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Development of a systematic classification and taxonomy of collaborative design activities

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An interdisciplinary review of literature relevant to collaborative design is used as a basis to propose a taxonomy for the classification of collaborative design situations. The taxonomy includes top-level attributes of *team composition*, *communication*, *distribution*, *design approach*, *information*, and *nature of the problem*. Three taxonomic-oriented measures are introduced and used to evaluate the taxonomy: orthogonality, completeness, and usability. This taxonomy is an initial step towards the creation of new agent-based collaborative support tools structured upon a fundamental understanding of the collaborative process with a theoretical foundation. More significantly, the taxonomy provides a valuable way of organising the research literature in collaborative design that is at present dispersed across many domains and disciplines.

Keywords: collaborative design; classification of design; information; team; communication; distribution

1. Introduction

Companies in a wide range of industries are finding that success in the modern marketplace requires effective competition in global markets with reduced cost and lead-time (Andersson 2001). The concept of collaborative design has emerged both as an effect of globalisation and as a prospective tool for enabling this product development approach (Rouibah and Caskey 2003). The opportunities and limitations presented by collaborative design, however, are not well understood, and the actual gains of applying collaborative design are not clear. An interdisciplinary survey of recent collaborative design research shows a focus on developing tools to facilitate communication of ideas and information within collaborative design teams (Ostergaard 2002). As the information exchange requirements of the teams have not been fully explored, these tools may be inadequate or poorly directed. This absence of a common language, shared understanding, and organisation of issues of collaborative design provides a motivation for this work. It is posited that further research into collaborative design will provide a clearer understanding of the communication issues faced by collaborative design teams and will allow for development of better-directed tools.

In order to facilitate the effective application of collaborative design, information flow in collaborative design may be analysed and the factors that introduce resistance to the process identified. The first step is to create a taxonomy that classifies issues affecting collaborative design. A model

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of the collaborative design process may then be constructed to clarify at which interfaces and in what manner these issues impact the design process (Ostergaard 2002). This model development is the subject of continuing research (Ostergaard *et al.* 2004).

This paper offers a taxonomy for collaborative design that seeks to capture relevant and associated issues, creating a common framework that can be used to guide research and tool development for supporting collaborative design. This paper begins with a brief background of collaboration in design. This is followed by a hierarchical classification of the characteristics of collaborative design through six major factors: team composition, communication, distribution, design approach, information, and nature of problem. Each major factor is decomposed to lower level attributes and leaf taxons. A preliminary evaluation of the taxonomy is presented. Finally, conclusions and summary are provided.

2. Background

Engineering design has been defined as the process of formulating a plan for the satisfaction of a human need through a cycle of steps that include problem definition, conceptualisation, embodiment, and detailing (Shigley and Mischke 1989, Pahl and Beitz 1996, Ullman 2003). This process is traditionally achieved in a design environment consisting of collocated teams with project managers and selected technical discipline specialists working on individual tasks (Monell and Piland 2000). The individuals working on the tasks may not necessarily share a common vision of the overall design process. We argue that this is a distinguishing characteristic of collaborative design versus concurrent or cooperative design: shared objective. In collaborative design, participants contribute to an interactive design team structure with a goal of achieving a common task by sharing expertise, ideas, resources, or responsibilities (Chiu 2002). The team may be multi-disciplinary, and the members, information, and resources may be distributed across geographic, organisational, or temporal boundaries. Additionally, design tasks may be performed in parallel (concurrently) or in series (sequentially). The collaborative design process is carried out by agents, which include team members and/or reasoning systems. Thus, collaborative design is defined as a collection of agents (human or artificial) that are working towards a *common shared goal* using shared resources or knowledge.

A survey of design tools developed to facilitate collaborative design shows that the tools are based on insufficient models or simply on presumed needs (Ostergaard 2002). Current tool evaluation and validation is typically conducted in the field after the tools have been developed (Knutilla *et al.* 2000). A more efficient and effective approach is to base design tools on a model that clearly defines areas of resistance in the collaborative design process. Tools that have been developed to support collaborative design include computer-supported collaborative work tools, team management tools, group decision-making tools, and group idea generation tools.

3. Development of the taxonomy

The French botanist de Candolle is credited with the introduction of the term *taxonomy* to the current lexicon (de Candolle 1813). *Taxonomy* is derived from *taxis* (arrangement) and *nomos* (study). Thus, taxonomy is a study of arrangements. The roles of taxonomies include the transmission of information (Jeffrey 1982), rapid recall of information and property predication (Dunn and Everitt 1982), clarification of information (Derr 1973), and the organisation of large bodies of information (Gershenson and Stauffer 1999).

The development of a collaborative design taxonomy is believed to aid in the identification and organisation of collaborative design issues. The taxonomy may be used to illustrate and extract the relationships and dependencies among the factors, especially in developing experimental studies of the collaborative design process. While some research efforts have been made to organise particular issues in collaborative design, such as the classification of conflicts (Klein 2000), a thorough organisation of issues in collaborative design does not appear to exist in the literature. Taxonomies have also been applied in general engineering design research, such as for engineering decision support systems (Ullman and D'Ambrosio 1995), mechanical design problems (Dixon *et al.* 1988), idea generation methods (Shah 1998), and design requirements (Gershenson and Stauffer 1999).

Six top-level attributes of collaboration are identified from the literature, thus composing the top level of the taxonomy: team composition, communication, distribution, design approach, information, and nature of the problem. This taxonomy and associated references are illustrated in Table 1. The attributes are further subdivided based on the established literature. The full taxonomy includes six primary-level attributes, 27 secondary-level attributes, 28 tertiary-level attributes, and 44 evaluatable taxons. This taxonomy is illustrated here in outline format. The base

Table 1. Collaborative design taxonomy.

Team composition	Nature of the problem
Group	Type (novel, routine)
Size (number)	Concurrency (serial, parallel)
Culture (type)	Coupling (level)
Individual	Abstraction (level)
Personality (type)	Scope (number of domains)
Expertise (level)	Complexity (level)
Team member relations (positive, neutral, negative)	
Leadership styles (autocratic, consultative, collective, participative, leaderless)	
Communication	Information
Mode	Form (design artefact, background)
Verbal (Boolean)	Management
Written (Boolean)	Ownership (set, get, change, validate, inherit)
Graphic (Boolean)	Permission to change (set, get, change, validate, inherit)
Gestures (Boolean)	Security (set, get, change, validate, inherit)
Quantity	Change propagation (set, get, change, validate, inherit)
Frequency (number)	Perceived level of criticality (level)
Duration (time)	Dependability
Syntax	Reliability (level)
Language (type)	Completeness (level)
Translators (number)	
Proficiency of the team	
Techniques (level)	
Technology (level)	
Dependability of resources	
Reliability (level)	
Availability (level)	
Intent (inform, commit, guide, request, express, decide, propose, respond, record)	
Distribution	Design approach
People	Design tools (consistently applied, applied occasionally, not applied)
Geographically (co-located, distributed)	Evaluation of progress (self-assessment, assessed by outside parties)
Organisationally (within boundaries, outside boundaries)	Degree of structure (company policy, chosen by team, free)
Temporally (same time zone, different time zones)	Process approach (generative, variant)
Information	Stage (clarification of task, conceptual, embodiment, detail)
Geographically (co-located, distributed)	
Organisationally (within boundaries, outside boundaries)	
Temporally (same time zone, different time zones)	

leaf taxons are found in parentheses. These terminating taxons represent the lowest developed level in the taxonomy. It is at this level that a collaborative design situation may be described with specifying values for all the taxons.

This collaborative design taxonomy was developed by first surveying relevant literature in the fields of psychology, sociology, political science, and engineering design. Issues that were found to impact collaborative design were sorted into appropriate categories, such as communication and team composition. Applying the taxonomy to simulated design cases highlighted missing components of the taxonomy. The literature was then revisited to find supporting evidence for these additional issues. This process was repeated until no further items were found to be missing upon application to design cases. The results of this algorithm are presented here in the form of the collaborative design taxonomy.

While dependencies exist among some attributes in the taxonomy, such as distribution of personnel and communication mode, a discrete division of factors results in an orthogonal organisation, an essential characteristic of taxonomies. Figure 1 shows the dependencies in the taxonomy based

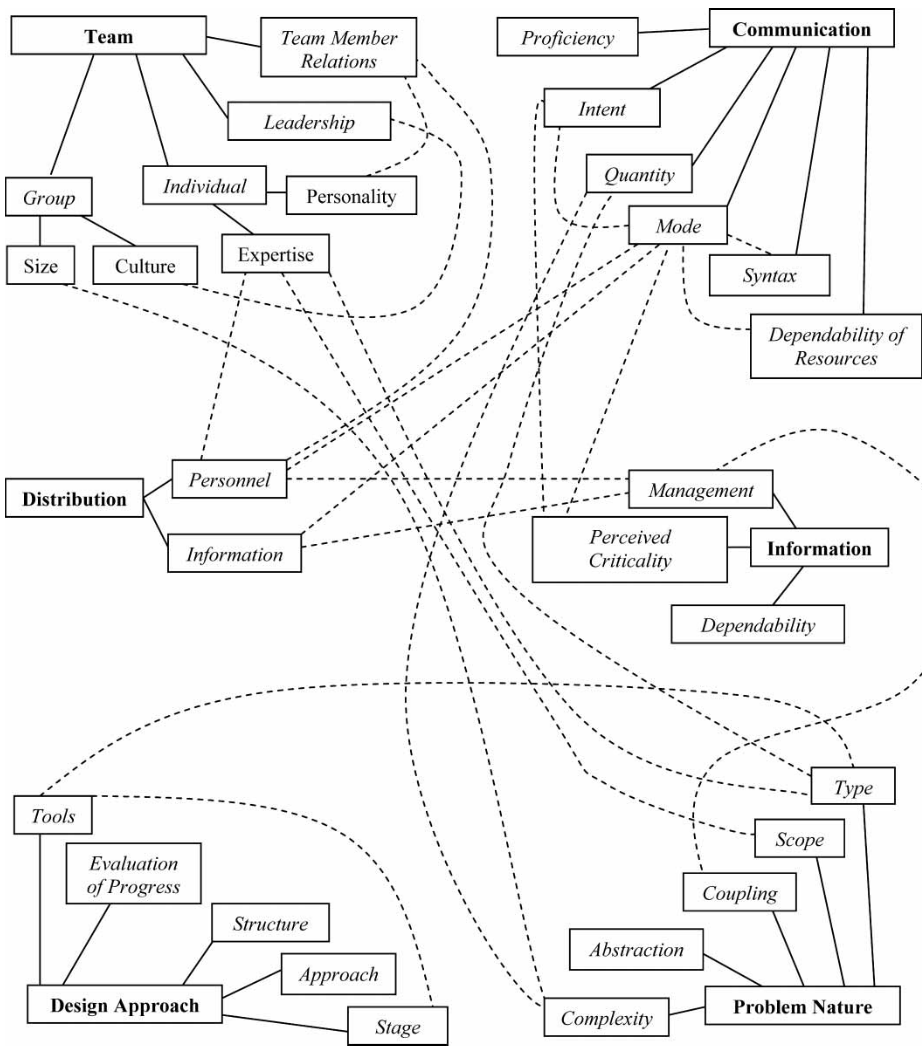

Figure 1. Dependencies among factors in the collaborative design taxonomy.

on the subsequent justification from literature. Orthogonality ensures that an instance of collaborative design may not be found under two different classifications. (The orthogonality of the taxonomy is discussed in detail in Section 4.) The solid lines in Figure 1 indicate the direct hierarchical relationships between the factors as found in the taxonomy. The dashed lines indicate the indirect relationships between factors across axes in the taxonomy. It is these indirect relationships that confound development of a truly orthogonal and independent taxonomy.

The factors organised in the taxonomy span the potential space of collaborative design, but they may not achieve completeness. For example, additional investigation in the areas of information management and exchange may improve that branch of the taxonomy by identifying additional issues not yet found in literature. A trade-off is made between attempting to provide a complete taxonomy for collaborative design and providing a classification system that is useful in investigating the subject.

A description of the effects of the primary collaborative design attributes follows. The sublevels for each factor of the taxonomy are illustrated with explanation and justification from the literature.

3.1. *Team composition*

Extensive research has been conducted in the fields of psychology and sociology to analyse the impact of team composition on effective and timely team performance (Barrick and Mount 1991, Hurley 1995, Denton 1997, Willaert *et al.* 1998). With regard to collaborative design teams, these issues can be divided into characteristics of the group, characteristics of individuals, team member relations, and management styles as presented in Table 2.

Researchers have noted that the size of the team should match the magnitude and complexity of the task (Denton 1997, Willaert *et al.* 1998). Teams that are too large may become unmanageable and necessitate a support structure, while creativity may be inhibited if teams are too small (Willaert *et al.* 1998). A team size between six and 15 is proposed to be workable and compatible with problem-solving, decision-making, and spontaneous communications (Hof 1992, Hudak 1992, Yesersky 1993). Studies of the quantitative effect of a range of group culture variables on innovative productivity found that group cultures that emphasise participative decision-making, characterised by openness and involvement in decision-making, are associated with higher levels of innovation (Hurley 1995). Participative decision-making was found to increase the commitment and perceived freedom to innovate. The organisational hierarchy, as well as the leadership styles within the design team may influence this area of the group culture. Higher levels of innovation are also experienced in group cultures that emphasise learning and education in career and people development.

Table 2. Team composition issues in collaborative design.

Team composition		References
Group	Size (number)	Willaert *et al.* (1998), Hof (1992), Hudak (1992), Yesersky (1993), Denton (1997)
	Group culture (type)	Hurley (1995), Redelinghuys and Bahill (2006)
Individual	Personality (type)	Costa and McCrae (1988), Day and Silverman (1989), Digman (1990), Barrick and Mount (1991), Tett *et al.* (1991), Kichuk and Wiesner (1997), Reilly *et al.* (2002), Lopez-Mesa and Thompson (2006)
	Expertise (level)	Denton (1997), Baird *et al.* (2000), Broadbent and Cross (2003)
Team member relations (level)		Austin (1975), Azmodeh and Davison (1997), Leifer (2000), Lurey and Raisinghani (2001)
Leadership styles (type)		Vroom and Jago (1978), Norrgren and Schaller (1999)

Table 3. Personality/performance relationships (Reilly *et al.* 2002).

Personality factor	Incremental innovation team	Radical innovation team
Conscientiousness	Decreased performance	Increased performance
Extraversion	No impact	Increased performance
Stability	Decreased performance	No impact
Agreeableness	Decreased performance	Increased performance
Openness	Increased performance	Decreased performance

A review of the diverse theories (Costa and McCrae 1988, Day and Silverman 1989, Barrick and Mount 1991, Tett *et al.* 1991) that have been developed to relate individuals' personalities and their performance in the workplace is presented in Reilly *et al.* (2002). The five-factor personality model (Digman 1990) brings some order to the field of personality research. The five-factor personality model proposes that the following traits be used to describe interpersonal behaviour: conscientiousness, extraversion, stability, agreeableness, and openness to experience. Conscientiousness is the extent to which team members are careful, thorough, achievement oriented, responsible, organised, and self-disciplined. Extraversion indicates whether team members are sociable, talkative, assertive, and active. The degree to which team members are calm, enthusiastic, poised, and secure is described as stability. Agreeableness is the extent to which team members are good-natured, gentle, cooperative, forgiving, and hopeful. Openness describes the level of imagination, sensitivity, and intellect of the team.

These factors can be expected to affect different types of teams in different ways. In order to clarify these effects in the context of design teams, new product development teams may be separated into two categories: those performing incremental innovation (i.e. re-designs) and those performing radical innovation (e.g. high uncertainties, products that are still evolving) (Reilly *et al.* 2002). Proposed relationships between the team's average level of each personality factor and the overall team performance are described in Table 3. These relationships suggest preferred team composition for particular design types.

The level and area of expertise of team members affects the collaborative design team (Broadbent and Cross 2003). The amount of knowledge or experience perceived to be required before making a contribution to the team may negatively affect productivity of younger engineers (Baird *et al.* 2000). Varying levels of experience on a team, however, may facilitate success in innovation by combining heuristic understanding that may be gained with age with the optimism of youth or inexperience (Denton 1997, Baird *et al.* 2000). Additionally, the type of design problem may dictate which areas of expertise should be included in the team composition, even while including several disciplines in a team both enriches and complicates many areas of the design process (Ullman 2003).

In a collaborative design process that is composed of human engineers, inter-personal factors may influence the process. Design teams serve, in part, as social networks and design may be considered a social activity (Leifer 2000, Lurey and Raisinghani 2001). In this capacity, teams should provide members with satisfaction and opportunities for personal development. If team members are not satisfied with the way the team functions, then the performance of the team is inhibited. Within the social network of design teams, informal 'permissions' of communication are developed as engineers work together closely (Azmodeh and Davison 1997). These permissions grant team members rights, such as joining in informal discussions and interrupting independent works. Permissions may develop in distributed teams, but they form much more slowly and, thus, impact the team's exchange of information. Studies have confirmed that social interaction, such as team member introductions, pooling of knowledge, and team maintenance, does account for a portion (10–20%) of design time (Austin *et al.* 2001). These activities are not typically included in design models, however.

Table 4. Vroom–Yetton model of leadership styles (Vroom and Jago 1978).

Leadership style	Who defines problem	Who makes decisions
Autocratic	Leader	Leader (may solicit group input)
Consultative	Leader	Leader with solicited group input
Collective	Leader	Group
Participative	Group	Group
Leaderless	Varies	Varies

Although engineering design is mainly a technical activity, it truly functions as a social activity. Lloyd (2000) proposes that design is a process of building on individual, social, and organisational experiences. If a collaborative design team is distributed, its ability to collectively utilise these experiences may be hindered. Group cohesiveness has been identified as positively related to team success (Kichuk and Wiesner 1997). This cohesiveness largely depends on the composition of the group, particularly the personality characteristics discussed earlier. Team member relations were found to have a major positive relationship to team performance and team satisfaction (Lurey and Raisinghani 2001). This relationship may be expected when considering the social network aspect of design. In many global organisations, flexible inter-unit communication has been stressed as an important source of internal cohesion (Ghoshal *et al.* 1994). This may explain the recent popularity of team-building exercises to enhance inter-unit communication (Marschan *et al.* 1996).

In addition to team cohesiveness, leadership styles may also influence collaborative design. The Vroom–Yetton model may be used to classify leadership styles (Vroom and Jago 1978). The model, summarised in Table 4, includes autocratic, consultative, collective, participative, and leaderless styles. A leader with an autocratic style defines problems in the course of the design process. The autocratic leader may make decisions without group input, with group input, or only with feedback after the decision has been made. A consultative leader defines problems in the course of the design process and solicits ideas from individuals or the entire group. One collective style of leadership is the group decision style in which the leader shares the problem definition with the group and the group proceeds to develop solutions. In the participative style of selective leadership, the entire group proceeds through the whole decision-making process. In this style, the leader serves as process facilitator. Finally, teams may be leaderless. In leaderless teams, leaders often emerge for specific problems and vary throughout the design process.

Empirical studies of interdisciplinary teams found that a team needs to be led through the design activity (Austin *et al.* 2001). Further, the team needs to agree on who should lead and what leadership style should be used in order for the group to work effectively. If a leader or leadership style is not selected, a lack of synchronisation may result as individuals proceed in various directions. Other research has found positive relationships between leadership style and team performance, work climate, and team learning (Norrgren and Schaller 1999, Lurey and Raisinghani 2001).

3.2. *Communication*

Communication is expected to be a vital factor in most team situations, but it becomes especially important when design teams are distributed. By definition, collaborative design teams share expertise, ideas, resources, or responsibilities, which necessitates a strong communication system. Communication exchanges occur between actors (senders and receivers) in the design process at various collaborative design interfaces. Characteristics of these exchanges may facilitate the process or may introduce resistance. These factors and their sublevels are shown in the taxonomy in Table 5.

Table 5. Communication issues in collaborative design.

Communication		References
Mode	Verbal (Boolean)	Adler (1991), Leckie *et al.* (1996), Anderson *et al.* (2001)
	Textual (Boolean)	Adler (1991), Leckie *et al.* (1996), Anderson *et al.* (2001)
	Graphic (Boolean)	Leckie *et al.* (1996), Anderson *et al.* (2001)
	Gestures (Boolean)	Leckie *et al.* (1996), Anderson *et al.* (2001)
Quantity	Frequency (number)	Barthelemy *et al.* (1998), Chiu (2002)
	Duration (number)	
Syntax	Language (type)	Adler (1991), Summers *et al.* (2001)
	Translators (number)	Adler (1991), Summers *et al.* (2001)
Proficiency of team	Techniques (level)	Case and Lu (1996), Deus (2000), Anderson *et al.* (2001)
	Technology (level)	Orlikowski (1992), Case and Lu (1996), Anderson *et al.* (2001)
Dependability of resources	Reliability (level)	May and Carter (2001)
	Availability (level)	Deus (2000), May and Carter (2001)
Intent (inform, commit, guide, request, express, decide, propose, respond, record)	Searle (1969), Austin (1975), Yates and Orlikowski (1992), Yoshioka and Herman (1999)	

Team members' selection of particular communication modes may be influenced (positively or negatively) or even governed by the sender's perception of the importance of the information to be communicated, dispersion of the team over time and space, the task in the design process, team composition, and other factors (Leckie *et al.* 1996, Anderson *et al.* 2001). Accessibility impacts the choice of information carrier (Anderson *et al.* 2001). That is, the scientists and engineers in their study tended to choose communication methods based on a principle of least effort. Furthermore, collaboration technologies are necessary to overcome the inherent impedance to communication encountered by distributed design teams (Case and Lu 1996). Examples of this impedance are network delays and different protocols, or rules determining the format and transmission of data, between environments. While an abundance of tools has been developed to help facilitate communication within these teams, the actual communication needs have not been fully explored. Research in this area may show that existing collaborative design tools are inadequate or poorly directed.

The quantity of communication, measured by frequency and duration, may affect the performance of the team. The frequency of communication has been found to be dependent on the type and scale of design problems (Chiu 2002). The distribution of teams may also impact usage levels and the quantity required for effective communication. For example, a certain threshold of communication may be required to achieve adequate transfer of information, and the ability to achieve that threshold may be inhibited by the distributed nature, as well as other characteristics, of collaborative design teams. Note that the quantity of communication is not necessarily related to the quality of communication (Barthelemy *et al.* 1998).

Effective communication may be further inhibited if team members use various languages in their communication (Adler 1991). This includes spoken and written languages, as well as information and query languages. Also, the needs of agents receiving information may determine the required syntax or view of the information (Summers *et al.* 2001). Upon investigation, it may be found that a common language is desirable or that translators may be found to be more efficient.

The proficiency of the scientists and engineers in using various communication media might influence form selection, frequency, and success (Anderson *et al.* 2001). Additionally, strategies for training and support must be prepared by organisations implementing collaborative solutions

(Deus 2000). In empirical studies, it was found that users' acceptance of groupware or collaborative technology is influenced by the nature and form of training they receive (Orlikowski 1992).

Furthermore, if communication systems are not reliable, low user satisfaction will probably negate enhanced functional capabilities the systems are intended to provide (May and Carter 2001). To have sufficient reliability and availability to enable effective collaboration, the network and systems infrastructure must be able to support the requirements of the collaboration tools (Deus 2000).

A number of researchers have offered classifications of communication by intent (Austin 1975, Searle 1969, Yates and Orlikowski 1992, Yoshioka and Herman 1999). Ten purposes for communicative actions have been proposed: inform, commit, guide, request, express, decide, propose, respond, and record (Yoshioka and Herman 1999). Some modes of communication and information forms may have more than one purpose. The intent of the information exchange may have an impact on other collaborative design factors, such as communication mode and perceived level of criticality.

3.3. *Distribution*

Collaborative design teams and associated information may be collocated, but are more likely to be distributed across some variety of boundaries, including geographic borders, organisational boundaries, and boundaries of time. The distribution attributes are illustrated in Table 6.

While a distribution may be desired or necessary to achieve an ideal combination of expertise in the team, the dispersion may also make it difficult to realise the full benefits of that expertise. The distribution of the team may govern various aspects of the team composition, such as culture and expertise.

Dispersion of team members may have a significant impact on the team's choice of communication techniques, frequency of communication, and language (Lurey and Raisinghani 2001). Research to compare the graphic communication of distributed teams with those of collocated design teams showed that remote designers spent 51% more time making graphic acts (drawings, sketches, etc.) than their collocated counterparts (Garner 2001). However, the actual production of drawings and sketches decreased significantly when teams were distributed.

The availability of communication resources may also be inhibited, primarily by geographic and organisational boundaries. In distributed agent design work, it is suggested that cohesion and efficient operation in distributed design teams requires more computational design support versus the needs of non-distributed teams (Prasad *et al.* 1998, Lees *et al.* 2001). Research in communication impedance, or the difficulty in communicating when teams are not collocated, supports this supposition (Case and Lu 1996).

Table 6. Distribution issues in collaborative design.

Distribution		References
Personnel	Geographically (co-located, dispersed)	Lurey and Raisinghani (2001), Case and Lu (1996), Garner (2001), Lees *et al.* (2001)
	Organisationally (within, without)	Lees *et al.* (2001), Prasad *et al.* (1998)
	Temporally (same time, different)	Fadel *et al.* (2000), Lindemann *et al.* (2000)
Information	Geographically (co-located, dispersed)	Case and Lu (1996), Deus (2000), Garner (2001)
	Organisationally (within, without)	Case and Lu (1996), Deus (2000), Garner (2001)
	Temporally (same time, different)	Fadel *et al.* (2000), Lindemann *et al.* (2000)

Information may also be distributed in the same manner as team members. This distribution offers additional challenges to efficient coordination of the design team. When information is distributed across geographic or organisational boundaries, supplementary resources, such as a sufficient information technology infrastructure, information management tools, and communication aids, are typically required to facilitate information exchange (Case and Lu 1996, Deus 2000). These issues will be discussed in more detail in Section 3.5.

Anecdotally, case studies have demonstrated that the time distribution, such as results from spanning multiple time zones in a project team, is an important factor in the effectiveness of a collaborative design project. In a multinational around-the-clock student design project, it was found that the information exchange without synchronous overlapping generated many issues that impacted the effectiveness of the design teams (Fadel *et al.* 2000, Lindemann *et al.* 2000).

3.4. *Nature of the problem*

In design, characteristics of the design problem may influence the design process and solution. The nature of the problem, then, may be considered an attribute of collaborative design (Table 7). The type of design problem may be classified as novel or routine. A novel design problem has no clear predecessors that can be used as design guides, and instead uses new solution principles (Pahl and Beitz 1996). A routine design problem, however, is a re-design in which the design domain is well understood and can be constructed largely from existing formulae or rules (Ullman 2003).

The degree of coupling of subtasks has a large influence on the communication requirements of the team (Case and Lu 1996). When tasks are loosely coupled, collaboration technologies with high communication impedance are acceptable. Design problems with highly coupled tasks, however, require that obstructions to communication be at a minimum. Because the degree of coupling of tasks varies throughout the design process, resources should be available to meet the needs of highly and loosely coupled tasks. Coupling of tasks may also impact the information management requirements of the team, notably in the area of change propagation (Dinsmore 1990).

Design teams must typically deal with abstraction of the design problem at some level (defined as concrete, intermediate, and vague in the taxonomy). It has been suggested that design is a continuous process of refining the design problem to a less abstract state (Ullman 2003). Furthermore, some design tools and techniques are better suited for certain levels of abstraction than others. Design teams may be better equipped than individual designers to handle this ambiguity because of the range of experiences and expertise present within the group (Denton 1997). Further, abstraction may be viewed as a positive aspect of design as it may enable designers to negotiate various problems while maintaining freedom in proceeding through the design process (Minneman and Leifer 1993, Shah *et al.* 2001).

If the design problem spans a wide range of disciplines, collaborative design teams may be better equipped to handle the problem than a traditional design team (Denton 1997). As noted earlier, the ability to utilise resources from various organisations and locations may enable a team

Table 7. Nature of the problem issues in collaborative design.

Nature of the problem	References
Type (novel, routine)	Pahl and Beitz (1996)
Concurrency (serial, parallel)	Peart (1971), Kliem (1986), Dinsmore (1990)
Coupling (level)	Case and Lu (1996)
Abstraction (concrete, intermediate, vague)	Ullman and D'Ambrosio (1995), Denton (1997), Shah *et al.* (2001), Ullman (2003), Summers and Shah (2004)
Scope (number of domains)	Hazelrigg (1996), Pahl and Beitz (1996)
Complexity (level)	Summers and Shah (2003), Blouin *et al.* (2004)

to be constructed with a desired composition of expertise. A multi-disciplinary team, however, may encounter communication and organisational challenges.

The collaborative design factors organised in the proposed taxonomy provide a wide-ranging description of issues that impact the collaborative design process. As described above, these factors may inhibit progress or success of a design team, or they may facilitate advancement of a design. Beyond providing a basic illustration of collaborative design, the taxonomy may be a useful aid in designing studies of the collaborative design process and evaluating the coverage of collaborative design models.

3.5. *Information*

The information that is created, used, or modified in the collaborative design process is an attribute of the process. The information issues are composed of management, perceived level of criticality, and dependability (Table 8).

Design information can be characterised as a design artefact or as process knowledge (Chan and Finger 1998). Design artefact knowledge is the actual design data and structures, such as technical charts/graphs, object attributes, and design reports, in which design data are represented. Process knowledge, or the expertise or resources that enable manipulation of design data, can be separated into reasoning (rule-based, history-based, first-principle) and tasks (search, analysis, modification).

Effective management of design information is crucial in collaborative design. The most important areas of information management in this context are ownership, permissions, security, and change management. The rights and responsibilities of various agents change throughout the design process, and administration of these ownership and permission issues is closely related to change management (Ahmed *et al.* 1992, Rezgui *et al.* 1996). The primary goals of managing information change are to maintain a design history and to ensure that all agents use the most current information (Rezgui *et al.* 1996). Potential applications of design histories include design process management, design reuse, versioning management, and design maintenance (Shah *et al.* 1996).

The perceived level of criticality of information (high, medium, or low) may have a strong relationship with the selected communication method. Expected impact on the task and progress of the design may influence the perceived level of criticality (Anderson *et al.* 2001). If the information is considered highly critical, agents will probably select modes of communication in which they have the highest aptitude and confidence in reliability. The quantity of communication related

Table 8. Information issues in collaborative design.

Information		References
Form (design artefact, background)		Shah *et al.* (1996), Chan and Finger (1998)
Management	Ownership (set, get, change, validate, inherit)	Ahmed *et al.* (1992), Rezgui *et al.* (1996)
	Permission to change (set, get, change, validate, inherit)	Ahmed *et al.* (1992), Rezgui *et al.* (1996), Andersson (2001)
	Security (set, get, change, validate, inherit)	Ahmed *et al.* (1992), Rezgui *et al.* (1996)
	Change propagation (set, get, change, validate, inherit)	Ahmed *et al.* (1992), Rezgui *et al.* (1996)
Perceived level of criticality (level)		Anderson *et al.* (2001)
Dependability	Reliability (level)	Parks and Nelson (1999), Parks (2001)
	Completeness (level)	Dixon *et al.* (1987), Summers and Shah (2001), Summers *et al.* (2001)

to a particular information exchange may also be influenced by the perceived importance of the information.

The dependability of information may affect collaborative design both in terms of completeness and reliability. Effectiveness of computer hardware and software used in the aforementioned information management systems may impact the reliability and completeness of information available to the designer. Design information, such as specifications, functional structures, and configurations, is likely to be incomplete in early stages of the design process, and this level of completeness may influence the design approach (Dixon *et al.* 1987). The impact of this incomplete information on the progress of the design studies has been studied and shown to be a significant influence on the process (Parks 2001). Some information may be exchanged in the design process even though the information is not yet fixed or validated (Summers *et al.* 2001). Actors (humans or computer-based reasoning systems simulating designers) in the design process should consider the level of reliability of these assumed values in decision-making and other design activities. Some options for addressing the reliability issue are probabilistic design and sensitivity analysis (Pahl and Beitz 1996).

3.6. *Design approach*

The design approach itself is a characteristic of the collaborative design process. The tools employed, the methods used for evaluation of progress, the degree of structure of the design approach, and the type of solution approach all factor into describing the collaborative design process. These characteristics are illustrated in Table 9.

The selection of design tools to apply in various phases and tasks of the collaborative design process may impact the efficiency and productivity of the team. These tools or approaches include idea-generation methods, decision-making techniques, risk analyses, software choices, and others. Some tools or approaches may be conducive to use in team environments or particular types of problems (Ullman 2003). Team members from different organisations or locations may prefer some tools to others, resulting in difficulty in reaching a consensus about which tools to use. In an analysis of the design approach at a product development firm, it was found that the absence of a product design specification hinders task clarification activities and objective evolution of the design (Parks 2001).

Studies into the effects of regular self-assessment on the physical outcome (i.e. the team's design plans) of design teams found positive relationships between the two items (Brusseri and Palmer 2000). This was marked by higher self-rated and group-related effectiveness when teams completed a self-assessment halfway through the design process (versus having teams stop mid-way to assess the room in which they were working). Higher levels of group satisfaction were also found when teams participated in a self-assessment.

Table 9. Design approach issues in collaborative design.

Design approach	References
Design tools (consistently applied, occasionally applied, not applied)	Parks (2001), Ullman (2003)
Evaluation of progress (self-assessment, external assessment)	Brusseri and Palmer (2000)
Degree of structure (company policy, chosen by team, free)	Parks (2001)
Process approach (generative, variant)	Austin *et al.* (2001), Goel *et al.* (1997), Cherng *et al.* (1998)
Stage (clarification of task, conceptual design, embodiment design, detail design)	Austin (1975), Shigley and Mischke (1989), Pugh (1991a, 1991b), Parks (2001), Ullman (2003)

Similarly, the degree of structure in methodology and team organisation may impact the team's performance. Furthermore, it is suggested that more structure may be required for distributed teams to be productive because of the physical barriers they face (Lurey and Raisinghani 2001). In studying team design efforts in various workshop environments, it was found that designers believe they have performed better as a team when they agree on and follow a design process (Austin *et al.* 2001). However, no evidence was found by Austin to prove that an increase in actual productivity or success of the design team could be related to the team following a systemic design procedure. Other research, however, found a significant positive relationship between ratings of teams' processes and of teams' designs (Brusseri and Palmer 2000). Further, Parks' (2001) methodical design process assists in the solution development for problems in which engineers have no previous experience.

The direction and progress of the collaborative design team is affected by the process approach. The primary approaches have been classified as generative and variant (Goel *et al.* 1997). Using the variant process, the goals of the new design are achieved by adapting existing design specifications of a similar subject. Conversely, the generative process is an original design effort. Designers of feature-based modelling systems take these processes into account (Cherng *et al.* 1998), and design of other systems for collaborative design may need to make the same considerations.

The stage of the design process also characterises work in collaborative design. While a number of authors (Shigley and Mischke 1989, Pugh 1991b, Pahl and Beitz 1996) have proposed definitions for the stages of the design process, the stages defined by Pahl and Beitz are among the most popular and will be referenced in this taxonomy. These stages include clarification of the task, conceptual design, embodiment design, and detail design.

4. Validation of taxonomy

In order to validate the taxonomy, four metrics have been identified. These metrics were used in an iterative manner, providing guidance for restructuring, redefining, expanding, and constraining the taxonomy during development. The four metrics are derived from the work on taxonomy development as argued by Derr (1973) and Gershenson and Stauffer (1999):

(A) orthogonality – ensures that there is no overlap between taxons,
(B) spanning – breadth of the taxonomy seeks to cover as much as possible,
(C) precision – depth of the taxonomy seeks to go into detail, and
(D) usability – ensures the greatest possible ease of communication between researchers.

Perceptual orthogonality seeks to ensure that each instance can be represented uniquely in the taxonomy. This quality provides for unambiguous description of the subject domain. Spanning is the quality of a taxonomy that measures the representational expressiveness of a taxonomy. It is argued that a taxonomy be exhaustive in coverage of a selected domain (Derr 1973). Others suggest that it is impossible to classify an entire domain (Gershenson and Stauffer 1999). Rather, one attempts to classify one's understanding of the domain. This leads to the metric of precision or the depth of the taxonomy that is chosen. The deeper the organisation, the more expensive the search for appropriate descriptions. Finally, the usability of the taxonomy is employed as a measure of value. Using these metrics, we will seek to answer the following questions in this paper:

- What is lacking in the taxonomy? (B, C)
- What are the relationships between the categories and taxons? (A)

Further work in this area of collaborative design and a descriptive taxonomy will seek to answer these additional questions:

- Is this taxonomy of value in describing collaborative situations? (D)
- How do current models of collaboration (specifically collaborative design) fit within this taxonomy? (A, B, C, D)
- What are the most pivotal (important) categories in the taxonomy? (B, D)
- What categories require significantly more research? (C, D)
- What other domains might be of interest to this research? (B)

These questions may be explored through the use of case studies and empirical studies in future work, but are not examined in detail here.

4.1. *Perceptual orthogonality*

The collaborative design taxonomy proposed here is evaluated with respect to perceptual orthogonality. Each taxon has been chosen so that the information represented is not found in any other taxon. For instance, the type of distribution of the collaborative team members (geographic, organisational, and temporal) contains different information to the team composition taxons. While the information contained within each taxon is unique, the taxons may influence the choices made for other taxons. Thus, the perceptual orthogonality evaluation is conducted by forming a matrix that compares the interaction between each taxon. The orthogonality (or influence) of the top-level characteristics is illustrated in a 6×6 matrix in Table 10. The notation for the comparison is: 9 – strong influence of the row on the column, 3 – moderate influence of the row on the column, and 1 – weak influence of the row on the column. Consider the team composition (group size, individual characteristics, leadership structure) in relation to the top-level taxon of communication. If the group size is large, then the effectiveness of various modes of communication degrade, a moderate influence noted by '3' in Table 10. The design problem has a strong influence on the choice of team composition, the information involved, and the design process employed, as noted by '9' in Table 10. Excluding the design problem, the five remaining top-level taxons have 'total of influence' values of team = 7, communication = 10, distribution = 5, information = 2, and design process = 3. While this suggests that the design problem, with a total of 28, is a key influencer in the selection of values for the other top-level taxons, we maintain that issues captured in the design problem taxon are not captured in the other taxons.

Deconstructing the taxonomy, each high-level taxon and its descendents are examined in a similar influence orthogonality manner with self-referencing matrices. Table 11 illustrates the self-referencing orthogonality matrix for the team taxon. It can be seen that team leadership and the team relations are influenced slightly by the other team aspects, primarily the group size, group

Table 10. Top-level influence matrix.

	Team	Communication	Distribution	Problem	Information	Process	Total of influencer
Team		3	1			1	5
Communication	3		3			1	7
Distribution	3	3		1	1		8
Problem	9	1			9	9	28
Information		3				1	4
Process	1	1	1		1		4
Total of influenced	16	11	5	1	11	12	

Note: 9 – strong influence of the row on the column, 3 – moderate influence of the row on the column, and 1 – weak influence of the row on the column.

Table 11. Self-referencing orthogonality matrix: team.

	Team: group: size	Team: group: culture	Team: individual: personality	Team: individual: expertise	Team: relations	Team: leadership	Total of influencer
Team: group: size		1			3	3	7
Team: group: culture			1		1	3	5
Team: individual: personality					1	1	2
Team: individual: expertise						3	3
Team: relations						1	1
Team: leadership					3		3
Total of influenced	0	1	1		8	11	

Note: 9 – strong influence of the row on the column, 3 – moderate influence of the row on the column, and 1 – weak influence of the row on the column.

culture, and individual expertise. Despite these influences, each of these issues is only moderately influenced by other issues.

Table 12 illustrates the self-referencing orthogonality matrix for the communication taxon. While there is slight influence of many issues against the others, there is no strong interrelationship in collaborative effectiveness between these issues. Communication frequency, duration, and reliability are those factors that are the most influenced, while the communication proficiency in terms of techniques and technology are the most influential. Thus, care should be given to these issues in structuring collaborative design teams.

Table 13 illustrates the self-referencing orthogonality matrix for the distribution taxon. The most influenced issue is that of temporal information distribution, just as the distribution of people across organisations is a prime influencing agent.

Table 14 illustrates the self-referencing orthogonality matrix for the design problem taxon. The factors that seem to drive the other issues more than others include problem concurrency and problem coupling. This agrees well with the research focused on decomposition and coordination of design problems (Haftka and Gurdal 1992, Renaud and Gabriele 1993, Blouin *et al.* 2004). Interestingly, the problem complexity is directly influenced by many of the other design problem factors, aligning also with the significant amount of research efforts focused on complexity management (Ahn and Crawford 1994, Bashir and Thomson 2001, Summers and Shah 2003).

The self-referencing matrix for the information taxon is presented in Table 15. Three factors are of interest in this taxon: the information management ownership and change, and the information reliability. The information ownership and change empowerment issues appear to influence several of the other information issues. For example, the ownership of information can change the reliability of that information. Consider a junior engineer being given ownership of an assembly model. Design reviews may be more likely to suggest changes to the junior engineer's models over those of a senior engineer based upon their perceived reliability in the information generated. Likewise, the reliability of the information is dependent upon several other factors, such as the form of information.

Finally, Table 16 illustrates the evaluation matrix for the design process taxon. The design tools seem to be influenced by all other factors in the design process category, while also influencing the progress monitoring and the structure of the design process. It is important to realise that many of these factors are decided simultaneously during the design of a collaborative design methodology. However, by separating and examining each of these factors independently, design managers and researchers can begin to manipulate specific situations to accommodate specialised needs and to study the effects of each of these factors and associated decisions upon the overall effectiveness of the design process.

Table 12. Self-referencing orthogonality matrix: communication.

	Communication: mode: verba	Communication: mode: written	Communication: mode: graphic	Communication: mode: gestures	Communication: quantity: frequency	Communication: quantity: duration	Communication: syntax: language
Communication: mode: verbal					1	1	1
Communication: mode: written					1	1	1
Communication: mode: graphic					1	1	1
Communication: mode: gestures					1	1	1
Communication: quantity: frequency	1	1	1	1		1	
Communication: quantity: duration	1	1	1	1	1		
Communication: syntax: language	1	1	1	1			
Communication: syntax: translators	1	1	1	1	1		
Communication: proficiency: techniques	1	1	1	1	1	1	1
Communication: proficiency: technology	1	1	1	1	1	1	
Communication: dependability: reliability					1	1	
Communication: dependability: availability					1	1	
Communication: intent	1	1	1	1			1
total of influenced	7	7	7	7	10	9	6

Table 12. Continued

	Communication: syntax: translators	Communication: proficiency: techniques	Communication: proficiency: technology	Communication: dependability: reliability	Communication: dependability: availability	Communication: intent	Total of influencer
Communication: mode: verbal	1			1	1		6
Communication: mode: written	1			1	1		6
Communication: mode: graphic	1			1	1		6
Communication: mode: gestures	1			1	1		6
Communication: quantity: frequency				1	1		7
Communication: quantity: duration				1	1		7
Communication: syntax: language	1			1			6
Communication: syntax: translators							5
Communication: proficiency: techniques			1	1			9
Communication: proficiency: technology		1		1			8
Communication: dependability: reliability							2
Communication: dependability: availability							2
Communication: intent							5
total of influenced	5	1	1	9	6	0	

Note: 9 – strong influence of the row on the column, 3 – moderate influence of the row on the column, and 1 – weak influence of the row on the column.

Table 13. Self-referencing orthogonality matrix: distribution.

	Distribution: people: geographic	Distribution: people: organisation	Distribution: people: temporal	Distribution: information: geographic	Distribution: information: organisation	Distribution: information: temporal	Total of influencer
Distribution: people: geographic			1	1		1	3
Distribution: people: organisation	1		1	1	1	1	5
Distribution: people: temporal						1	1
Distribution: information: geographic						1	1
Distribution: information: organisation						1	1
Distribution: information: temporal							0
Total of influenced	1	0	2	2	1	5	

Note: 9 – strong influence of the row on the column, 3 – moderate influence of the row on the column, and 1 – weak influence of the row on the column.

Table 14. Self-referencing orthogonality matrix: problem.

	Problem: type	Problem: concurrency	Problem: coupling	Problem: abstraction	Problem: scope	Problem: complexity	Total of influencer
Problem: type						1	1
Problem: concurrency			3	1	1	1	6
Problem: coupling		1		1		3	5
Problem: abstraction						3	3
Problem: scope						3	3
Problem: complexity							0
Total of influenced	0	1	3	2	1	11	

Note: 9 – strong influence of the row on the column, 3 – moderate influence of the row on the column, and 1 – weak influence of the row on the column.

A cross-topic orthogonality check is illustrated for distribution and communication in Table 17. This illustrates how the sub-issues identified in the taxonomy may have influence upon other sub-issues. For a complete set of comparisons, the reader is referred to Ostergaard (2002). It should be noted these comparisons are also subjective and qualitative in nature, and will evolve over time based upon further investigation of specific combinations of these factors. However, these factors do not appear to be either entirely influenced by or a sole influencer of any other factor. Thus, the perceptual orthogonality is accepted here as adequate, although requiring further experimentation to completely demonstrate this conclusion.

4.2. *Completeness*

While completeness is a subjective quality of the taxonomy, a derivation of the taxonomy based upon a broad survey of the relevant research areas for collaborative design provides a strong foundation for the classification. The methodology for developing the taxonomy can be examined to demonstrate that a broad literature survey drove its development.

To develop this collaborative design taxonomy, we first surveyed relevant literature in the fields of psychology, sociology, computer science, and engineering design. Issues found to impact collaborative design were sorted into appropriate categories, such as communication and team composition. Applying the taxonomy to design cases highlighted missing components of the taxonomy. These design cases came from industry surveys, case studies published in the literature, and student design projects. The literature was then revisited to find supporting evidence for these additional issues. This process was repeated until no further items are found to be missing upon application to the design cases.

While this does not prove the completeness of the taxonomy, it does demonstrate a systematic approach employed to capture as much of the collaborative design domain as possible. Continual reflection and industrial study according to the methodology defined above will be used to augment this taxonomy as needed.

4.3. *Usability*

Finally, the usability of a taxonomy is primarily determined by whether the taxonomy is employed in organising the knowledge of a specific domain. While this taxonomy has been developed systematically based upon a broad literature survey and has been examined from an orthogonal perspective, the assessment of the usability of this taxonomy is limited to an evaluation of the depth of the taxonomy and application of this taxonomy in deriving collaborative design user studies and in developing new collaborative design tools. First, it may be argued that the depth is a function of the usability. If the number of levels in the taxonomy is great, then the taxonomy may

Table 15. Self-referencing orthogonality matrix: information.

	Information: form	Information: management: ownership	Information: management: change	Information: management: security	Information: management: propagation	Information: criticality	Information: dependability: reliability	Information: dependability: completeness	Total of influencer
Information: form							1	1	**2**
Information: management: ownership			3	3			3		**9**
Information: management: change		1		1	3		3	3	**11**
Information: management: security					3		3		**6**
Information: management: propagation							3	3	**6**
Information: criticality	1			1	1		1		**4**
Information: dependability: reliability	1			1	1				**3**
Information: dependability: completeness					1		1		**2**
Total of influenced	**2**	**1**	**3**	**6**	**9**	**0**	**15**	**7**	

Note: 9 – strong influence of the row on the column, 3 – moderate influence of the row on the column, and 1 – weak influence of the row on the column.

Table 16. Self-referencing orthogonality matrix: design process.

	Process: tools	Process: progress	Process: structure	Process: approach	Process: stage	Total of influencer
Process: tools		3	3			**6**
Process: progress	3		3			**6**
Process: structure	3	3				**6**
Process: approach	3	1	1			**5**
Process: stage	3	1	1			**5**
Total of influenced	**12**	**8**	**8**	**0**	**0**	

Note: 9 – strong influence of the row on the column, 3 – moderate influence of the row on the column, and 1 – weak influence of the row on the column.

become too cumbersome to use. Furthermore, if the taxonomy is fairly flat, containing most of the classifications or distinguishing factors at the same level, then the organisational power of the taxonomy is limited. Thus, a taxonomy ought to take the form of a balanced tree from graph theory. We have arbitrarily selected four levels to be the maximum depth of the taxonomy to restrict the depth to a usable level. This choice may be re-evaluated over time and with experience.

A second approach to demonstrating the usability of the taxonomy includes the application of the taxonomy in defining experimental collaborative design research projects and in developing a new design review tool selection matrix. The taxonomy has been used to guide the development user studies investigating modes of communication in design review, information sharing, and group cohesiveness (Ostergaard *et al.* 2003, Wetmore and Summers 2004). Further, the taxonomy was used directly to expand the number of considerations used in selecting a design review tool, thus forming the basis for the proper review selection matrix (Wetmore 2004).

5. Discussion

This paper has presented a descriptive classification for collaborative design situations in the form of a collaborative design taxonomy. This classification appears to be the first systematic approach for classifying collaborative design situations. The classification is derived from established literature in multiple domains. Six top-level characteristics have been identified and expanded down to levels where specific values may be applied to the taxons. This taxonomy has been evaluated with respect to orthogonality, demonstrating that the characteristics are generally independent. Interaction among the taxons, however, should be considered when determining appropriate levels for the values. This is reserved for future investigation.

The collaborative design factors organised in the proposed taxonomy provide a description of collaborative design situations. These factors may inhibit progress or success of a design team, or they may facilitate advancement of a design. Furthermore, the taxonomy has been a useful aid in designing studies of the collaborative design process and evaluating the coverage of collaborative design models.

A new collaborative design model is being developed as a natural progression from the taxonomy with additional influence from related research (Ostergaard *et al.* 2004). The relationship between information flow and resistance to that flow in collaborative engineering design suggests that an analogy to electrical circuits may be useful. The use of this analogy in an information-based model is expected to clearly highlight areas of resistance, where the greatest need for collaborative design tools may exist. This work to develop a taxonomy and ongoing work to construct an associated collaborative design model are initial steps toward creation of new collaborative support agent-based tools structured upon a fundamental understanding of the collaborative process with a theoretical foundation.

Table 17. Cross-topic orthogonality matrix.

		Distribution						
		People			Information			
Communication		Geographically	Organisationally	Temporally	Geographically	Organisationally	Temporally	Total of influencer
Mode	Verbal	1		1				**2**
Written			1	1		1	**3**	
Graphic	1		1	1		1	**4**	
Gestures	1		3				**4**	
Quantity	Duration	3		9			9	**21**
Frequency	1	1	3			3	**8**	
Syntax	Language		1	1				**2**
Translators			1			1	**2**	
Proficiency	Techniques		1	1		1	1	**4**
Technology	1	1	1	1	1	1	**6**	
Dependability	Reliability	3	3	9	1	3	9	**28**
Availability	3	1	1	1	1	1	**8**	
Intent	Inform							**0**
Commit			1				**1**	
Guide		1	1				**2**	
Request						1	**1**	
Express							**0**	
Decide	1	1	1	1		1	**5**	
Propose							**0**	
Respond			1			1	**2**	
Record				1	1	1	**3**	
Total of influenced			**15**	**10**	**33**	**7**	**7**	**31**

Note: 9 – strong influence of the row on the column, 3 – moderate influence of the row on the column, and 1 – weak influence of the row on the column.

References

Adler, N., 1991. *International dimensions of organizational behavior*. Boston, MA: PWSKent Publishing Company.

Ahmed, S., Wong, A., Sriram, D., and Logcher, R., 1992. Object-oriented database management systems for engineering: a comparison. *Journal of Object Oriented Programming,* 5 (3), 27–44.

Ahn, J. and Crawford, R., 1994. Complexity analysis of computational engineering design processes. Presented at *Design engineering technical conferences – design theory and methodology*: ASME.

Anderson, C., Glassman, M., McAfee, R., and Pinelli, T., 2001. An investigation of factors affecting how engineers and scientists seek information, *Journal of Engineering and Technology Management,* 18 (2), 131–55.

Andersson, A., 2001. Information exchange within the area of tool design and sheet-metal-forming simulations. *Journal of Engineering Design,* 12 (4), 283–91.

Austin, J., 1975. *How to do things with things with words.* Cambridge, MA: Harvard University Press.

Austin, S., Steele, J., Macmillan, S., Kirby, P., and Spence, R., 2001. Mapping the conceptual design activity of interdisciplinary teams. *Design Studies,* 22 (3), 211–32.

Baird, F., Moore, C., and Jagodzinski, A., 2000. An ethnographic study of engineering design teams at rolls-royce aerospace, *Design Studies,* 21 (4), 333–55.

Barrick, M. and Mount, M., 1991. The big five personality dimensions and job performance: a meta analysis. *Personnel Psychology,* 44, 1–26.

Barthelemy, J., Waszak, M., Jones, K., Silcox, R., Silva, W., and Nowaczyk, R., 1998a. Charting multidisciplinary team external dynamics using a systems thinking approach. Presented at *7th AIAA/USAF/NASA/ISSMO symposium on multidisciplinary analysis and optimization,* St. Louis, MO.

Barthelemy, J., Waszak, M., Jones, K., Silcox, R., Silva, W., and Nowaczyk, R., 1998b. Charting multidisciplinary team external dynamics using a systems thinking approach. Presented at *7th AIAA/USAF/NASA/ISSMO symposium on multidisciplinary analysis and optimization,* St. Louis, MO: AIAA.

Bashir, H. and Thomson, V., 2001. In *Canadian society of valile atlalysis,* SCAV, Ottowa, Cananda.

Blouin, V.G., Summers, J.D., Fadel, G.M., and Gu, J., 2004. Intrinsic analysis of decomposition and coordination strategies for complex design problems. Presented at *10th AIAA/ISSMO multidisciplinary analysis and optimization conference,* Albany, NY: AIAA.

Broadbent, J.A. and Cross, N., 2003. Design education in the information age. *Journal of Engineering Design,* 14 (4), 439–46.

Brusseri, M. and Palmer, J., 2000. Improving teamwork: the effect of self-assessment on construction design teams. *Design Studies,* 21 (3), 223–38.

Case, M. and Lu, S., 1996. Discourse model for collaborative design. *Conzputer-Aided Design,* 28 (3), 333–45.

Chan, B. and Finger, S., 1998. Supporting conceptual design: a model for reflective-interactive design. Presented at *Third workshop on knowledge intensive CAD,* Boston, MA: Kluwer Academic Press.

Hazelrigg, G., 1996. *Systems engineering: an approach to information-based design.* Upper Saddle River, NJ: Prentice Hall.

Hof, R., 1992. From Dinosaur to Gazelle: HP's evolution was painful but necessary. *Business Week,* 65.

Hudak, G., 1992. Concurrent engineering: what are the risks and benefits?. Presented at *Technical program: NEPCON west 1992,* Anaheim, CA.

Hurley, R., 1995. Group culture and its effect on innovative productivity. *Journal of Engineering and Technology Management,* 12 (1–2), 57–75.

Jeffrey, C., 1982. *An introduction to plant taxonomy.* New York, NY: Cambridge University Press.

Kichuk, S. and Wiesner, W., 1997. The big five personality factors and team performance: implications for selecting successful product design teams. *Journal of Engineering and Technology Management,* 14 (3-4), 195–221.

Klein, M., 2000. Towards a systematic repository of knowledge about managing collaborative design conflicts. Presented at *6th international conference on artificial intelligence in design,* Worcester, MA.

Kliem, R., 1986. *The secrets of successful project management.* New York, NY: John Wiley & Sons, Inc.

Knutilla, A,, Steves, M., and Allen, R., 2000. Workshop on evaluating collaborative enterprises, workshop report. Presented at *9th international workshop on enabling technologies,* Gaithersburg, MD.

Leckie, G., Pettigrew, K., and Sylvain, C., 1996. Modeling the information seeking of professionals: a general model derived from research on engineers, health care professionals, and lawyers. *Library Quarterly,* 66 (2), 161–93.

Lees, B., Branki, C., and Aird, I., 2001. A framework for distributed agent-based engineering design support. *Automation in Constrliction,* 10 (5), 631–37.

Leifer, L., 2000. The case for distributed collaborative learning-based design. Presented at *CoDesigning 2000: an international conference,* Coventry University, UK.

Lindemann, U., Anderl, R., Gierhardt, H., and Fadel, G., 2000. 24 Hr. Design and Development: An Engine Design Project. *In:* Scrivener, S., Ball, L. and Woodcock, A., ed. Chapter B. *Collaborative design,* New York, NY: Springer.

Lloyd, P., 2000. Storytelling and the development of discourse in the engineering design process. *Design studies,* 21 (4), 357–73.

Lopez-Mesa, B. and Thompson, G., 2006. On the significance of cognitive style and the selection of appropriate design methods. *Journa1 of Engineering Design,* 17 (4), 371–86.

Lurey, J. and Raisinghani, M., 2001. An empirical study of best practices in virtual teams. *Information and Management,* 38 (8), 523–44.

Marschan, R., Welch, D., and Welch, L., 1996. Control in less-hierarchical multinationals: the role of personal networks and informal communciation. *International Business Review,* 5, 137–50.
May, A. and Carter, C., 2001. A case study of virtual team working in the european automotive industry. *International Journal of Industrial Ergonomics,* 27 (3), 171–86.
Minneman, S. and Leifer, L., 1993. Group engineering design practice: the social construction of a technical reality. Presented at *International conference on engineering design (ICED1993).*
Cherng, J., Shao, X., Chen, Y., and Sferro, P., 1998. Feature-based part modeling and process planning for rapid response manufacturing. *Computers and Industrial Engineering,* 34 (2), 515–30.
Chiu, M., 2002. An organizational view of design communication in design collaboration. *Design Studies,* 23 (2), 187–210.
Costa, P. and McCrae, R., 1988. Personality in adulthood: A 6-year longitudinal study of self-reports and spouse ratings on the NEO personality inventory. *Journal of Personality and Social Psychology,* 54, 853–63.
Davison, R. and Azmodeh, M., 1997. Performance management of public atm networks: a scaleable and flexible approach. Presented at *Proceedings of the 5th IFIP/IEEE integrated network mananement,* San Diego, CA: Chapman & Hall, Ltd.
Day, D. and Silverman, S., 1989. Personality and job performance: evidence of incremental validity. *Personnel Psychology,* 42, 25–36.
de Candolle, A., 1813. *Exposition des Principes de la Classification Naturelle et de l'Art de Decrire et d'Etudier les Vegetaux;* Paris, France: Deterville.
Denton, H., 1997. Multidisciplinary team-based project work: planning factors. *Design Studies,* 18 (2), 155–70.
Derr, R., 1973. *A Taxonomy of social purposes of public schools.* New York, NY: McKay Publishing.
Deus, L., 2000. Collaboration marketplace evolving to meet emerging needs. *The Edge Perspectives,* 1 (1).
Digman, J., 1990. Personality structure: emergence of the five-factor model. *In:* Porter, L., ed. *Annual review of psychology,* Palo Alto, CA: 417–40.
Dinsmore, P., 1990. *Human factors in project management.* New York, NY: American Management Association.
Dixon, J., Duffey, M., Irani, R., Meunier, K., and Orelup, M., 1988. A proposed taxonomy of mechanical design problems. Presented at *Computers in engineering conference*, San Francisco, CA.
Dixon, J., Howe, A., Cohen, P., and Simmons, M., 1987. Dominic I: progress toward domain independence in design by iterative redesign. *Engineering with Computers,* 2, 137–45.
Dunn, G. and Everitt, B., 1982. *An introduction to mathematical taxonomy.* New York, NY: Cambridge University Press.
Fadel, G., Lindemann, U., and Anderl, R., 2000. Multi-national around the clock collaborative senior design project. *In:* ASME, ed. *ASME curriculum innovations awards,*
Garner, S., 2001. Comparing graphic actions between remote and proximal design teams. *Design Studies,* 22 (4), 365–76.
Gershenson, J. and Stauffer, L., 1999. Taxonomy for design requirements from corporate customers. *Research in Engineering Design,* 11, 103–5.
Ghoshal, S., Korine, H., and Szulanski, G., 1994. Interunit communcation in multinational corporations. *Management Science,* 40, 96–110.
Goel, A., Bhatta, S., and Stroulia, E., 1997. KRITIK: an early case-based design system. *In:* Maher, M. and Pu, P., ed. *Issues and applications of case-based reasoning in design,* Mahwah, NJ: Erlbaum, 87–132.
Gurdal, Z. and Haftka, R.T., 1992. *Elements of structural optimization.* Norwell, MA: Kluwer Academic Publishers.
Monell, D. and Piland, W., 2000. Aerospace systems design in NASA's collaborative engineering environment. *Acta Astronautica,* 47 (2-9), 255–64.
Norrgren, F. and Schaller, J., 1999. Leadership style: its impact on cross-functional product development. *Journal of Product Innovation Management,* 16 (4), 377–84.
Orlikowski, W., 1992. In *Sloan school working paper.* MIT, Cambridge, MA.
Ostergaard, K.J., 2002. In *Mechanical engineering.* Clemson Univeristy, Clemson, SC.
Ostergaard, K.J., Summers, J.D., and Fadel, G.M., 2004. Resistance based modeling of collaborative design. Presented at *Design engineering technical conferences (DETC2004),* Salt Lake City, UT: Design Automation.
Ostergaard, K. J., Wetmore, W., and Summers, J. D., 2003. A methodology for the study of the effects of communication styles on design review effectiveness. Presented at *Design engineering technical conferences,* Chicago, IL: ASME.
Pahl, G. and Beitz, W., 1996. *Engineeing design: a systematic approach.* New York, NY: Springer.
Parks, C. and Nelson, N., 1999. Discussion and decision: the interrelationship between initial preference distribution and group discussion content. *Organizational Behavior and Human Decision Processes,* 80 (I), 87–101.
Parks, J., 2001. In *Mechanical engineering,* University of Texas, Austin, TX.
Peart, A., 1971. *Design of project management systems and records.* Boston, MA: Cahners Books.
Prasad, B., Wang, F., and Deng, J., 1998. A concurrent workflow management process for concurrent product development. *Journal of Engineering Design,* 9, 121–135.
Pugh, S., 1991a. *Integrated methods for successful product engineering.* London, UK: Addison Wesley.
Pugh, S., 1991b. *Total design,* Wokingham, UK: Addison-Wesley.
Redelinghuys, C. and Bahill, A.T., 2006. A framework for the assessment of the creativity of product design teams. *Journal of Engineering Design,* 17 (2), 121–41.
Reilly, R., Lynn, G., and Aronson, Z., 2002. The role of personality in new product development team performance. *Journal of Engineering and Technology Management,* 19 (1), 39–58.
Renaud, J. and Gabriele, G.A., 1993. Improved coordination in nonhierarchic system optimization. *AIAA Journal,* 13 (12), 2367–73.
Rezgui, Y., Brown, A., Cooper, G., Yip, J., Brandon, P., and Kirkham, J., 1996. An information managment model for concurrent construction engineering. *Automation in Construction* 5 (41), 343–55.

Rouibah, K. and Caskey, K., 2003. A workflow system for the management of inter-company collaborative engineering processes. *Journal of Engineering Design* 14 (3), 273–93.
Searle, J., 1969. *Speech acts: an essay in the philosophy of language*. Cambridge, UK: Cambridge University Press.
Shah, J.J., 1998. Experimental investigation of collaborative techniques for progressive idea generation, Presented at *Design engineering technical conferences (DETCI998),* Atlanta, GA: Design Theory and Methodology.
Shah, J.J., Bliznakov, P., Rogers, M., Jeon, D., and Urban, S., 1996. Database infrastructure for supporting engineering design histories. *Computer-Aided Design,* 28, (3), 347–60.
Shah, J.J., Vargas-Hernandez, N., Summers, J.D., and Kulkami, S., 2001. Collaborative sketching (C-sketch): an idea generation technique for engineering design. *Journal of Creative Behavior,* 35 (3), 168–98.
Shigley, J. and Mischke, C., 1989. *Mechanical engineering design.* St. Louis, MO: McGraw Hill, Inc.
Summers, J. D., Lacroix, Z., and Shah, J. J., 2001. Collaborative mechanical engineering design: representation and decision issues. Presented at *Le travail humain: modeling cooperative activities in design,* Paris, France: Presses Universitaires.
Summers, J.D. and Shah, J.J., 2001. Leadership style selection rules for agent architecture in engineering design. *In:* Cuginin and Wozny, ed. *From knowledge intensive CAD to knowledge intensive engineering,* the Netherlands: Kluwer Academic Press.
Summers, J.D. and Shah, J.J., 2003. Developing measures of complexity for engineering design. Presented at *Design engineering techinical conferences,* Chicago, IL.
Summers, J.D. and Shah, J.J., 2004. Representation in engineering design: a framework for classification. Presented at *Design engineering technical conferences,* Salt Lake City, UT: ASME.
Tett, R., Jackson, D., and Rothstein, M., 1991. Personality measures as predictors of job performance: a meta-analytical review. *Personnel Psychology,* 44, 703–42.
Ullman, D., 2003. *The mechanical design process.* New York, NY: McGraw-Hill, Inc.
Ullman, D. and D'Ambrosio, B., 1995. Taxonomy for classifying engineering decision problems and support systems. *Artificial Intelligence for Engineering Design, Analysis, and Manufacturing* 9, 427–38.
Vroom, V. and Jago, A., 1978. On the validity of the Vroom-Yetton model. *Journal of Applied Psychology,* 63 (2), 151–62.
Wetmore, W., 2004. In *Mechanical engineering.* Clemson University, Clemson, SC, pp. 179.
Wetmore, W. and Summers, J.D., 2004. Influence of group cohesion and information sharing on effectiveness of design review. Presented at *Design engineering technical conferences,* Salt Lake City, UT: ASME.
Willaert, S., deGraaf, R., and Minderhoud, S., 1998. Collaborative engineering: a case study of concurrent engineering in a wider context. *Journal of Engineering and Technology Management*, 15 (1), 87–109.
Yates, J. and Orlikowski, W., 1992. Genres of organizational communication: a structurational approach to studying communication and media. *Academy of Management Review,* 17, 299–326.
Yesersky, P., 1993. Concurrent engineering: your strategic weapon in today's jungle. *CMA Magazine: The Management Accounting Magazine,* 67 (6), 24–7.
Yoshioka, T. and Herman, G., 1999. MIT, Cambridge, MA.