CONCURRENT ENGINEERING: Research and Applications

# A Risk-based Global Coordination System in a Distributed Product Development Environment for Collaborative Design, Part II, Application

Yuming Qiu,[1] Ping Ge[1,*] and Solomon C. Yim[2]

[1]Rogers Hall 204, School of Mechanical, Industrial, and Manufacturing Engineering, Oregon State University Corvallis, OR 97331, USA

[2]Owen Hall 220, Department of Civil Engineering, Oregon State University, Corvallis OR 97331, USA

**Abstract:** This is the second of a two-part paper introducing a risk-based global coordination system in a distributed environment for collaborative design. Part I represents the basic concepts and a theoretical framework, and this paper describes a practical application in a National Science Foundation/George E. Brown, Jr Network for Earthquake Engineering Simulation. Core concepts, theoretical framework, and methodology developed in Part I are demonstrated through a collaborative design project. When an experiment is to be conducted, multiple stakeholders distributed at different geographical locations are required to work together, to achieve a desired experimental design, both individually and as a group, regardless of personal preference. A risk-based global coordination mechanism with a local risk assessment approach provides a quantitative base for negotiation and coordination among multiple, distributed stakeholders. The case study shows that globally consistent, quantitative risk analysis with considerations of all stakeholders' assessments provides a basis for them to understand each other better and help build up consensus for success of the collaborative design project.

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

## 1. A NEES-sponsored Research Collaborative Network

An existing distributed research network is chosen to demonstrate the risk-based global coordination methodology developed in Part I [1]. Figure 1 shows the organizations and corresponding services of the NEES sponsored research collaborative network [2]. A distributed environment refers to a group of networked decision stakeholders at different geographical locations, who have a shared objective, but diverse expectations/concerns for the outcome of a particular coordinated effort [3].

Each circle or ellipse in Figure 1 represents a stakeholder. The National Science Foundation (NSF) created the George E. Brown, Jr Network for Earthquake Engineering Simulation (NEES) to provide researchers the tools to improve our understanding of earthquakes effects, including tsunami impacts on utility systems and other critical components societal infrastructure. NEES is a network of 15 large-scale experimental sites distributed at universities across the US, featuring advanced tools including permanent and mobile shake tables, centrifuges that simulate earthquake effects, and a tsunami research facility. NEES Consortium, Inc. (NEESinc), together with its board of directors, governs the entire NEES site operations. The stakeholders are usually distributed geographically, offer diverse services and have different objectives. Nevertheless, they work together to achieve the shared NEES objective to support a full spectrum of complex research projects.

Figure 2 shows a three-dimensional representation of the relationships and interaction flow in the distributed network. The $X$ axis represents intra-relationships among groups (elliptical areas) within similar categories (square areas). For example, 'Physical Facility' and 'Local IT' in some cases may belong to different groups, but they both belong to a 'NEES Equipment Site'. The $Y$ axis describes the organizational hierarchy of a stakeholder; the $Z$ axis shows inter-relationships among stakeholders within different categories. For instance, 'NSF' and 'Academic Client' are neither the same stakeholders nor in the same category, thus they are distributed at different $Z$ positions. The distributed

*Author to whom correspondence should be addressed.
E-mail: christine.ping-ge@orst.edu
Figures 1–4 appear in color online: http://cer.sagepub.com


1063-293X/07/04 0369–12 $10.00/0 DOI: 10.1177/1063293X07085016

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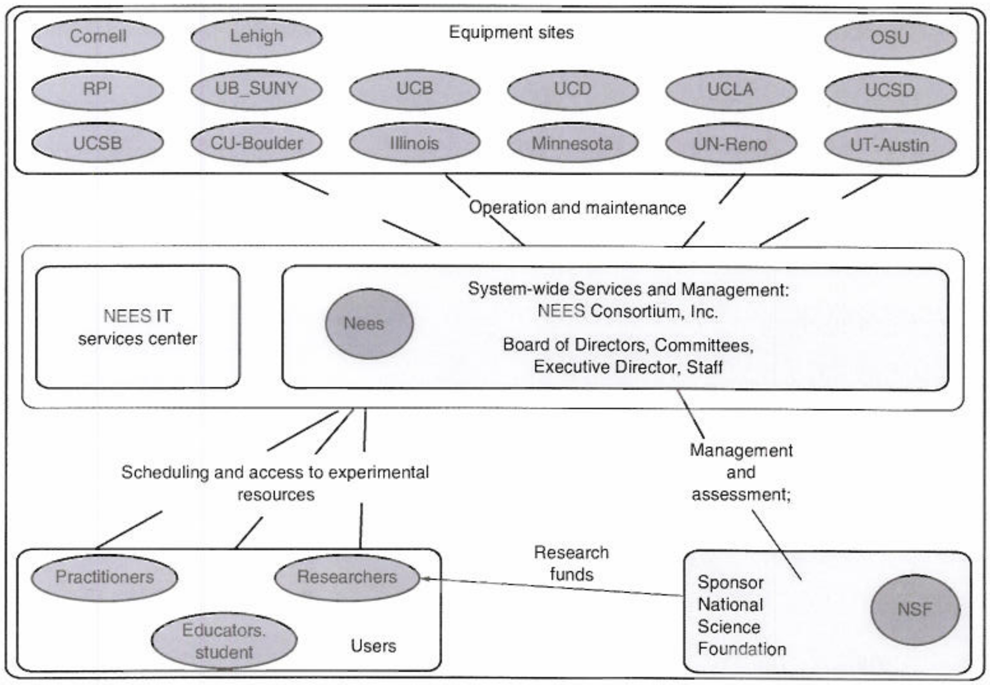


**Figure 1.** NSF/NEES organizational structure and services.

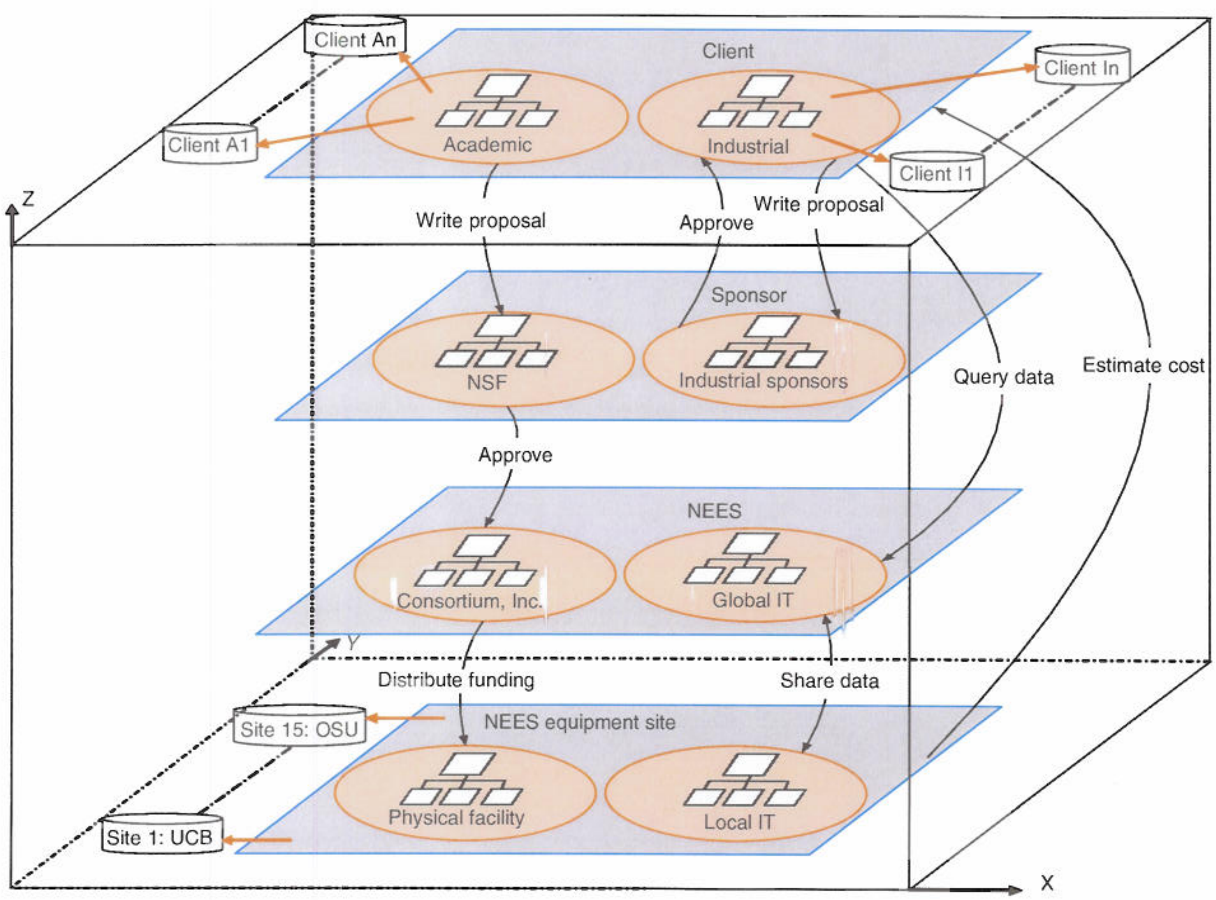


**Figure 2.** Interaction flow in a NEES-sponsored research network.

network shown consists of several stakeholders, and each stakeholder represents a group of members. This two-level hierarchical structure leads to the interactions at both levels: The $XY$ plane shows members' intra-interactions within a stakeholder (intra-stakeholder), and the $Z$ direction represents inter-interaction among multiple stakeholders (inter-stakeholder).

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 many other researchers. Our initial idea was directly motivated by one of the 15 experimental sites: The O.H. Hinsdale Wave Research Laboratory at Oregon State University (OSU-HWRL) [4], which specializes in tsunami related physical experiments. OSU-HWRL houses the Tsunami Wave Basin, one of the world's largest facilities for studying the effects of highly nonlinear environmental waves including tsunami and storm surge. It also supports state-of-the-art 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 involves 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. Stakeholders' interactive flow usually begins with a domestic (and potentially international) client requesting time to conduct an experiment at the facility. Once the facility receives the client's request, the OSU-HWRL will work with the client to develop an experimental design. Discussions might include a tsunami simulation analysis, a physical specimen (such as a simulated shoreline with a specific topography and/or structure), measurement equipment (sensors, signal conditioners, data acquisition systems, etc.) and personnel requirements. It is not uncommon at the OSU-HWRL for multiple projects to be simultaneously supported and therefore the site must schedule resources carefully to ensure that all clients are sufficiently served. Clients may be from academic institutions, industrial organization, and/or US, state and local government with funding sources for example from NSF, NEES, US Army Corps of Engineers, Office of Naval Research, Seagrant or private companies. Each of these sponsors has their own criteria and method for evaluating the results of funded research.

At the preliminary design phase, risk is a crucial criterion for stakeholders to negotiate and make decisions [5,6]. If stakeholders cannot agree on risk assessment, the collaboration may breakdown, causing all parties to fail to achieve their individual goals. NSF (and most sponsors) are 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 coordination and negotiation.

## 2. Highlighting the Critical Research Questions

The negotiation process among involved stakeholders in the NEES-sponsored research network occurs at two levels as shows in Figure 3. The vertical direction illustrates the intra-stakeholder hierarchy. For example, the OSU-HWRL includes four members: Director, a site operations manager, research associate, electrical engineering and data collection staff. During the collaboration, each member performs his/her own risk assessment which influences the OSU-HWRL group's decision making process. This level of negotiation requires all members of the group to create a representative uniform risk assessment. This is referred to as local level negotiation. As presented in Part I [1], the following research question is raised to address the technical challenge at the local level:

1. How do stakeholder members identify, represent, and synthesize their risk evaluations?

In order to facilitate the method development, this question is decomposed into the following two sub-questions:

*1.1 How does each individual member assess his/her risk evaluation?*

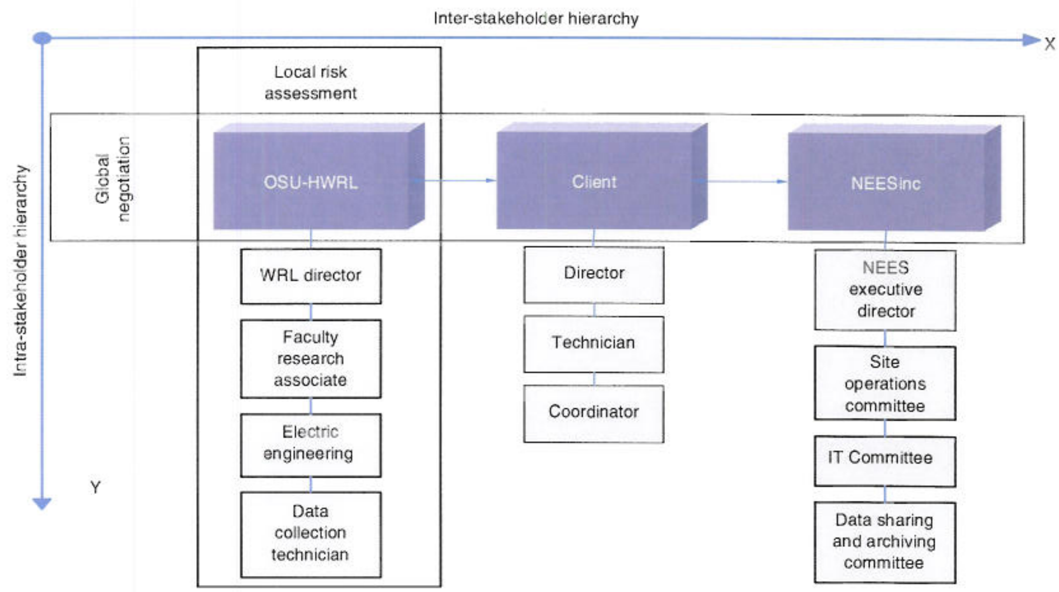


**Figure 3.** Inter- and Intra-Stakeholder Levels in NEES-sponsored research network.

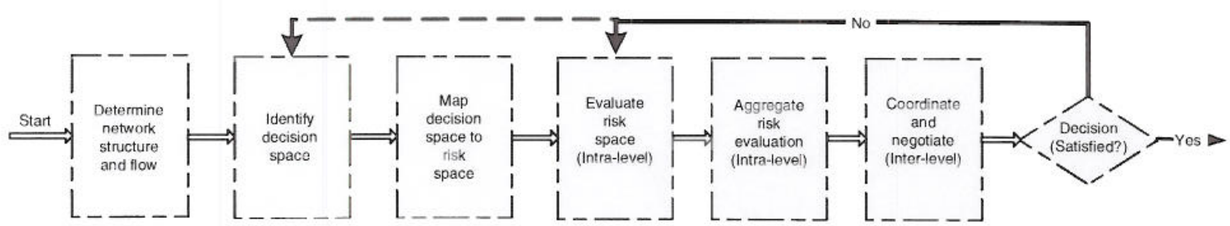


**Figure 4.** Risk-based Global Coordination in the NEES-sponsored research network.

*1.2 How does a stakeholder synthesize and create a uniform risk evaluation from its members?*

The horizontal direction in Figure 3 portrays the inter-relationships among OSU-HWRL, clients and NEESinc. NEES connects them to form a distributed network, although they belong to different organizations. With incomplete or limited knowledge and different preferences, these stakeholders may have inaccurate and misleading risk evaluations. This in turn may cause conflicts and barriers for their collaboration. Thus a global negotiation tool is needed to achieve consistent risk assessment leading to better decision making. We refer to this process as 'global level coordination', and present, the following research question to address the technical challenge:

2. How do different stakeholders coordinate and achieve consistent risk assessments?

A risk-based approach [1] has been developed to answer these questions. The theoretical framework and design methodology is presented in Part I [1]. This article (Part II) focuses on the application of the concepts to the NEES-sponsored collaborative research network as described in section 1.

## 3. Global Coordination in the NEES-Sponsored Research Network

Based on the methodology in Part I [1], the detailed steps to achieve the risk-based global coordination are illustrated in Figure 4. A total of seven steps are involved, which are examined in the following example using the NEES-sponsored research network. Three representative stakeholders (an academic client, the OSU-HWRL and NEESinc) are chosen from the collaborative environment. The risk-based collaborative design 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 overlapping risk items. If stakeholders are satisfied with the evaluated risk, then this cycle of negotiation is successful, and the stakeholders may then make adjustments to their decision space based on the risk space. If stakeholders are not satisfied with the evaluated risk, then either another negotiation cycle takes place, or the client changes the proposal which then starts a new negotiation cycle. The data collected for this study is from a practical scenario.

**Step 1: Determine Network Structure and Flow**

Three stakeholders form a stakeholders' set:

$$S = \{\text{OUS-HWRL, NEESinc, Client}\} \quad (1)$$

Each stakeholder has an interactive relationship with the other two. Their network structure can be represented by a Sociomatrix **M** [7,8] in Table 1.

Their interactive flow set is summarized in Table 2. For example, prior to writing a proposal to NEESinc, the client first consults OSU-HWRL for feasibility of the proposed experiment and also obtains cost estimates of the experiment. If the proposal is funded, and negotiations between the client and OSU-HWRL regarding details of the experimental plan and scheduling are successful, then the experiment can proceed. After conducting the experiment, the client analyzes the data and publishes his/her research results.

**Step 2: Identify Decision Space**

Both the stakeholder and members should identify their decision space. For stakeholders, the specific decision space is shown in Table 3. For example, OSU-HWRL needs financing and a schedule to keep the entire facility running properly, which requires human resources. All of these requirements are aggregated and form OSU-HWRL's decision space. Stakeholders then share decision space. For example, a client develops a research topic that can utilize OSU-HWRL's facility. 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.

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 4. For example, 'A' needs financing and a schedule to keep the whole facility running properly, while 'B' may be less concerned about this and more concerned about sensors, associated instrumentation and data acquisition systems.

***Table 1. Sociomatrix M for OSU-HWRL, NEESinc and Client.***

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

**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 5.

**Step 4: Evaluate Risk Space (Intra-level)**

Risk likelihood and consequences are usually ranked by several levels [9,10], and their quantification has been

***Table 2. Stakeholders' interactive flow set (see Equation (4)–(6) in Part I [1]).***

| 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 | |

*Table 3. Stakeholders' decision space (see Equations (7)–(9) in Part I [1]).*

| Stakeholders | Function | | Range |
|---|---|---|---|
| OSU-HWRL | Finance | Source of Funds | Moderate |
| | | Allocation of expenditures | Moderate |
| | Human Resource | Salary | Moderate |
| | | Responsibilities | Narrow |
| | Schedule | Equipment | Narrow |
| | | Human | Moderate |
| | Equipment/Faciltiy | Staging area | Narrow |
| | | Sensors | Narrow |
| NEESinc | Finance | | Narrow |
| | Human Resource | | Moderate |
| | Outcome | | Moderate |
| Client | Finance | | Narrow |
| | Schedule | | Moderate |
| | Outcome | | Moderate |

*Table 4. 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 |

*Table 5. Risk space in relation to 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 |

summarized in Part I [1]. 'A' and 'B' can then assign risk evaluations for all risk items, and fill the property tables summarized in Table 6.

**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 overlapping risk items need to be negotiated locally between 'A' and 'B'. For example, (see underlined sections in Table 7), 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 overlapping risk item can achieve a uniform evaluation in the stakeholder group. A final risk property table for the OSU-HWRL is shown in Table 7.

This stakeholder's risk property table contains rich information directly supporting global coordination: 'probability' and 'consequence' provide information for global negotiation; 'desire' shows stakeholders' strong or weak desire and set potential boundaries for global negotiation; 'related stakeholders' clarifies other stakeholders involved in the negotiation. The final risk property table provides a strong qualitative and quantitative basis for global coordination. The three stakeholders' risk space with subjective risk assessment is summarized in Table 8.

**Step 6: Coordinate and Negotiate Globally (Inter-level)**

Once risk space is determined, negotiation [11–13] is needed to achieve a consistent and satisfactory result for all stakeholders. Overlapping risk items can be identified by comparing all stakeholders' risk items, and then categorizing them as 'changeable' or 'nonchangeable' items. Currently, these procedures are conducted manually.

**(a) *Changeable Risk Items***

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 nonchangeable. '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

***Table 6. 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 |

***Table 7. OSU-HWRL's risk property table as a group.***

| 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 8. Risk space and subjective risk assessment ((see Equations (10)–(12) in Part I [1]).***

| 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 | Sost 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 |

that the data failure probability is below 10% initially. 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 increase 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.

'Time and schedule conflicts' occur for example if the facility has some important experiments to be performed with an associated probability of unavailability of equipment at 90%, during the same time the client has requested time in the schedule. In order to resolve this, the client (who must conduct experiments at the facility), and the facility (who wants to retain the client), negotiate. The facility proposes a a date as close to the clients request as possible that has a 10% probability of equipment unavailability, which is acceptable to the client and agreement is reached.

Risk can come in many forms, and there may be no objective risk assessment available in some cases, especially for 'changeable risk items', whose assessment depends on a specific stakeholder's decision space. For example, those facility managers may consider the long-term survival of the facility to be more important than specific projects, or vice versa. Stakeholders can assign different risk probability and consequences and desire to reflect their preferences. For example, the facility can assign a 'strong' desire rating and a consequence 'I' for the risk of 'facility out of work' which helps to ensure long term survival of the facility. This high rating can then be used to deny a client's request, if it has a high risk of facility damage. There also may be risks due to loss of funding for a specific activity as well as risks associated with poorly planned. These risk items are not independent, and their relationships should be considered and can be illustrated by a fault tree. The negotiation result of one risk item depends on other interrelated risk items, and usually there is a trade-off between them. For example, if the probability of 'inadequate experimentation' for the facility is high, then the facility can deny a specific client's proposal, especially if it has a high probability of funding loss.

### (b) *Non-Changeable Risk Items*

To determine overlapping risk items ($ORS_j$), a matching table including corresponding risk evaluations of $ORS_j$ is summarized in Table 9. Each stakeholder can form a risk function **F** related to $ORS_j$, and then negotiate the overlapping risk items from a global perspective to achieve their Objective Risk Assessment (ORA). Define:

***Table 9. Overlapping risk space and their subjective evaluation (SRA: Subjective Risk Assessment).***

| Overlapping 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 |

| | |
|---|---|
| $X$: | 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. |

An overall objective function can be constructed, and a multi-objective optimization problem can be formulated as follows:

$$\begin{cases} X = \{X_1, X_2, X_3, X_4, X_5, X_6\}, \\ \text{where } X_j = \mathrm{ORA}(\mathrm{ORS}_j) \\ \text{Min.} \quad W\{\text{F-OSU-HWRL}(X), \\ \text{F-NEESinc}(X), \text{F-Client}(X)\} \\ \text{F-OSU-HWRL} \\ (X) = X_1 \times 10 + X_2 \times 4 + X_3 \times 7 \\ \qquad + X_4 \times 4 + X_5 \times 0 \\ \text{F-NEESinc} \\ (X) = X_1 \times 10 + X_6 \times 7 \\ \text{F-Client} \\ (X) = X_1 \times 10 + X_2 \times 7 + X_3 \times 7 \\ \qquad + X_4 \times 7 + X_5 \times 7 + X_6 \times 10 \\ \text{s.t} \\ X_3 <= 30\% (\text{the OSU-HWRL has a 'strong'} \\ \quad \text{desire for this value to be below } 30\%) \end{cases} \tag{2}$$

The goal of the optimization is to find a globally consistent **X**, which can minimize the objective function **W**. Different distributed environments can lead to a different negotiation function **W**. Two example

***Table 10. 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 |

criteria, 'local convergence' and 'global convergence' are explained below.

### 3.1. 'Local Convergence' Criterion

'Local convergence' means negotiation processes can be performed locally. All risk functions in Equation (2) are linear, and the variable $X_j$ can be decomposed completely. Assume that each stakeholder's decision power is equal, which means all stakeholders can negotiate single risk items $X_j$ one by one, and then achieve a good negotiation result by combining all overlapping 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 $X_2$, the original risk functions in Equation (2) can be truncated to contain only the risk item $X_2$, and a sub multi-objective optimization problem including only $X_2$ is formed as:

$$\begin{cases} \text{MIN.}\quad W\{\text{F-OSU-HWRL}(X_2),\text{F-Client}(X_2)\} \\ \text{F-OSU-HWRL}(X) = X_2 \times 4 \\ \text{F-Client}(X) = X_2 \times 7 \end{cases} \tag{3}$$

Given the values for $X_2$ from individual stakeholders at the very beginning:

$$\text{From OSU-HWRL}: \quad X_2^{(1)} = \text{SRA}(\text{ORS}_2) = 30\%$$
$$\text{From Client}: \quad X_2^{(2)} = \text{SRA}(\text{ORS}_2) = 50\%$$

The 'center of gravity' of $X_2$ for both stakeholders is calculated as:

$$X_2\text{-centerofgravity} = \frac{(X_2^{(1)} \times W_1 + X_2^{(2)} \times W_2)}{(W_1 + W_2)} \tag{4}$$

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:

$$X_2 = \frac{(30\% \times 4 + 50\% \times 7)}{(4+7)} = 42.7\%$$

Similarly other variables can be negotiated in this way. The final negotiated results are summarized in Table 10 (Note: $X_3$ is required to be lower than 30% in the constraint).

From this example, the method is simple and converges easily. However, it can only be applied when all risk functions are linear, and the result is very sensitive to every stakeholder's evaluation.

### 3.2 'Global Convergence' Criterion

'Global convergence' means the negotiation processes should consider all risk items $X$ simultaneously and globally. A global negotiation function is selected as the displacement between negotiated (objective) risk assessments and multi stakeholders' subjective risk assessments. The detailed process is as follows:

- First, each stakeholder constructs its risk function F for any overlapping risk items.
- Second, an 'arbitrator' determines all stakeholders' rankings based on their reliabilities and roles, and assigns each stakeholder a weight factor.
- Third, the overall objective function W is constructed using the weight factors and risk functions.
- Fourth, a multiple objective optimization problem is formulated and calculated.

For this mock-up example, the following symbols are defined:

V-OSU-HWRL
= F-OSU-HWRL ($X$) evaluated at OSU-HWRL's evaluation probabilities
$= 10\% \times 10 + 30\% \times 4 + 30\% \times 7 + 30\% \times 4 + 10\% \times 0$

V-NEESinc
= F-NEESinc ($X$) evaluated at NEESinc's evaluation probabilities
$= 0\% \times 10 + 10\% \times 7$

V-Client
= F-Client ($X$) evaluated at Client's evaluation probabilities
$= 30\% \times 10 + 50\% \times 7 + 50\% \times 7 + 50\% \times 7 + 10\% \times 7 + 50\% \times 10$

Then the overall objective function W can be:

$$W = K_1 \times (\text{F-OSU-HWRL }(X) - \text{V-OSU-HWRL})^2 + K_2 \times (\text{F-NEESinc }(X) - \text{V-NEESinc})^2 + K_3 \times (\text{F-Client }(X) - \text{V-Client})^2$$
$$= K_1 \times [(X_1 - 10\%) \times 10 + (X_2 - 30\%) \times 4 + (X_3 - 30\%) \times 7 + (X_4 - 30\%) \times 4 + (X_5 - 10\%) \times 0]^2 + K_2 \times [(X_1 - 0\%) \times 10 + (X_6 - 10\%) \times 7]^2 + K_3 \times [(X_1 - 30\%) \times 10 + (X_2 - 50\%) \times 7 + (X_3 - 50\%) \times 7 + (X_4 - 50\%) \times 7 + (X_5 - 10\%) \times 7 + (X_6 - 50\%) \times 10]^2$$

Then the global coordination problem (Equation (5)) can be expressed as:

$$\begin{cases} \text{Minimize} : W \\ \text{s.t.} \\ X_3 <= 30\%. \\ (\text{The final value is less that } 30\%) \end{cases} \tag{5}$$

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 10 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 the necessary expertise and experience. Further convergence may not be obtained if weight factors are not set up properly.

**Step 7: Decision Making**

After one cycle of negotiation, the global coordination result ($X^*$) can be formed and 'downloaded' to all stakeholders. Each stakeholder can then compare their value against the global result. If all are satisfied, then a temporary globally consistent result is achieved, and the experimental set up proposed at the very beginning of the process 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 network, resulting in breakdown of the collaboration.

## 4. Summary and Discussion

A risk-based approach [1] has been developed to facilitate the coordination and negotiation among distributed stakeholders in collaborative design. The theoretical framework and design methodology is presented in Part I [1]. This companion paper (Part II) focuses on the application of the concepts and theoretical development in Part I to the NEES-sponsored collaborative research network as described in section 1. The application shows that the risk-based coordination model can provide a systematic, well-structured process to perform the global negotiation. For changeable risk items, the negotiation process can help stakeholders modify their decision space via risk probability consistency. For nonchangeable risk items, the method can obtain more reasonable results, and further assist stakeholders in making better decisions. Arbitrators can choose different negotiation criteria based on the network structure and interaction flows as long as all stakeholders agree.

Examples are used from the NEES-sponsored collaborative research network environment. However, 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) some stakeholders cannot accept others' initial risk evaluations; (4) stakeholders are willing to collaborate and desire a negotiation that involves compromise.

Compared to the simulated processes presented here, the practical negotiation process is highly complicated. For a more complex network structure, the coordination method (Equation (19) [1]) is still applicable although more expected risk functions or constraints are involved likely requiring expansion of the method. Because this is an iterative process, one potential problem is that time is needed in order to reach an agreement. Negotiation efficiency then becomes another important issue, and some techniques, such as decomposition and sub-negotiation, have been developed, but they are not usually based on risk. Thus more research is needed.

In complex decision making, performance, cost, and schedule should be considered simultaneously when trading off different alternatives, since they are internally related. In addition, risk is another important decision factor, and is directly associated with each of the previous factors. Our current work aims at modeling performance risk, cost risk, and schedule risk, and then integrating them based on a monetary measure to yield a consistent framework for collaborative decision making in distributed product development environment.

## Acknowledgment

Partial support from the Oregon State University Mechanical Engineering Department is gratefully acknowledged. The authors would like to give their sincere thanks to the colleagues at the NSF/NEES-Sponsored Tsunami Research Facility housed at the O.H. Hinsdale Wave Research Laboratory at the Oregon State University for sharing information and especially the assistance of Site Operations Manager, Melora Park, with the manuscript. Operation and maintenance of the OSU NEES facility is supported by the George E. Brown, Jr Network for Earthquake Engineering Simulation (NEES) Program of the National Science Foundation under Award Number CMMI-0402490.

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### Yuming Qiu

Yuming Qiu received his BS in Mechanical Engineering and Computer Science from the University of Science and Technology of China. He received his MS in Mechanical Engineering from the University of Science and Technology of China in 2001. He is currently a PhD candidate in Mechanical Engineering at Oregon State University (OSU). Yuming's major areas of interests are computer-aided design and manufacturing, risk-based design, collaborative system design, and optimization. His publications have appeared in the *Chinese Mechanical Engineering Design*, *Robotics*, and the *Proceedings of the ASME International Design Engineering Technical Conferences*. Besides his Ph.D program, Yuming is actively involved in the Industrial Assessment Center at OSU to help the Oregon manufacturing companies improve their energy efficiency.

### Ping Ge

Professor Ge obtained her BS and MS in Automotive Engineering from the Tsinghua University, Beijing, P.R. China, and her PhD in Mechanical Engineering from the University of Southern California. She joined as a faculty member, the design/mechanics group at the Oregon State University in 2001. Professor Ge teaches engineering design courses and supervises design projects at both undergraduate and graduate levels. Her research interests include design theory and methods for designing sustainable systems, negotiation support in collaborative design, and human and social dynamics in design teams. Her work has been published in the *Journal of Mechanical Design, Journal of Engineering Design, Journal of Design Research, and Nuclear Engineering Research and Design.*

Professor Ge is the elected secretary of the ASME design theory and methodology committee in the Design Engineering Division, and an active member of ASME, ASEE, and Design Society.

**Solomon C. Yim**

Professor Yim received his BS in Civil Engineering with honors from Rice University, his MA in Mathematics, MS, and PhD in Structural Engineering, Mechanics, and Materials from the University of California at Berkeley. Prior to joining Oregon State University (OSU), Dr Yim conducted industrial research for three years at the Exxon Production Research Company in Houston, TX. He has been a faculty member at the School of Civil and Construction at OSU since 1987. Dr Yim was the Principal Investigator (PI) of the design and construction of the NSF Network for Earthquake Engineering Simulation Tsunami Research Facility (NEES TRF) project (2000–2004) and is the PI of the NEES TRF Operation and Maintenance Project from inception (2004) to present. He served as a founding member of the NEESinc Board of Directors (2004–2006) and continues to serve on various committees in the organization. Dr Yim's responsibilities in the O&M project include operation and maintenance of the facility, scheduling, budgeting, and personnel assignment for experiments at the facility.