Case Study

Design Process Communication Methodology: Improving the Effectiveness and Efficiency of Collaboration, Sharing, and Understanding

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Abstract: Designers struggle to (1) collaborate within projects, (2) share processes across projects, and (3) understand processes across the firm or industry. Overcoming each challenge requires communication of design processes. This paper aggregates concepts from organizational science, human-computer interaction, and process modeling fields to develop the design process communication methodology (DPCM). The DPCM consists of elements that represent and contextualize processes and methods that enable designers to capture and use the processes. These elements and methods enable a methodology that is computable, embedded, modular, personalized, scalable, shared, social, and transparent. The authors operationalize the DPCM via the process integration platform, a cloud-based process communication application where individuals exchange and organize files as nodes in information dependency maps. This paper provides evidence of the DPCM's testability and proposes metrics for evaluating the DPCM's effectiveness and efficiency in communicating design processes. The DPCM lays the foundation for commercial software that shifts focus away from incremental and fragmented process improvement toward a platform that nurtures emergence of (1) improved multidisciplinary collaboration, (2) process knowledge sharing, and (3) innovation-enabling understanding of existing processes. **DOI:** **10.1061/(ASCE)AE.1943-5568.0000122.** © *2013 American Society of Civil Engineers.*

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Introduction

Design processes disproportionately influence the life-cycle value of the resulting products (Paulson 1976). Although the total cost of design is relatively small, the design phase of an architecture/engineering/construction (A/E/C) project greatly influences the total project value. Also, the final project value generally increases with the number of different design options considered (Akin 2001; İpek et al. 2006). However, despite information technology advances in the last two decades, the number of design options explored for any one design decision is typically less than five and almost always a small percentage of the possible design space available (Flager et al. 2009; Gane and Haymaker 2010). Research leading to new information management systems can improve design processes to increase project value per staff-hour expended. Improving design processes requires not just isolated technological improvements but also process change within companies. This change requires process communication (Ford and Ford 1995). To improve process communication, this paper synthesizes literature to develop the design process communication methodology (DPCM). The DPCM consists of elements that represent and contextualize processes and methods that describe how designers capture and use these processes by interacting with a computer. By laying the foundation for the development of commercial software that communicates design processes, the DPCM aims to increase the value per staff-hour expended by the A/E/C industry.

To achieve this impact, this paper contributes the DPCM to fill a gap between the project information management (PIM) and the design process management (DPM) research fields. PIM lacks methodologies for effectively (i.e., able and/or accurate) communicating processes, whereas DPM literature describes methodologies for communicating processes but lacks sufficiently efficient (i.e., quick and/or with little effort) methods for the industry to adopt these methodologies.

In developing the DPCM, the authors adopted the perspective that organizations within A/E/C create information to represent the product through a process (Garcia et al. 2004). The process can be viewed through three lenses: conversion, flow, and value generation (Ballard and Koskela 1998). The authors choose the information flow lens because of the relatively large potential for capturing information exchanges automatically. The design process is then organizations exchanging information that leads to a plan for the building product. The virtual design team of Jin and Levitt (1996) similarly applied this information processing view of the organization to A/E/C, which was first described by Weber (1947) and then adopted by March and Simon (1958) and Galbraith (1977). This paper scopes the focus further to only include digital information

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exchange from scheme design to construction documentation on A/E/C projects involving complex (Homer-Dixon 2000; Senescu et al. 2011) products, organizations, and/or processes.

This section uses this information-processing lens to describe how the A/E/C industry can improve design processes through improving the following three types of process communication:

1. The organization can collaborate more effectively and efficiently within the project team. In this case, the organization does not significantly change the topology of information exchanges on a project, but executes the exchanges better through improved comprehension of the project team's processes. For example, the information may be more consistent throughout the project or a particular project team member may make a discipline-specific decision with more insight about how that decision impacts other disciplines.
2. One project team may share a process between project teams. For example, a team may learn about a process using more effective software that they then implement in their project.
3. A team may consciously develop an improved process. Developing improved design processes requires investment, which requires a claim that the return will be an improvement on the current state. Organizations must understand their current processes across the firm or industry to strategically invest in process improvement. For example, a team may understand that across the firm they repeatedly count objects in their building information model (BIM) and then manually enter quantities into a cost-estimating spreadsheet; therefore, they invest in developing a script that performs the process automatically.

A/E/C struggles to collaborate around processes, share processes, and understand processes effectively and efficiently as project complexity increases (Senescu et al. 2011).

Considering all three types of information exchange (i.e., communication), explicitly and in unison, is important because otherwise there are cost-benefit mismatches in communication. That is, many previous communication improvement efforts do not consider that "the person responsible for recording information is typically not the person who would benefit from the information once it is recorded" (Ding et al. 2009; Eckert et al. 2001). Also, team members frequently have conflicting obligations to the project and to the firm (Dossick and Neff 2010). This paper's consideration of the objectives of different groupings of professionals results in a discretization of communication types that is orthogonal to the common 3C functional model consisting of communication, coordination, and cooperation (Fuks et al. 2008). This paper holistically considers collaboration, sharing, and understanding, and uses a literature review of organization science, human-computer interaction (HCI), and process modeling to answer the question: how can design processes be communicated effectively and efficiently within project teams, between project teams, and across a firm or industry?

Before the literature review, this paper first uses a case study method to describe three observed design process communication challenges that motivated this research (next section). In the following section, the authors look to PIM and DPM research fields for solutions to the observed challenges. Not finding a holistic solution, the authors describe how these fields lack a methodology that both effectively and efficiently communicates design processes. After describing the literature review research method, the paper explains the results of the literature review: the aggregation of concepts from the organizational science, HCI, and process modeling research fields that result in the development of DPCM. From the literature review, the authors conclude that the DPCM should have the following characteristics: computable, embedded, modular, personalized, scalable, shared, social, and transparent. Next, the paper explains how the methods and elements of the DPCM enable these characteristics. The paper then describes the operationalization of the DPCM as a process integration platform (PIP), a cloud-based application where team members exchange and organize files as nodes in information dependency maps in addition to folder directories. The authors then propose metrics for validating the DPCM's impact on design process communication. The paper concludes with two sections discussing limitations of this paper, additional work conducted to validate the DPCM, and conclusions.

Case Study of Collaborating, Sharing, and Understanding Challenges

Although Senescu et al. (2011) provide evidence of the generality of communication challenges in A/E/C, this section uses three examples from the design of a university building to provide context to the problems the DPCM addresses. The first author gathered these observations directly and through interviews during his role as structural engineer on this project.

Designers Struggle to Collaborate

When designing the building, researchers identified six discrete stakeholder groups with 29 project goals. The design team evaluated seven mechanical heating/cooling options with respect to these goals. They divided one building into five different zones and assigned five of the seven mechanical options to these zones. The team created a Microsoft Excel spreadsheet to gain consensus on the mechanical heating/cooling decision. The spreadsheet showed the underfloor air distribution system as the best option. In the same project folder, the design team also created *AutoCAD* files with the floor plans to communicate the mechanical systems in the various zones to owner representatives. These *AutoCAD* files showed that the designers frequently chose heating/cooling options other than the underfloor air distribution option decided on in the spreadsheet.

The problem was not that the design team chose the incorrect systems or that their process for designing the mechanical systems was inconsistent. The problem was that the process was not communicated and was, therefore, opaque to everyone but the mechanical engineers. The mechanical engineers saved the spreadsheet and the *AutoCAD* files in the project folder with no representation of the dependencies between any of the supporting files responsible for causing this apparent inconsistency. If the team knew the process, they would have known that the *AutoCAD* files were the most up-to-date and not intended to be dependent on the spreadsheets. Instead, the apparent inconsistency between the two files inhibited acoustics, lighting, and structural engineering consultants from designing their building systems to be consistent with the mechanical system. This inefficient collaboration caused negative rework (Ballard 2000). Designers do not communicate the process effectively and efficiently, making collaboration within project teams challenging.

Designers Struggle to Share Processes

The stakeholders explicitly communicated the importance of material responsibility when choosing structural systems (Haymaker et al. 2011). The structural engineer created schematic *Revit* structure models of steel and concrete options. The engineering firm had recently purchased *Athena*, software that uses a database to output the environmental impact of building materials. Despite a three-dimensional object-oriented model (containing a database of structural materials and quantities) and a database of the environmental impacts of those materials, the structural engineer was unable to find a process for conducting an environmental impact analysis comparing the concrete and steel options. Several months later, the structural engineer met a researcher who had worked to develop a process for performing model-based assessments of the environmental impact of construction materials with the Australian office of the same engineering firm (Tobias and Haymaker 2007).

In this case, a clear demand for an improved process existed in the California office. The engineer could not find a process, even though the same firm had already performed this process in Australia. This example illustrates that designers struggle to share processes between projects teams.

Designers Struggle to Understand Processes

With the goal of informing the design team's decision regarding the quantity and size of louvers on the south façade of the building, daylighting consultants created video simulations of sunlight moving across a space. The process required manual manipulation of geometry and materials to reformat the information; therefore, each new software package could interpret the data representing the building. This process was not productive because the consultants spent 50% of their time on these nonvalue-adding tasks and considered only 2–3 options, resulting in a suboptimal design.

The individual consultants lacked incentive to invest time in process improvement. Their tools did not capture their process, place them in peer communities to improve the process together, and did not provide transparent access to other processes that could form the basis for improvements. Managers lacked a transparent method for understanding process productivity rates and, therefore, could not develop a monetary justification for encouraging process innovation. A/E/C organizations struggle to understand their processes across the firm or industry to strategically invest in increased process productivity.

Lack of Effective and Efficient Design Process Communication Methodologies

Within DPM, the design rationale (Moran and Carroll 1996) and design process improvement (Clarkson and Eckert 2005) research fields have already developed effective design process communication methodologies to overcome the collaboration, sharing, and understanding of challenges faced by the university building design team. However, these research methodologies have not been widely adopted by the industry (Conklin and Yakemovic 1991; Moran and Carroll 1996; Regli et al. 2000). For example, the design structure matrix (DSM) communicates design processes through task dependencies for both improved collaboration and process sharing (Eppinger 1991; Steward 1981; Tang et al. 2010). However, the DSM generally communicates planned processes, and "it is difficult to describe the relationship between the process plan and the process that actually occurs. . .hardly any company goes to the trouble of comparing the [process] model with the process that actually exists" (Clarkson and Eckert 2005). In fact, the university building design team did not take the time to plan their processes and did not capture their actual processes.

Unlike the DSM, the multiattribute, collaborative design, assessment, and decision integration (MACDADI) and decision dashboard were intended to become intertwined with the process of making design decisions by communicating components of the rationale, such as design options, goals, and stakeholders (Haymaker et al. 2011; Kam and Fischer 2004). However, these methods of capturing design rationale do not address findings demonstrating that design rationale systems are rarely implemented in practice (Conklin and Yakemovic 1991; Ishino and Jin 2002; Moran and Carroll 1996).

The lack of adoption of process communication methods is not only because of the lack of tools capable of effectively communicating design processes [Chachere and Haymaker (2011) provide an overview]. Rather, the lack of adoption stems largely from the lack of incentive for designers to communicate processes at the instant they are designing. Therefore, it is not sufficient to merely have the methodology and tools to effectively communicate the process. The act of communication must also require little effort; it must be efficient.

This need for efficiency prompted the authors to also investigate the PIM research field because PIM focuses on improving the efficiency of information exchange (Froese and Han 2009). Many recent PIM efforts focus on improving the efficiency of product information exchange to address the A/E/C industry's interoperability challenges (Shen et al. 2010; Young et al. 2007), frequently by applying BIM and/or cloud computing. For example, Singh et al. (2011) researched methods for exchanging product data through BIM servers, and Leite et al. (2011) researched the effort versus reward of BIM at varying levels of detail. Despite acknowledgment that the benefits of BIM only come with design processes change, PIM researchers have focused more on the benefits of BIM (i.e., communicating product information), not on communicating information about a project team's processes. The challenges faced by the university building design team stemmed from ineffective process (not product) communication.

One of the challenges of applying process communication research in practice is that process modeling approaches are abstract and, therefore, have limited value for project-specific design collaboration or for sharing of processes between projects. Though, these standardized processes can enable sufficient understanding for strategic investment in improvement. For example, the Georgia Tech process for product modeling (GT-PPM) (Lee et al. 2007) and the information delivery manual (IDM) (Wix 2007) modeled standard information exchanges to lay the foundation for improving interoperability. However, the audience of these two efforts was software developers who will improve the efficiency of product information exchange, not designers who need improved process communication for collaboration and sharing.

Outside of construction, the information value-based mining for sequential patterns (VMSP) (Ishino and Jin 2006) and the component-based records method (Ding et al. 2009) are intended to efficiently capture information exchange for collaboration and process sharing. Ishino and Jin (2006) wrote a customized tool that captures changes in a computer-aided design tool, and attempts to derive design rationale from those changes. VMSP requires intense software customization and is not readily scalable to the hundreds of tools used in professional A/E/C practice. Ding et al. (2009) recognized the importance of minimizing effort in capturing information, but his target users already document their processes, and their method requires processing records of design activities at a later date. In A/E/C, minimal documentation of processes exist because designers are unwilling to write even a few words to capture processes (as required by the component-based record method), and their firms are not willing to invest resources in postprocessing captured processes. Although these methods [and others discussed by Ding et al. (2009)] are worthwhile investments for A/E/C companies, such methods are unlikely to be adopted. This paper focuses on filling this gap: to communicate the process to satisfactorily address the challenges illustrated by the university building team, but with near-zero effort from the team to increase the likelihood of adoption.

In summary, PIM does not address the need to communicate information exchanges for collaboration, leverage information systems to enable process sharing (Malone et al. 1999), or understand processes for strategic investment in improvement (Ballard and Koskela 1998; Hartmann et al. 2009). PIM lacks methodologies for effectively communicating processes, whereas DPM literature describes methodologies for communicating processes, but lacks a sufficiently efficient method for the industry to adopt these methodologies. The following section uses a literature review to draw on findings from other research fields to address the need for both effective and efficient process communication.

Synthesizing Existing Concepts to Develop DPCM

This section synthesizes concepts from organizational science, HCI, and process modeling fields to guide the development of the DPCM. The authors chose these three fields because of the importance of developing a methodology that would be adopted by organizations, facilitate the creation and accessibility of design processes in a computer, and specify a grammar for representing the processes. The authors reviewed a combined 92 papers in these three research fields by utilizing a snowball approach. Out of these papers, the authors found that 57 of the papers had concepts relevant to the development of a methodology for communicating design processes. The authors aggregated these concepts into eight characteristics recommended for communicating design processes: computable (four papers), embedded (16 papers), modular (13 papers), personalized (10 papers), scalable (nine papers), shared (18 papers), social (12 papers), and transparent (16 papers). The rest of this section discusses a subset of the 57 papers used to develop the DPCM.

Organization Science to Enable Adoption

This section first explains why highly interdependent tasks inhibit process standardization and why process documentation should be embedded. Research on institutions suggests that technology should be transparent, social, and shared to best allocate human capital and creativity. Institutional research on matrix organizations suggests hierarchically structured information is not suitable in A/E/C, which the authors interpret to mean information should be represented in a way that makes processes transparent. Finally, knowledge management research calls for embedding and socializing of design process knowledge acquisition, structuring, and retrieval so processes can be shared.

A/E/C Requires Coordination without Standardization

Standardization permits coordination when situations are relatively "stable, repetitive and few enough to permit matching of situations with appropriate rules" (Thompson 1967). In A/E/C, the International Alliance for Interoperability developed the industry foundation class (IFC) to standardize data schema for describing buildings. The GT-PPM (Lee et al. 2007) and IDM (Wix 2007) models also depend on a standard design process. The new capabilities of simulation software, the complex demands of stakeholders, and the global nature of design teams make design processes increasingly complex, dynamic, and based on performance (not precedence). Organizations with variable and unpredictable situations inhibit process standardization. Instead, coordination must be achieved by mutual adjustment, which "involves the transmission of new information during the process of action" (March and Simon 1958). Extrapolating to design processes, coordination should occur by embedding the process documentation in the minute-to-minute work of designers rather than by developing standard coordination methods. This lack of embedment inhibited the case study project team from collaborating to make a mechanical system decision because they were not aware of each other's processes. This concept explains the relative lack of process standardization and convergence to a single product model in A/E/C.

Form New Institutions around Processes

Institutionalism research explains relationships between firms and information. In Coase's model (1937), a firm forms when the gains from setting up the firm, including organizational costs, are greater than setting up a market, including transaction costs. The open source software institution does not fit within Coase's model; therefore, Benkler (2002) proposed the alternative peer production model. Benkler (2002) claimed that this third type of institution "has certain systematic advantages over the other two in identifying and allocating human capital/creativity." In describing the necessary conditions for processes to be implemented and shared in this peer production model, Benkler broke down the act of communication into three parts. First, someone must create a humanly meaningful statement. Second, one must map the statement to a knowledge map; therefore, its relevance and credibility is transparent. Finally, the statement must be shared. In utilizing these advantages and conditions, a process communication environment can mimic the success of the open source software industry.

Berger and Luckmann's (1967) explanation of the firm provides insight as to how to instantiate Benkler's peer production model. Berger and Luckmann explained that many menial tasks take much effort to complete. They argued that habitualization is human nature because it frees energy for creativity and "opens up a foreground for deliberation and innovation." In building design, habitualization is possible because many individual tasks are repeated. Thompson's standardization (1967) is difficult because the same collection of tasks (i.e., a process) rarely occurs more than once with the same actors. Berger and Luckmann argued that habitualization of tasks is the reason why institutions form because institutions can invest in technology to perform standard tasks, providing an advantage over the sole practitioner. A larger institution that collectively develops more institutional habits can then focus more on creative endeavors. For these institutions to exist, "there must be a continuing social situation in which the habitualized actions of two or more individuals interlock" (Berger and Luckmann 1967). But what happens when the quantity and diversity of tasks and actors is so great that these social institutions do not occur naturally? Individuals in the organization must continuously waste energy on tasks that from an institutional perspective seem habitual, but from the perspective of the individual are unique (e.g., daylighting consultants in the case study thought they were the only ones performing the tasks). Can technology facilitate social situations where individuals interlock to create reciprocal typification? Habitualization (i.e., recognition of one's own repetitive tasks) combined with reciprocal typification (i.e., when two people recognize each other's habits) are critical for the formation of a peer-production institution. Technology is needed to socialize (i.e., promote collective engagement) and share (i.e., distribute among the organization) information exchange and make typification transparent; therefore, institutions can form around common processes. For example, a community focused on finding the environmental impacts of structural materials could have made the process described in the case study habitual within the organization. To reach this point, however, the community must first find a way to socialize and share this process.

Use Processes to Structure Information for the Matrix

Programmers in the open-source software movement are simultaneously part of Benkler's peer production model and Coase's traditional firm. Designers also exist within this peer production model

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and the traditional A/E/C matrix organization. The matrix organizations in large A/E/C design firms generally form by project, geography, and/or discipline, but the firm stores information hierarchically in folder directories. Just as Davis and Lawrence (1977) claimed that new business conditions required a change to the matrix organization, analogously, expanded uses of digital information require a deconstruction of the hierarchical information structure. Information now serves multiple purposes. A project team uses a building object, such as a window for architectural rendering, daylighting analysis, and energy analysis. Designers exert much effort to create this object; therefore, it no longer belongs to just one project, but is utilized on multiple projects. In addition, with increased cloud-computing power and demand to view trade-offs, more designers exchange more information, more frequently. As shown by the mechanical system design problem, it is difficult to maintain information consistency. Organizing the information by dependency brings the transparency needed for consistency.

Knowledge Management without Management

An organization's knowledge is a resource. In this knowledge-based theory of the firm, the organization is a social community that transforms knowledge into economically rewarded products and services (Grant 1996; Khanna et al. 2005). Conklin (1996) described a project memory system to define and share this knowledge. The project memory system is necessary because organizations lack ability "to represent critical aspects of what they know." Whereas Conklin generally applied this system to capturing knowledge from meetings, the same lessons apply to capturing design process knowledge. A process communication environment that acts as "an evolutionary stepping stone to organizational memory" would allow designers to track information exchanges on a project (e.g., in Australia) from which designers on another project (e.g., in California) could deduce design process knowledge.

Once Conklin's stepping stone from project to organization enables knowledge acquisition, the knowledge must be structured. Hansen et al. (1999) described two aspects of knowledge structuring: codification and personalization. Codification relies on information technology tools to connect people to reusable explicit knowledge (Javernick-Will and Levitt 2010). Personalization relies on socialization techniques to link people, and they can share tacit knowledge. Technology can provide the general context of knowledge and then point to individuals or communities who provide more in-depth knowledge. Knowledge management is not just acquisition and structuring (Kreiner 2002), but also easy retrieval (Javernick-Will et al. 2008). For example, knowledge can be made sharable by capturing and structuring it in ways "that create and preserve coherence and 'searchability'" (Conklin 1996). In the case study, the lack of design process knowledge sharing inhibited the material environmental impact analysis process from being utilized by other project teams outside Australia.

The type of sharing discussed in the knowledge management literature also exists in Benkler's peer production model. Hower, Benkler's model requires minimal, if any, management. Combining the peer production model with knowledge management research provides guidance for developing a methodology for self-perpetuating acquiring, structuring, and retrieval of design process knowledge that is completely embedded in the design process and requires minimal management.

HCI to Create and Access Processes

HCI research provides points of departure for facilitating the designer's interaction with the digital representation of the process. HCI research is founded on cognitive science research that describes how humans interact with computers (Winograd 2006). This foundation enables HCI researchers to develop better methods for humans to interact with computers.

This section first describes how cognitive science research calls for personalized process views, and then describes HCI research that contributes to making a communication environment sharable, scalable, social, and transparent.

Cognitive Science Calls for Personalized Graphical Representations

"The power of the unaided mind is highly overrated. . .The real powers come from devising external aids that enhance cognitive abilities" (Norman 1993). Because "solving a problem simply means representing it so as to make the solution transparent" (Simon 1981), enhancing a designer's ability to collaborate, share, and understand processes requires representing the process in ways transparent to the designer.

Graphical representation of information dependencies can be personalized to the designer. For example, more analytical-minded decision makers made better decisions when presented with a graph representation of information dependency, as opposed to an interaction matrix (Pracht 1986) [nearly identical to the DSM used in A/E/C (Steward 1981)]. In the case study, more personalized views of the mechanical system design process would have permitted process transparency and a more collaborative design decision.

HCI Advocates Information Interaction and Visualization

"How can information environments best be shaped for people?" (Pirolli 2007). Information visualization is the "use of computer-supported, interactive, visual representations" of abstract, nonphysical data to amplify cognition (Card et al. 1999). For example, the human eye processes information in two ways. Controlled processing, such as reading, "is detailed, serial, low capacity, slow. . .conscious." Automatic processing is "superficial, parallel. . .has high capacity, is fast, is independent of load, unconscious, and characterized by targets 'popping out' during search" (Card et al. 1999). Therefore, visualizations to aid search and pattern detection should use features that can be automatically processed. Designers will be able to better draw meaning from information dependency graphs if the graphs use process views at appropriate scales (i.e., levels of detail), and spatial layouts indicative of topology (Card et al. 1999; Nickerson et al. 2008). These strategies will make the environment more transparent.

The capabilities of the human eye also influence information scent: the perceived value of choosing a particular path to find information (Pirolli 2007). To promote an accurate and intense scent for designers to find useful shared processes, search results should show actual information dependency maps and prioritize the most useful processes in the search results.

Heer et al. (2007) showed that social groups will reveal more patterns than the same number of individuals. Combining conversation threads with visual data analysis helps people to explore the information broadly and deeply, suggesting a promising opportunity for supporting collaboration in design activities. The environment should allow the community to point to specific locations in the graphs to discuss patterns socially.

Process Modeling to Represent the Process

Process modeling research creates a formal grammar for communicating processes. Austin et al. (1999) provided an overview of A/E/C process modeling techniques. A/E/C researchers delineate process

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modeling research by different views of the process or by the objectives of the modeling. The next sections are organized according to two modeling objectives: improving coordination and planning, and automation. This literature claims models should be embedded, scalable, shared, transparent, social, modular, and computable.

Process Models Aimed at Improving Coordination and Planning

Narratives attempt to overcome the challenges of multidisciplinary, iterative, and unique design processes (Haymaker 2006). To facilitate coordination, Narratives create task-specific views of information flow (consistent with Norman's views in the aforementioned discussion of cognitive science). Haymaker also expressed the need to facilitate coordination by representing the status of information. Although the Narratives research called for embedding of process modeling into the design process, and identified and facilitated the need to make the source, status, and nature of the information dependencies transparent, these concepts remain unvalidated.

As opposed to Narrative's graph view, which communicates a planned or historically implemented process, DSM uses a matrix view to plan, and algorithms to improve, the process. Originally, DSM tracked the dependencies of activities (Steward 1981), but the analytical design planning technique (ADePT) extended DSM by utilizing data flow diagrams (Fisher 1990) and integrated computer-aided manufacturing definition for function modeling 0 (IDEF0) (Austin et al. 1999) to model not just tasks but also information flow between tasks (Austin and Baldwin 1996; Austin et al. 2000; Baldwin et al. 1998). An important part of both modeling techniques is their ability to take a complex system and scale it down into subsystems.

In the case study, embedding such process descriptions in the design process may have permitted the owner representatives to be more confident in the mechanical system decision by quickly and accurately comprehending the process. Similarly, the vision of integrated practice includes "a world where all communication throughout the process are clear, concise, open, transparent, and trusting: where designers have full understanding of the ramifications of their decisions" (Strong 2006). Therefore, the process, not just the product models, should be shared with the entire project team, and the information on which decisions are dependent should be transparent.

Process Models Aimed at Improving Automation

Comprehending how project teams coordinate aids development of automated information flow; therefore, recent process modeling efforts support both goals. "Interoperability exists on the human level through transparent business exchanges" (American Institute of Architects 2007). The importance of associating people with information exchange to develop automation is analogous to Hansen's claim that knowledge must be social, not just codified.

The IDM aims to provide a human-readable integrated reference identifying best practice design processes, and the data schemas and information flows necessary to execute effective model-based design analyses at varying scales of detail (Wix 2007). The IDM contrasts with the focus of *Narrator* on designer communication, but are similar to the *Geometric Narrator*, which emphasizes the use of process models to perform modular computations on information (Haymaker et al. 2004).

DPCM

The aforementioned points of departure provide characteristics of an effective and efficient methodology for communicating processes. This section defines these characteristics and describes elements and attributes of the DPCM that represent and contextualize processes, and methods that describe how designers capture and use these processes by interacting with a cloud-based communication environment (as indicated in the following two sections and Fig. 1). The contribution of this paper, DPCM, is the combination of the elements, attributes, and methods that enable the characteristics.

Elements and Methods Enabling Characteristics

Embedded

Users simultaneously organize and exchange information and communicate processes. They save or open Information, and can open previous versions of Information. Each Information Node contains a list of previous versions of the files. The status of the Information can be up-to-date, being worked on, or out-of-date. These information management elements and methods encourage the users to use the environment as the primary means of exchanging information while they work. The ability to effortlessly Draw Arrows after saving a file embeds process capturing in this information management work flow.

Scalable

The environment scales to the tens of thousands of files exchanged on the largest construction projects, and also scales across the industry to apply to many different types of projects.

The environment enables scaling within a project by providing access to representations of information dependencies through a Frame. A Frame is a type of Node that itself contains views onto a collection of other contained nodes. Unlike the Nodes that exist in a single nonhierarchical network, the Frames are organized hierarchically. Therefore, the user can choose to open each Frame via a hierarchy or network type of Window. This hierarchical organization enables the representation of processes at multiple levels of detail and ensures users are not overwhelmed by visualizations of networks containing dozens of Nodes not relevant to their task.

The environment scales across the industry because it uses a discretization and format of information common across the industry: the file and URL. Because every project uses digital files or URLs to describe the building, the environment can be utilized across the industry.

Personalized

The communication environment personalizes communication to each user. Because the Frame is simply a view onto the Nodes, a single Node can exist within multiple Frames. Therefore, designers can create custom views of the Nodes and their relationships that are comprehensible and relevant to them. They just Drag and drop nodes into their personal Frames without affecting how others see the Nodes.

Transparent

The environment enables the comprehension of processes by the designers. The environment achieves transparency through arrows between Information and Frame Nodes. Each arrow represents an information Dependency. That is, the end Node is dependent on the start Node if Information contained within the start Node was used to create the Information in the end Node.

The environment additionally enables transparency by assigning each Node an information Ribbon. The Ribbon contains a description of the information contained within the Node. For each Frame Node, the Ribbon displays the difference in time between the

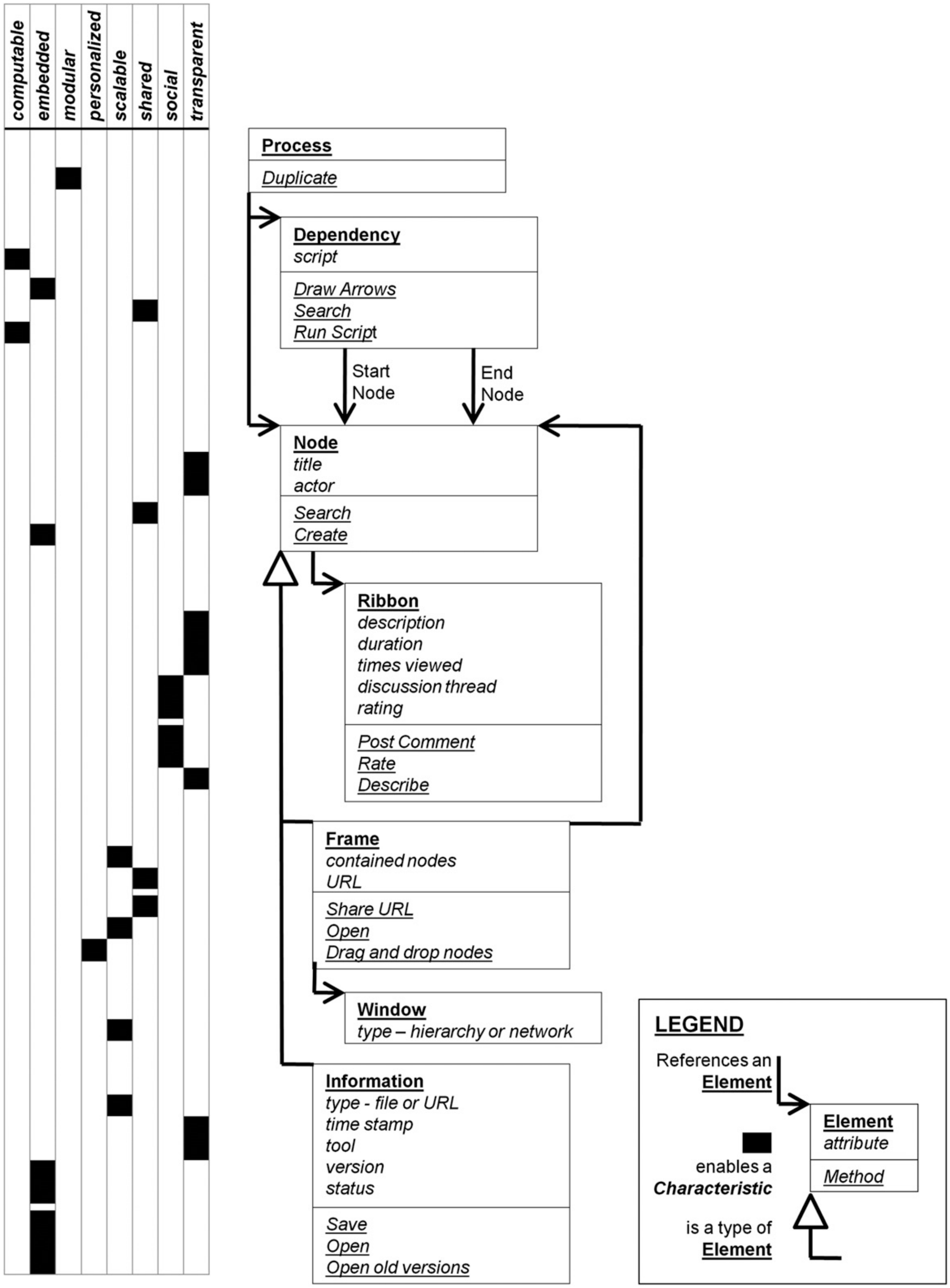

Fig. 1. DPCM: elements represent and contextualize a process and methods enable designers to capture and use the process model; these elements and methods enable the characteristics

most recently uploaded file and the oldest file, indicating the latency as a result of the initiation of the process, the duration. The Ribbon also shows how many times (times viewed) users opened the Frame, an indication of the popularity or importance of the process. Also, each Information Node has a time stamp showing when the file was last uploaded, and what tool was used to create the file based on the file suffix. All Nodes have a title and an actor that denotes the person responsible for the Node.

Social

The environment promotes social engagement with project information and dependencies. Within each Node's Ribbon, users can

Post comments about the Information and the processes in the discussion thread. They can also Rate the process in terms of its productivity.

Shared

The environment facilitates the distribution of the processes. Users can Search Dependency paths and individual Nodes. Also, users can share their views of processes with others because each Frame has a URL that can be sent to other users.

Modular

The environment enables users to combine several parts of other processes into a new process. It also allows geographically separated users to work on different parts of a process and then combine their work. This modularity contrasts with strategies aimed at representing all project information within a single type of data schema and instead encourages discrete modules of information dependent on each other. Users can mix and match Process modules containing all of the aforementioned elements and Duplicate the Process modules and customize them to specific projects.

Computable

The environment enables users to attach scripts to a Dependency that would automate information flow from the start Node to the end Node. Defining each Dependency as a computable relationship between two pieces of Information enables the gradual development of improved interoperability between tools.

DPCM Applied to Observed Problems

The authors developed the DPCM based on the literature review and then operationalized the DPCM as a cloud-based application called the PIP. The PIP is a combination between a file sharing tool and a flowchart building tool that enables team members to exchange and organize files as nodes in information dependency maps in addition to folder directories. Once the PIP became usable by project teams, the authors began iterative cycles of literature review, methodology development, tool development, tool implementation, and ethnographic observation according to the ethnographic-action method (Hartmann et al. 2009). This section demonstrates how by operationalizing the DPCM as a PIP, the DPCM addresses the three types of communication challenges described in the case study.

Collaboration with the PIP

If the PIP had been available to the mechanical engineering team on the university building project, they could have used the PIP to collaborate around their digital files. The user sees two personalized home page Windows: a hierarchy view on the left of the screen and a network view on the right (Fig. 2). In this case, the mechanical engineer wants to use an Architecture Model file and a Daylighting Analysis file as input to an energy analysis. The engineer navigates through the Frame hierarchy to a more detailed process level showing the architecture and daylighting models. This hierarchical organization of the Frames enables the process to be scaled to many files. The engineer then Drags and drops the Information Nodes containing the Architecture Model file and the Daylighting Analysis file into the Energy Analysis Frame. The Frames are, therefore, personalized in that the same Information Node containing the Architecture Model file exists within the context of the Daylighting Analysis Frame and within the context of the Energy Analysis Frame. The mechanical engineer then double clicks on each file to open it on their desktop. The ability to open and save files directly in the PIP enables the process capturing to be embedded in the design process. The engineer then imports the *Revit* model into the energy analysis tool. Looking at the daylighting analysis results, the energy required for artificial lighting into the energy analysis tool is then manually entered. After completing the energy analysis, the engineer then Creates an Information Node and saves the energy analysis file to that Node. As the architecture model and daylighting analysis was used as input to the energy analysis, the engineer can also Draw

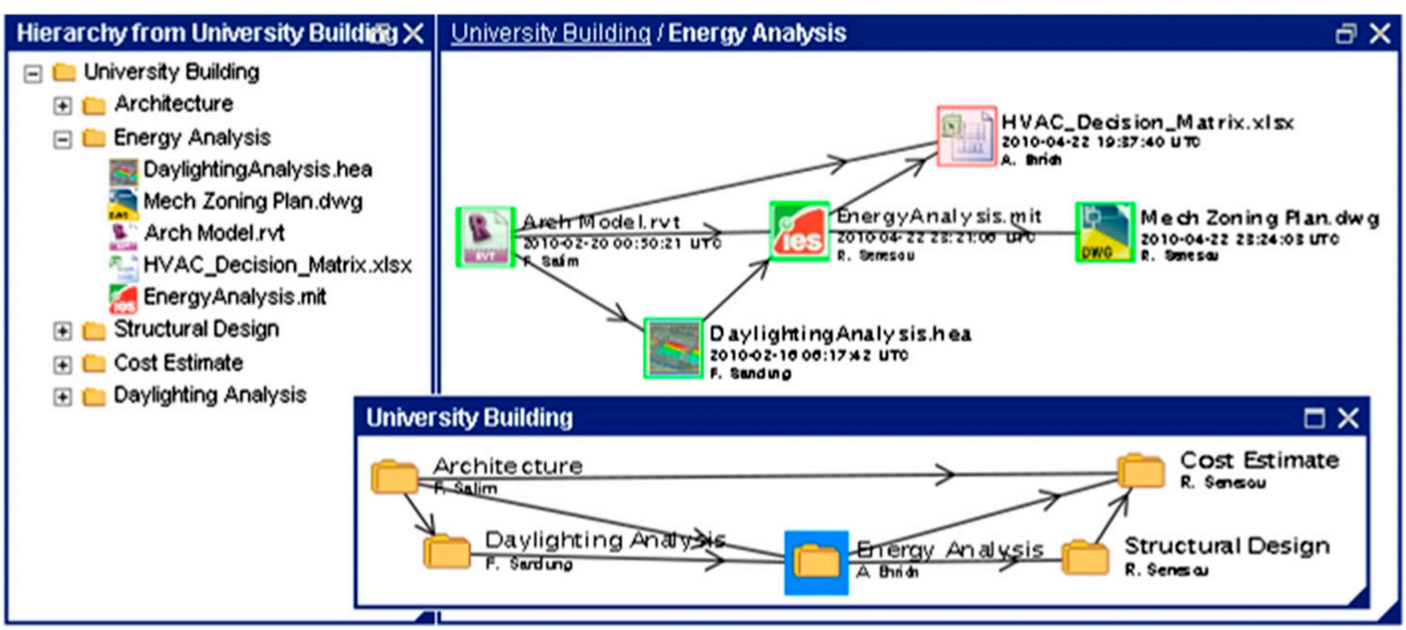

Fig. 2. Collaboration in the PIP: users navigate to the appropriate process level via the hierarchy view or by double-clicking folder icons; users create nodes, upload files to those nodes, and draw arrows to show relationships between the nodes; in the actual interface, green highlights indicate the node is up-to-date, and red indicates an upstream file has changed since the node was uploaded

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Arrows from those two nodes to the new energy analysis node to represent this Dependency and make the process transparent. With the energy analysis complete, the results can then be used to create a decision matrix in Excel. The Excel file can be uploaded to a new Node, with an arrow drawn to it. When the architectural design changes, prompting the upload of a new energy analysis file, the downstream decision matrix file status is no longer up-to-date (indicated by red highlight in the interface) because it was created based on an outdated energy analysis file. Based on the new energy analysis, the mechanical engineer creates an *AutoCAD* file with a displacement ventilation system that is dependent on the new energy analysis. Now, the rest of the project team knows to integrate their designs with the *AutoCAD* file and not the outdated decision matrix. Using the PIP makes the mechanical design process transparent to the entire team; therefore, they can comprehend information relationships, consider trade-offs, and make related information consistent.

Sharing Processes with the PIP

In addition to facilitating collaboration, other teams can also share design processes with the structural engineer on the university building project, allowing calculation of the environmental impact of materials. Because the PIP is cloud-based, sharing is enabled by the structural engineer Searching for a Process where a project team started with input Arch.ifc to denote an architecture model with an IFC file format and produced a life-cycle assessment (LCA) (Fig. 3). The results display three projects, and the engineer browses to find the most relevant Process. The engineer can Duplicate the relevant Process module and paste it within the university building Frame to be used as a planning template, which can then be populated with project-specific Information.

Understanding Processes with the PIP

With the PIP, professionals can understand processes across the firm or industry; therefore, they can identify popular, but inefficient, processes and strategically invest in improvement. Each Node has a Ribbon containing information that describes the process within the Frame or the Information contained within the Node. The PIP offers a process-centric discussion thread for users to Post Comments and Rate process productivity (Fig. 4). By socially discussing processes, a community of designers can discuss where the firm should invest in process improvement. A community of daylighting consultants could see that their process is viewed often (times viewed), but that the process duration is long. They could discuss the inefficiencies of the process and decide to collectively program a script to extract information from a *Revit* file and convert it to a format that would be interoperable with the daylighting analysis software. The consultants could then save that script in the PIP and drive computable information flows automatically.

Validation Metrics

The previous section explained the operationalization of the DPCM as a PIP, and how the PIP hypothetically addresses challenges faced by the building design team. This section presents metrics (Table 1) to validate that DPCM effectively and efficiently communicates processes.

Motivation for the Metrics

Validating the DPCM requires measuring the effectiveness and efficiency for each type of communication. Each type of communication requires four steps: (1) capturing, (2) structuring, (3) retrieving, and (4) using processes. Benkler (2002) described these steps as part of the information-production chain needed for collaboration in the peer production model (see the previous section on forming new institutions around processes). Knowledge management research described these steps as needed for the sharing of processes across projects (see the previous section on knowledge management) (Carrillo and Chinowsky 2006; Javernick-Will and Levitt 2010; Kreiner 2002; Tang et al. 2010). Finally, innovation literature cites these steps as required for companies to understand

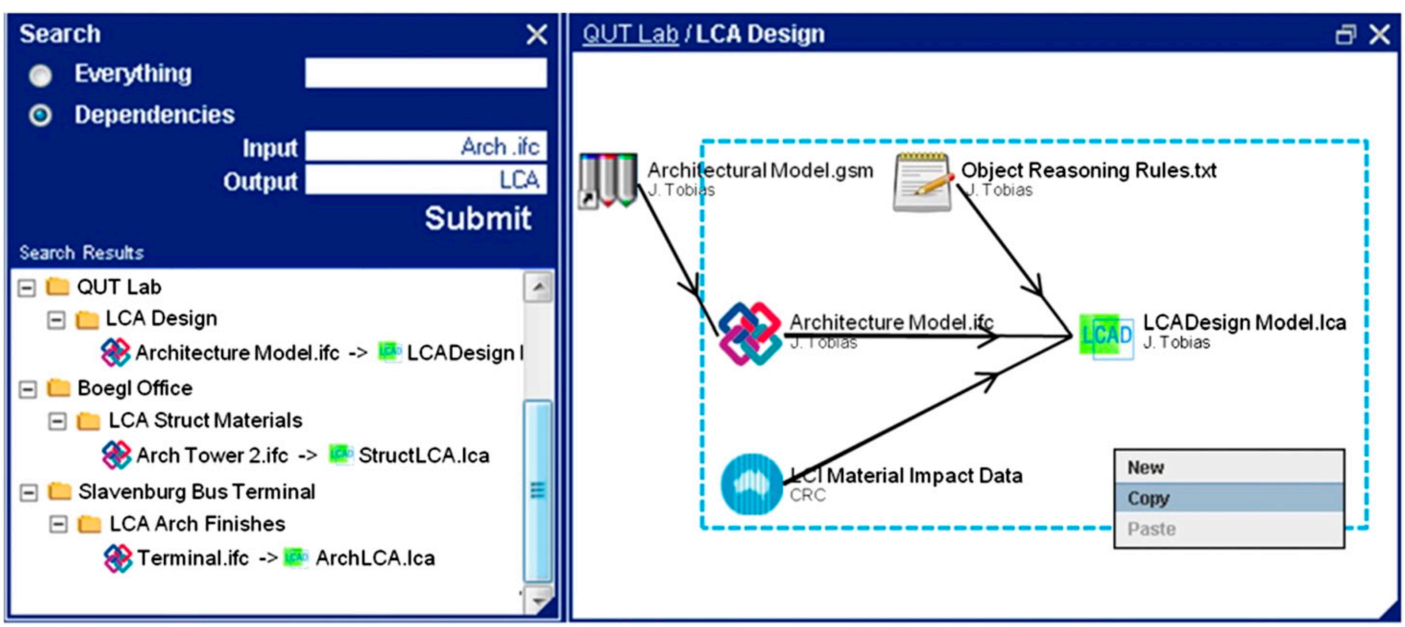

Fig. 3. Sharing processes in the PIP: users search information dependency paths to find processes with the input available and the output desired, and users can then copy processes to new projects

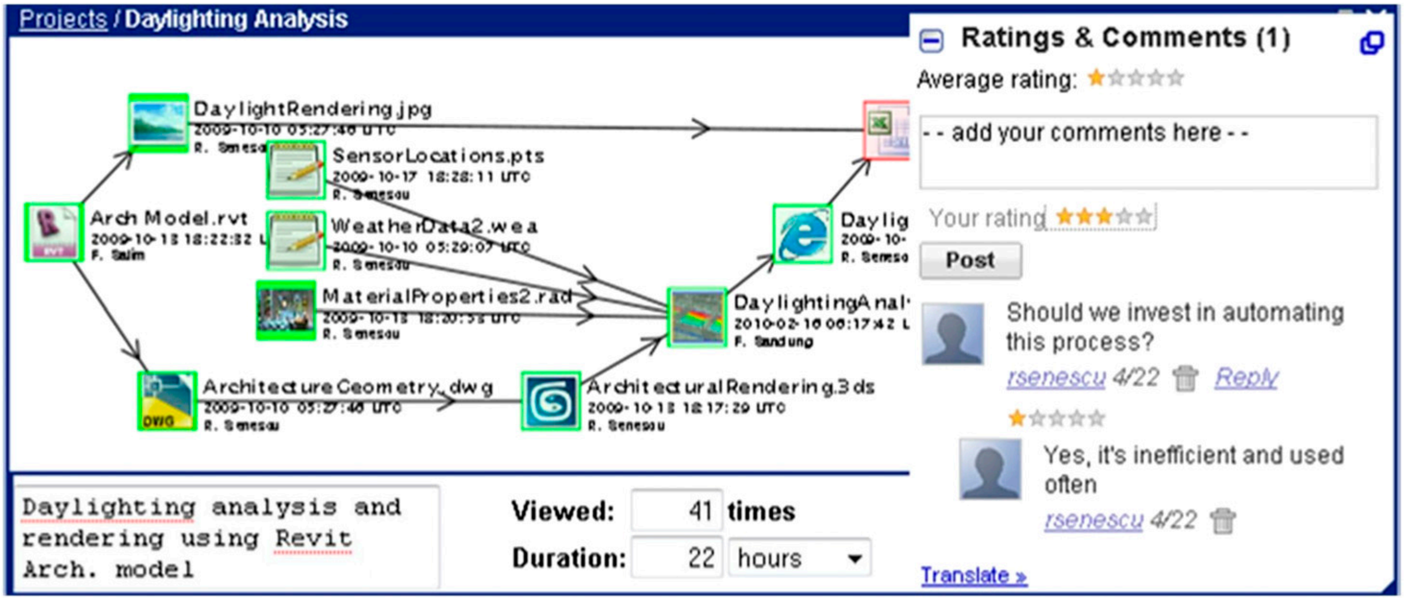

Fig. 4. Understanding processes in the PIP: PIP tracks some process metrics automatically; therefore, users can evaluate the most popular and time-consuming processes; discussion threads are associated with each node; therefore, project teams can discuss individual files or entire processes

Table 1. Metrics to Assess Process

Steps for communication	Types of communication: Collaboration within projects	Sharing processes between projects	Understanding processes across firm/industry
Capturing processes			
Effective	(1.1) Percentage of dependencies captured		
Efficient	(1.2) Frequency of value-adding information transfer between designers (1.3) Number of positive design iterations		
Using processes			
Effective	(2.1.1) Number of statements about trends (2.1.2) Number of positive design iterations	(2.2.1) Score of projects mimicked	Enables insight
Efficient	(2.1.3) Number of complete and accurate designs options (2.1.4) Internal information consistency (2.1.5) Number of statements of confusion	(2.2.2) Number of errors committed implementing the shared process	Time to achieve insight

their processes to make strategic investments in process improvement (Hargadon and Sutton 2000).

Historically, these different types of communication were independent. Companies have different systems (both technical and organizational) for project management, knowledge management, and research and development. However, for each type, the literature suggests steps for improving collaboration, sharing, and understanding that are similar. Because of this similarity, at the same time one is exchanging information to collaborate within a project, that professional can also contribute to sharing processes across projects and to understanding of processes across the firm or industry. Therefore, the following sections measure capturing and structuring of processes and then the retrieving and using of processes within projects, between projects, and across the firm or industry. The sections combine capturing and structuring into simply capturing, and retrieving and using into simply using. The authors apply this simplification because as the efficiency of communication increases, it becomes increasingly difficult to distinguish among each pair of steps.

Effectiveness and Efficiency of Capturing Processes

In typical design projects it is difficult to determine the theoretical or ideal information dependencies. Measuring how accurately the process model matches the actual process is nearly impossible. However, in a controlled design experiment, the theoretical information dependencies are known, and capturing effectiveness can be measured as the percentage of true dependencies captured by the process model (as shown in 1.1 in Table 1).

A communication method that captures a high number of dependencies in a controlled environment should also capture a relatively high number of the dependencies in practice. Design projects consist of "production work that directly adds value to final products, and coordination work that facilitates the production work" (Jin and

Levitt 1996). An efficient process communication methodology will not decrease the time spent on production work and will not increase time spent on coordination work. That is, capturing processes accurately should not cause any burden on other aspects of the project. Two measurements indicative of burden are (1.2) frequency of value-adding information transfer between designers, and the (1.3) number of positive design iterations.

Design iteration and exchange of information between designers are valuable parts of production work. When design teams are burdened with managing information, they iterate and exchange information less frequently.

In the university building example, project managers planned the process through a series of milestones. The milestones provided a coarse view of the process resulting in the capture of zero information dependencies. The authors hypothesize that applying the DPCM would capture a much larger percentage of dependencies without the burden caused by, for example, the DSM method, which required hours of upfront effort (Austin et al. 1999).

Effectiveness and Efficiency of Using Processes

Once the DPCM enables the capturing of processes, designers can use the processes for the three types of communication.

Using Processes for Collaboration within Projects

The ability of a team to collaborate effectively around a process can be measured by the (1.1.1) number of statements about design trends and the (1.1.2) number of positive design iterations. These two metrics both indicate multidisciplinary collaboration effectiveness. Successful design solutions require global consideration of multidisciplinary trade-offs and the resulting iteration that enables the best solutions to be found (Akin 2001; İpek et al. 2006). Without collaboration, teams will optimize locally within their discipline silos.

Inefficient project teams perform negative rework without ever completing an internally consistent and complete design (Ballard 2000). The lack of upfront collaboration means most problems are resolved during construction when the cost of resolution is highest. Therefore, the efficiency of collaboration around a process can be measured by the (1.1.3) number of complete and accurate design options produced.

A team that collaborates efficiently will produce multiple design options as they iterate toward a final design. During the design process, efficiency can be measured by (1.1.4) internal information consistency.

For example, in the mechanical engineering problem, the structural engineer may have assumed no underfloor air distribution in the structural design based on the HVAC Decision Matrix file, whereas the electrical engineer may have assumed that the all the wires could be placed in the underfloor space based on the mechanical zoning plans. This inconsistency would delay the completion of an accurate design option. These types of inconsistencies cause statements of confusion; therefore, collaboration effectiveness can also be assessed by the (2.1.5) number of statements of confusion. These metrics allow researchers to assess the relative ability of different communication methodologies to impact the effectiveness and efficiency of collaboration within projects.

Using Processes for Sharing between Projects

Effective use of other projects' processes requires retrieving productive processes. For example, in professional practice many processes for leveraging the BIM to perform LCAs of structural systems may exist.

Researchers need a scoring system to evaluate whether the communication methodology enables retrieval of productive processes: the (1.1.1) score of projects mimicked.

The actual scoring system used may vary depending on the type of design task [Clevenger and Haymaker (2011) provided one system]. Regardless of the scoring system chosen, retrieving and attempting to use an appropriate process is insufficient. A project team must be able to use another project's process efficiently. Efficient use of a shared process should minimize the (1.1.2) number of errors committed implementing the shared process.

Errors may include redundant steps, such as using more tools than required, using tools incompatible with other tools, or missing critical analysis. For example, the structural engineer on the university building project may retrieve the Australian LCA process in Fig. 3, but if the structural engineer forgets to implement a critical part of the process, then the methodology does not enable efficient sharing of processes.

Using Processes for Understanding across the Firm or Industry

A/E/C companies consider information technology investments to be costly and risky; however, investments proceed based on gut feel without understanding current processes and how the specific investment will improve them (Marsh and Flanagan 2000). An effective process communication method enables the firm or industry to effectively use their understanding of current processes to strategically invest in process improvement. Unlike the aforementioned communication types, the authors evaluate effective understanding qualitatively by investigating the ability of a communication methodology to provide insight in answering the following questions:

1. What are the most important types of information in projects?
2. Who are the most critical individuals in projects?
3. What information flows between tools are most common?
4. What are the latencies between tools or between people?
5. How well is information distributed within the team?
6. What is the relationship between information distribution and project performance?

Unlike the quantitative metrics previously discussed, the DPCM's effectiveness in answering these questions requires case study research observing how teams use the PIP across multiple projects.

The authors measure understanding efficiency as the time required to achieve the insights. The time is trivial for the DPCM because data visualization tools provide nearly instantaneous access to process information (i.e., no effort is required to structure processes after capture).

Limitations and Ongoing Work

The previous section proposes metrics to be used to validate the impact of the DPCM on process communication. This paper does not go as far as validating the DPCM's ability to effectively and efficiently communicate process because this validation is provided by Senescu and Haymaker (2013). Rather, this paper provides theoretical justification for the DPCM based on a literature review. This section addresses limitations of the literature review, explains the ongoing validation of the DPCM, and discusses challenges the authors may encounter when applying the DPCM in practice.

Scope of the Literature Review

This paper synthesized findings in organizational science, HCI, and process modeling to develop the DPCM. The snowball method applied may leave portions of these fields unexplored, but the review does not aim to comprehensively summarize these fields. Rather, the aim is to extract relevant findings to fill the gap between the existing DPM and the PIM research by providing a methodology that is both effective and efficient at communicating processes.

Current and Ongoing Validation

This paper validates the DPCM as a theory by showing it is testable. The authors demonstrate testability by operationalizing the DPCM as a web application (PIP) and demonstrating how the PIP addresses the challenges faced by the university building design team. Providing additional evidence of the testability, over 200 students used the PIP in class projects, design charrettes, and on graduate student research projects (Fig. 5). This adoption of the tool demonstrates both the perceived usefulness of the DPCM and the ability of future research to measure the impact of the DPCM on communication effectiveness and efficiency.

Ongoing work asks: what is the impact of the DPCM on a project team's ability to effectively and efficiently communicate design processes within a project team, between project teams, and across multiple project teams? Ongoing work uses three validation methods to answer this question. First, Senescu and Haymaker (2013) developed the mock simulation design charrette (MSDC) to obtain values for the collaboration and sharing metrics shown in Table 1. The MSDC is an A-B testing method where control groups use folder directories, whereas performing design processes and experimental groups use the PIP to perform design processes. Second, Senescu and Haymaker (2013) used the same ethnographic-action method to validate understanding of design processes by the students using the PIP on their class projects. Third, the first author developed a commercial application that automatically captures how professional project teams exchange information when interacting with folder directories. After 2 months of silent (control time period) observation on professional projects, the application will reveal the dependencies between files (experimental time period) using a cloud-based application similar to the PIP. The research will then apply the collaboration and sharing metrics to compare how teams collaborated around information and shared design processes before and after using the commercial implementation of the DPCM.

Application to the Industry

In ongoing attempts to apply the DPCM in the industry, the authors discovered two methods for improved operationalization of the DPCM.

First, the PIP required users to manually draw arrows to communicate processes. Though this activity took about 1 s, it did require behavioral change. Consequently, Senescu et al. (2012) developed a method for determining the dependencies between files automatically based on how users opened and edited files. This automated information-dependency algorithm (AIDA) used existing behavior to determine dependencies rather than requiring users to change their behavior when interacting with files. Because the AIDA is not perfect, the authors envision a hybrid approach with automatic recommendations of dependencies combined with the ability to edit those dependencies using the DPCM dependency methods.

The second method relates to how the PIP would work with the BIM. Increasingly, design tasks occur within BIM software applications. Although the DPCM information attribute type suggests a file or a URL, this attribute type could easily be extended to include other groupings of information, such as building objects. The most common BIM application, *Revit*, provides an application programming interface (API) that enables outside tools, such as the PIP, to reveal both the product objects within a file and the process tasks performed on those objects. To ensure generality, the authors intentionally focused the DPCM on files and URLs, the most common denominator across all industries. Taking advantage of the DPCM's scalability, future work may operationalize the DPCM to function within specific BIM applications and at deeper levels of product and process detail, such as dependencies between building objects.

Conclusions

The DPCM contributes to PIM and DPM by laying the foundation for the development of commercial software that communicates design processes to increase the value generated per staff-hour expended by the A/E/C industry. The paper demonstrates the need for such a methodology both based on three examples of communication struggles in practice and by a review of the DPM and PIM research fields. The authors develop the DPCM by synthesizing concepts from organizational science, HCI, and process modeling research to conclude that achieving effective and efficient process communication requires a methodology that is computable, embedded, modular, personalized, scalable, shared, social, and transparent. The DPCM enables these characteristics through its

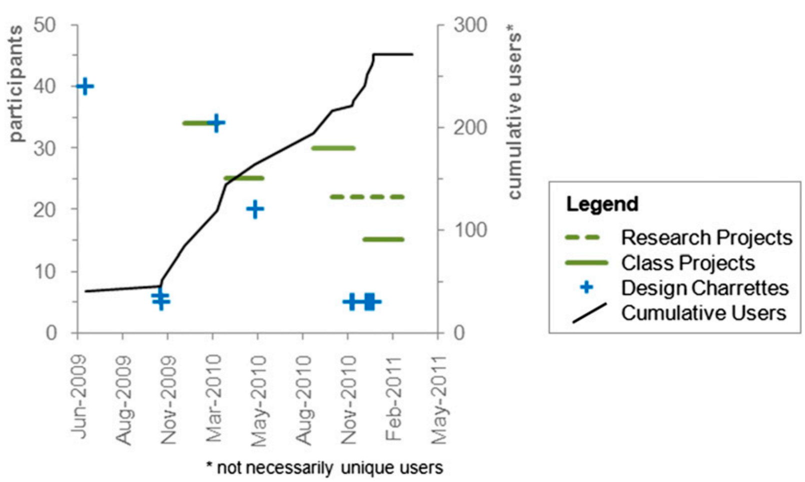

Fig. 5. Use of the PIP by students at Stanford University: PIP is a process-based file sharing web tool that acts as a model for DPCM; its use demonstrates that the DPCM can be practically applied and tested

elements that represent and contextualize processes and methods for capturing and using processes.

This paper demonstrates how the operationalization of the DPCM via the PIP addresses the challenges faced by a university building design team. The DPCM's operationalization, the proposed metrics, and the PIP's use by over 200 student designers demonstrate that the theoretically justified methodology is testable. Senescu and Haymaker (2013) describe the results from the PIP's use to provide evidence that the DPCM enables effective and efficient process communication. By developing the DPCM, this paper lays the foundation for commercial software that shifts focus away from an incremental and fragmented process toward a platform that nurtures emergence of (1) improved multidisciplinary collaboration, (2) process knowledge sharing, and (3) innovation-enabling understanding of existing processes.

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