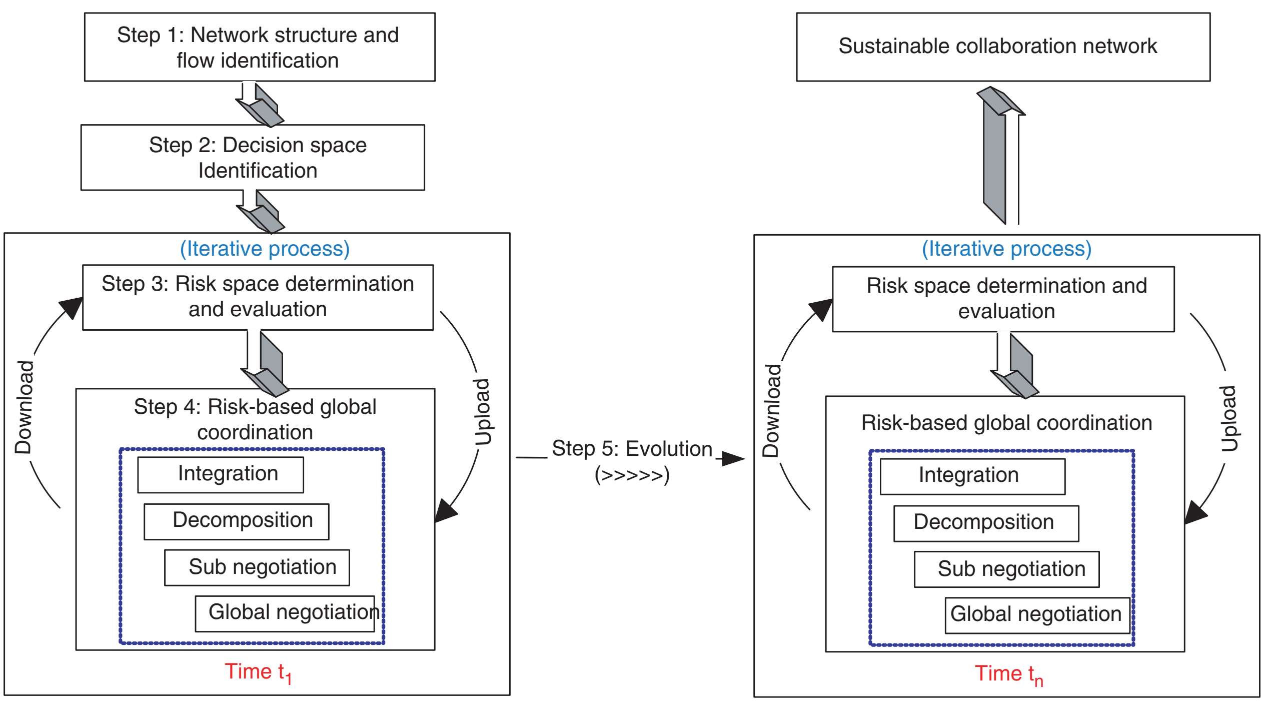

Figure 3. A risk-based global coordination model in distributed product development environment.

4.3 Risk Space Determination and Risk Assessment

Based on the decision space, an intermediate risk space can be constructed for negotiation.

Risk space set **RS** is expressed as:

$$\mathbf{RS} = \{\mathrm{RS}^{(k)}, \quad k = 1, \ldots, n\} \tag{10}$$

where $\mathrm{RS}^{(k)}$ is a table, which represents the kth stakeholder's risk space.

$$\mathrm{RS}^{(k)} = \{\mathrm{RSI}_j^{(k)}, \quad j = 1, \ldots, L^{(k)}\} \tag{11}$$

where $L^{(k)}$ is total number of the kth stakeholder's risk items, and $\mathrm{RSI}_j^{(k)}$ is the jth risk item:

$$\mathrm{RSI}_j^{(k)} = [\text{Item, Associated stakeholder, Likelihood, Consequence}] \tag{12}$$

where Item gives the description of this risk item; Associated Stakeholder is the other stakeholder who cares about this risk item; Likelihood is the probability of this risk item; Consequence is the severity of the risk.

Denote $P_j^{(k)}$ and $C_j^{(k)}$ as the probability and consequence of the kth stakeholder's jth risk item, then the expected risk function [17] can be used to calculate the total expected risk $F^{(k)}$ as follows:

$$F^{(k)} = \sum_{j=1}^{L^{(k)}} P_j^{(k)} \times C_j^{(k)}. \tag{13}$$

Of course, members can have his/her own risk space and conduct his/her own corresponding evaluation, but usually a stakeholder group cannot achieve this directly. A stakeholder's risk space should include, not just simply add, all of its members' risk spaces. The process to obtain stakeholders' risk space can be explained as follows: first, conduct individual members' risk evaluations; second, synthesize them to form a uniform stakeholder's risk evaluation. Below, member's and stakeholder's risk assessment is introduced to answer the first questions proposed in section 3.4.

4.3.1 INDIVIDUAL MEMBER'S RISK ASSESSMENT

Consistent risk evaluations across members are useful for collaboration, but implicitness and heterogeneity usually impose barriers. Each member can have his/her specific risk evaluations, or even risk definitions. To help members understand each other better, a standard uniform construct to capture risk information is introduced here, as shown in Table 1.

Risk Item is the risk description of each item. A risk item is usually measured by its probability and consequence. Desire indicates the evaluator's willingness to negotiate on this item, and can be assigned either strong or weak rating. Strong means the evaluator insists that the probability or consequence of the risk item must be satisfied. Such types of risk items become constraints and set boundaries for later local or global coordination. Weak means the property of this risk item can be changed leaving room for negotiation. Confidence indicates how much assurance the evaluator has his/her evaluation. For example, 100% shows full confidence, and 10% indicates little confidence in the evaluation. Category indicates the risk type such as a hardware failure, software failure, or human resources conflict. This property can be used to link and group similar risk items, and then form the Fault Tree.

A compiling process is used to partially reconcile disparate risk definitions among a stakeholder's members during the risk assessment, as shown in Figure 4. First, each member defines all his/her own risks and fills in the table according to his/her belief, and second, the table is shared with other members. Once all shared risk tables are available, members can determine overlapping risk items via communication, and then negotiate on the specifics of the definitions and evaluations.

i. Decision Space and Dimensions Identification. (Figure 4(a))

This step is to determine a member's decision space. Each member's decision space is unique, and contains several decision dimensions, such as D.D.1 to D.D.m in Figure 4a. These decision dimensions are then used to derive risk space.

ii. Risk Items Derivation. (Figure 4(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 and Tumer [2] and Tumer and Stone [3] developed a functional basis for functional modeling in product

Table 1. Risk property table for individual member's risk evaluation.

Risk item	Probability	Consequence	Desire	Confidence (%)	Category
XXXX	Level	Level	Strong/weak	X	XXXX

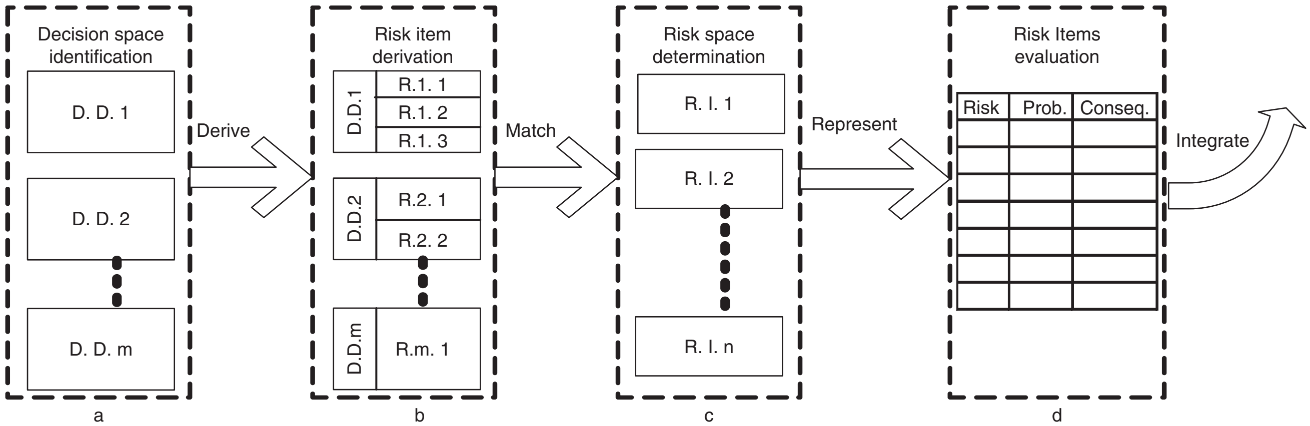

Figure 4. Compiling an individual member's risk assessment.

design and used this basis to further yield a FFD. More research is needed to determine if adaptation of this method to our work is possible.

iii. Risk Space Determination. (Figure 4(c))

Many risk items can be identified, but risk space is not a simple sum of them. Several different decision dimensions may include the same risk item causing duplication in the set of all risk items. This step identifies and removes the replications, and clarifies all the risk items used to form risk space.

iv. Risk Evaluation and Quantification (Figure 4(d))

After determining risk space, each member can evaluate individual risk items and then populate the property table. Since risk is associated with likelihood and consequence, some literature [20] suggests ranking them into several levels which can then be used to quantify these levels. For example, 80% is assigned to indicate the risk likelihood of frequent. The likelihood levels and their quantification used in our approach can be summarized in Table 2. The consequence categories and their quantifications are summarized in Table 3.

4.3.2 STAKEHOLDER'S RISK ASSESSMENT

During the global negotiation, stakeholders interact with each other, not members. This requires each stakeholder group to have a single uniform evaluation. Thus a stakeholder group's risk assessment needs to be constructed based on its members' evaluations. After all members conduct his/her risk assessment, a final uniform risk assessment for the stakeholder group can be synthesized. The process goes as follows:

1. collect all stakeholder members' risk property tables;
2. compare the tables, and determine the overlapping risk items;

Table 2. Likelihood estimation.

Description	Specific individual item	Level	Quantitative rank (*a priori*) (%)
Frequent	Likely to occur frequently	A	80
Probable	Will occur several times	B	50
Occasional	Likely to occur some times	C	30
Remote	Unlikely but possible to occur	D	10
Improbable	So unlikely to occur	E	~0

Table 3. Consequence estimation.

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

3. negotiate the probabilities and consequences for the overlapping risk items; and
4. fill the stakeholder's risk property table.

The property table for a stakeholder group is constructed in Table 4.

Compared with the member's property table, Table 4 the confidence property is removed and related stakeholders is added. Each member is confident about his/her evaluation, which is useful to achieve a uniform group evaluation with a high assurance via local negotiation. When a stakeholder's risk assessment is the synthesis of its members' individual assessment, such individual assurance property disappears, so there is no need of Confidence in stakeholder's risk table. Related stakeholders is added and used to form a linking table so that relationships between stakeholders can be retrieved. This linking table can indicate overlapping risk items and their sources, and thus form the negotiation space. For example, risk item $x1$ comes originally from

Table 4. Risk property table for stakeholder group's risk evaluation.

Risk item	Probability	Consequence	Desire	Category	Related stakeholders
XXXX	level	Level	Strong/weak	XXXX	XXXX

stakeholder $S1$, and has influence on two stakeholders, $S2$ and $S3$. Then related stakeholders connects these three stakeholders so that they can negotiate $x1$ during collaboration.

4.4 Risk-based Global Coordination

When each stakeholder has formed its uniform subjective risk space, the second question proposed in section 3.4 needs to be answered. Each stakeholder can upload the risk evaluations to the global coordination system and share with others. Thus each stakeholder can understand others' risk evaluations, find out which items are overlapping, identify the evaluation differences, and determine the negotiation content.

Suppose stakeholder S_k has a risk space $\mathbf{RS}^{(k)}$ derived from its decision space $\mathbf{DS}^{(k)}$. The first step in the global coordination process is to integrate all $\mathbf{RS}^{(k)}$ and form a global risk space **RS.** Then the overlapping risk items are determined in **RS** to form negotiation space **ORS:**

$$\mathbf{ORS} = \{\mathrm{ORS}_j, \quad j = 1, \ldots, \mathrm{P}\} \tag{14}$$

where ORS_j is the jth overlapping risk item, and P is the total number of overlapped items.

ORS_j is evaluated by [P-probability, C-consequence]. Risk consequence is a subjective term and depends on a specific stakeholder. For example, a sensor failure is serious for stakeholder A, but may not be that important for stakeholder B, causing negotiation of this risk consequence to be difficult. Usually risk probability is objective and not depending on stakeholders. However, inconsistent evaluations across stakeholders may exist, and possibly lead to erroneous decision making. Thus risk probability is selected as a negotiation content to capture possible inconsistencies in the negotiation.

The negotiation process is designed to get consistent values based on all of the stakeholders' evaluations. Denote x_j as the Objective Risk Probability Assessment (negotiated result) of overlapping risk item ORS_j, and $x_j^{(k)}$ as the kth stakeholder's Subjective Risk Probability Assessment for ORS_j.

Denote the set of all variables x_j as vector $\mathbf{X}$:

$$\mathbf{X} = \{x_j, \quad j = 1, \ldots, \mathrm{P}\}, \tag{15}$$

where $x_j = \mathrm{ORA}(\mathrm{ORS}_j)$.

If the stakeholder S_k has no evaluation for ORS_j, then it is assumed that S_k does not care about this risk item, and the associated consequence $C_j^{(k)}$ is set to zero. Based on Equation (13), the expected risk function for the kth stakeholder associated with overlapping risk items is:

$$F^{(k)} = \sum_{j=1}^{P} x_j \times C_j^{(k)} \tag{16}$$

If S_k has some special requirements in its decision dimension, then these requirements will be transformed into constrains on the negotiation in the form:

$$G_i^{(k)}(X) \leq 0, \quad i = 1, \ldots, n_G \tag{17}$$

$$H_l^{(k)}(X) = 0, \quad l = 1, \ldots, n_H \tag{18}$$

In the global coordination scheme from Figure 3, there are two optional steps; decomposition and sub negotiation which are useful for a large scale distributed network. In a distributed network with many stakeholders, it will be more effective to achieve a global satisfactory result if we first consider each stakeholder's separately. Decomposition and sub negotiation are identified as strategies when such conditions exist and are used to improve the negotiation efficiency. The stakeholders can be decomposed into several sub groups based on their relationships [13–16], and then each sub group can viewed as a smaller size distributed network. The proposed methodology can be applied to this smaller network in order to achieve a satisfactory negotiation result. Finally, integration of all the sub negotiation results can form the global negotiation result. However, these last two steps are not the focus of this paper.

After all negotiation contents are identified, the problem is how to conduct the negotiation. There are several existing negotiation methods in game theory, such as fair division, mediation of disputes, arbitration procedure, etc. [9, 22]. Arbitration procedure [22] is used in our method, but it still requires specific criteria to achieve the arbitration decision [23,24]. A negotiation criterion should first be formed, and it depends on the collaborative network structures and flows. Possible criteria could be the quickest convergence (least iteration), key stakeholders, Equal stakeholders etc. For example, an all stakeholders are equal collaborative network prefers an equal arbitration criterion for all, but a key-stakeholder network needs the criterion to favor the key stakeholder. A global coordination function **W** is used to represent the arbitration criterion, which is a composite function created from all stakeholders' expected risk value, and is based on the selected arbitration criterion.

Human social dynamics also affects the coordination process. Different trust networks, power structures etc. may achieve totally different negotiation results. Usually all risk assessments are intuitive and potentially biased. Each stakeholder tends to value their own work and risk evaluations the most. The network structure and latent social roles can somehow reflect the potential bias using a weight scheme, and accordingly the coordination function can use the scheme to adjust different risk evaluations to achieve a desired consistency level. Based on the definitions and formulas, the global negotiation problem can be summarized as a multi-objective optimization problem:

$$\begin{cases} \text{Min.}\mathbf{W}(F(X)^{(1)}, F(X)^{(2)}, \ldots, F(X)^{(k)}, \ldots, F(X)^{(n)}) \\ X = \{x_j, j = 1, \ldots, P\} \\ \text{s.t.} \\ G_j^{(k)}(X) \leq 0, \quad i = 1, \ldots, n_G, \quad k = 1, \ldots, n \\ H_j^{(k)}(X) = 0, \quad l = 1, \ldots, n_H, \quad k = 1, \ldots, n \end{cases} \tag{19}$$

When one cycle of negotiation (a negotiation run) is completed, the global coordination result (***X****) will be formed, and then distributed to all stakeholders who then forward the result to their members. Each stakeholder then compares their (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. Steps 3, 4 and maybe step 2 can be repeated until all participants are satisfied, or the collaboration breaks down. Thus, the end result of this process may lead to either an agreement or a well-informed disagreement among stakeholders.

4.5 Evolution and Update

For long term collaboration, stakeholders may change their decision space and associated risk evaluations over time, even though a consistent collaboration network 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 also 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.

5. Conclusions and Future Work

Global coordination is important for collaborative design in a distributed product development environment. This method provides a mechanism to facilitate the global coordination and negotiation from a risk perspective unlike a traditional method that considers performance and cost. By explicitly trading heterogeneous risk information and evaluations across diverse stakeholders, globally consistent and coherent risk probability evaluations can be determined which improves the effectiveness and efficiency of collaborative design. Two research questions are proposed concerning distributed collaboration, and are answered in a risk-based global coordination system.

Limitations of this method include: (1) simplified social dynamics is assumed (i.e., all stakeholders and members are rational); (2) requirement of all risk evaluations being available; (3) only probability consistency is considered with the assumption of consequence evaluation available. Our method currently assumes stakeholders can understand and quantify risk items from prior experience, and the global coordination function **W** can be formed and accepted by all involved stakeholders. Also we assume that everyone is capable of learning and sharing knowledge, and negotiate rationally and are willing to compromise [9]. Negotiating rationally means that a stakeholder can make the best decisions based on maximizing interests and accepting potential risk. The implementation of this method is still at an early stage, and a practical application is demonstrated in a companion paper [18]. These preliminary results show that the present model has the potential to support integrative negotiations for collaborative design in distributed environment systematically. One advantage of our method compared to a central decision maker strategy, is that our method allows independent decision making by individual stakeholders within a central coordination system.

The next step is to enhance the structural rigor of the problem formulation and methodology implementation.

At the intra-level, more systematic methods are currently under investigation that are capable of identifying and representing risk items, mapping decision space to risk space, forming negotiation space, and constructing risk function in a distributed environment. At the inter-level, the validity and reliability of the global coordination function **W** must fundamentally consider social dynamics.

Our method is an iterative process and in the case study presented in Part II [18], a simple network is chosen which would likely require few iterations for stakeholders to reach a consistent decision. However, future work involves a more complex network structure with complicated interactions and negotiations. In such a case, the iterative process could potentially slow or prevent arrival at a solution. Thus, better decomposition and sub-negotiation techniques are needed to improve the negotiation efficiency. This is a pilot study of risk-based design focusing on risk. Other current research underway by the authors [25] treats risk as another type of cost, and quantifies it in monetary units. It can then be combined with a traditional cost estimation, cost-benefit analysis to provide a more comprehensive design support.

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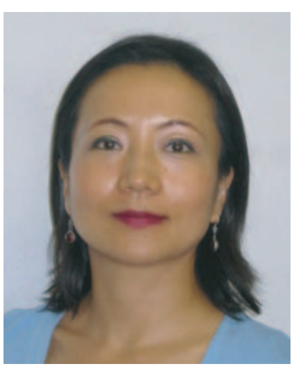
Ping Ge



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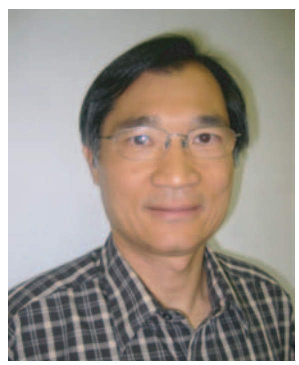
Solomon C. Yim



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