Knowledge Exploration in Design: Communicating Across Boundaries

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Abstract: The exploration and integration of information from multiple domains is increasingly important in the design process. For example, many engineering firms now use concurrent and life-cycle engineering design methods that emphasize the integration of software and mechanical engineering, manufacturing, marketing and distribution, maintenance and repair, disposal and recycling, and application (end-user) knowledge in order to create innovative and competitive artifacts and reduce design and development costs. Discovering how design participants explore and integrate information from multiple domains is a first step towards understanding how information technology could enhance this process. Based on field studies of four design situations in architecture, expert systems, telecommunications, and engineering design, this paper presents boundary spanning roles that emerge in the design context to support knowledge exploration. These roles provide access to information as well as filter and translate information across organizational, task, discipline, and personal boundaries. This paper further proposes a cognitive work model that could be implemented in information technology to support the boundary spanning roles design participants develop to cope with the complexity of knowledge exploration. This type of information system would support boundary spanning by providing advice on boundary spanning strategies, answering queries and presenting information based on boundary spanning roles, and performing gatekeeping functions.

1. Introduction

1.1 The Design Context

Due to today's mature markets, world-wide competition, fast technological changes, and stricter liability regulations, design situations increasingly include specialists from different domains as companies strive to create innovative and competitive artifacts and reduce design and development costs. For example, many engineering firms now use concurrent and life-cycle engineering design methods that emphasize the integration of software and mechanical engineering, manufacturing, marketing and distribution, maintenance and repair, disposal and recycling, and application (end-user) knowledge during the design process. No individual can acquire the current and rapidly-expanding knowledge from such a wide variety of domains and thus communication, or collaboration, among domain specialists has emerged as a fundamental component of the design process.

Domain specialists come to design situations with specialized knowledge and pre-existing individual and social patterns of work activities, language usage, and personal beliefs. That is, they have unique life-worlds[1] or domains. As design participants, they must collaborate and mutually explore and integrate one another's life-world and specialized knowledge so that they can come to a working understanding of their design situation and how the artifact will best support its various goals and constraints that emerge from it functional contexts such as manufacturing, marketing and distribution, maintenance and repair, disposal and recycling, and application (end-user) domains (Bucciarelli, 1988; Rasmussen, 1990; Sonnenwald, 1993; Peng, 1994).

A basic question therefore is: how can this exploration and integration of knowledge from different domains during the design process be supported by information technology? In many design situations, it may be difficult for participants to collaborate and mutually explore one another's life-world due to the uniqueness of each life-world. This uniqueness creates boundaries that separates

[1] *Life-world* is a term introduced by Schutz and Luckman (1973) to mean "the quintessence of a reality that is lived, experienced, endured . . . a reality that is mastered by action and the reality in which-and on which-our action fails" (Schutz & Luckman, 1973, p. 1).

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participants through differences in knowledge, language, expectations, motivation, and perceptions of quality and success. Design participants need to span these boundaries.

In this paper, related research in boundary spanning is first reviewed. Second, the qualitative research approach used to discover the boundary spanning roles design participants developed to cope with knowledge exploration is presented. Third, the boundary spanning roles that emerged in the design context are presented. Fourth, information technology to support design participants in these boundary spanning roles is discussed.

1.2 Previous Research

A conceptual framework for exploring this boundary spanning behavior is role theory. Goffman (1961) defined the concept, role, as "the activity the incumbent would engage in were he to act solely in terms of the normative demands upon someone in his position" (Goffman, 1961, p. 85). An individual may perform one or more roles and may change roles. Role performance, or role enactment, is the actual conduct of an individual while assuming a role. Role performance occurs primarily through interaction with others. Others have expectations with respect to an individual's role performance and these expectations help shape an individual's behavior. The individual's performance, in particular their communicative behavior, is the elementary unit of analysis in role theory.

A boundary spanning role is defined as "communication and information processing behavior between two or more networks" or groups (Fisher & Ellis, 1990, p. 293). Boundary spanning roles have been studied in other organizational contexts (e.g., Allen, Lee & Tushman, 1980; Tushman, 1977, 1979; Tushman & Katz, 1980). Boundaries are typically presented as formal project, department (or laboratory), and company (or corporate) boundaries. Boundary spanning roles identified include the internal star (individuals whose interaction with their project or department or organization members occurred more frequently than average), external star (individuals who had a high frequency of communication external to their project), and gatekeeper (individuals who had a high frequency of interaction both outside and inside their projects). Sociometric surveys and semi-structured interviews have been used to characterize the content and frequency of boundary spanning activity and its relationship to project and employee performance. Results from these studies all emphasize the importance of boundary spanning activity to high project performance generally (e.g., Allen, Lee & Tushman, 1980; Curtis, Krasner, & Iscoe, 1988; Kraut & Streeter, 1993; Tushman & Katz, 1980) but differences due to task type, task process, and organizational context appear to influence role characteristics and project and individual performance. For example, Hauptman (1986) proposed that boundary spanning activity in software development is not similar to boundary spanning activity in development or research projects in R&D organizations based on the results of a sociometric study of software development projects. Furthermore, because knowledge exploration is critical to the design process, it is important to understand the nature of information exchanged via boundary spanning roles in design. Therefore, it is necessary to study actual design situations to discover boundary spanning roles and relevant to design.

2. Research Approach

Because few studies have explored boundary spanning roles in design situations, four field studies of actual design situations in architecture, expert systems, telecommunications, and engineering design were conducted in order to develop a model that characterizes boundary spanning roles that emerge during the design process. The first two field studies involved case histories of design situations. Because design situations typically last from many months to several years, case histories provided the opportunity to study multiple, diverse design situations. To complement the retrospective case history data, data from two ongoing design situations were also collected.

2.1 Architecture Field Study

The design situation in the first case history focused on the construction of a single-family house over a ten-month period in 1983. Participants in this design situation included the new house owners and their family, a construction firm with four owner-employers, and an architect and his assistant. Membership within each group was stable (i.e., it did not change during the design process). The designer group was located in Boston, MA, several hours away from the construction site and users' current homes and work sites near Amherst, MA. Throughout the design process, a fast-track, "design-as-you-go" approach was used. In the fast-track approach, the architect created plans for artifact components as construction tasks proceed. Data for the case history came from the book *House* (Kidder, 1985). It was selected for analysis because of its wealth of data about communication among participants during a design situation. Descriptions of design tasks, interactions among the architect, builders, and owners (including the owners' extended family), participants' perceptions of the design situation, and design outcomes are provided in the 300-page book.

2.2 Expert Systems Field Study

The design situation in the second case history focused on the development of an expert system. called XSEL (the eXpert SELling assistant), that was intended to assist sales people in configuring computer systems which satisfy customer needs. End-users were sales people, their managers, and office staff at Digital Equipment Corporation (DEC) offices throughout the US; software designers and software engineers were employees at Carnegie Mellon University and DEC. New group members joined each group during the design process which occurred over a five-year period, from 1981 to 1985. Design methods used to create the expert system included the ETHICS (Effective Technical and Human Implementation of Computer-based Systems) participatory design method (Mumford, 1985) which prescribes activities that facilitate user involvement in the design process and an iterative/prototype design approach which prescribes a succession of development and evaluation tasks until a system contains a sufficient number of features to be labeled "completed."

Data for this case history included the book *XSEL's Progress: The Continuing Journey of an Expert System* (Mumford & MacDonald, 1989), which provides a history of the design situation from the perspective of a group manager, a business case study of the design situation (Leonard-Barton, 1987), published and unpublished papers by designers and developers (e.g., McDermott, 1982), an article on the culture of the corporation during that period (Rifkin, 1986), an interview with a participant, and several documents that describe predecessor design situations.

2.3 Telecommunications Field Study

The third design situation investigated took place in engineering organizations of a research and development (R&D) corporation that employs several thousand technical employees in the United States. The superordinate goal in this design situation was to create a telecommunications network architecture and management system that would support data, voice, and video communications. The design participants included approximately 7 electrical engineers, 1 marketing representative, and 5 telecommunication network analysts, and 45 end-users. They had bachelors, masters, and doctorate degrees in disciplines such as electrical engineering, operations research, and business administration, and their on-the-job experience ranged from 3 to 37 years. The designers and developers worked in separate office buildings, located up to 50 miles apart, and users worked in locations throughout the US. Most participants did not work full time on the project, others worked full time for intermittent time spans.

Multiple, coordinated research methods , including unstructured interviews, participant observation, document collection, sociometric surveys, and critical incident interviews, were used to gather data about communication. Using multiple methods provided flexibility for gathering data from a range of data sources, including design participants, others in the corporation, technical papers, meeting minutes, viewgraphs, and memoranda. Data from 41 unstructured interviews, 19 participant observation periods, 125 documents, 2 sociometric surveys, and 14 critical incident interviews were collected over a 14 month period.

2.4 Engineering Design Field Study

The fourth design situation analyzed took place in northern Europe; its goal was to create a new sensor to be used for environmental purposes. The design team included 27 participants with on-the-job expertise and technical degrees in mechanical engineering, chemical engineering, material science, electrical engineering, software engineering, production, environmental engineering and applications, and marketing. Over a 3-month period, semi-strucutred interviews were conducted with 24 participants. The average interview lasted two hours and during each interview, the participants described their design tasks and the nature and content of their work-related interaction. 154 such interactions were described: 134 of which were reciprocally-mentioned (i.e., participant A described interacting with participant B and participant B described interacting with participant A.)

2.5 Data Analysis

To analyze the field study data, a semantic concept analysis, empirical coding, and sociometric data analysis were done to discover who interacted with whom, the content of the interaction, and the meaning participants gave to the interaction. This multiple method approach appears to reflect the multi-perspective nature of boundary spanning in design perhaps more than any single method can. By looking at boundary spanning from multiple vantage points, as provided through interviews, documents, observation, and surveys, we may be more likely to discover the shared experiences and perceptions of design participants. Furthermore, by analyzing multiple, diverse design situations we may be more likely to discover general patterns that may be constant over a variety of design situations. As a result, new boundary spanning roles and boundary spanning roles not previously found in design situations, and the type of information exchanged via these roles during the design process was discovered.

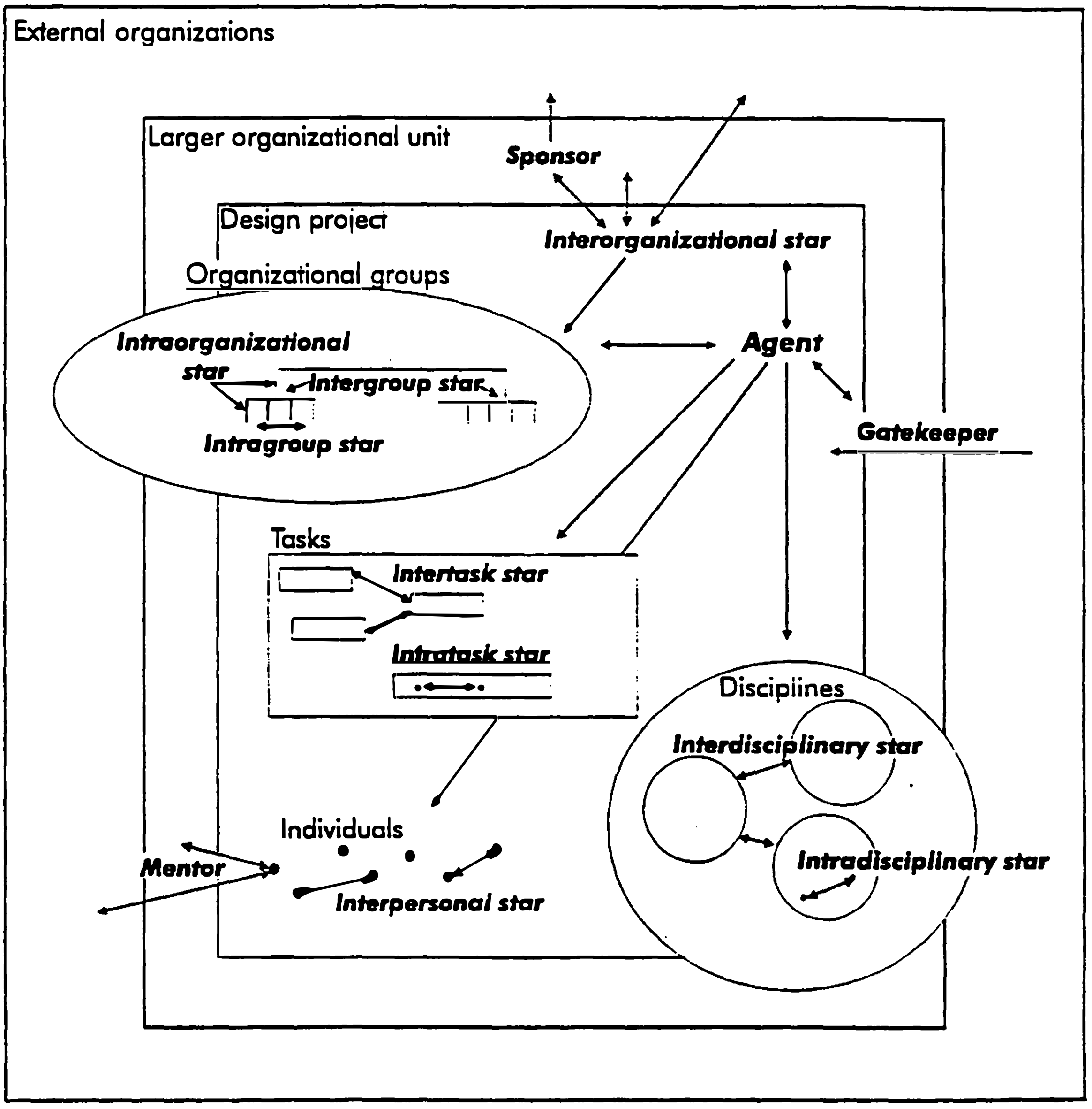

Figure 1. Boundary spanning roles during the design process

3. Boundary Spanning in Design Situations

The boundary spanning roles that emerged in the four design situations analyzed are illustrated in Figure 1. Organizational boundary spanning roles that have been observed in other contexts emerged during the field studies and were found to have specialized goals in the design context. Furthermore, new roles that span task, discipline, personal. and multiple boundaries were discovered. These roles provide access to information as well as filtering and translating information.

3.1 Organizational Boundary Spanning Roles

Five roles emerged with respect to formal, organizational boundaries: sponsor, interorganizationai star, intraorganizational star, intergroup star, and intragroup star. Due to the dynamic nature of design and the high degree of uncertainty throughout much of the design process, our studies suggest that these five roles may be more important in the design context than in other organizational contexts where organizational information is more static.

The purpose of the *sponsor role*[2] is to help secure acceptance and funding for the design project within the larger organizational unit. and to help insure the design project's goals and strategies match the organization's goals and strategies.

The purpose of the *interorganizational star* is to interact with others in the larger organizational unit(s) and relevant external organizations in order to come to an understanding about how the design project (and/or future design projects) can meet the larger and external organizations' goals and strategies. During these interactions, the design project's goals, plans, budget, and tasks as well as the larger organization's goals and strategies are discussed. The interorganizational star may also act as a filter and share knowledge about the larger organization's goals and strategies with the organizational groups within the design project. These responsibilities are often part of the formal organizational position titled 'project leader.'

Similarly, *intraorganizational stars* transmit and filter information about the project's goals and subgoals, plans, tasks, and detailed budget information among formal organizational levels within the design project. A person in this role might have a formal organizational title such as 'group leader'. *Intergroup stars* discuss design plans and tasks with other intergroup stars in the design project. They represent their group in these interactions, coordinating activities and strategies across organizational groups in the design team. They share task results and problems amongst themselves. Occasionally, the same person will assume the roles of intraorganizational star and intergroup star although during the design process additional intergroup stars (who are not interorganizational stars) may emerge.

Intragroup stars facilitate interaction among members of their group. The purpose of this interaction is to provide socio-emotive support to group members. Intragroup stars help resolve conflicts that may arise among group members, encourage group members to support decisions made by the group's intergroup and intraorganizational stars, and help new or disenfranchised members become full members in the group.

3.2 Task Boundary Spanning Roles

Two roles, *intertask star* and *intratask star*, span task boundaries with the goal of successful task completion. For example, intertask interaction includes discussion about interfaces between artifact components and task results that impact other tasks. Conflict may occur between intertask stars when their design tasks have different priority measures and/or conflicting constraints. Intratask interaction includes discussion about how a task can be done or how problems that occur can be solved. As one intratask star explained, "We discuss problems. He has more experience than me but often he wants to know what I've been thinking. I tell him...then he says, you could be right but it could also be this too."

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[2]Also identified in management science literature, c.f., March & Simon (1967.)

3.3 Discipline Boundary Spanning Roles

In many design situations, multiple disciplines (or domains) are involved, e.g., concurrent engineering methods prescribe the inclusion of experts from manufacturing, marketing and distribution, maintenance and repair, disposal and recycling, and end-user application disciplines in the design process. The roles, *interdisciplinary star* and *intradisciplinary star*, help span boundaries amongst these different disciplines. Interdisciplinary stars interact using knowledge from their disciplines to create new knowledge and solve design problems. In describing interaction with another interdisciplinary star, a person explained, 'together we can come up with interesting concepts and solutions...it's intellectually inspiring...very rewarding.' The purpose of the intradisciplinary star is to provide information about new knowledge and developments within their discipline to others in the same discipline. Similar to the gatekeeper role, the intradisciplinary star can provide this information based on implicit or explicit information needs. For example, in one design situation, an intradisciplinary star read trade newspapers, journals, and electronic bulletin boards and provided his colleagues with regular periodic summaries of new developments in their discipline. In another situation, colleagues met in informally to get feedback on their design decisions with colleagues in their discipline but not necessarily in the same design team.

3.4 Personal Boundary Spanning Roles

To span personal, or individual, boundaries, two additional roles emerged: the *mentor* and *interpersonal star*. The purpose of the mentor role is similar to that described in management literature. That is, its purpose is to provide individuals with information from the larger organizational unit and external organizations that might benefit the individual's career. This type of information could be job and career opportunities, colleagues interested in similar problems, and services and benefits provided by the organization. Another purpose of the mentor role is to provide the larger organizational unit with information about how individuals could help the unit achieve its goals. The purpose of the interpersonal star is to facilitate interaction among individuals on the design team. To some extent, every team member may assume this role at times because getting to know one another personally through discussions about families, hobbies, personal experiences, etc. is a common activity among many design team members. It allows participants to learn each other's language and interaction style which supports interaction about more potentially difficult discussions about design constraints and problems.

3.5 Multiple Boundary Roles

Two roles that span multiple boundaries are the agent and gatekeeper role. The purpose of the *agent* role is to facilitate interaction among all design participants, arbitrating conflict among participants and insuring that their information needs are met to enable them to complete their tasks. The agent in the expert design team defined his role as: "A Convener/Facilitator: I will help define agenda items, keep the group focused on its task; ask critical questions; mediate conflict, and ensure that the group meets its work objectives and time targets." (Mumford & MacDonald, 1989, p. 87). Agents may be interorganizational stars as well and have the formal job title 'project leader.'

Another role that may span a variety of boundaries in the design project team is the *gatekeeper* role. In design situations, as in other organizational settings (c.f., Tushman, 1977), the purpose of the role is to provide team members with information from outside the design situation. The information can be about related competitive products, product components that could be used in the artifact, new design methods and tools, potential customers, or potential business partners or consultants. However, the gatekeeper role in design situations has an additional characteristic; the information provided by the gatekeeper is based on implicit and explicit needs of design participants. That is, a gatekeeper may proactively provide design participants with information that the gatekeeper believes may be or may become relevant to the them in addition to answering explicit information queries. For example, one gatekeeper scanned professional newspapers and periodically provided design participants with summaries of articles he believed were relevant to them.

The 13 boundary spanning roles that emerged in the field studies illustrate that design participants develop a variety of complex roles to explore and integrate knowledge during the design process.

These roles do more than simply provide access to information; they also filter and translate information across organizational, task, disciplinary, and personal boundaries. We propose that information technology may assist knowledge exploration in design by supporting these boundary spanning roles and performing some boundary spanning tasks.

4. Implications for Information Technology in Design

When boundary spanning roles do not emerge in design situations and/or when the goals of a role are not met, problematic situations develop during the design process. For example, in one design situation, the agent role did not emerge; an artifact was never created and design participants reported they did not want to work together on future projects. In another design situation, when an intraorganizational star did not transmit project organization and project status information to his group members, they reported job dissatisfaction and suboptimum task performance. Thus, the complex and critical nature of knowledge exploration in design suggests that information technology (IT) may help reduce this complexity for design participants by supporting boundary spanning roles and performing some boundary spanning tasks. In particular, IT could (a) suggest boundary spanning strategies, (b) retrieve and present information based on roles, and (c) perform gatekeeping tasks.

4.1 Boundary Spanning Strategies

During our field studies, design participants expressed difficulty in selecting appropriate boundary spanning strategies when seeking information from others and when providing information to others. For example, one design participant explained: "They [other design participants] keep wanting opinions which I can't give but will be damned if I don't. It's difficult to handle these guys." To address these types of problems, an information system could help design participants reflect on alternative boundary spanning strategies by providing answers to queries such as: "What information do I have that other team members may need?" "Who can provide me with the information I need?" "What strategies can I use to get information I need?"

4.2 Information Retrieval and Presentation Based on Roles

Information technology could also be used to provide access to information based on roles. Traditionally, information retrieval (IR) systems match terms in user queries to terms in documents or document abstracts without taking into account users' characteristics. Alternatively, a design participant's characteristics such as their role(s), task(s), and preferred interaction and cognitive style(s) could be used in an IR system to help find and present additional, relevant information documents, drawings, and information sources. For example, consider the query 'show me the user interface'. An interorganizational star preparing for a meeting with end-users might expect the system to respond to this query by providing access to a script that illustrates the user interface in the end-users' application domain. An intertask star responsible for creating the user interface might expect the system to provide access to the user interface development shcedule and program flowcharts. In comparison, an intradisciplinary star with the same query might expect the system to provide access to the latest version of the interface protoyope and test results to review the interface with a colleague.

4.3 Gatekeeping Tasks

Today, gatekeepers search for information potentially-relevant to their colleagues and disseminate that information in forms meaningful to their colleagues. For example, in one design situation, a gatekeeper created bi-monthly (paper) bulletins for his colleagues that briefly summarized new products. He understood that his colleagues needed to learn about a constantly changing variety of products with minimal effort, and only occasionally needed to learn about a product in-depth. Therefore, each bulletin was a comprehensive list of new products with brief product descriptions and pointers to additional information.

IT could support this type of gatekeeping activity. Profiles of information needs, i.e., IR queries, could be built based on design participants' roles and tasks. These profiles could be used in conjunction with IR algorithms to automatically search for relevant information among project and external documents such as electronic professional newspapers, bulletin boards, journals, and

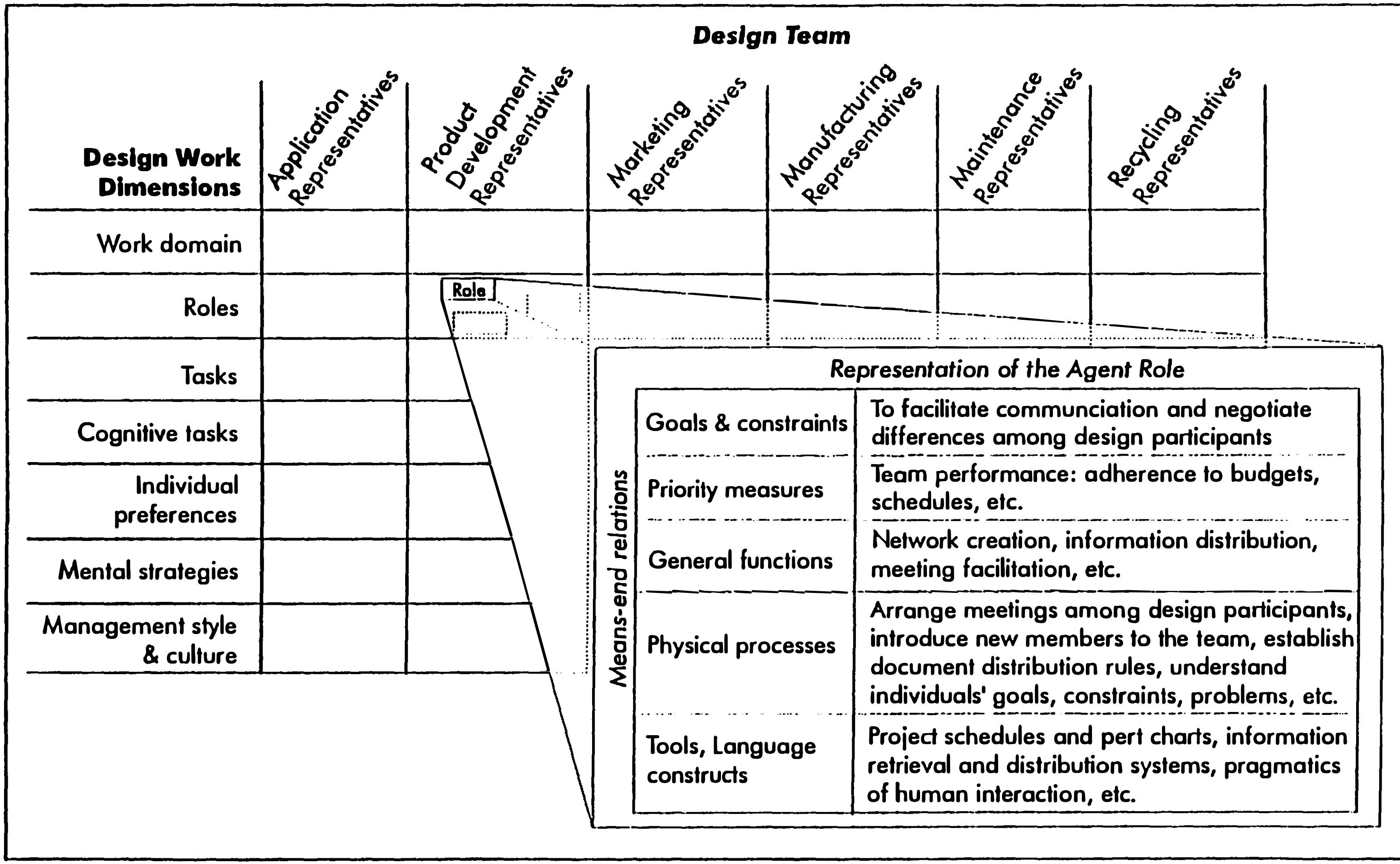

Figure 2. Conceptual representation of the design context

newsletters. The results of the searches could then be edited and presented to design participants based on their preferred interaction and cognitive styles.

4.4 Conceptual Representation of the Design Context

To implement these features in IT, a rich conceptual representation of the design context is required. We have selected the MOHAWC (MOdels of Human Activities in Work Context) cognitive work framework (Rasmussen, Pejtersen, & Goodstein, 1994) as a starting point to represent the design work context. As illustrated in Figure 2, our proposed implementation of the framework includes dimensions of the design context that characterize the work performed by design team members. These dimensions include the work domain, roles, tasks, cognitive tasks, individual preferences, mental strategies, and management style and culture.

Furthermore, each dimension can be described using a means-end representation that identifies concepts within a dimensions and the many-to-many relationships and mappings between them. The means-end representation describes goals and constraints, priority measures, general functions, physical functions, and tools or objects. For example, the goal of the agent boundary spanning role is to facilitate communication and negotiate differences between design participants. Typical priority measures used to evaluate agent goals include design team performance such as adherence to budgets and time schedules, and artifact completion. General functions that an agent performs to satisfy performance measures may include network creation (establishing and helping to maintain communication among design participants), document distribution (insuring project documents are distributed appropriately), and facilitating meetings among design participants. When performing these general functions, the physical processes an agent might perform includes holding conversations with design participants in order to learn about their goals and functions, introducing new members to the design team, and establishing document distribution rules, etc. These physical processes are, of course, achieved via actors using tools and language constructs. For example, project schedules and pert charts can be used to track the status of design tasks, and an information retrieval and distribution tool can be used to distribute project documents. This level also includes the pragmatics of human interaction - the semantics, syntax, and social conventions or constructs that people use when interacting with one another. There is a many-to-many mapping between elements in each abstraction level. For example, there are many ways in which an agent can interact with a design team member, including face-to-face conversations, email messages, phone conversations, and memos. An agent might select one or more of these means based on contextual factors such as the work locations and work hours, and based on individual preferences such as preferred interaction styles.

The means-end representation of this and other boundary spanning roles is a first-step towards creating and evaluating prototypes that support the boundary spanning roles design participants develop to cope with the complexity of knowledge exploration.

5. Summary

The discovery of how design participants explore and integrate knowledge from different domains is first step towards understanding how information technology could enhance this process. The boundary spanning roles that emerged from field studies of four design situations include roles previously described in other organizational settings and new roles that span task, discipline, and personal boundaries. These roles not only provide access to information but filter and translate information as well, illustrating the complex nature of knowledge exploration in design. Information technology may reduce this complexity for design participants by supporting boundary spanning roles. Using a conceptual representation of the design context that includes a means-end representation of boundary spanning roles, an information system could suggest boundary spanning strategies, retrieve and present information based on boundary spanning roles, and perform gatekeeping tasks. Any tool that incorporate these ideas should, of course, be integrated with other information and personal communication tools, such as CASE systems, traditional information retrieval systems, existing organizational and administrative systems, and electronic mail, fax, and telephone systems. Future research includes further analysis of cooperative patterns among design team members and their information search strategies, and the creation and evaluation of prototypes that incorporate the ideas proposed in this paper.

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