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Physical and Digital Artifact-Mediated Coordination in Building Design

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Abstract. We conducted an ethnographic field study examining how a building design team used representational artifacts to coordinate the design of building systems, structure, and architecture. The goals of this study were to characterize the different interactions meeting participants had with design artifacts, to identify bottlenecks in the design coordination process, and to develop design considerations for CSCW technology that will support in-person design coordination meetings of building design teams. We found that gesturing, navigation, annotation, and viewing were the four primary interactions meeting participants had with design artifacts. The form of the design information (2D vs. 3D, digital vs. physical) had minimal impact on gesture interactions, although navigation varied significantly with different representations of design information. Bottlenecks in the design process were observed when meeting participants attempted to navigate digital information, interact with wall displays, and access information individually and as a group. Based on our observations, we present some possible directions for future CSCW technologies, including new mechanisms for digital bookmarking, interacting with 2D and 3D design artifacts simultaneously, and enriched pointing techniques and pen functionality.

Key words: artifacts, construction, design coordination, design development, design information, ethnographic study, interactive workspaces, meetings

1. Introduction

Building design is a complex process that requires a team of designers from numerous disciplines, each contributing a particular body of knowledge to the overall effort. The design process is iterative in nature, involving the exploration and analysis of many alternatives. Successful management of the design process is critical to the efficient delivery of cost-effective and quality projects (Chua et al. 2003). Studies have shown that 78% of quality problems are attributable to design (Koskela 1992), and that approximately 20–25% of the construction period is lost due to deficiencies in design (Undurraga 1996).

The increasing technical complexity of buildings, specialization of engineering knowledge, and cost-consciousness of owners has made the design process "intensely collaborative" (Schmidt and Wagner 2004). The decisions made during building design involve and affect many stakeholders, including architects, engineering consultants, construction managers, facility maintenance organizations, facility users, and property managers. Coordination among stakeholders, therefore, is critical to ensure that the design meets the functional, aesthetic, and economic requirements of the owner.

We examined how a project team used design artifacts such as drawings and models to accomplish *design coordination* during the design development phase of a new building project, which is described in detail in Section 4. We define design coordination, or simply *coordination*, as the process used by a design team to identify and resolve conflicts and potential issues between different elements in a building design to ensure that the different systems work together to meet the requirements set by the client. Although 'coordination' has many other meanings in CSCW (e.g., negotiating with others to divide up work effectively), we use the term specifically to refer to coordinating design elements.

Design development (DD) is the middle stage of the building design process that occurs after the basic appearance, building elevations, layout of floors, room configurations, and overall features of the project have been defined (Oberlender 2000). In this phase, the building systems are designed in accordance with recognized safety and performance standards in order to produce contract documents, the plans and specifications for constructing the project, that are developed in the final design phase. These building systems include civil, landscaping, structural, envelope, mechanical, electrical, plumbing, controls and fire protection. The design development phase focuses on developing practical and pragmatic solutions for the different systems and the critical feature is *decision making*, which can range from broad design aspects to details (Mehta et al. 2008). Throughout the design development process, multiple stakeholders meet regularly to review and coordinate their designs and verify their compliance with the project requirements. The system designs are iteratively updated to accommodate each discipline's requirements.

Design artifacts, or *representational artifacts*, directly represent the building design information, and are therefore critical to design coordination. They include digital and physical 2D schematic diagrams and 3D models. The 2D drawings primarily consist of plans, elevations, sections and details. These drawings are typically referred to as the *stick set* since they are held together at one edge by a yardstick-like clamp. The stick set has a standard format and is divided into different sections to represent the different building systems. It typically includes architectural, civil, structural, mechanical, electrical, plumbing, landscaping, and fire protection drawings. Generally, at the design development stage, the architectural drawings are much more developed than the other drawings.

Digital technology has become integral to the design development process, with much of the design work being done on computers. Design coordination in these multidisciplinary meetings, however, is still largely accomplished using paper printouts of 2D schematic diagrams and related project information. In recent years, there has been a growing interest by building design teams to leverage digital representations of design information during these meetings, particularly as more teams adopt a 3D design process (Engineering News Record 2006). A 3D design process encourages the transition to digital meeting spaces because 3D design information cannot be easily printed. Digital 3D models offer several potential advantages, including fewer design conflicts and errors (Staub-French and Fischer 2001; Khanzode et al. 2005), improved data access and integration (Kam et al. 2003; Bakis et al. 2007), and enhanced visualization and interaction (Messner et al. 2006; Ganah et al. 2005). However, it is still unclear how project teams currently interact with paper and digital design artifacts during coordination meetings, and how to best integrate digital representations into existing meeting practice.

This paper presents the results of an ethnographic field study examining how a building design team used design artifacts during design coordination meetings. The goals of this study were to characterize the different low-level interactions meeting participants had with representational artifacts, and to identify design considerations for CSCW technology that will support in-person coordination meetings of building design teams. We focus specifically on spatial design information because interactions with design information are critical to coordination (e.g. as well-documented by Henderson 1999) and because 3D design information is one of the driving reasons to move towards digital meeting spaces. Prior studies have examined architectural practice (e.g., Schmidt and Wagner 2004) and the engineering design process (e.g., Henderson 1999) but few have specifically studied the coordination process and the lower level interactions project teams have with paper and digital design artifacts. These interactions are what we have attempted to capture.

We studied a particular building project team as they transitioned from paper-based meetings to digital meetings. We selected this project because it was being designed simultaneously using traditional 2D drawing practices as well as 3D design, and because it was a ‘green’ building, which typically requires more extensive collaboration (Andrews et al. 2006). Our study involved observation of coordination meetings and interviews with various members of the project team. We developed a taxonomy that characterized the different types of interactions that team members had with visual representations of design information during coordination meetings, along with the goals of those interactions. We then identified bottlenecks related to design representations, and examined to what extent the bottlenecks were caused by availability or suitability of interaction methods for the users’ goals. We used these prior results to draw implications for design.

We found that gesturing, navigation, annotation, and viewing were the four primary interactions meeting participants had with design artifacts. Viewing simply involved looking at or reading the artifact and was not studied in detail.

Gestures served a variety of purposes including orienting the listener to a spatial area, describing design elements, and relating items or documents. Navigation supported a variety of participants' goals including looking up information, describing and explaining designs, and relating different design information. Physically annotating the design information was rare; participants typically made annotations off to the side or on a separate sheet of paper. Interestingly, participants often made drawing-like actions over the design information (what we call *air draw*) without actually touching their pen to the artifact. Bottlenecks in the design process primarily centered on navigation with digital information, interaction with wall displays, and access to information individually and as a group. To address these obstacles, we outline possible directions for future CSCW technologies, including new techniques for navigation (e.g., mechanisms for bookmarking), pointing (e.g., differential marking), and multi-user interactions (e.g., peripheral wall displays integrated with a central display).

In the sections that follow, we summarize related studies of artifact use in building design and design coordination (Section 2). We then describe our methods in detail (Section 3) and provide background information on the building project that we studied (Section 4). Sections 5 and 6 summarize our characterization of existing practices and the bottlenecks that we observed. We conclude with a discussion of design considerations resulting from this study.

2. Related work

In this section, we begin by summarizing the role of representational artifacts in the process of architectural and engineering design. We then focus more specifically on the role of artifacts in design coordination, the focus of our study. Following a general discussion of design coordination, we describe existing taxonomies similar to our own taxonomy of low-level interactions with representational artifacts. Finally, we summarize existing collaboration technology that may be useful for design coordination.

2.1. Role and form of representational artifacts in design

Collaborative design has been well studied throughout the history of CSCW. For example, Olson et al. (1992) characterized the process of design meetings and the ways in which design issues are raised, alternatives are discussed, and decisions are made. We are interested in the role of representational artifacts in design, which is also well documented, particularly in architecture. An extensive review is provided by Purcell and Gero (1998). Schmidt and Wagner (2004) describe the importance of representational artifacts in architectural design as, "...[they] constitute the field of work...they are what is looked upon, inspected, gestured at, discussed, modified, annotated, etc.". Design typically begins with a series of sketches, and later includes more structured drawings such as plans and sections

(Purcell and Gero 1998). These representational artifacts serve a variety of important roles; for example, they provide an external representation of the information in a designer's head, allow designers to see and reinterpret the design, and are central to communication (Purcell and Gero 1998). Drawings impose constraints on the design but still allow a degree of uncertainty (Gross et al. 1988). For communication purposes, drawings both embody the current status of the design and prompt discussion of design modifications (Luck 2007).

Representational artifacts used in the design process have a variety of different forms, including 2D drawings, 3D physical models, and 2D and 3D computer aided design (CAD). Benefits of using a 3D building design process were described in the introduction. However, even when using a 3D design process, there are advantages to using both 2D and 3D representations of the design information. While 3D information provides an overview of the object being designed and effectively conveys 3D shape, 2D information is better for displaying interior details, making precise measurements, and enabling simpler navigation (Tory 2004).

Most studies of artifacts in architectural design have focused on sketching. Sketching is a critical activity in early stages of design because it brings out the serendipitous, opportunistic nature of design (Visser 1990), has a more ambiguous quality than computer-based drawings (Goel 1995), and externalizes the design process, enabling the designer to bridge between abstract design concepts and concrete forms (Goldschmidt 1991). Suwa and Tversky (1996) suggested that expert knowledge was paramount in allowing designers to assess the quality and relationships between sketches and potential designs.

A related series of studies have examined artifact use in engineering design. Brereton and McGarry (2000) observed how ordinary objects such as pens and rubber bands were drawn into a small group design exercise, acting as starting points, thinking props, and memory triggers. In a series of ethnographic studies, Henderson (1999) examined the central role of visual representations in engineering design and the interaction between digital and physical forms of this information. She argued that sketches are the most important artifact in design generation because they enable visual thinking, revision, and communication among designers. Other artifacts play important roles in coordination, as described below. Tang and Leifer (1988), and a subsequent study by Tang (1991), have examined low-level interactions such as gestures in relation to design information for engineering design. They demonstrated that it is not just the design artifacts themselves that are important for collaboration, but also the mechanics of interaction with the artifacts. Similarly, Robertson (1997) observed how the individual embodied actions of designers facilitated communication among members of a group. Creating, gesturing, and annotating shared artifacts served to structure and organize the group discussion.

With the exception of Henderson (1999), these studies focused on the process of design. By contrast, we are interested in coordination, or the means by which designers and stakeholders with different backgrounds and roles coordinate their design ideas. Although design and coordination are interrelated and some designing occurs during coordination meetings, the coordination process is significantly different from design and deserves separate attention. There are typically more participants, and a greater diversity of participants, in coordination meetings, and the focus is on communicating design intent and making design decisions rather than creating design artifacts collaboratively in the meetings. We discuss coordination in the next section.

2.2. Role of artifacts in coordination

Grønbæk et al. (1993) described the diversity of representational and other artifacts used in a construction project, and the importance of having easy access to these artifacts to coordinate work with others. The process of design coordination has been described at a high level by Perry and Sanderson (1998), Henderson (1999), and Schmidt and Wagner (2004). These researchers recognized the role of CAD diagrams as *boundary objects* (Star and Griesemer 1989), which serve as interface between different communities of practice, such as architects, engineers, and owners. They also recognized the importance of standards, which provide consistency across disciplines and firms. In addition, Luck (2007) found that design artifacts helped mediate users' understanding of the design and discussion of possible improvements.

Henderson (1999) further described engineering diagrams as *conscription devices*, arguing that in order to participate in the design process, people must actively engage one another and communicate via the visual representations. She also argued that formal drawings serve as boundary objects to a much greater extent than early sketches because formal drawings keep track of minute details and are widely shared. It is therefore unsurprising that all members of the project team who we interviewed recognized the stick set as an important boundary between disciplines.

Schmidt and Wagner (2004) described the ways in which design artifacts, such as CAD drawings, act as central support for group activities in architectural practice. These are supplemented with *coordinative artifacts*, such as distribution lists, which act specifically to coordinate people's activities. Schmidt and Wagner introduced the concept of *ordering systems*, describing how people coordinate their activity through these artifacts, by changing the state of artifacts. Most of Schmidt and Wagner's work focused on internal practices within an architectural firm. However, they also described how organization and layering of information in CAD diagrams enables external consultants to contribute to the building design in an ordered fashion (i.e. design coordination). Similarly, Perry and Sanderson (1998) described how information is sometimes included in representational artifacts to support coordination. For example, stamps and signatures on diagrams were used to indicate who should be contacted for queries about the information.

These prior studies have focused on coordination at a high level of abstraction, documenting the representational nature of artifacts, the processes surrounding their creation and modification, and the ways in which they are shared. However, these studies have not characterized the low level mechanics of how participants interact with representational artifacts during coordination meetings. Our study addresses this gap in current literature.

2.3. Interactions with artifacts

In Section 5, we present a taxonomy characterizing how people interacted with representational artifacts in the meetings we observed. Some aspects of this taxonomy are similar to results from prior observational studies of gesture, navigation, and annotation. Tang and Leifer (1988) and Tang (1991) describe how listing, drawing, and gesturing interactions with artifacts are used to store information, express ideas, represent ideas, and mediate interactions between participants. Robertson (1997) examined individual actions that related to objects, people, or the workspace. She found that such individual actions supported group activities by enhancing awareness and communication. Bly (1988) and Robertson (1997) both observed that an absence of attention-focusing interactions such as gestures, noticeably detracts from the collaboration process. Our analysis of low level interaction mechanics is similar in many ways to Tang and Leifer (1988); however, we focus on design coordination rather than pure design, we characterize gestures in a more fine-grained way, and we consider navigation among multiple design artifacts.

Gestures have been extensively studied from a linguistic perspective, examining gestures in conversation or narration (e.g., see Kendon 2004; McNeill 1992). Because gestures play an important role in face-to-face communication, substantial research has also be devoted to systems that communicate gestures to remote participants (e.g., Kirk et al. 2005; Barthelmess et al. 2005). We studied gestures in relation to design artifacts. Hence, the gestures we characterize are primarily *deictic* (McNeill 1992); they refer to information in an artifact or to the building being designed. Prior research by Eisenstein and Davis (2006) demonstrated that in the presence of a diagram, 96% of gestures related to the diagram and deictic gestures were far more common than without a diagram.

Our taxonomy also characterizes how people navigate design artifacts to obtain different views of the design information. Darken (in Jul and Furnas 1997) defines two main components of navigation: *wayfinding*, determining where you are and how to get to your destination, and the actual movement, which we call *positioning*. Substantial research has been devoted to improving wayfinding in 3D virtual environments (e.g. Jul and Furnas 1997) as well as hypertext (e.g. Dillon et al. 1990). By contrast, our observations focus mainly on positioning.

A third category of interactions that we observed was annotation. Annotation of design drawings has been identified as a frequent and important function in architecture, engineering, and construction (Schmidt and Wagner 2002; Schmidt and Wagner 2004; Perry and Sanderson 1998; Mackay et al. 1995). A common architectural practice is to annotate translucent paper layered on top of a drawing, so as not to directly alter the drawing itself (Schmidt and Wagner 2002), a practice which our participants reported, but which we did not observe. Instead, we observed that participants sometimes avoided marking up the diagrams by making drawing-like actions without touching their pen to the page, an interaction we call air-drawing. We also observed written marks on both the information itself and in the margins of the page, similar to the results of Marshall's (1997) study of annotations in college textbooks.

2.4. Collaboration technology

Many examples of prototype tools and digital infrastructures for supporting various aspects of architectural planning exist in the literature. The Luminous planning table (Underkoffler and Ishii 1999) and Build-it (Lauche 2005) attempted to integrate multiple forms of physical and digital media to support the design process. The iRoom infrastructure originally developed by Johanson et al. (2002) has also been extended and applied to design and construction meetings, perhaps most notably for the Center for Integrated Facilities Engineering (CIFE) at Stanford (Fischer et al. 2002; Kunz et al. 2002). Other meeting support systems such as the Tivoli electronic whiteboard, the i-LAND roomware system, and the Dynamo multi-user surface contain digital elements that might be desirable for computer-supported design development (Pedersen et al. 1993; Streitz et al. 1998; Izadi et al. 2003). In practice, however, integration of digital infrastructure into collaborative building design has been limited and has encountered many challenges. By studying existing work practice, we hope to identify ways in which digital technology could be better integrated.

3. Methods

We conducted a seven month ethnographic field study of a building design project for a university campus. We chose to study one group in depth rather than multiple groups because this would better enable us to gain a deep understanding of a team's work practice, something that would not be practical in a study with greater breadth. We took an approach inspired by grounded theory (Glaser and Strauss 1967; Glaser 1992), and studied collaborative work practice via systematically collecting and analyzing qualitative data. Using this method, we developed a taxonomy (described in Section 5) that explained how different representations of design information facilitated collaboration during coordination meetings. The main advantage of our approach is that results are 'grounded' in the data; our predictions about designing collaboration technology are based on an understanding of real work practice. At the same time, this approach means that our results cannot be directly generalized away from the design team and project under study. In the discussion, we attempt to identify observations that we believe are unique to this particular design team and building project; however, observation of other design teams is needed to corroborate our own evidence.

3.1. Data collection

We observed 20 weekly in-person coordination meetings throughout the design development process, and conducted interviews with the most frequent meeting participants: the architects, construction manager, electrical consultant, and mechanical consultant. The second author actively participated in the building project as a 3D design consultant and attended several meetings in this role. The other authors acted as passive observers during meetings. Meetings were videotaped and interviews were audio-recorded for further analysis. We also had access to a document-sharing system (Autodesk Buzzsaw), which the building design team used to share and archive documents relevant to the meetings, including CAD drawings, CAD models, agendas, meeting minutes, consultant reports, schedules, and cost plans.

3.2. Data analysis

Our analysis primarily centered on video data and field notes collected at ten different three hour coordination meetings. Ten additional three hour meetings were observed but not analyzed in depth. Interview data was used to validate findings and identify issues that participants felt were critical in reference to integrating digital media into their work practice. Documents accessed from the Buzzsaw system helped us to understand what information participants were viewing during specific meetings; this was most helpful when the information was not easily visible on the video.

We used an open-coding approach to video analysis similar to Tang (1991). Our approach was based on Interaction Analysis (Jordan and Henderson 1995), but we did not analyze video as a group. Because of the large amount of video data, we transcribed only short sections of interest. Our open-coding iteratively characterized the ways in which the design team interacted with design information, and the goals participants were trying to achieve by means of the interactions. Codes were considered valid only if they appeared repeatedly in different sections of the video. We focused on physical interactions with design information, but used participants' speech to understand the intent and purpose of those interactions. We also performed a separate quantitative video analysis of eight meetings, where we counted different interactions with artifacts. The quantitative analysis was used mainly to provide numeric evidence supporting our claims.

Extensive observations and interviews with members of the project team enabled us to gain a thorough understanding of the attitudes, roles, and objectives of different participants. Although much of this information is not directly reported in this paper, it provided useful context and helped to validate our assumptions.

4. Background on the building project

The building project followed in this study was a sustainability research building called the Centre for Interactive Research on Sustainability (CIRS), as shown in Figure 1. The project was unique in several ways. In particular, the building aimed to be the most sustainable development in North America and therefore required innovative design of many building systems such as lighting, heating, water use, and waste management. In addition, the building was to be shared by five different academic organizations and therefore involved five distinct user groups. We were attracted to this project because it was designed simultaneously using traditional 2D drawing practices as well as 3D design. This allowed us to compare the use of 2D and 3D design information for coordination purposes within the same design team and design project. However, the unusual aspects of this building project must be taken into account when generalizing to other design teams and building projects.

Typical coordination meetings had 10–25 co-located participants. This number may be a bit larger than other design projects because this project was both inter-institutional and sustainable. Table 1 shows the network of stakeholders involved in the design development process. Weekly meetings were the only time that all the key stakeholders came together to discuss how the many different parts of a building would interact and affect the overall project requirements. The prime

Figure 1 3D rendering of the Center for Interactive Research on Sustainability Project (source: Busby Perkins + Will).

Table 1 Network of stakeholders involved in the CIRS design process.

Classification	Key stakeholders	Role
Client	University property developers	Carry out the planning and development of institutional projects as directed by the university Board of Governors
Project manager	General project consulting	Task force coordination, fundraising, partnerships, agreements, equipment procurement, etc.
Governing authorities	City of Vancouver, Ministry of Health, Ministry of Environment	Set standards for construction and building footprint, e.g. building shadow, effluents, potable water quality, etc.
Users	Facility tenants, research clusters, task forces	Set requirements for functionality and goals for sustainability through research clusters and user task forces
User task forces	Educational, government, non-profit, and industry tenants	Reach agreements that clearly define the use of and responsibility for the shared space
Operational task forces	Local experts from academia and industry	Develop a comprehensive communications strategy, manage the facility when built, and develop the bureaucratic network that will govern operations as a whole
Prime design consultants	Architectural, mechanical, electrical, landscaping, and code consultants	Facilitate and moderate design discussions, coordinate designs, generate overall design in accordance with sustainability goals
Other design consultants	Water and wastewater, living wall, solar hot water collection, photovoltaic system, IT, security, codes, surveyors, quality control, geotechnical, cost, transportation, acoustics	Provide specialized expertise, coordinate design details, supply products and installation services
Construction consultants	General construction, mechanical, and electrical construction consultants	Provide overall construction expertise, evaluate the constructability, cost and schedule implications of design alternatives, and provide feedback to designers

design and construction consultants and client representatives attended most meetings. Other project members typically attended only when their issues were included on the agenda. Occasionally, an absent participant would take part in the meeting by speakerphone. Most meetings were held at the architects' office.

Most coordination meetings focused on design issues, although certain meetings focused on other project requirements (e.g., cost, schedule, regulations, etc.). In general, the discussion focused on communicating the design status of the different disciplines (e.g., structural design), identifying interactions between the different systems designs (e.g., influence of the structural design on the mechanical systems), identifying potential implications of design decisions on other project requirements (e.g., influence on construction cost), soliciting information from others (e.g., feasibility of using steel piles for the foundation design), and identifying outstanding issues (e.g., deadline for the geotechnical report). The outcomes of meetings included specific design decisions (e.g., decision to use a timber rather than a reinforced-concrete structure), clarification of particular design problems (e.g. geotechnical issues associated with the foundation design) and action items that needed to be researched and addressed at the next meeting (e.g., calculating the costs of different chilled slab options).

Our analysis focused on two distinct types of meeting content:

- *Design development (DD) meetings* focused on refining the design of various systems in the building. For example, participants discussed the impact of building layout and window glazing options on interior lighting, assessed the suitability of different structural designs for the water-laden construction site, and compared the impact of locating mechanical structures on the roof, in the basement, or outdoors at ground level.
- *Value engineering (VE) meetings* focused on reducing the cost of the building project. Part way through design development, the construction managers created a detailed cost estimate and found the project was approximately 20% over budget. In three successive meetings, the design team evaluated all of their prior design decisions in an attempt to reduce the construction cost. Suggestions to reduce the cost ranged from many minor design changes (e.g. reduced interior finishing) to major design alterations (e.g. removal of most of the basement and narrowing of the atrium).

Early meetings of both types took place using primarily paper-based information (*paper-based meetings*). Later meetings took place in a digital meeting space containing two touch-sensitive Smartboard wall displays with a dedicated computer workstation (*digital meetings*). Digital meetings made extensive use of the document sharing system Autodesk Buzzsaw to access relevant project information. Table 2 summarizes the ten meetings we examined in depth, including the type of meeting, types of design information used, meeting environment, and stakeholders present.

Our analysis focuses specifically on spatial design information including: 2D drawings, 2D digital drawings, a 3D physical model, and images rendered from a digital 3D model. One of the architects was responsible for compiling and maintaining 2D drawings in the stick set. The architectural drawings were usually updated on a weekly basis and the consultant drawings were updated at specific milestones. The stick set was stored at the architect’s office and could be easily

Table 2 Types of spatial design information used during different types of meetings.

Meeting Number	Stakeholders present	Meeting type	Overview of meeting agenda	Meeting environment	Design artifacts
1	Owner (1), CM (3), Mechanical (2), Electrical (1), Architect (3)	DD	Review timeline and electrical, mechanical & plumbing strategies	Paper-based	Stick set
2	Owner (1), CM (3), Structural (1), Code (1), Soils (1), Mechanical (1), Electrical (1), Architect (2)	DD	COV meeting update, Transportation plan, Code analysis, Soils report, Finalize core structure design	Paper-based	Stick set
3	Owner (1), PM (2), Structural (1), Mechanical (3), Landscape (1), Architect (2)	DD	Mechanical design update, Landscape update, Soils/Geotechnical update	Paper-based	Stick set
4	Owner (1), User (2), CM (3), Mechanical (2), Structural (1), Landscape (1), Geotechnical (1), Architect (3)	DD	Constructed wetland, Green roof, Mechanical update, Structural update, Geotechnical update	Paper-based	Stick set
5	User (3), Owner (2), Electrical (2), Architect (2), Mechanical (3), Cost consulatant (3), CM (4), Structural (1), Landscape (1)	VE	Review of cost estimates and value analysis	Paper-based	Stick set (present but not used), Pin-up wall, 3D physical model
6	Owner (1), User (2), Structural (1), CM (4), Electrical (3), Mechanical (3), Architect (3), Cost Consultant (1), Landscape (1)	VE	Brief clarification of estimated costs and proposals	Paper-based	Stick set
7	Owner (1), Architect (3), Mechanical (3), User (2), CM (4), Code (1), Electrical (3), Cost Consultant (2), Structural (1)	DD, VE	Living wall, Code, Cost review	Paper-based	Stick set, 3D physical model
8	Architect (4), Structural (1), CM (4), User (5), Electrical (2), Mechanical (1)	DD	Progress update, Visionwall details	Digital	Stick set (present but not used), 2D digital dwgs
9	Electrical (3), CM (4), Mechanical (3), Structural (1), User (1), Architect (2)	VE	Costing and Feasibility study	Digital	Stick set, 2D digital dwgs
10	Architect (4), CM (2), Electrical (2), Mechanical (2), User (2), Water consultant (4)	DD, VE	Update cost plan, Façade feedback, PV design, Water and wastewater treatment	Digital	Stick set, 2D digital dwgs, 3D digital images

DD Design Development; *VE* Value Engineering accessed for project meetings. The stick set represented the most current state of the design and was present at every meeting. In meeting 5, 2D paper drawings were also placed on the walls (the 'pin-up wall').

The 2D digital drawings we observed in meetings were simply digital versions of the different pages captured in the stick set. They were posted on Buzzsaw as AutoCAD drawing files and also in PDF format. Surprisingly, the 2D architectural drawings were created separate from the 3D architectural model. On typical 3D projects, the different 2D drawings are created directly from the 3D model, which is one of the key benefits of moving to 3D. Based on discussions with the architects, they decided to create separate 2D and 3D designs in parallel because they were worried about the learning curve in using a new type of 3D software and did not want that to delay the submission of the permit drawings. Consequently, the status of the 3D model always lagged slightly behind the development of the 2D drawings.

In the analysis below, we contrast interactions during different types of meetings (value engineering vs. design development), as well as interactions with different representations (2D vs. 3D and digital vs. physical).

5. Characterization of interactions with design artifacts

Here we describe the taxonomy of interactions with design artifacts that emerged from our grounded analysis. Because the team's design coordination activities depended heavily on communicating design details, low-level interactions with design artifacts were critical to maintaining workflow and effective communication. In particular, we characterize the ways in which participants interacted with design information, either cognitively or physically, the low-level goals they were trying to achieve via these interactions, and the number of people involved in different types of activities. Figure 2 summarizes our taxonomy, which is explained in detail through the remainder of this section.

5.1. Goals/subtasks

High-level goals of the meetings usually involved making important design decisions requiring extensive discussion, explanation, and analysis of alternatives. Our focus was on understanding the ways in which design information was used to support these higher-level goals. Sub-goals involving design information could be organized in a few simple categories, as shown in Table 3. These categories share similarities with existing taxonomies of data analysis tasks (e.g., Wehrend and Lewis 1990). We chose to develop our own categories rather than use an existing taxonomy in order to accurately represent the activities of the group we observed. We recognize that this may be only a subset of the activities of project teams in general.

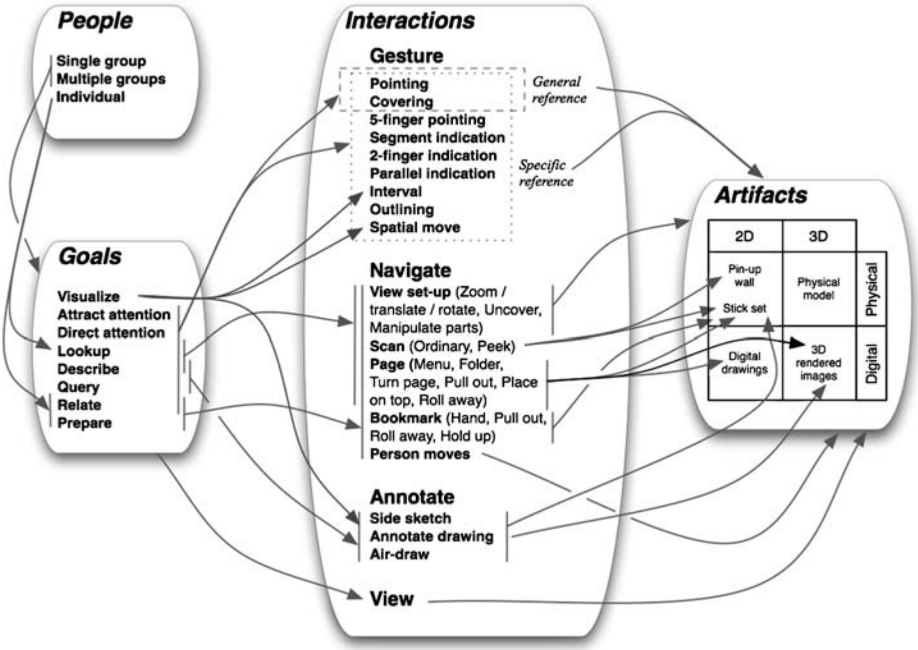


Figure 2 Taxonomy developed that characterizes the different types of interactions that people had with design artifacts during coordination meetings, along with the apparent goals of those interactions. *Arrows between items* indicate a relationship between the items. *Arrows to or from a group of items* indicate that all items in the group are involved in the relationship.

5.2. Interactions

We define interaction as cognitive or physical engagement with artifacts; in other words, the active use of artifacts. We specifically focus on artifacts containing design information. The most obvious interaction is to simply view the information that is currently visible, an action required to support all of the users' goals related to all types of design information. The more interesting interactions from a CSCW perspective involved physical engagement. We characterized three major types of physical engagement, gesturing, navigating, and annotating, which we discuss in detail below.

5.2.1. Gesturing

By far the most common physical interaction with design information during meetings was to refer to it via pointing and gesturing. In fact, pointing and gesturing accounted for 80% (615 out of 774) of physical interactions with design

Table 3 Goals of artifact interactions.

Goal	Description
Visualize	Visualize or imagine elements of the building design that are not visible in the representational artifact, either mentally or by drawing
Attract attention	Attract the attention of the group or a subgroup using an artifact to ensure they are prepared to listen
Direct attention	Direct the attention of others to a particular artifact or sub-area under discussion
Lookup	Look up information in a design artifact
Describe	Describe an idea or explain a concept to others with the help of an artifact
Query	Ask a question about the design information shown in an artifact
Relate	Understand relationships between the information in two or more design artifacts or between two or more parts of the same artifact
Prepare	Prepare an artifact for later anticipated activities

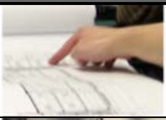
information in the meetings we observed. We do not attempt to provide a complete classification or analysis of gestures. Rather, we identify and categorize the most common and consistent types of gestures used in reference to design information. Our intent is twofold: (1) to better understand how physical references to design information support collaboration and (2) to identify gestures that are used consistently enough that they may be natural input methods for a digital system. We discuss potential input techniques later in Section 7.

We distinguish between two types of reference actions, similar to Poddar et al. (1998):

- *General reference*: the participant referred to the document or its contents as a whole. For example, the architect told a living wall consultant that he had several questions about how the living wall would affect the overall design, but that he would like to hold the discussion without the rest of the group. While saying this, the architect placed his hand on the stick set to indicate that the design information was relevant, even though the stick set was rolled up so no specific design information was visible at the time.
- *Specific reference*: the participant referred to a specific part of the design information, such as the width of the atrium or the position of the stairwell.

We observed several distinct types of gestures, as listed in Figure 2 and described in detail with examples in Table 4. These categories captured gestures that had a distinct visual form and were used by more than one individual. Some similar gesture types have been observed in other work. Bekker et al. (1995) described movements to demonstrate an action as *kinetic gestures* and movements to indicate distance, location, and size as *spatial gestures*. Our spatial move gesture is a hybrid of these two types since it is a kinetic gesture specifically

Table 4 Types of gestures with artifacts that we observed.

Gesture	General Description and Frequency	Example	
Pointing	Use a hand, finger, or pen to point directly at the artifact or a specific part of the contents. Very frequent.	One of the building's end users pointed to indicate a particular part of the building (specific reference).	
Covering	Move a hand or pen over an area or along a line. Movement indicated the extent of a sub-area, or the whole artifact. Form of the movement varied. Very frequent.	While describing his seismic assessment of the building site, the geotechnical engineer placed his hand over an area on the stick set and said, "….because of the soft ground at this end of the site…."	
5-finger pointing	Use all five fingers of one hand to surround a small area of interest. Occasional.	An architect placed all five fingers over an area on the stick set to indicate the parking area that he wanted to discuss.	
Segment indication	Place a hand, arm, or pen along an edge or long, thin object of interest. Rare.	The structural engineer placed the edge of his hand above the 3D model at successive locations to indicate positions of structural beams.	
2-finger indication	Use two fingers (usually a thumb and another finger) to indicate the space or length between them. Frequent.	The electrical engineer used his thumb and forefinger to indicate a wide electrical conduit. He held his hand as shown and moved it across the model to indicate the conduit location.	
Parallel indication	Place both hands or two pens in parallel to indicate the space in between. Rare.	An architect indicated a subsection of the building using two hands, explaining that a prototype green roof should not be over that portion because there were offices below.	
Interval	Use one hand to indicate one area and the other hand to indicate a second, related area. Rare.	The structural engineer compared piling options by using one hand as an anchor and moving the other hand to indicate what would happen near the anchor in an earthquake, saying, "….if this was an anchor, then this whole thing would tilt this way…."	
Outlining	Use a hand, finger, or pen to circle or outline the area of interest. Frequent.	The electrical engineer circled two areas on the screen to indicate the position of the theatre and an adjacent server room used to support the theatre's computer equipment.	
Spatial move	Move a hand to indicate physical movement of a component. This may follow specifying the component of interest. Frequent.	An architect requested that the structural engineer investigate the cost of a new alternative, saying, "So you're being tasked with moving the flexible shear out of here [left image] and into here [right image] and looking at pricing."  	

focused on spatial movement. Kirk et al. (2005) describe this type of gesture as *mimicking*, because it mimics the movement of a physical object. Kirk et al. also noticed instances of *covering* an object with the hand to identify it, although in their case a remote participant used covering to indicate that an object should be ignored. Murphy (2005) described many hand shapes similar to ours for an earlier phase of architectural design. Both our observations and Murphy's observations included a thumb and forefinger used to indicate width (two-finger indication), a cupped hand (five-finger indication), and a swinging hand or pen to indicate how a door pivots (spatial move). Murphy also observed a number of movements specifically related to door function. One example involved pinching fingers together to indicate doors closing; we observed a similar pinching motion to indicate narrowing the width of an atrium (two-finger indication plus spatial move). These similarities demonstrate consistency across groups and design phases, showing promise that these hand shapes could be used as natural methods of input.

Referring to design information via gesture served a wide variety of purposes. By indicating the spatial area or document under discussion, gestures served first to orient the listener to an area being *described* or an area under question during a *query*, similar to previous work by Detienne and Visser (2008), Heiser et al. (2004), and Hutchins and Palen (1997). Extensive gestures were used to *describe* design elements and explain the rationale behind an existing design or a proposed design change. Spatial move gestures were particularly important for *describing* movement, which could be either physical movement (e.g. movement of smoke in a fire simulation) or a design change resulting in the movement of a building component to a new location. Gestures were also used extensively when *relating* items or documents. For example, an architect gestured back and forth between two walls of the 3D physical model while explaining how different sun exposure affected the choice of exterior glazing on the North and South sides. Hutchins and Palen (1997) described a similar relationship function where a pilot used gesture to relate different parts of an airplane's fuel system. Gestures also served to help gain the attention of others, either the entire group or a small subset, as previously noted by Tang (1991). By gesturing toward the design information, a person could indicate that they wished to speak without disrupting the current speaker.

On a few occasions, gestures helped participants to mentally *visualize* elements of the design that could not be seen, such as the way a door would swing. Typically, a spatial move gesture was used to enact a simulation of physical movement, similar to gestures described by Tang (1991) for interface design. Our *visualize* category was specifically inspired by an architectural study by Murphy (2005), who demonstrated that gestures help architects mentally visualize the 3D functional nature of the building. Unlike Murphy, however, we observed only a few gestures to visualize ideas. The vast majority of gestures served to direct attention to spatial areas, objects, or documents, to help the participant describe a concept or ask a question. This difference may be due to the different nature of design and coordination meetings. It may also be due to the narrowly focused door design case presented by Murphy, since doors have unique functions such as opening and sliding that are different from most other building elements.

Form of the design artifact (2D vs. 3D, digital vs. physical) appeared to have minimal impact on gesture interactions. Most gestures were observed with all artifact types, as shown by the arrow to the 'artifacts' box in Figure 2. However, many people touched the paper when gesturing around the 2D drawings, whereas they did not touch the computer screen, which would have provided input to the computer. Some interesting 3D versions of the gestures were observed with the 3D physical model. These were similar in form to the 2D gestures, but sometimes the hand was bent or moved in 3D space. For example, when discussing the glazing on different parts of the building, an architect placed his hand above the roof of the 3D model and bent his fingers downwards over the edge to indicate a side of the model that he could not reach. The most important variation in gesturing that we observed was related to the information's position. When design information (either digital or paper) was posted on the wall, people referenced items remotely more often than when the information was on the table. In the remote case, more verbal description was needed to identify specific areas.

5.2.2. Navigating

Navigating involved changing which design information was visible, or altering one or more participants' view of the information. Table 5 describes the different types of navigation that we observed.

Navigation supported a variety of participants' goals, including looking up information, describing and explaining designs and their rationale, and relating information. Navigation played a particularly important role in relating information that was shown in different pages, such as on two different floorplans, because participants needed to frequently flip back and forth between pages. Frequent navigation often led to bottlenecks, as described in Section 6 below.

Navigation was also commonly used to prepare for subsequent activities. One of the architects frequently changed the visible page in the 2D drawings while a group discussion was ongoing, in anticipation of future use of the new page by the group. This process allowed the group to use information relevant to the current topic without having to wait for it to be found. Any of the paging and scanning methods could be used for this purpose. In the digital meetings, a different member of the architectural team performed similar preparatory navigation using the digital 2D drawings.

Navigation was very different with different representations of design information, as can be seen in the last column of Table 5, and in the arrows between interactions and artifacts in Figure 2. Minimal navigation was possible with the 3D physical model, as it could only be moved, rotated, and have minor details adjusted (Figure 3a). An advantage of the 3D model was that it allowed participants to easily use a bird's-eye view as well as side views of the building

Table 5 Types of navigation with artifacts that we observed.

General description	Examples	Artifacts
View set-up		
Zoom/translate/rotate the artifact to change the current view	3D physical model was rotated to show different perspectives. See Fig. 3a	All
	Participants pulled physical 2D drawings toward themselves to obtain a better view.	
	Digital 2D drawings and 3D rendered images were zoomed and translated to show an overview or details of different parts	
Uncover the artifact	Other papers and personal items were moved from on top of the stick set to allow access	Stick set
	Other digital windows were minimized or moved aside to view design information	2D digital
		3D digital images
Manipulate parts of the artifact	Physical parts were adjusted to align them. A physical model of exterior shades was moved around to assess lighting	3D physical model
Scan		
Ordinary scan: look through several pages to find one of interest	Participants paged quickly through the stick set	Stick set
	Participants moved around to scan pages on the pin-up wall. See Fig. 6a	Pin-up wall
Peek scan: scan pages by viewing only a small part of each page	Participants scanned the title block in the bottom corner while others continued using the current page. See Fig. 3c	Stick set
Page		
Menu: load the new page by selecting it from a list	For digital 2D drawings, pre-loaded drawings were selected from a menu. See Fig. 3b	2D & 3D digital
Folder: load the desired page from a digital folder	Digital drawings that were not pre-loaded were loaded from the folder system	2D & 3D digital
Turn page of the artifact, like turning pages in a book	This was the most common method of changing pages in the stick set	Stick set
Pull out a page from a stack so that both the old and new pages are visible	When the stick set was not clamped together, pages could be pulled out and placed side-by-side for comparison	Stick set

Place on top: pull out the new page and place on the top of a stack	When the stick set was not clamped together, a new page was sometimes pulled out and placed on top	Stick set
Roll away the pages above the desired page	Another common way to navigate the stick set. Groups of pages were loosely rolled or folded to keep them out of the way	Stick set
Bookmark		
Hand: position hand or fingers between pages	Participants occasionally placed hands or fingers between pages in the stick set to bookmark for the near future	Stick set
Pull out a page partially from a stack	Pages that were pulled out for comparison could be left sticking part way out of the stack for later access. See Fig. 4a	Stick set
Roll away a group of pages	When pages were rolled away, the top page of the group could be easily accessed by unrolling	Stick set
Hold up a group of pages in the air while the page underneath is viewed	A page was sometimes held up vertically, allowing it to be viewed by lowering one's hand. This was convenient for comparing back and forth between two pages. See Fig. 4b	Stick set
Person moves	With the pin-up wall, participants viewed different drawings by walking. See Fig. 6a	All
Person moves to obtain a different view	Participants gathered around the stick set to see details, and moved closer to all artifacts to refer to specific information	

Figure 3 Navigation with different design artifacts. **a** Rotating the 3D physical model to obtain a different view. **b** Paging through digital 2D drawings via menu navigation. **c** Peek scanning. By lifting only a corner of the stick set, the individual can scan additional pages while the current page remains visible to the rest of the group.

without the need for any navigation. However, the information content of the 3D physical model was limited since it only contained information about the building's overall shape and exterior details. Hence the 3D physical model was not useful for discussions of interior details. Although the digital 3D CAD model could have accomplished this purpose, it was not used during meetings because 3D navigation through the model was perceived to be too slow, even when using a powerful computer system.

The richest variety in navigation methods occurred with the 2D paper drawings, as shown by the many arrows to the 2D physical artifacts in Figure 2. The tangible nature of paper enabled participants to scan, bookmark, and compare pages in a variety of ways that were not possible with the digital versions. See Table 5 for a complete list of interactions. Such tangible affordances of paper have many benefits for collaborative work (Marshall and Bly 2005; Sellen and Harper 2002; O'Hara and Sellen 1997; Mackay 1999). For instance, paper-based documents allow readers to easily scan forward to preview material, to locate material by its physical location in the document, to anticipate turning a page by lifting a corner of a page, and to bookmark pages using fingers or by folding a corner of the page (Marshall and Bly 2005). As a specific example in our study, a landscape consultant had placed his landscape plan on top of the stick set to share with the group. The architect wanted to compare the landscape plan to one of the architectural drawings. To accomplish this, the architect first searched for the relevant plan by holding pages above it up in the air (*scanning*). Once the relevant diagram was located, he pulled it most of the way out of the stack, allowing a side-by-side comparison with the landscape plan. He then slid the architectural diagram back into the stack, leaving it sticking out approximately 1/3 of the way, allowing it to be easily located later (*bookmarking*), as shown in Figure 4a. In another instance, a bookmarked page was held up in the air while participants interacted with a page below it. This enabled participants to easily switch back and forth between the two pages by simply lowering the one held in the air, and even reference both pages simultaneously, as shown in Figure 4b. Bookmarking was also accomplished by placing hands or fingers to mark pages in the stick set.

Figure 4 Mechanisms for bookmarking. **a** Pulling out. The bookmarked page sticks out from the stack. **b** Holding up. The bookmarked page is held up by the woman at the right side of the image. The architect on the left side references information on the bookmarked page by pointing.

In contrast, digital drawings had to be loaded one at a time and completely obscured each other. Digital drawings were usually selected from a list of pre-loaded documents, as shown in Figure 3b. Extensive translation and zoom operations were also very common, likely because the entire drawing could not be viewed at once with full detail. Overall, navigation accounted for 51% (40 out of 78) of interactions with digital design artifacts, as compared with 16% (110 out of 696) for paper and physical design artifacts, indicating that participants had to devote substantially more effort to navigating in the digital environment. These navigation limitations with the digital drawings led to many bottlenecks, which we describe in Section 6.

5.2.3. Annotating

Unlike prior research reported by Perry and Sanderson (1998), we found that physically annotating the design information to create marks on the design was rare—approximately 2% (17 out of 774) of physical interactions. However, annotations did occur with both the 2D paper drawings and the digital 3D rendered images, as shown in Figure 2. With paper drawings, participants made marks both on the drawing information itself and on the side of the page. We refer to these actions as *annotate drawing* and *side sketch* in Figure 2. Only annotate drawing actions were observed with 3D rendered images.

Extensive brainstorming sketches were not drawn directly on top of 2D paper drawings. Instead, they were drawn as a side sketch or on a separate page. For example, the electrical consultant pulled out a blank sheet of paper, layered it on top of the stick set, and sketched an idea on the blank paper to avoid writing on the stick set itself. In another instance, an architect created a side sketch on the roof plan showing a possible slab design to support the roof. While sketching, he thought aloud, describing the assembly and its effect on rainwater. By contrast, in a digital meeting the same architect drew directly over top of a 3D rendered image, using a SmartBoard pen, while brainstorming an idea to remove a section of the building's top level as a way of improving the exterior appearance, as shown in Figure 5. However, the architects reported that sketching and annotating documents using the SmartBoard was awkward. This was likely due to several factors: there were parallax problems (Elliot and Hearst 2002), fine motor control is difficult on a vertical surface (Inkpen et al. 2005), and pen strokes could not be varied by pen angle or pressure as with an ordinary pencil sketch.

Although marking up paper documents was uncommon, participants often made explicit drawing-like actions over the design information without actually touching their pen to the artifact. For example, while brainstorming structural options, the architect drew a grid over the roof plan without touching his pen to the drawing, while suggesting that they could use such a steel grid structure. This action enabled the group to mentally *visualize* the proposed structure, in relation to other parts of the building. The appearance of these *air draw* actions suggests that participants rarely wanted to permanently mark up paper drawings. This hesitation seemed to be reduced with the digital system, where the marks could be easily erased.

5.3. Individuals, groups, and parallel work

Eighty percent (309 out of 387) of physical interactions with design information were used to support design discussions by the group or a subgroup. However, design information was also commonly used by individuals during the course of a meeting, either to prepare for anticipated group activities or to look up information privately (20% of interactions). As mentioned above, the architects often changed the visible page in the drawing set in anticipation of future use in the current discussion (i.e. to prepare). This action occurred for both digital and paper versions of the 2D drawings, by two different architects, and without the explicit attention of other meeting participants. Consultants often used paper drawings to look up information privately. For example, in a value engineering meeting, the cost consultant took the

Figure 5 Annotation. Architect digitally annotates a 3D rendered image of the building.

stick set from the center of the table and browsed through it page by page for several minutes, trying to understand the ripple effects of the cost-saving design changes being proposed. Similarly, a value engineering facilitator, who was unfamiliar with design details, spent several minutes during the middle of a meeting perusing design diagrams on the pin-up wall. This allowed him to familiarize himself with the design at a convenient time when he did not need to play an active facilitation role. Impacts of different representations of design information on this type of individual use are further discussed in Section 6 below.

Individuals and the group occasionally used the same design information simultaneously. For example, in a paper-based design development meeting, the group held a discussion about the design of the green roof, for which the top page of the stick set was relevant, but not actively in use. Meanwhile, one of the architects scanned through several pages below the current one, in search of some information. In doing this, he lifted only the lower right corners of the pages, where document identification information was written. This minimized disturbance to the rest of the group and allowed the top page to remain visible, as shown in Figure 3c above. We refer to this type of interaction as *peek scanning*.

6. Bottlenecks

As the project team transitioned from a traditional paper-based meeting environment to a digital meeting environment, we observed that the driving factors influencing the interactions with design artifacts were *time* and *workflow*. If an activity or interaction took longer or disrupted workflow it was typically carried out using traditional practice. These constraints were implicit in many of the bottlenecks we observed, as described below.

6.1. Navigating digital information

Navigation was the key bottleneck in the digital environment. One architect acted as a *driver*, controlling most interaction with the digital displays via a mouse and keyboard. This architect usually pre-loaded all the relevant documents (e.g., 2D digital drawings and 3D rendered images) prior to the meeting. The necessity of this pre-loading operation is illustrated by the following 55 second excerpt involving discussion of the costs of different parking options, where both digital and paper versions of the 2D drawing were available:

00:00 A specific reference to spatial information is made in the discussion about parking, "....the 32 already exist down there."

00:08 Stick set is slid from the far end of the table to the middle and rotated 90 degrees. A participant in front of the stick set begins to page through it.

00:15 Architect controlling the computer begins searching through folders to locate the relevant 2D digital drawing.

00:28 Relevant 2D paper drawing is displayed, after two participants work together to turn the pages. Participants begin discussing the parking issue using the paper drawing.
00:41 Relevant 2D digital drawing has been located and has finished loading. The architect begins zooming and translating to set up a good view.
00:55 Digital drawing is finally ready for use. However, the group has already been using the paper version for some time so the digital version is not used.

Here time is the driving factor leading to use of paper drawings rather than digital. The above example also demonstrates another navigation bottleneck: the need to zoom and translate. Digital 2D drawings almost always needed to be zoomed and/or translated because screen resolution limited the amount of detail that could be seen when the entire page was shown. Notice in the above example that even once the correct file was loaded (which took 26 s), it still took another 14 s to find a good view via zoom and translation. This compares with 20 s in total to find the appropriate view with the paper drawings. Surprisingly, the architects did not consider screen resolution to be problematic, even when asked directly. This is consistent with a study by Elliot and Hearst (2002), who found that architects did not identify low screen resolution as a limitation for sketching on a large screen.

Although participants could interact directly with the touch screens, they preferred to ask the driver for navigation operations related to the digital information. For example, a second architect gestured sideways and asked the driver, “Could you just slide it over a bit?”. This occurred in part because some participants could not reach the screens, and probably in part because participants were unfamiliar with the touch screen technology. Although the navigation requests did not create a large bottleneck, navigation would likely be more efficient and less disruptive to workflow if individuals could easily control the display directly.

Even when the relevant documents were pre-loaded, navigating between digital pages created bottlenecks. The primary problems were an inability to display more than one document at once, and an inability to bookmark pages for later reference. On two occasions, the architect tried to display two documents side-by-side on the two digital displays, which did not work as he expected. This meant that for some discussions, he needed to frequently switch back and forth between multiple views, making workflow awkward. For example, a discussion about where to place mechanical and electrical equipment involved viewing three different 2D digital drawings. Specifically, the participants needed to see the roof and basement plans, because these were potential locations for the equipment, plus a cross-section showing floor heights, to determine whether the equipment would fit vertically. Similarly, the architect switched back and forth between the basement plan and a cross-section view during the discussion of a bicycle storage room in the basement. Each time he wanted to switch to a different page, the architect needed to choose the file from a loaded-items menu at the bottom of the screen, searching through the entire list. No shortcut was available for rapidly switching back and forth between a subset of the documents, which occurred often.

The slow speed of navigating the 3D digital model, and the difficulty of finding an appropriate view, were seen as such obstacles that the 3D model was not used in the meetings. To address this limitation, the architect created various pre-rendered 3D views before the meeting. However, these images were rarely used. 3D images were used only for discussions about the exterior, and they were prepared in anticipation of a specific discussion. 3D images were never used spontaneously based on the nature of the discussion, and nobody took advantage of their presence for use in other discussions.

6.2. Individual information lookup

Individuals sometimes used representations of design information to look up information individually during the course of a meeting. Examples include the activities of the value engineering and cost consultants described in Section 5.3. The most effective interface for this sort of individual use was the paper pin-up wall. The pin-up wall was out of the way of the main meeting activity and displayed all images at once to support easy browsing. This allowed the value engineering consultant to browse the design information with minimal disruption to group workflow, as shown in Figure 6a.

By contrast, individual browsing with the stick set was difficult and disruptive. When the cost consultant viewed the stick set, as discussed previously, he first needed to drag the stick set from its central location on the table and rotate it 180 degrees, briefly disrupting several participants who had personal items in the way. The large format of the stick set made it difficult to turn pages without blocking other participants' views or getting in their way. Because there was not room to open the stick set fully, the participant was forced to fold the unused top pages over twice to make a small roll, as shown in Figure 6b. Turning to a new page then required partially unfolding the upper pages, turning to the next page in the set, and re-folding the unused top pages back into a roll. This complicated operation was repeated ten times to view different pages in the set. Folding the

Figure 6 Individual use of the **a** pin-up wall and **b** stick set.

large format paper was awkward, and at one point blew another participant's paper off the table, causing a disruption.

We did not observe individual use of the digital design information during meetings. Although multiple displays could be set up to create a digital version of the pin-up wall, the meeting environment available to participants in our study contained only two screens. We did not observe any participants viewing this information privately on a laptop, though everyone had access to the same information on Buzzsaw. We think this was because participants did not want to disrupt the flow of the conversation and appear to be working separately or disconnected from the others. Participants also chose to have a driver mediate interaction with the digital information as noted previously. These factors would have made it nearly impossible for an individual other than the driver to browse design information on the shared screens during the course of a meeting without causing substantial disruption to the group activity.

6.3. Accessibility of information

6.3.1. Physical positioning of information

Physical positions of design artifacts within the meeting room strongly affected their accessibility, sometimes leading to bottlenecks. When the 3D physical model was present, it was used preferentially over the 2D paper drawings, the only other design information present at the same time. Unlike the 2D drawings, the model naturally integrated elevation and plan views of the building, but did not represent any interior design details. To make room for the model, the stick set was either located underneath the model or was rolled up and placed to the side. In these cases, it would have taken more time to access the stick set then when the model was not present. In one meeting involving the 3D physical model, the pin-up wall was set up and could be used in place of the stick set. However, in another meeting involving the model, the stick set was the only version of 2D drawings available. In this case, accessing the 2D drawings required substantial time and effort, which in many cases was deemed not worthwhile.

It is well known that positioning information on tables versus walls affects the ways in which participants interact with the information and each other (e.g. Rogers and Lindley 2004; Inkpen et al. 2005). This was no exception in our study. When design information was posted on a wall, as with the paper pin-up wall and the digital design information, many participants could not reach the display from their seat. Participants did move to the design artifacts to ask complex questions or explain complex concepts, but getting up and moving around the table to reach the information took some time. Hence, for simple queries, participants were more likely to gesture from afar. This required additional verbal descriptions to indicate the area of interest, as previously reported by Hawkey et al. (2005). For example, to indicate the location of the control room, the architect said, "....the top portion with the stair connection directly down, that's the control room", whereas the electrical consultant, who was standing at the display, then simply said, "and this would be the server room" indicating it by pointing.

Accessing wall displays was particularly difficult for participants sitting in front of the display, who needed to turn around to see the information. In several instances, participants sitting in front of the digital display chose to use the paper stick set instead of the digital drawings, even when the digital drawing most relevant to the discussion was loaded on the digital display. Positioning of the information was likely a factor in this decision.

6.3.2. Searching for information

In most cases, meeting participants knew exactly where to find information relevant to the discussion. However, cases where they did not know where to find the information presented significant bottlenecks. This often happened when the need for the information was not anticipated prior to the meeting. For example, when a mechanical consultant wanted to show the group some images of water filtration systems, it took him ten minutes to locate the images on his laptop. Although the group continued to discuss other issues during this time, the time delay severely interrupted workflow. This disruption was most severe for the mechanical consultant, who had a difficult time simultaneously searching for the images and participating in the group discussion.

In the digital meetings, the architect controlling the computer experienced significant difficulty in locating relevant documents. Buzzsaw was the central repository for all project documents and was used extensively in the digital meetings. Although this information was organized in a formal hierarchy (Figure 7), project team members had a great deal of flexibility in terms of where they might save the documents, at least within their own designated space. Consequently, the architect had a difficult time locating documents created by other disciplines. In one instance, the document containing the key sustainability goals could not be found so the project team spent several minutes re-writing these out by hand, a substantial disruption to workflow.

6.3.3. Sharing digital information with the group

To prepare for digital meetings, the architects made an effort to post all information relevant to the meeting agenda on the Buzzsaw site. However, we noticed that other members of the project team did not make the same effort. In fact, the cost information relevant to the value engineering meetings was not posted on Buzzsaw before the meeting, even though the participants knew it would be critical. Rather it was handed out in paper form at the meeting, which disrupted the meeting for several minutes because they did not bring enough copies. We believe this was an issue of control on the part of the Construction

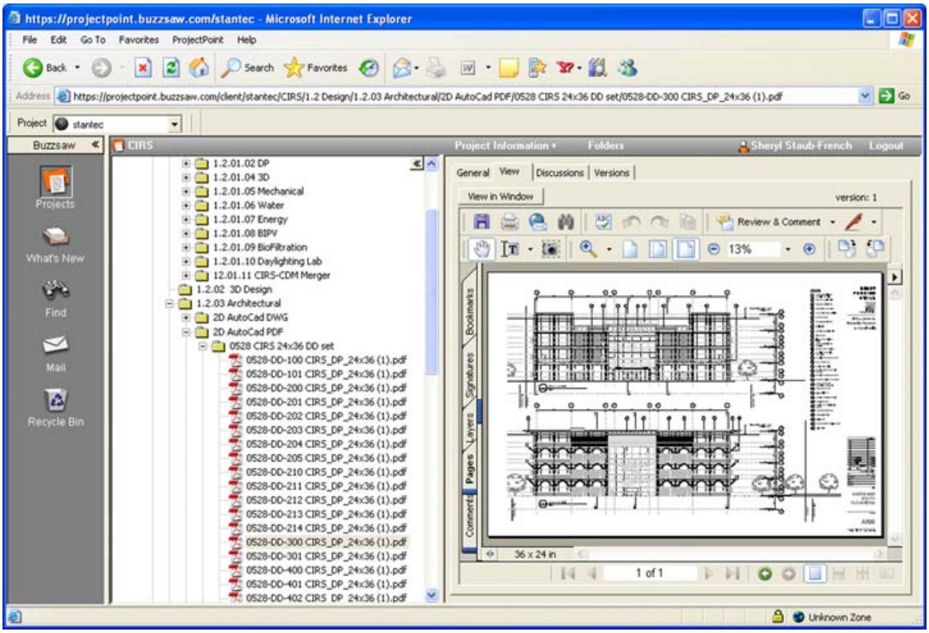


Figure 7 A screenshot of the Autodesk Buzzsaw document sharing system. Participants used Buzzsaw as a central repository for all project documents including CAD drawings, CAD models, agendas, meeting minutes, consultant reports, schedules, and cost plans.

Manager and an issue of culture in terms of the meeting process. The Construction Manager wanted to control when the information was shared and what information was focused on in the discussion. In many ways, this makes sense since costs are a particularly sensitive issue on projects and there are many assumptions behind the numbers that require explanation. If the cost information was distributed electronically before the meeting, many participants would likely have come with questions and that could have disrupted the discussion. Although the Construction Manager could have utilized the electronic version with the large-screen displays to facilitate the discussion, this would have required him to stand in front of the group to be able to reference the specific cost items. We think he preferred the more collaborative style of discussion around the table enabled by the paper-based document. It is also worth noting that the Construction Manager was not worried about sharing this information electronically as it became a part of the meeting minutes in electronic form.

When relevant information was not on Buzzsaw, the team members generally preferred to make paper copies rather than transferring the digital version of the document to the meeting room server so that it could be displayed on the screens. In another instance, a participant turned his laptop around to share information with the group, even though there was a projector in the room and many participants could not see the small laptop screen. These examples demonstrate the need for interactions with technology that support fast, efficient workflow during meetings. For example, transferring information to a digital display must be possible in a very lightweight manner or it may not be perceived as worthwhile. Alternatively, a process of transferring important data to a central repository prior to meetings could be encouraged.

7. Design implications

Here we present some possible directions for future CSCW technologies based on our observations. Although many of these observations showed advantages for physical interfaces, we do not assume that physical interfaces are uniformly superior to digital ones. Similar to Terrenghi et al. (2007), our approach is to suggest new techniques that will support the functionality of physical interfaces within digital systems. We suggest simplifying navigation, enabling digital bookmarking, using enriched pointing techniques as input, and enabling both group and individual access to information.

7.1. Simplify and enhance navigation

Extensive bottlenecks related to navigation in the digital environment suggest that navigation mechanisms need to be drastically simplified for meeting situations. Participants need to rapidly switch between pages with minimal navigation and search. A thumbnail bar could be useful for this purpose. Thumbnails could show a small image, but it may be more helpful to show information similar to the title block on 2D drawings since scanning the stick set often involved viewing primarily this information. Participants also needed a rapid way to navigate within a 2D drawing (translate and zoom). Something as simple as an overview button may have been helpful for this task.

New navigation mechanisms are also needed to interact with both 2D and 3D design artifacts simultaneously. The value of combining 2D and 3D views to help people better understand and navigate 3D content has been well established (Tory 2004). For example, 2D drawings provide easy access to details, whereas 3D views provide a more realistic representation of the design, and give users a real sense for how a particular spatial area will look. Grossman et al. (2001) demonstrate how 2D and 3D views can be integrated on a large screen display for automotive design. However, further research is needed to extend these ideas so that they can support the much more complex CAD models used during design coordination.

Moreover, it may also be useful to combine digital and tangible forms of the 2D and 3D design information. Henderson (1999) suggests that physical and digital representational artifacts play fundamentally different roles in a design project and that designers will iteratively move between the representations to accomplish their goals. While digital information can potentially provide great flexibility in terms of viewpoints and layers, physical artifacts such as the stick set were often easier to manipulate. Similarly, systematic studies comparing digital and physical media (Rogers et al. 2006; Terrenghi et al. 2007) have shown that physical media make it easier to gain an overview or scan the objects, examine details of an object, use complex bimanual manipulation, and use physical objects to gain the attention of others.

Ullmer et al. (1998) contended that removable media would persist in the online age and that from a user interface standpoint, exchanging media between digital whiteboards, projectors, and computers was still far from seamless. They designed a tangible user interface based on physical icons (phicons) called mediaBlocks as a conceptual solution to the problem of bridging the gap between physical and digital representations. Streitz et al. (1999) devised the i-LAND work environment based on their observation that the ease of forming subgroups in a meeting room is largely dependent on lightweight access to furniture and multiple information devices (e.g. diagrams, pictures, and calendars hanging on walls). Subsequent work by Aliakseyeu et al. (2006) continue to suggest that preserving the advantages of traditional work practice is vital if integration of digital media is to be successful. Their group designed an augmented reality system called the Visual Interaction Platform to enhance early architectural design activities such as sketching on paper with an emphasis on elementary tasks such as positioning and overdrawing.

We envision a system similar to the Jump System (Terry et al. 2007) that supports tangible queries of paper-based drawings, the Luminous Planning Table (Ben-Joseph et al. 2001) and Build-it (Lauche 2005) that integrate digital and tangible media, or paper augmented digital documents (Guimbretiere 2003), which enable marks written on paper versions of a document to be recorded in the digital version. However, additional functionality is needed to support building design coordination and to further improve interactive navigation. Specifically, there is a need for dynamic and customized 3D navigation and for transparent and bi-directional coordination of views. For example, users could create digital 3D views automatically through interactions with 2D drawings (either paper-based or digital). Users could interact with the 2D drawing to locate a specific area, such as a room on a specific floor, and create relevant 3D views of that area to display. Functionality would also be needed to customize the 3D views created, such as controlling the orientation of the view and adjusting filtering and transparency of different design elements in the view. Similarly, users could create digital 2D cross-sections of the building through interactions with 3D physical or digital models, and then customize the 2D views they created. As the number and types of views multiplies in a digital meeting process, there will be an increasing need to provide a mapping of these views and an orientation to the overall project. The approach must also support bi-directional flows between the different types of artifacts. For example, supporting links between the paper-based drawings and the digital views so that users can orient themselves across artifacts.

7.2. Design mechanisms for digital bookmarking

Our observations of the architect navigating the stick set revealed four subtle mechanisms for bookmarking, or instances where pages were physically indexed for later use: hand, pull out, roll away, and hold up, as described in Table 5. By contrast, no bookmarking methods were available in the digital environment. Such mechanisms would have been helpful for navigating back and forth between relevant 2D diagrams, and for remembering key zoom/translate states within a single diagram. Digital environments could use the paper bookmarking mechanisms as metaphors for designing digital bookmarking mechanisms. For example, a bookmarked thumbnail image could be pulled out slightly relative to other thumbnails, or documents could be shown in a virtual 'stack', where some pages were pulled out part way.

7.3. Enrich pointing techniques

Although it is well known that pointing takes on many different meanings in the course of social communication, pointing usually only has one meaning in CSCW systems and GUI interaction in general, that of selecting particular items on a display (Kendon 1996). We observed that pointing took on different meanings in design development meetings depending on the participant's goals. There may be opportunities to take advantage of this by enriching interaction. Instead of assuming that pointing should ultimately manipulate the display in a uniform fashion (whether that is moving a mouse cursor or selecting an object with one's finger), it could be useful to develop pointing techniques that take into account the various context-dependent meanings of pointing. Examples based on our observations include:

7.3.1. Multi-fingered pointing

We observed many consistent gestures to identify sub-areas, lengths, or lines of interest related to spatial design information. These included five-finger pointing, segment indication, two-finger indication, covering, and outlining. Consistency of these gestures across different individuals, different types of meetings, and different representations of design information suggests that they may be useful input mechanisms. With the right kind of input technology, these gestures could be tracked and used for selecting or highlighting areas or items on a graphical display. For example, finger-finger input could be used to control a 'spotlight' that could be moved around to highlight different sub-areas. This functionality could be used to extend existing remote collaboration tools such as Barthelmess et al. (2005), where gestures are tracked in order to highlight the area of focus for remote participants who cannot see the gesture. Automatically classifying the gestures could be done in a manner similar to Poddar et al. (1998). However, note that development of such a system should be approached with some caution.

First, because gestures cannot be fully understood without the context of speech (McNeill 1992), an automatic system may need to rely on both gestures and spoken keywords to disambiguate meaning (Poddar et al. 1998). In addition, some researchers (e.g. Kirk et al. 2005) suggest that it may be better to show the actual hands if possible, rather than attempting to automatically interpret gestures.

7.3.2. Anchoring

Participants in meetings sometimes used one hand or a pen as an anchor while pointing to other objects relative to the anchor (interval gestures). A two-handed pointing technique such as this could be used to manipulate one part of the display relative to another. This type of input may be useful for examining 'what-if' scenarios similar to the structural engineer's assessment of different anchor points in an earthquake situation, as described in Table 4. This form of interaction would enable users to see effects of the what-if analysis visually rather than mentally.

7.3.3. Differential marking

We noticed that participants were hesitant to annotate the stick set, possibly because erasing such markings would have proven difficult or time-consuming. An interesting annotation technique based on pointing could make use of the fact that touching a display with one's finger and touching it with a pen are different. Temporary annotations that disappear after a few seconds could be accomplished by touching the display with one's fingers while using a tracked pen could leave a permanent mark. This might encourage annotation of the display to explain concepts or to try out new ideas since annotation would not always be permanent or require explicit erasing actions to remove.

7.4. Augment pen functionality

We noticed that people often held their pen differently depending on whether they were using it to annotate, using it to gesture or point, or using it to indicate an anchor or line. This suggests that tracking how pens are used, perhaps by building pressure or tilt sensors into the pens themselves, could allow a system to determine how they are being used and adjust their functionality accordingly. Tracked pens could also be used to provide more natural methods of navigating digital 3D models; for example, rotating the pen could be used to change the viewpoint. Furthermore, providing users in an interactive workspace with pens linked to their own identity could be valuable. Besides facilitating multiple input, this would allow annotations to be linked to who created them. Annotations could be selectively erased by filtering them by both author and time. This would allow people to annotate the display without worrying that their annotations would interfere with others at a later time. This could also be used to facilitate a trace of who made specific annotations to particular documents.

7.5. Support information access by both groups and individuals

None of the design representations that we observed ideally supported both group and individual interaction. For example, the stick set was an effective representation for the group sitting near it. However, it was difficult for participants at the end of the table to see details during group discussions and even more difficult for them to look up information privately. The pin-up wall made it easy for individuals to browse the information privately, but was too far away for most people to see details or gesture towards specific information during group discussions.

These observations are consistent with previous studies of group work around large shared displays. Many recent studies have shown that the orientation of a display has a substantial impact on collaboration (e.g., Rogers and Lindley 2004; Inkpen et al. 2005). For example, horizontal displays may encourage more pointing interactions (Inkpen et al. 2005), more closely coupled work, and greater sharing of input devices among members of the group (Rogers and Lindley 2004). By contrast, vertical displays provide a shared perspective and allow people to stand back for a holistic view (Inkpen et al. 2005). Hawkey et al. (2005) observed that proximity was also an important factor. In particular, a distant display encourages remote gestures toward the display that are often difficult to understand.

Digital environments could consider combining elements of both the stick set and pin-up wall. For example, design diagrams could be shown on a series of peripheral wall displays and pulled onto a central display, perhaps on a tabletop, for group discussion. In addition, participants may find it useful to have their own private display of the same design information, in addition to any public displays, as suggested by Scott et al. (2004). This would allow individuals to examine different pages or views than the group.

8. Conclusions

This paper presents the results of a 7-month ethnographic field study examining the design coordination process of a building project team. A unique aspect of this study is that we observed the project team interacting with different types of digital and physical design artifacts in different meeting environments. We gained a better understanding for how references to design information support collaboration, and for the kinds of interactions that may be effective input methods for a digital system.

We developed a taxonomy that characterized the different types of interactions that team members had with visual representations of design information during coordination meetings, along with the apparent goals of those interactions. We found that gesturing, navigation, annotation, and viewing were the four primary interactions meeting participants had with design artifacts. We observed nine different types of gesture interactions with design artifacts, five different types of navigation techniques each with different sub-types, and three different annotation techniques. Our characterization of low level interaction mechanics during coordination meetings extends existing knowledge about the role of representational artifacts in co-located collaboration.

We also examined how interactions changed with different design artifacts in the different meeting environments:

- Form of the design information (2D vs. 3D, digital vs. physical) had minimal impact on gesture interactions. Most gestures were observed with all information types. The most important variation in gesturing that we observed was related to the information's position.
- Navigation was very different with different representations of design information. The richest variety in navigation methods occurred with the 2D paper drawings.
- Physically annotating the design information to create marks on the design was rare, but did occur with both the 2D paper drawings and the digital 3D rendered images. Extensive brainstorming sketches were not drawn directly on top of 2D paper drawings.

We found that bottlenecks in the design coordination process occurred when meeting participants attempted to navigate digital information, interact with wall displays, and access information individually and as a group. Driving factors causing the bottlenecks were time and workflow. If an activity or interaction took longer or disrupted workflow it was typically carried out using traditional practice whenever possible. These observations suggest that a lightweight approach to infrastructure is necessary to be usable in meeting scenarios. We outline possible directions for future CSCW technologies that consider these constraints, including new mechanisms to simplify and enhance navigation (e.g., digital bookmarking), to enrich pointing techniques (e.g., differential marking) and pen functionality (e.g., include pressure or tilt sensors), and to support multi-user interactions (e.g., peripheral wall displays connected to a central display and individual displays).

Future work will continue ethnographic field studies examining the CIRS project team at different stages of the project life-cycle, including detailed design and construction, where different types of design artifacts play a prominent role. We also plan to deploy and test different types of interactive displays, such as touch sensitive tabletop displays, and different types of artifact interaction technologies, such as the JUMP system discussed previously. Finally, we will develop new tools for artifact-centered design and management of construction projects that implement some of the design guidelines identified in this paper.

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