A distributed linking system for supporting idea association during the conceptual design stage

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Design is an interactive endeavor involving the evolution of ideas between two or more participants in discussion, especially during the conceptual design stage. Idea association is an important behavior for generating diverse ideas through the dynamic exchange of varied knowledge possessed by the participants. To better understand the dynamics that take place, this research applies a cognitive theory (role playing) that models the distributed interactions. By using the Dynamic Agent Role Interplay System (DARIS), some computational components within the distributed interactions are computed and evaluated. Finally, a distributed linking model named Dynamic Idea Maps II (DIM-2) is computerized to support the idea association in a distributed collaboration environment. The computational mechanism will be elaborated by means of a design experiment.

Keywords: distributed design, artificial intelligence, case based reasoning, computational models, conceptual design

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Idea association, or the association of ideas, is originally attributed to the Ancient Greeks, even Aristotle. During the design process, designers apply idea association to generate ideas, and then interact with the other participants (Lai, 2005a). Idea association can be regarded as the catalyst that triggers the interaction among the participants. By

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linking the designer's long-term memory internally and the various participants' knowledge externally, diverse design ideas can be generated.

The issue of *linking* is the first step in understanding such an interaction of idea association. The process of linking is called *linking process*. The linking within the idea association involves a series of actions and reactions by the participants according to the ideas they encounter (Lai et al., 2005). Idea association is regarded as a reflective reaction based on the breadth of the designers' knowledge and the situations in which they find themselves (Osborn, 1963). In the linking process, distributed knowledge and information can be linked dynamically.

In the computational domain, *agents* (or *software agents*) are autonomous entities that have reactive and communicative capabilities to interact with external and internal situations. This leads to our approach: applying the agent technology to build a distributed linking model of a multi-designer collaboration environment. This will be elaborated in the following sections.

1 Background review

1.1 Idea association

'Idea association is a method by which one idea leads to another idea by linking long-term memory' (Webster Dictionary). Since ancient times idea association has been considered an important step in linking internal human thought with the external living environment (Rapaport, 1974). Linking is both the process and the result of idea association and is the key factor for understanding its issues. Several researches from the fields of philosophy and psychology have emphasized the importance of 'linking' within idea association. For example, Leibniz (1703) argued that idea association sought to comprehend the emerging unity of reason and cause by means of linking. Locke (1690) believed that idea association is a behavior of intuition and reflection, which links ideas to human knowledge. From behavioral observation, Lewin (1922) employed topology to explain the linking relationships between environmental experience and human sensation. All these researches present different approaches for defining and clarifying idea association; but with one concept: linking.

To solve design problems, idea association is used to 'link' the design ideas of the participants according to their individual long-term memory and their specialized knowledge (Osborn, 1963). The linking behavior of idea association involves the interaction of both individual knowledge and set-of-knowledge. Such dynamic interactions engaged with distributed knowledge are called *distributed interactions* (Chang and Lai, 2004). The Ancient Greeks organized the linking of diverse ideas into three principles: *similarity*, *contrast* and *contiguity*. The three principles provide the effective idea-linking strategies used in conceptual design (Lai, 2005a).

1.2 Agent

To help solve the distributed interactive nature of our problem, the concept of software agents and their applications are brought into our implementation considerations. Briefly speaking, an agent is an autonomous piece of software that senses and acts on the environment in which it is situated. Wooldridge and Jennings (1995) contend that an agent system should be composed of social ability and reactivity. The three important characteristics of agents are autonomy, reaction, and communication.

Different agent frameworks are determined by the domain problems and their distributed behaviors. For example, Deen and Johnson (2003) provide a cooperating knowledge-base system model based upon agents, cooperation blocks, and cooperation-block hierarchies. Schroeder (2000) uses communicating-agent animation and the relationships between agents and spatial distance to visualize the argumentation process. Each agent has its own different situation and thus particular knowledge about the corresponding environment. The resulting cooperation between the agents forms a network of distributed cooperation.

Agents are also used in collaborative and dynamic design situations that are similar to our approach. Ligtenberg et al. (2001) advise a multi-actor-based land use model to deal with the allocation problem of spatial planning. Liu et al. (2002) and Anumba et al. (2002) propose collaborative design environments, in which designers and software agents interact with each other to tackle various design problems. Another example is the conceptual framework of object-agents proposed by Aly and Krishnamurti (2002), where each object-agent is a design object activated to perform design tasks. To focus on distributed interaction in the design process, an agent-based framework called DARIS (Chang and Lai, 2004) employs role-play theory to frame the action and reaction among diverse sources of design knowledge. DARIS provides the means to implement our idea association.

Generally, in computer science, agents or multi-agents are used to implement distributed interactions. Without the barriers of geographic limitations and different time zones, these knowledge entities (human or machines) involve distributed interactions, and thus the process of idea association. For this reason, we feel that the agent technology is suitable for providing the computational mechanism needed to implement the distributed linking model described in this paper.

1.3 Summary

Idea association involves distributed interactions by a group of participants. Agents (computer software) provide the computational mechanisms to implement the distributed interactions of idea association. However, considering the reactive nature of idea association, it is often hard to analyze the distributed interactions in an actual design situation. To understand the distributed interactions better, we need to investigate the behavior of idea association, or more specifically, the behavior of 'linking' ideas, by using the computational approach.

To further explore the behavior of idea association in the next section, a distributed linking model designated DIM-2 is proposed and elaborated in Section 3. In Section 4, the agent-based framework (DARIS) will be presented and illustrated. In Section 5, by employing DARIS, the distributed linking model for supporting idea association is computed and evaluated. Section 6 will elucidate how DIM-2 is used in linking design ideas in a practical example. This is followed by a discussion and summary in Section 7.

2 Design process as linking ideas in the conceptual design stage

As the design process is an evolution of many ideas, idea association plays an important role in linking and generating diverse design ideas during the conceptual design stage. By linking the designers' long-term memories internally and the various participants' knowledge externally, diverse and evolving design ideas are generated. These design ideas will serve as leads to development of possible design alternatives (Petrovic, 1997). Focusing on the idea association (or 'linking' ideas) described above, this section will further explore the usage and applicability of idea association in the conceptual design stage.

2.1 Linking ideas using design cases

From the Greek, the word 'idea' means 'the appearance of a thing'. Rhodes (1961) defines idea as: '… a thought which has been communicated to other people in the form of words, paint, clay, metal, stone, fabric, or other material.' Besides communication, ideas need to be related to the task at hand and they need to provide a solution for a design problem (van der Lugt, 2000). Therefore, an idea is considered as a solution for solving a specific problem within a given task, including design problems, abstract concepts and concrete examples (Lai, 2005b). By applying different media (such as sketches, text, keywords, or photo-images), an idea can be effectively represented from different points of view (Figure 1).

There is a tendency to use design cases as references and to extract past experiences to generate ideas (Maher et al., 1995). Designers are used to decomposing a design into several architectural elements and using the attributes of these elements as keys to search for relevant ideas within a particular design case (Lai, 2005a). With this approach, linking idea can be treated as searching for relevant ideas among design cases.

Humans are unique in their capacity to use symbols to represent the meaning of ideas and to construct relationships between ideas that explain how things appear or function (Novak, 1991). In architectural design, designers are used to applying a domain's conceptual vocabulary as symbols to represent these attributes and elements within the design context, and construct their relationships accordingly (Oxman, 1994, 2004) (Figure 2). These ideas and their relationships mostly contribute to a designer's long-term memory.

2.2 Linking ideas using the three principles of idea association

As mentioned before, the three principles of idea association: similarity, contrast and contiguity, are used to link ideas (Lai, 2005b). Similarity principle links ideas with similar attributes; conversely, contrast principle links different ideas based on their dissimilarity. The reasoning relationship between different ideas can be linked using the contiguity principle. However, these principles can differ according to the context and type of ideas that are exchanged.

In the idea association process, designers apply the similarity principle to link design ideas with 'similar' solutions. However, the contiguity principle can be applied to find the same solutions for ideas with different design problems. Because designers often describe design concepts using conceptual vocabulary (Oxman, 1994), contrasting conceptual

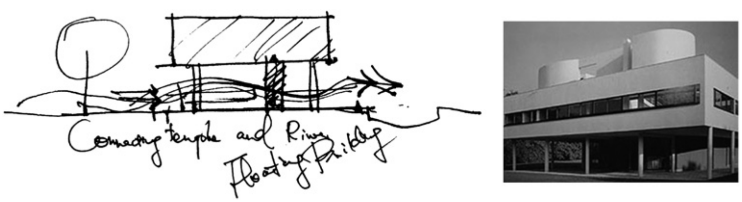

Figure 1 A design idea in the conceptual design stage

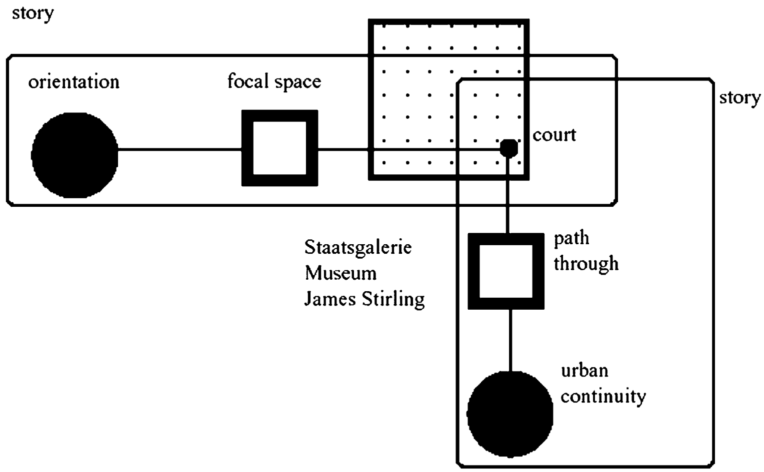

Figure 2 Two design ideas of an architectural precedent (after Oxman, 1994)

vocabulary can be used to link contrasting design ideas, such as public and private, solid and void, linear and center, etc. Consequently, these three principles embody the different relationships among the design ideas.

2.3 Linking ideas as role-playing

In our pilot study (Lai, 2005a), idea association involved dynamic action and reaction of the participants' internal and external knowledge through a linking process. Role-playing is a natural choice for our representation purposes. For example, in the process of idea association, designers always play different roles and then utilize the different principles of linking described above to connect and generate diverse ideas. For example, when designing a house, designers sometimes play the role of the client to link conceived ideas with a real-life situation, before slipping back into their primary role of designer and exploring further design possibilities suggested by the experience.

Linking ideas tends to focus on how to react to distributed knowledge through dynamic interactions. By studying such interactions through role-playing we can gain a greater understanding of the process of idea association in the conceptual design stage. In cognitive psychology, the theory of role-playing (Yardley-Matwiejczuk, 1997) provides an important insight into distributed interactions, including multi-knowledge interaction, engagement and situated analysis.

2.3.1 Role-playing

Role-playing can be considered a way of approximating a 'real life' episode or experience during a process of action and reaction (Chang, 2006). Chang and Lai (2004) summarize the three important mechanisms of role-playing: *situation*, *engagement* and *scenario-based interaction*. Situation is what people encounter in real life or construct during experiments; depending on the situation, people act or react accordingly. The interactions between people are called scenario-based interactions. Engagement (*as-if*) represents the induction on the acting that the actors make during role-playing. The three mechanisms help us understand the distributed interactions of idea association. A description of each mechanism is shown below:

- Situation: Situation of role-playing investigates the behavior of designers encountering different design situations. Such design situations influence the participants' decisions on which role they play and which principle(s) of linking they apply.
- Engagement: The main behavior of role-play engagement is induction. By inducting different roles, designers can engage in a real design situation to link ideas.
- Scenario-based interaction: Based on the specific context of the given circumstances, designers interact with each other and with the material of the play during the design process.

In situation, linking ideas can be separated into a set of plays and interplays between internal and external knowledge. This leads to a scenario-based interaction that will be used as the model for describing the linking process of ideas. Engagement will be the concept for realizing the principles of linking different knowledge and the idea it is associated. Following the concept of interplay, this can be further elaborated for the linking mechanism.

2.3.2 Interplays in the linking process

Linking ideas, similar to role-playing, always engages the 'as-if' approach and act/react according to the internal design knowledge and external design situation. Therefore, each role can interplay with itself, other roles and the design environment (Chang, 2006). With the theory outlined by role-playing, we can identify the three important mechanisms of role-playing with respect to two interplays: *internal interplay* and *external interplay*. Through the linking process, participants can link ideas within these two interplays. The two interplays are described below:

1. Internal interplay: During internal interplay, each participant plays different roles and uses different design knowledge to link ideas to

the long-term memory. After many linkages have been made, the main player will always select the most connected idea as the outcome.

2. External interplay: To generate ideas in conjunction with those of other participants, each designer interplays with the other participants as well as the external design situation. The interplay also directly encourages the designer to play different roles and use different design knowledge to link their ideas.

During the role-playing process each designer will encounter reactions invoking further learning processes that will evolve into different design ideas during the linking process.

2.4 Toward a distributed linking model

Two lessons are learned from the distributed characteristics as well as the two interplays of interaction described above: when treating ideas as entities, linking is a distributed behavior; and the interaction involves both internal knowledge and the external situation, which can be refined at the different levels of interaction. With this understanding, we can define a linking model for its representation level as well as its conceptual framework.

3 DIM-2: a distributed linking model

To link ideas in the conceptual design stage, *knowledge representation* represents design ideas and memory organization possessed by the participants. The *linking principles* allow the participants to associate diverse ideas differently. Through the *dynamic linking process* (or simple *linking process*) during internal and external interplays, participants can interact with various design situations. Finally, participants can engage in *linking interactions* to learn through competition and the evolution of their ideas. Therefore, knowledge representations, linking principles, linking processes and linking interactions form the distributed interactions of idea association. These four components form the basis of our approach toward a distributed linking model (Dynamic Idea Maps II or DIM-2), which supports idea association during the conceptual design stage.

Autonomous, reactive, and communicative behavior agents can participate in the process of idea association to interact with internal and external design situations. The relationships among agent technologies and the distributed interactions of our linking model and idea association are shown in Figure 3. The mechanisms of the four components are described in the following section.

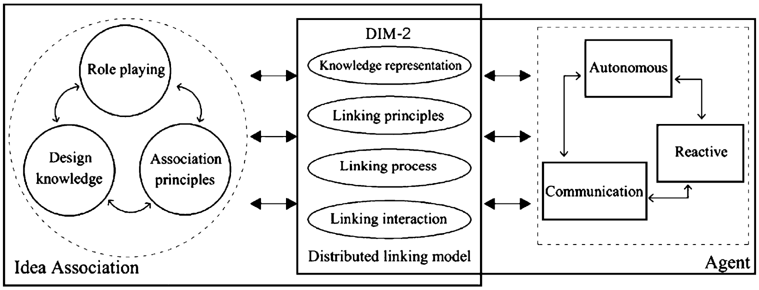

Figure 3 The relationships among idea association, agent and DIM-2

3.1 Knowledge representation

In DIM-2, *Issue-Concept-Form* (ICF) schemata proposed by Oxman (1994) provide a suitable mechanism for representing design knowledge as design ideas within prior design cases. These three properties can be respectively analogized as design problems, abstract concepts and concrete examples, as described above.

3.1.1 ICF schemata and characteristics

ICF schemata focus on the conceptual knowledge embedded within prior design cases. They represent design knowledge by decomposing prior design cases into separate independent chunks (called stories). Each story can be considered as a design idea (or *idea entity*), including the three *knowledge entities*. The knowledge entities are the *issue*, the design *concept* and the *form* of solution as described below:

- Issue: The design issues are related to the design tasks that are deliberated by the designer. It offers a convenient term to identify particular points in design problems.
- Concept: The design concept is the formulation of an opinion in relation to a design issue or a design sub-issue. It is an abstract form of ideation related to the design task.
- Form: The form is the specific design artifact that materializes the solution principle. It is important to note that this is one element of the total building design that directly relates to the design issue or sub-issue.

By linking the three knowledge entities (issue, concept and form), different idea entities are connected to each other (Figure 4). Cross-contextual linking permits an idea entity in one design case to be cross-linked with another idea entity in other design cases. These idea entities form a lexical vocabulary of issues, concepts, and forms related to the design

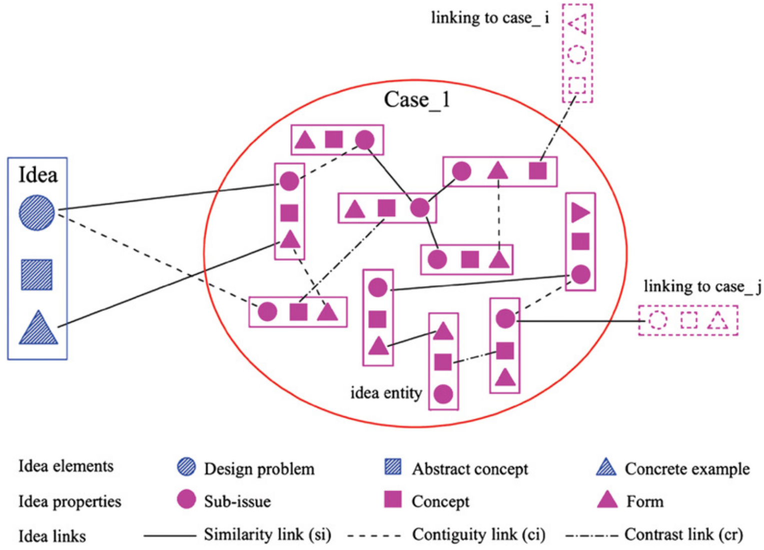

Figure 4 The relationships among idea entities, knowledge entities and principles

problem. These characteristics provide the computational mechanisms of the linking principles in DIM-2.

3.1.2 ICF map as memory organization

The idea entities are organized into a graph-like structure of nodes and links. Such structures are called *maps*. The map of idea entities represented by the Issue-Concept-Form structure is called an *ICF map*. Three sets of ICF maps (inclusive ICF maps, *internal ICF maps* and *external ICF maps*) represent the different design knowledge possessed by the role, the designer and the participants, respectively. When the nodes of the maps are the knowledge entities (issue, concept, or form), these maps are called *knowledge maps*. The ICF and knowledge maps together form an individual *idea map*. The knowledge maps, the internal ICF map and the external ICF map will be described in detail later. The types of links among these idea entities are represented by the principles (similarity, contrast and contiguity). Therefore, from any issue, concept or form node in the idea structure, any related idea entity can be linked (Figure 4).

The issue is represented by the domain conceptual vocabularies. The concept is represented by a group of domain concepts with descriptions, and the form is represented by a solution that can satisfy the issue with the mechanism embedded in the concept. That is to say, the ICF map explicitly organizes a designer's memory so that it links design ideas in a particular manner.

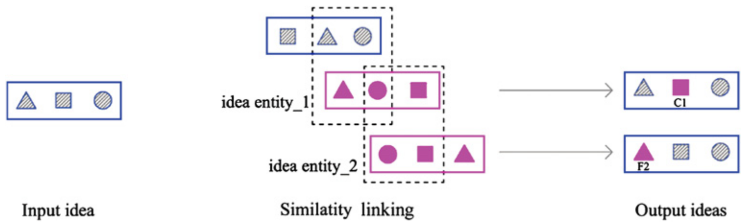

Figure 5 Similarity principle

3.2 Linking principles

The three principles for linking idea entities are: similarity, contrast and contiguity. Each linking principle has an individual linking mechanism and purpose for linking idea entities. To provide a more semantic and flexible linking mechanism, any two properties within an idea entity can have a semantic matching with two properties of any other idea entity.

3.2.1 Similarity

Similarity focuses on linking other idea entities with similar design solutions for a specific design problem. By matching the similar conceptual vocabularies of any two properties (issue and concept, or issue and form), all related idea entities with new form properties or new concept properties will be linked (Figure 5).

3.2.2 Contrast

Contrast focuses on linking other idea entities with contrasting design solutions including concepts and forms. By matching the similar conceptual vocabularies of two properties (issue and contrast concept), all related idea entities with new contrast form properties will be linked (Figure 6).

3.2.3 Contiguity

Contiguity focuses on linking different design problems with the same design solutions. By matching two similar properties (concept and form), all related idea entities with new issue properties will be linked (Figure 7).

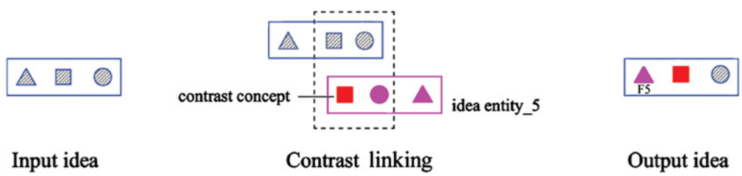

Figure 6 Contrast principle

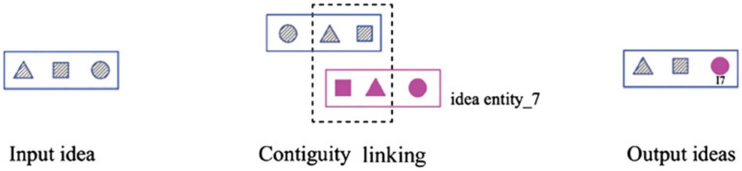

Figure 7 Contiguity principle

Three knowledge maps with a graph-like structure provide various matching mechanisms for similarity assessment. The purpose is to provide a dynamic and effective textual matching. The three knowledge maps, which function as a dictionary, are the *issue map*, the *concept map* and the *form map* (Figure 8).

3.3 Linking process

The linking process involves two levels of interplay: internal interplay and external interplay (Figure 9). In these two interplays, participants engage in idea linking and idea decision-making through different network topologies. The details of these two interplays are described below.

3.3.1 Internal interplay

During internal interplay, designers link their design ideas to their long-term memory in order to generate further ideas. According to the different design situations, designers can play different roles to link ideas to their individual memories (or idea maps) by applying different linking principles and using different skills. By playing the different roles, an ICF map composed of the collective knowledge of the different roles is generated. This is called an internal ICF map.

When more than one linked idea is found during this process, the final idea will be decided on according to the number of idea links that reflect the preference of the interplay. If the number of links is the same, the idea can be randomly selected. Different roles have different knowledge maps for interpreting the conceptual design vocabularies within the entities of issue, concept and form.

3.3.2 External interplay

External interplay takes place between different participants and design situations (including a design task, design issues, and time duration). In

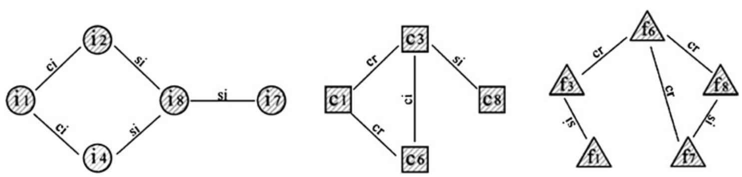

Figure 8 Three knowledge maps: issue map, concept map and form map

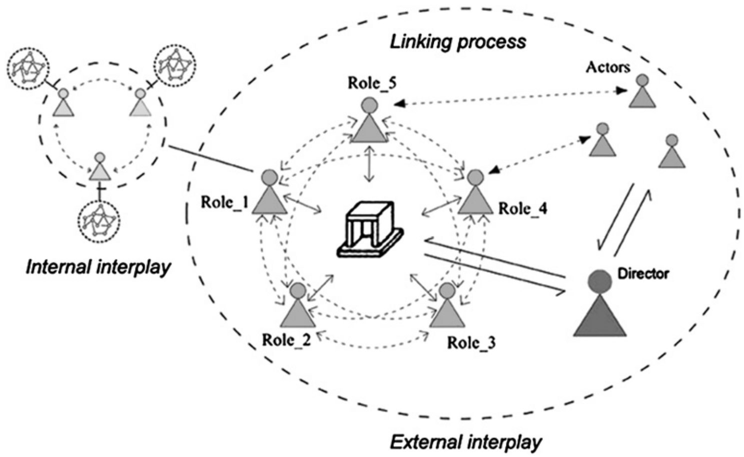

Figure 9 Two levels of interplays in a dynamic linking process

a typical design situation, a designer (role) generates an idea entity, and puts the idea entity 'onto the stage'. The other participants (roles) react to the idea entity in order to link and generate new ideas. Then, the designer changes roles to respond to the external interplay. During the internal interplay, the designer applies different linking principles, an internal ICF map and knowledge maps to link ideas. Through the interplay of the different participants, an ICF map composed of the collective knowledge of the participants is generated. This is called an external ICF map.

There are four network topologies in the linking process: ring, star, peer-to-peer and cluster (hierarchy) (Chang, 2006) (Figure 10). Depending on the situation, the designer can change the different network topologies, in either the external or internal interplay. For example, during a brainstorming session, participants can apply a ring-type linking process to link ideas in the external interplay. During internal interplay, the designer can also apply the ring-type linking process to interplay with his own imagination. Each network topology has different communication mechanisms among the roles to exchange information.

3.4 Linking interactions

Linking interaction can be considered as a learning process among the participants. In the linking process, either design ideas are competing with others for a particular design issue or the design concepts will be influenced (evolved) by other winning ideas. These form the base for our learning types: competing and evolving. Competition among the design ideas are treated as the participants (roles) who are competing to survive in the linking process. Designers and ideas start to evolve into

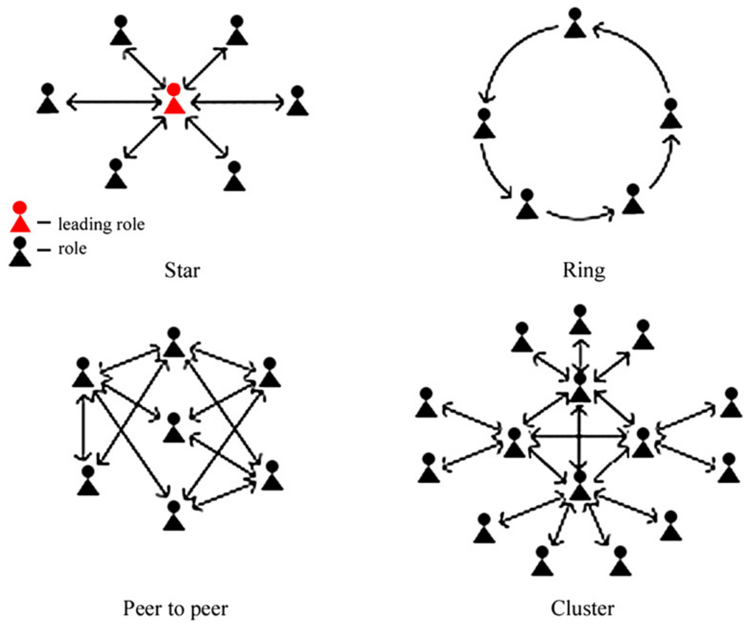

Figure 10 Four network topologies: star, ring, peer-to-peer and cluster

entirely different areas of knowledge or preserve the core ontology of the original design in the evolving process.

To realize DIM-2, this research implements a distributed linking system based on the DARIS system framework (mentioned above) for distributed interactions in a multi-designer collaboration environment. The mechanism and framework of DARIS technology will be described below following a description of our computational approach to DIM-2.

4 *DARIS: a distributed interaction framework*

DARIS is an agent-based role-play framework for implementing the distributed interactions in a multi-designer collaboration environment. Based on the separation of role/actors and stage/scenes (Chang, 2006), DARIS describes the individual interactions in terms of their capability and situated reactions. DARIS is composed of three interactive layers: *internal*, and *external design situation layers*, and a *communication layer*. Five different agent entities (*user*-, *role*-, *director*-, *scene*-, and *stage-agents*) interact dynamically in the three computational layers (Figure 11).

The internal design situation layer contains a set of role agents. Each role agent has its own role knowledge and set of skills, which react to the situation assigned to it. Then, according to the design situation,

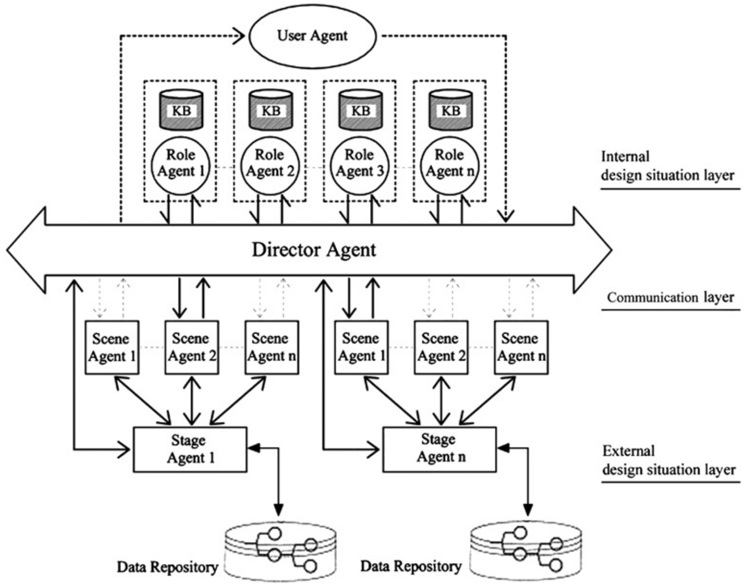

Figure 11 The agent-based role-play framework of DARIS (after Chang and Lai, 2004)

the outcome of the reflective action is reported back to the communication layer. The external design situation layer, comprising the stage-agents and scene-agents, describes an interplay environment (when, where and who), with which the role agents will involve themselves. The input of interplay comes from the communication layer and stores the in-play objects with the data repository objects.

The communication layer provides communication for the role agents as well as for the role agents and the play. This layer contains only one agent who will coordinate (direct) all the plays and the role agents. These agent entities are described in the following section.

4.1 Agent entities

In DARIS, five agent entities interact with each other within the three layers. They are:

- Director Agent (DA): The director agent, who comprises a dominant User Agent (UA) and an agent register, plays the same role as the director of the play. The major task of the director agent is to be responsible for the other agents' participation and to guide the process of the whole play.
- User Agent (UA): The user agent provides a vehicle for directly interacting with the user as well as facilitating the agents' interactions. After role agents finish the user specified task, the user agent is notified and relays the result to the user.

- Role Agent (RA): Each role agent is regarded as an actor who plays a role in a particular scene. An RA has an individual knowledge base, which includes an actor's and a role's design knowledge, to solve specific design problems.
- Scene Agent (ScA): The scene agent controls three main tasks: defining the role-list, enforcing the time schedule, and evaluating the interplay outcomes of the role agents by comparing them with the design goals. There is only one current ScA within any StA action.
- Stage Agent (StA): The stage agent ensures the sequential order of the ScA. Once the outcomes of the interplay are found satisfactory by the ScA, they are sent back to the StA. The StA then either sends the outcomes back to the UA for user-approval or stores the acts in the data repository.

The script constitutes a list of events that compose a stereotypical episode. During these sequential events, the agent entities dynamically interact with each other depending on the different design situations.

4.2 DARIS technology

The agent-interactive environment of DARIS is implemented on top of JADE (Java Agent DEvelopment Framework) with JESS (Java Expert System Shell) as the reasoning engine inside the agents. The ACL (Agent Communication Language) among these agents is based on the FIPA (Foundation for Intelligent Physical Agents) communication language.

Each UA has an individual FIPA platform to control these agents in DARIS. On each platform, these agents are active in the JADE run-time environment (called container). Each DARIS agent is realized as a JADE agent that can communicate with all other agents using the communication facilities provided by JADE. To communicate among these FIPA platforms, UAs use the HTTP message transport protocol to exchange ideas emanating from different geographical locations.

5 Computing DIM-2 using DARIS

To implement the distributed linking model, we map the four components of DIM-2 to the mechanisms of DARIS using these three strategies. They are (1) combining the knowledge base in the RA with the design knowledge and linking principles in the internal design situation layer; (2) constructing the knowledge of the ScA and StA by editing the script in the external design situation layer; and (3) selecting a network topology of the linking processes in the communication layer. Once the linking process has been completed, the communication between the RAs within the internal design situation layer will be used for competing and evolving the RAs' knowledge. Finally, human participants (DA and UAs) can dynamically interact with the internal and external interplays to link and generate ideas in the linking process.

5.1 Combining the knowledge base in the RA with the design knowledge and linking principles in the internal design situation layer

The first step in integrating DIM-2 into DARIS is to embed the design knowledge based on linking ideas into the RAs of DARIS. Each RA's design knowledge base will then include the actor's design knowledge (an ICF map and three knowledge maps), and a role's linking principle(s) for linking the idea entities in a specific scene.

5.1.1 Constructing ICF maps and knowledge maps

According to Oxman (2004), one of the main sources for the acquisition of knowledge is written language and textual description. In a design-task scenario, participants are instructed to analyze written references related to prior design cases. Based on the participant's individual interpretation, design cases are decomposed into several idea entities, which are represented by Issue-Concept-Form (ICF) schemata. The analysis of the content of issue, concept and form, which are elicited from the texts in the form of an ICF map, is regarded as an agent memory (database) for linking ideas. Each form entity is accompanied by an appropriate media representation such as a photographic image (Figure 12).

For examples, while designing a single-family house, a participant had a design idea for solving the design issue 'circulation' using the concept 'linear' and 'connect'. As a result, the linked form 'bridge' is represented by a photograph of a house in Malibu designed by Roto Architects as one of the alternative solutions.

Each participant constructs three knowledge maps to interpret various conceptual symbols or vocabularies. In each knowledge map, these various conceptual vocabularies (symbols) are linked together through the three linking principles (Figure 13). For example, in the Concept map, the symbol 'connection' has a similarity relationship to the symbol 'union'. In the Issue map, the symbol 'lighting' has a contiguity relationship to the symbol 'view'.

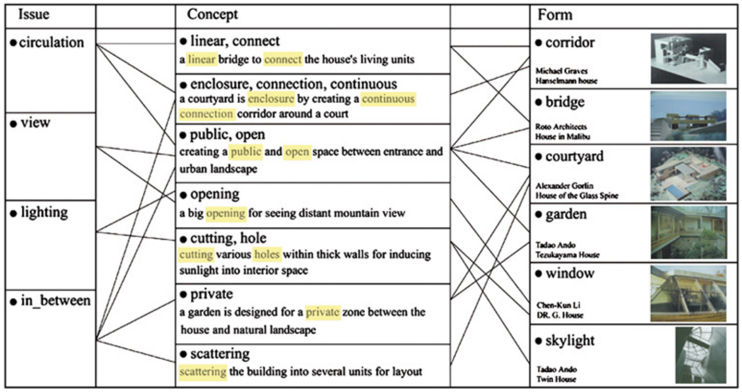

Figure 12 Constructing an RA's ICF map by a human participant

Participants can construct more than one set of maps (including ICF maps and three knowledge maps), and then embed these sets of maps with the knowledge bases of different RAs. Through the interplay of these RAs' knowledge bases, the participants (via UAs) can generate internal ICF maps within the internal interplays.

5.1.2 Constructing the knowledge bases of RAs

In addition to constructing the design knowledge of an RA, each RA should be endowed with one linking principle to link design ideas. These idea entities with an ICF map and keywords within three knowledge maps are all formatted as different sets of facts. The three linking

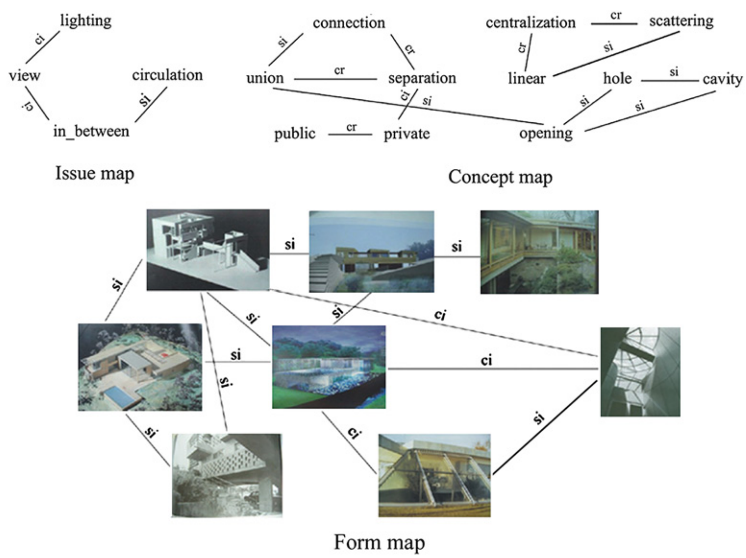

Figure 13 Constructing an RA's Knowledge maps by a human participant

principles are implemented using forward-chaining rules. These facts and rules are all stored in JESS containers.

To search for suitable RAs in a play, an RA's design knowledge is also composed of filters as *design skills* (or *skills* in short) within in either the actor or the role. These design skills are represented as a set of keywords. Each RA can extend its knowledge by assimilating new idea entities within the ICF map, or new conceptual vocabularies and their relationships within the three knowledge maps.

5.2 Constructing the knowledge of the ScA and StA knowledge by editing a script in the external design situation layer

Script is a structure for describing a sequence of events, which is composed of the related components that take place during the design process. By editing a script, these components can be matched to the knowledge of the ScA and the StA in the external design situation layer.

5.2.1 Editing a script

A script is considered as a guideline for a play in the idea association process and mainly includes a stage and several scenes. The stage is composed of a design task and its several deign issues, which need to be solved in each scene. The stage also depicts the time duration within each individual scene. Each scene is composed of the maximum allowed RAs (RA number) and skills required for its specific issue. The RA number provides information on how many RAs can participate in the scene. Skills provide information on what capabilities of the RAs are required to solve the design issue in the scene.

5.2.2 Constructing the knowledge of the StA and ScA

The components within stage and scenes described above are mapped to the knowledge of the StA and the ScA, respectively. The knowledge of the StA includes a design task, scene number, scene names (issue keywords) and time duration for each scene. Each ScA's knowledge includes the number and skills of the RA, which allow the Director Agent (DA) to search for suitable RAs to participate in different scenes.

The human agent who initiates a new play is assigned the role of director (DA) and is responsible for guiding the whole play. The DA is the only human agent who has the power to edit the script in the external design situation layer; this includes the power to terminate or to modify each scene during the process of the play. Through interplay with the DA and UAs, the ScAs will be able to store the outcome of the play as external ICF maps.

5.3 Selecting a network topology of the linking process in the communication layer

To exchange information among these agents, DIM-2 provides four network topologies (Figure 10) of linking processes in the communication layer. Based on the mechanisms of the FIPA agent communication language (ACL), each agent has its individual communicative action for reacting to various information in each network topology.

By using different performatives of FIPA ACL (such as CFP, Propose, or Inform), these agents can exchange information in both the external and internal interplays. Consequently, the UAs and DA can dynamically select a network topology to generate ideas in the idea association process.

6 How do you play?

To explain how to play in the idea association process using DIM-2, we conduct an experiment where three human designers ($UA_{Lai,}$, $UA_{Teng\text{-}wen,\ and\ UAKuntai}$), who are located in different geographical locations, are involved in a brainstorming session. The purpose of this meeting is to develop a design strategy for the spatial organization of a single-family house by generating design ideas during the conceptual design stage. To address the four design issues of circulation, view, lighting and in-between, successively, the three UAs insert additional software agents (RAs) to help in the design task.

A play has three steps in the distributed collaboration environment of DIM-2. They are: initializing a play, editing a script, and directing a play. Each step has its individual window for participants to input related information, as described below.

6.1 Initializing a play

To initialize a new play, the Initial Play window allows UAs and the DA to input basic information in order to participate in the play (see left window in Figure 14). In the play, UA_{Lai} is a director (DA) guiding the process of the entire play. In the Initial Play window, UA_{Lai} selects a new play and inputs the play name. For $UA_{Tengwen}$ and UA_{Kuntai} to participate in the play after the play begins, they input the play name and their location (IP address). In addition, UA_{Lai}, $UA_{Tengwen}$ and UA_{Kuntai} should individually input the Actors' information for the

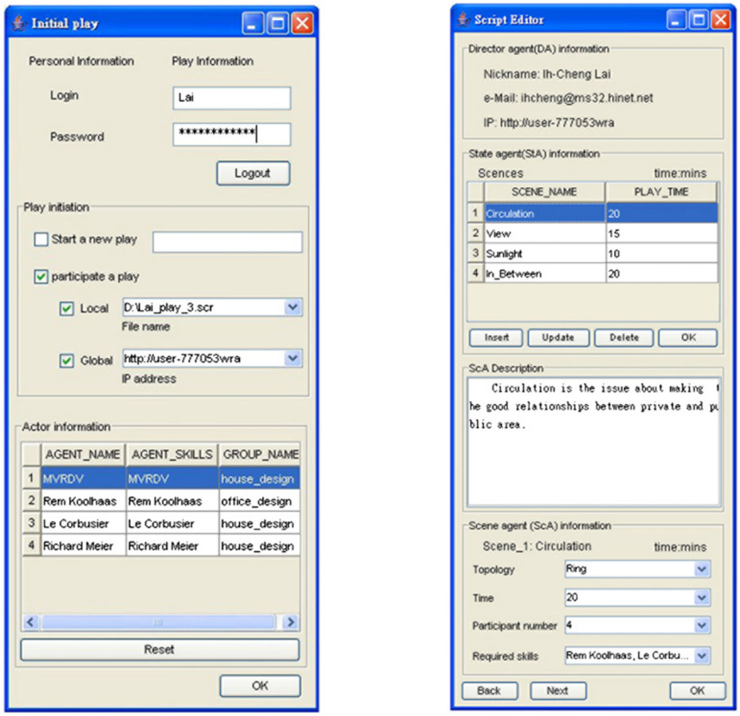

Figure 14 The Initial Play window and the Script Editor window

RAs' registration, including the agents' names, agents' skills and group name.

6.2 *Editing a script*

In the Script Editor window, only the DA (UA_{Lai}) of a given play can edit the script, which includes the knowledge of StA and ScA. Therefore, UA_{Lai} should input the StA's information, including the scene name and play time, in the Stage agent information frame (see right window in Figure 14). The scene name is a design issue for generating ideas. In this case, scene names include circulation, view, sunlight, and in-between. The play times are 20 min, 15 min, 10 min and 20 min, respectively.

UA_{Lai} also should input each ScA's information in the Scene agent information frame, including the number of participants and required skills. To exchange information among these agents, UA_{Lai} should also select one type of network topology for each scene. For example, in the 'Circulation' scene, the number of participants is not over four. The required skills are Rem Koolhaas, Le Corbusier, and house design. Also, these agents involve a ring topology linking process.

6.3 Playing as a linking process

After UA_{Lai} finishes editing the script, UA_{Lai}, $UA_{Tengwen}$ and UA_{Kuntai} start to generate design ideas in the Dynamic Idea Maps window. The Dynamic Idea Maps window includes three frames for the UAs' interaction. They are Play frame, System Status frame and Internal Interplay frame (see Figure 15).

The Play frame shows an external ICF map. The Status frame shows the linking information of the system. The Internal Interplay frame allows the DA and the UAs to input related information that link the diverse ideas by interacting with the internal interplay. In the Internal Interplay frame, the UAs and the DA should follow these four steps to generate a design idea related to the design issue 'circulation': (1) selecting an idea entity from the external ICF map, (2) selecting RAs and their linking principles for interplay, (3) inserting play time and topology in the internal interplay, and selecting an idea entity as an output from the internal ICF map. The new idea entity is automatically linked to the external ICF map.

In the Internal Interplay frame, UA_{Lai}, $UA_{Tengwen}$ and UA_{Kuntai} can also select 'automatic' to automatically generate a new idea entity following the same steps described above.

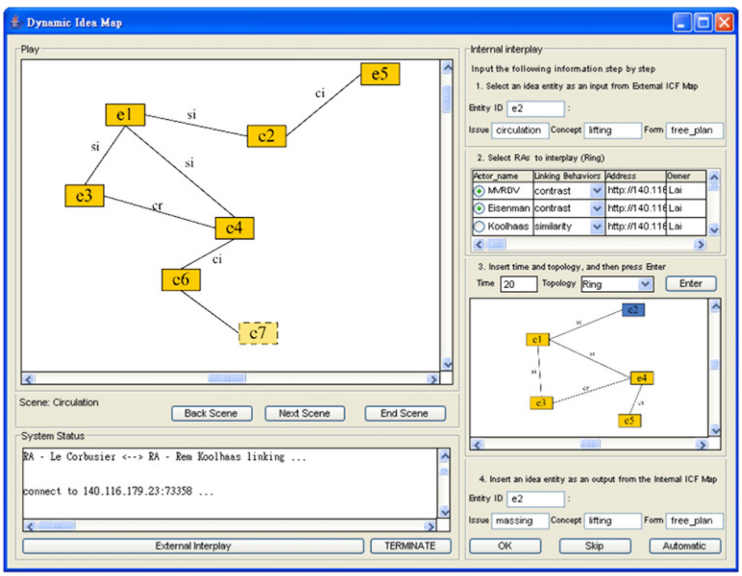

Figure 15 The Dynamic Idea Map window

UA_{Lai}, $UA_{Tengwen}$ and UA_{Kuntai} can see the script in the External Interplay window (Figure 16). However, only UA_{Lai} can modify the script during the process of the play, including a scene's issue, topology, time, and the RA's skills. If $UA_{Tengwen}$ and UA_{Kuntai} want to modify the script, they must request permission from UA_{Lai}.

When the time (20 min) is up, the outcome of this scene 'circulation' is shown in the Play frame (Figure 17). In the external ICF map, the description of each idea entity can be seen in the Idea Entity window.

7 Discussion and conclusion

By decomposing distributed interactions with actions and contents, our approach provides designers with a system where they can interact with different design situations during the process of idea association. By integrating agent technology, DIM-2 allows participants to dynamically link and generate diverse ideas in a distributed collaboration environment. Through the design experiment in the DIM-2 environment, we find some advantages that support idea association under real design situations:

1. Interacting multiple participants: DIM-2 provides three means for collaboration in the internal and the external interplays. They are human-to-human, human-to-machine and machine-to-machine. It will therefore be useful in the distributed interactions of idea association.

2. Connecting blocked linking processes: participants (human or machine) can dynamically change either the content or action to connect the blocked linking process, such as RAs' design knowledge, linking principles or topology types. If one RA has no idea entities, other RAs can automatically generate the next idea entity for output.

3. Recording the linking process to further the agents' learning: in DIM-2, the linking process can be recorded for the RAs' future learning, including competing, learning among the RAs and evolving

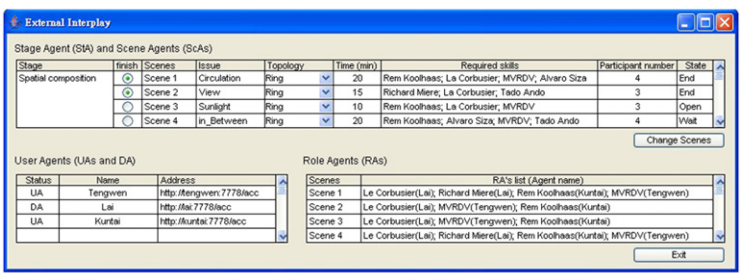

Figure 16 The External Interplay window

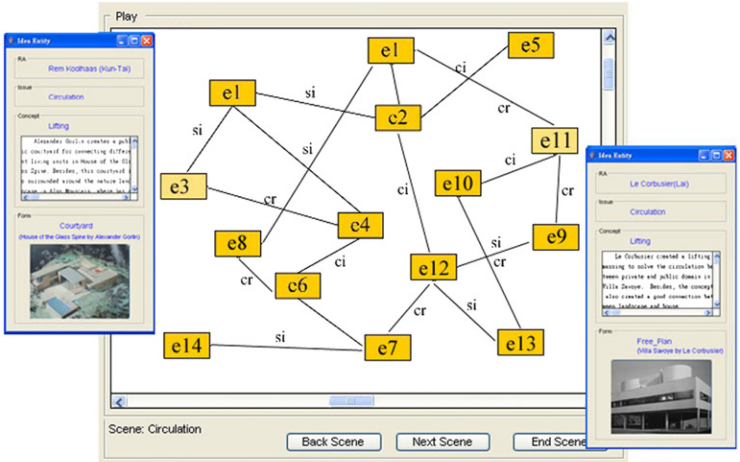

Figure 17 An external ICF map in the Play frame and two Idea Entity windows

learning within an individual RA's knowledge base. The recorded linking process allows designers to analyze the ICF maps in order to better understand the relationships between ideas and cases.

The generated ICF maps give designers inspiration in two different interplays, as well as allowing dynamic access to conceptual design knowledge within design cases. Because DIM-2 is not constrained by geographical limitations or different time zone barriers, it should be helpful to small design offices and design schools during the conceptual stage of their designs.

However, there are some limitations in implementing the distributed linking model. In real design situations, designers usually link ideas in a random jumping sequence among design issues ('flight of ideas'). In DIM-2, the design issues (or scenes) cannot be automatically changed due to the fixed order and time duration of each current implementation. In addition, the generated ICF maps, which contain lots of idea entities and links, are too large. This causes an information overload and graph layout problems. Consequently, how to re-organize the ICF map and how to dynamically jump across scenes will be our research for the future.

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