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

By

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Design Process Communication Methodology: improving the efficiency and effectiveness of collaboration, sharing, and understanding[1]

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1 Abstract

Architecture, Engineering, and Construction (AEC) designers struggle (1) to collaborate within projects, (2) share processes across projects, and (3) understand processes across the firm or industry. Overcoming each of these challenges requires communication of design processes. The paper aggregates concepts from organizational science, human computer interaction, and process modeling fields to develop the Design Process Communication Methodology (DPCM). DPCM is a social, technical, and representational environment for

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communicating design processes that is ***Computable, Embedded, Modular, Personalized, Scalable, Shared, Social***, and ***Transparent***. To apply and test DPCM, the research maps the methodology to software features in the Process Integration Platform (PIP). PIP is a process communication web tool where individuals exchange and organize files as nodes in information dependency maps in addition to folder directories. The paper provides evidence of the testability of DPCM and proposes metrics for evaluating DPCM's efficiency and effectiveness in communicating design process. 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 multi-disciplinary collaboration, (2) process knowledge sharing, and (3) innovation-enabling understanding of existing processes.

2 Introduction

Design processes disproportionately influence the life cycle value of the resulting products (Paulson 1976). While the total cost of design is relatively small, the design phase of a project greatly influences total project value. Also, final project value generally increases with the number of different design options considered (Akin 2001; Ïpek et al. 2006). Yet, despite information technology advances during the last half of the 20th Century, 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). Not surprisingly, the construction value per man-hour expended actually decreased from 1964 to 2003, while the rest of the American non-farm industry more than doubled (United States Department of Commerce, 2003). Research leading to new information management systems can improve design processes to increase project value per man-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). The Design Process Communication Methodology (DPCM) contributes to the project information management (PIM) and design process management (DPM) research fields by laying the foundation for the development of commercial software that communicates design processes to increase the value per man-hour expended by the Architecture, Engineering, and Construction (AEC) industry.

Organizations within the AEC industry 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 paths. The design process is then organizations exchanging information that leads to a plan for the building Product. Jin and Levitt's Virtual Design Team (1996) similarly apply this information processing view of the organization to the AEC industry – first described by Weber (1947) and later adopted by March and Simon (1958) and Galbraith (1977). This research scopes the focus further to only include digital information exchange from scheme design to construction documentation on projects involving complex (Homer-Dixon 2000; Senescu et al. 2011a) products, organizations, and/or processes.

This section uses this information processing lens to describe how the AEC industry can improve design processes through improving 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 employing more effective software that they then implement on 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 and then manually enter quantities into a cost estimating spreadsheet, and so they invest in developing a script that performs the process automatically.

The AEC industry struggles to collaborate around processes, share processes, and understand processes effectively and efficiently as project complexity increases (Senescu et al. 2011a).

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” (Eckert et al. 2001). Also, team members frequently have conflicting obligations to the project and to the firm (Dossick and Neff 2010). Holistically considering the three communication types, this paper asks: how can design processes be communicated efficiently and effectively within project teams, between project teams, and across a firm or industry?

This paper first describes three observed design process communication challenges that motivated this research (Section 3). Then, the authors look to the PIM and DPM research fields to find a solution to the observed challenges. Not finding a solution, the authors describe in Section 3 how these two research fields lack a methodology that both effectively and efficiently communicates design processes. Describing the literature review, Section 6 aggregates concepts from the organizational science, human computer interaction, and process modeling research fields to develop DPCM, which describes a representational, technical, and social environment for process communication. From the literature review, the authors conclude that DPCM should be ***Computable, Embedded, Modular, Personalized, Scalable, Shared, Social***, and ***Transparent***. Section 5.4 explains how PIM and DPM process communication or information management methodologies do not exhibit these characteristics. Sections 6 through 8 explain DPCM and propose a method for validating its impact on design process communication.

3 Examples of Collaborating, Sharing, and Understanding Challenges

While Senescu et al. (2011a) provides evidence of the generality of communication challenges in the AEC industry, this section uses the design of a university business school campus to provide three examples to provide context to the problems DPCM addresses. The first author gathered these observations directly and through interviews during his role as structural engineer on this project.

3.1 Designers Struggle to Collaborate

When designing the campus, 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 choice. In the same project folder, the design team also created AutoCAD files with floor plans to communicate the mechanical systems in the various zones to owner representatives. These AutoCAD files showed that the designers frequently chose options other than the underfloor air distribution.

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 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 documents inhibited acoustics, lighting, and structural engineering consultants to maintain information consistency and to comprehend information dependencies. This inefficient collaboration caused negative rework (Ballard 2000). It also inhibited effective multi-disciplinary system integration, which was necessary for meeting many of the stakeholders' environmental sustainability goals. Designers do not work in an environment where the project team communicates information dependencies, which makes collaboration *within project teams* challenging.

3.2 Designers Struggle to Share Processes

The stakeholders explicitly communicated the importance of material responsibility when choosing structural systems (Haymaker et al. 2008). 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 3D object-oriented model (containing a database of structural materials and quantities), a database of the environmental impacts of those materials, and a desire by the stakeholders to consider environmental impacts of materials in their design decision, 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 in California who had worked in Australia to develop a process for performing model-based assessments of the environmental impact of construction materials (Tobias and Haymaker 2007). The Australian research center had worked directly with the Australian offices of the same engineering firm at the time of the project.

In this case, a clear demand for an improved process existed in the California office. The engineer could not find a design process to compare options with respect to stakeholder goals, even though researchers in California and engineers from the same firm in Australia had already performed this process. This example illustrates that designers struggle to efficiently and effectively share processes *between projects teams*.

3.3 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 campus library, daylighting consultants created video simulations of sunlight moving across a space. The process required much manual manipulation of geometry and materials to reformat the information, so each new software package could interpret the data representing the building. This process was not productive as the consultants spent 50% of their time on these non-value adding tasks and considered only 2-3 options resulting in a sub-optimal design.

The individual consultants lacked incentive to invest time in process improvement. Their tools did not capture their process (and the resulting lack of productivity), place them in peer communities to improve the process together, nor provide transparent access to other processes that could form the basis for improvements. Also, managers lacked a transparent method for understanding process productivity rates and therefore, could not develop a monetary justification for encouraging process innovation. AEC organizations struggle to understand their processes *across the firm or industry* to strategically invest in increased process productivity.

4 Lack of Effective and Efficient Design Process Communication

Within design process management, the design rationale (Moran and Carroll 1996a) and design process improvement (Clarkson and Eckert 2005) research field have already developed effective design process communication methodologies to overcome the challenges faced by the university building design team. Yet, these research methodologies have not been adopted by industry (Conklin and Yakemovic 1991; Moran and Carroll 1996b). This lack of adoption is not due to the lack of tools capable of effectively communicating design processes. Rather, the lack of adoption stems from the lack of incentive for designers to communicate processes at the instant they are designing. Thus, it is not sufficient to merely have the methodology and tools to *effectively* communicate 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 project information management research field as PIM focuses on improving the efficiency of information exchange (Froese and Han 2009). The authors' intuition is that communicating information exchange would have been sufficient for addressing the university building design team's challenges. However, PIM does not address the need to communicate information exchanges for collaboration, leveraging information systems to benefit sharing across projects (Malone et al. 1999), and understanding of processes by the firm and industry (Ballard and Koskela 1998; Hartmann et al. 2009). PIM lacks methodologies for *effectively* (i.e., able and/or accurate) communicating processes, whereas DPM literature describes methodologies for communicating processes, but lacks a sufficiently *efficient* (i.e., quick and/or with little effort).methodology for industry to adopt these methodologies.

5 Synthesizing Existing Concepts to Develop DPCM

To address the lack of effective and efficient methodologies for communicating design processes in the PIM and DPM fields, the authors synthesized concepts from organizational science, human computer interaction and process modeling research fields to develop characteristics for the Design Process Communication Methodology. 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 92 papers in these three research fields by utilizing a snowball approach. After explaining the origins of the characteristics using a subset of the most influential papers, Section 5.4 evaluates some examples of PIM and DPM research efforts with respect to the characteristics.

5.1 Organization Science to Enable Adoption

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

5.1.1 AEC 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 AEC, the International Alliance for Interoperability developed the Industry Foundation Class (IFC) to standardize data schema for describing buildings. The Georgia Tech Process for Product Modeling (GT-PPM) and Integrated Delivery Manuals (IDM) also depend on a standard design process (Lee et al. 2007; Wix 2007). 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 project team described in Section 3.1 from collaborating to make a mechanical system decision, because they were not aware of each others’ processes. This concept explains why process standards have been relatively unsuccessful in practice and why convergence to a single product model has not emerged in AEC.

5.1.2 Form new institutions around processes

Institutionalism research explains relationships between firms and information. In Coase's (1937) model for the firm, 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, and so, Benkler (2002) proposes the alternative peer production model. Benkler claims that this emerging 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 breaks 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," so 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 explain that many menial tasks take much effort to complete. They argue 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" is difficult, because the same collection of tasks (i.e., a process) rarely occurs more than once with the same actors. Berger and Luckmann argue 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., the daylighting consultants in Section 3.3 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***, so 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 Section 3.2 habitual within the organization. To reach this point, however, the community must first find a way to socialize and share this process.

5.1.3 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 and the traditional AEC matrix organization. The matrix organizations in large AEC design firms generally form by project, by geography and/or by discipline, but the firm stores information hierarchically in folder directories. Just as Davis and Lawrence (1977) claim 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 and so, it no longer belongs to just one project, but is utilized on multiple projects. In addition, with increased computer power and demand to view tradeoffs, 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.

5.1.4 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) describes a "project memory system" to define this knowledge and make it available to others. The project memory system is necessary, because organizations lack ability "to represent critical aspects of what they know." Whereas Conklin generally applies 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. Preserving organizational knowledge requires more than just "capturing lots of information." The knowledge must be made ***sharable*** by capturing and structuring the knowledge in ways "that create and preserve coherence and 'searchability'" (Conklin 1996).

Once Conklin's stepping stone from project to organization enables knowledge acquisition, the knowledge must be structured. Hansen et al. (2005) describe 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 so they can share tacit knowledge. Information Technology can provide the general context of knowledge and then, point to individuals or communities that can provide more in depth knowledge. Knowledge management is not just acquisition and structuring (Kreiner 2002). Javernick-Will and Levitt (2008) address the additional importance of the future ability of others to retrieve the collected knowledge.

The lack of design process knowledge sharing inhibited the successful material environmental impact analysis process in Section 3.2 from being utilized by other project teams outside Australia. This sharing also exists in Benkler's peer production model. Yet, Benkler's model requires minimal if any management. Combining the peer production model with knowledge management research provides guidance for developing an environment for a self-perpetuating acquiring, structuring, and retrieval of design process knowledge that is completely ***embedded*** in the design process and requires minimal management.

5.2 Human Computer Interaction to Create and Access Processes

HCI specifies how to facilitate the designer's interaction with the digital representation of the process. Cognitive Science research develops models for *predicting* how humans will behave, but these models will not predict perfectly (Winograd and Flores 1987) and so, it is also important to research and *describe* how humans interact with computers (Winograd 2006). In the former, researchers use cognitive models for Artificial Intelligence (AI) whereas the latter, HCI, focuses on designing computer systems *for* humans; *not to model* humans. However, in the Human-Information Interaction (HII) and Information Visualization (two branches of HCI) fields, the distinction between AI and HCI blurs. For example, HII applies Information Foraging Theory, which itself draws on Cognitive Science research (Pirolli 2007). Programmers best develop systems *for* a user to search and comprehend information through descriptive research on how to *model* human searching and comprehending; HCI benefits from AI research. At the same time, the programmer can only *model* human searching and comprehending behavior through iteratively testing how humans search and comprehend; AI also benefits from HCI research.

This section takes this mutually beneficial perspective on HCI and AI. First, Cognitive Science research calls for ***personalized*** process views. Next, the section discusses practical implications of Cognitive Science with respect to HII and Information Visualization. These branches of HCI provide insight to make the communication environment ***sharable***, ***scalable***, ***social*** and ***transparent***.

5.2.1 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). Can a technical environment enhance a designer's abilities to collaborate, share, and understand? "Solving a problem simply means representing it so as to make the solution transparent" (Simon 1981). To illustrate, Norman (1993) presents the ticktacktoe game. As a mathematical word problem, finding a solution is difficult, but represented graphically in the game ticktacktoe, the solution is obvious. Similarly, the best representation of airline schedule depends on the user's objective; a communication environment should represent information according to the user's task (Norman 1993). In terms of processes, the graphical representation of information dependencies should be ***personalized*** to the user's skills. For example, more analytical-minded decision makers (as measured by the Witkin GEFT) made better decisions when presented with a graph representation of information dependency as opposed to an "Interaction Matrix" (nearly identical to the Design Structure Matrix used in AEC (Steward 1981)). The decision-making performance of heuristic type individuals was less sensitive to the graphical presentation of the information dependencies (Pracht 1986). More personalized views of the mechanical system design process in Section 3.1 would have permitted process transparency and a more collaborative design decision.

5.2.2 HCI advocates information interaction and visualization

This section seeks to find “how information environments can best be shaped for people” (Pirolli 2007). Providing methods for achieving this goal, Information Visualization is the “use of computer-supported, interactive, visual representations” of abstract, non-physical data to amplify cognition (Card et al. 1999). For example, the human eye processes information in two ways. Controlled processing, like 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 images, process views at appropriate ***scales***, 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 the designer to find useful ***shared*** processes, search results should show the actual information dependency graphs. Also, the environment should track the most useful processes and prioritize these processes in search results.

Heer et al. (2007) shows 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***.

5.3 Process Modeling to Represent Process

Process modeling research creates a formal grammar for communicating processes to collaborate, share, and understand. Austin et al. (1999) provide an overview of process modeling techniques used to communicate the building design process. AEC researchers delineate process modeling research by different views of the process or by the objectives of the modeling. For example, Ballard and Koskela (1998) view engineering processes through conversion, flow, and value generation and hypothesize that transparency of these views will result in design success from the perspective of that view. AEC researchers develop generalized process models with the intent of supporting new working methods, identifying gaps in product information models, and informing new information models (Wix 2007). Process models may also aim to facilitate collaboration, share better practice, or communicate decisions. Though process modeling research frequently overlaps multiple objectives, the next sections are organized according to research aimed at improving coordination and planning, and automation. This literature claims models should be ***embedded***, ***scalable, shared***, ***transparent***, ***social***, and ***computable***.

5.3.1 Process models aimed at improving coordination and planning

Narratives attempt to overcome the challenges of multi-disciplinary, iterative, and unique design processes (Haymaker 2006). To facilitate coordination, Narratives create task-specific views of information flow (consistent with the views suggested by Norman in Section 5.2.1). Haymaker et al. also express the need to facilitate coordination by representing the status of information. While the Narratives research calls for ***embedding*** of process modeling into the design process, and identifies and facilitates the need to make the source, status, and nature of the information dependencies **transparent**, these concepts are not validated.

As opposed to Narrative's graph view which communicates a planned or historically implemented process, the Design Structure Matrix (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) extends DSM by utilizing Data Flow Diagrams (Fisher 1990) and 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 sub-systems.

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). Thus, the process, not just product models, should be ***shared*** with the entire project team, and the information on which decisions are dependent should be ***transparent***.

5.3.2 Process models aimed at improving automation

Comprehending how project teams coordinate aids development of automated information flow, so 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.

IDMs aim 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 (Wix 2007). IDMs recognize that information must be tracked at varying ***scales*** of detail. To help identify best practice processes, the environment must also promote ***sharing*** by using metrics so designers can evaluate processes. IDMs contrast with Narrator's focus on designer communication, but are similar to Geometric Narrator, which emphasizes the use of process models to perform ***modular computations*** on information (Haymaker et al. 2004).

5.4 Gaps in PIM and DPM Research Relative to Characteristics

This section identifies gaps in PIM and DPM Research with respect to the characteristics described above.

5.4.1 Improving communication between AEC professionals

Several methods have advanced the design of process models for use by AEC professionals in practice. Narrator and Geometric Narrator form two fundamental points of departure. Geometric Narrator enables a designer to build a ***modular***, ***computable*** process but lacks a general infrastructure to easily ***share*** these processes (Haymaker et al. 2004). Narrator plans processes and visually describes processes retroactively (Haymaker 2006). Narratives incorporate Ballard's information flow view via information dependency arrows and the conversion view by showing the tool used to transform the information. Narrator addresses some of the ***sharing*** deficiencies (via a searchable database) of Geometric Narrator, but at the expense of its ***computable*** power and ***embedment*** in the design process. Neither Narrator nor Geometric Narrator can be ***shared*** widely on the Internet nor ***personalized*** to create views to individual users.

More powerful at process planning, DSM similarly plans the design process through task dependencies, but also more explicitly identifies iteration and includes methods for scheduling activities to minimize rework (Eppinger 1991; Steward 1981). Though these task sequence optimization methods are computable algorithms, it is not within DSM's scope to automate information flow, nor act as an information communication tool that links to particular information. Austin et al. (1999) demonstrated the ability to model 10,015 data flows on a hospital project, which required 40 hours to capture, though 91% of the data flows came from a generic process. While this Analytical Design Planning Technique focused on process ***modules*** that could be ***shared*** and reused across projects, most DSM research instead focuses on optimizing the ordering of design tasks without much concern for the effort and difficulty required to map out task dependencies. "While people have a tacit understanding of when a process plan is no longer relevant, it is difficult to describe the relationship between the process plan and the process that actually occurs… Process models are typically generated to plan, i.e., before the project, and hardly any company goes to the trouble of comparing the model with the process that actually exists. Process post mortems are rarely done, because everybody is busy moving onto the next project…" and there are rarely lessons learned about the process itself (Clarkson and Eckert 2005).

DePlan (Choo et al. 2004) attempts to tie ideal schedules derived from ADePT with the realistically possible execution of those plans based on constraints and resource limitations as described by LastPlanner (Ballard 1999). DePlan makes the plan dynamic, but there is still much additional overhead, and it is not integrated with information management systems, so it is likely relied upon only weekly - not ***embedded*** in design.

Critical Path Method (Kelley and Morgan 1959), Lean Production (Howell 1999; Koskela 1992; Krafcik 1988), Last Planner (Ballard 1999), and Virtual Design Team (Jin and Levitt 1996) are all fundamentally process planning techniques - not ***embedded*** in design.

While they offer insights to DPCM as process planning and control methodologies, they do not include concepts for communicating digital information and are not discussed here in more detail.

The Information Value Based Mining for Sequential Patterns (VMSP) is intended for ***embedment*** in the design process to capture design process knowledge (Ishino and Jin 2006). Ishino and Jin wrote a customized tool that captures changes in a CAD tool, and attempts to derive design rationale from those changes. VMSP requires intense customization of software tools and is not ***scalable*** to the hundreds of tools used in professional practice (a problem typical of many of the tools proposed by Moran and Carroll (1996a)). While also intended to be embedded in design and addressing ***shared*** processes, ActivePROCESS may also suffer from ***scaling*** issues when applied to problems more complex than the simple block design scenario because of the detail with which engineers would need to document all their design moves (Jin et al. 1999).

Decision Dashboard (DD) improves design rationale ***transparency*** by communicating options, alternatives, and criteria (Kam and Fischer 2004). DD contains some abilities to ***compute*** values associated with the process nodes from information contained in related nodes but does not intend to automate information flows. DD does not easily support multi-user ***sharing***. DD models design rationale, an important aspect of the design process to communicate. However, DD does not address research findings that demonstrate that design rationale systems are rarely implemented in practice, because designers struggle to document their rationale when performing design (Conklin and Yakemovic 1991; Ishino and Jin 2002; Moran and Carroll 1996b). Finally, DD focuses on one decision at a time and does not address how to organize the thousands of decisions made on a typical project; it is not ***scalable***.

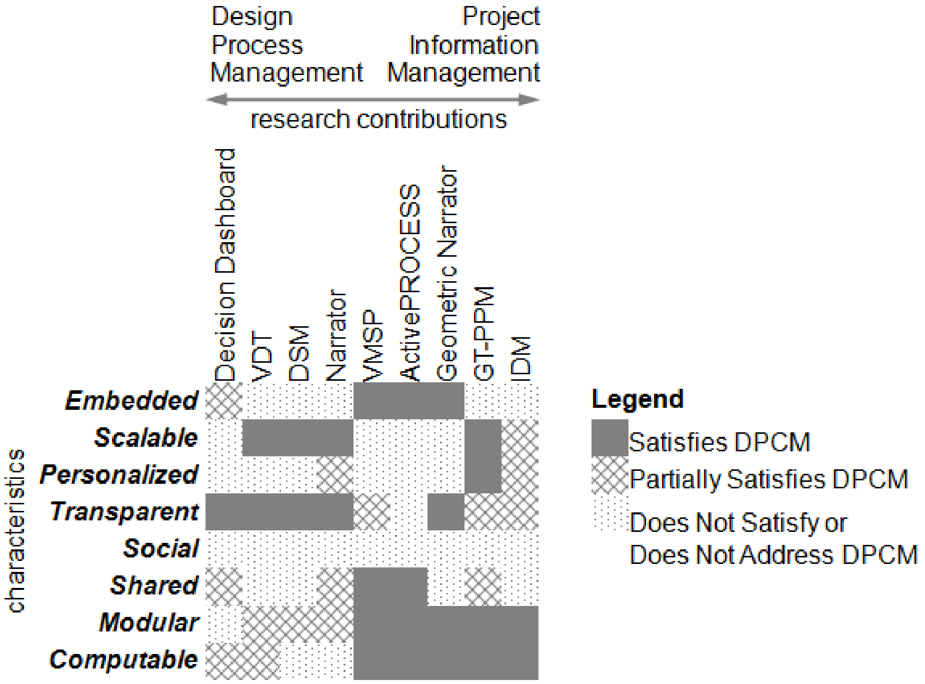


Figure 3-1. Comparison of existing research in PIM and DPM with the DPCM characteristics. The matrix is not intended to cover all research in these two fields, but to show a few indicative examples of current gaps in the research. While individual research may address some of these characteristics, the authors have not found a theory that addresses all of them.

As opposed to efforts such as GT-PPM (Lee et al. 2007) aimed at modeling processes to develop a product model standard, DPCM calls for a ***computable*** web of individual interoperability solutions. Many of the current process modeling approaches to improving interoperability are formulated at an abstract level to define general data exchanges and processes, and have limited value as a project-specific design guidance and management tool. That is, software developers, not designers, use these process models, and they are therefore not intended to be ***transparent***, and ***sharable*** from the perspective of the typical designer.

Generally, PIM research efforts focus on modular and computable methods (Figure 3-1) that enable more efficient exchange of information. The methods are either themselves intended to be embedded in the design process or are intended to facilitate the development of software embedded in the design process. DPM research focuses on process transparency for planning before design or story-telling afterwards and is more convincingly scalable to real projects. DPCM aims to satisfy all the characteristic gaps in the existing DPM and PIM research.

6 Theory - Design Process Communication Methodology

Gaps exist between the characteristics exhibited by the methodologies described in PIM and DPM literature and those characteristics recommended by organizational science, human computer interaction, and process modeling research. Modeling research recommend for a communication environment and what the existing PIM and DPM literature has contributed. These points of departure provide important characteristics for the development of a process communication environment. This section describes elements of DPCM that represent and contextualize the processes and methods that describe how designers capture and use these processes by interacting with a computer. The main contribution of this paper, the DPCM, is the combination of the elements and methods that enable the Characteristics.

6.1 Elements and Methods Enabling Characteristics

Embedded

Users use the environment simultaneously to organize and exchange information as well as communicate processes.

They *Save* or *Open* *Information*, and can *Open old 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 <u>*Frame*</u>. A <u>*Frame*</u> is a type of <u>*Node*</u> that itself contains views onto a collection of other *Contained Nodes*. Unlike the nodes which exist in a single non-hierarchical network, the frames are organized hierarchically. Thus, the user can choose to *Open* each frame via a *Hierarchy* or *Network* type of <u>*Window*</u>. This hierarchical organization enables the representation of processes at multiple levels of detail and ensures that 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 the *URL*. As every project uses digital files or URL's to describe some aspect of the building, the environment can be utilized across the industry.

Personalized

The environment personalizes communication to each user.

As the <u>*Frame*</u> is simply a view onto nodes, a single <u>*Node*</u> can exist within multiple frames. Thus, 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 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 most recently uploaded file and the oldest file, indicating the latency since 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 processes.

Users can *Search* *<u>Dependency</u>* paths and individual *<u>Nodes</u>*. Also, users can easily share their views of processes with others, because each *<u>Frame</u>* 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 thus, mix and match *<u>Process</u>* modules containing all of the above elements and *Duplicate* the *<u>Process</u>* modules and customize them to specific projects.

Computable

The environment enables users to attach *Scripts* to a *<u>Dependency</u>* that would automate information flow from the Start *<u>Node</u>* to the End *<u>Node</u>*. Defining each dependency as a computable relationship between two pieces of information enables the gradual development of improved interoperability between tools.

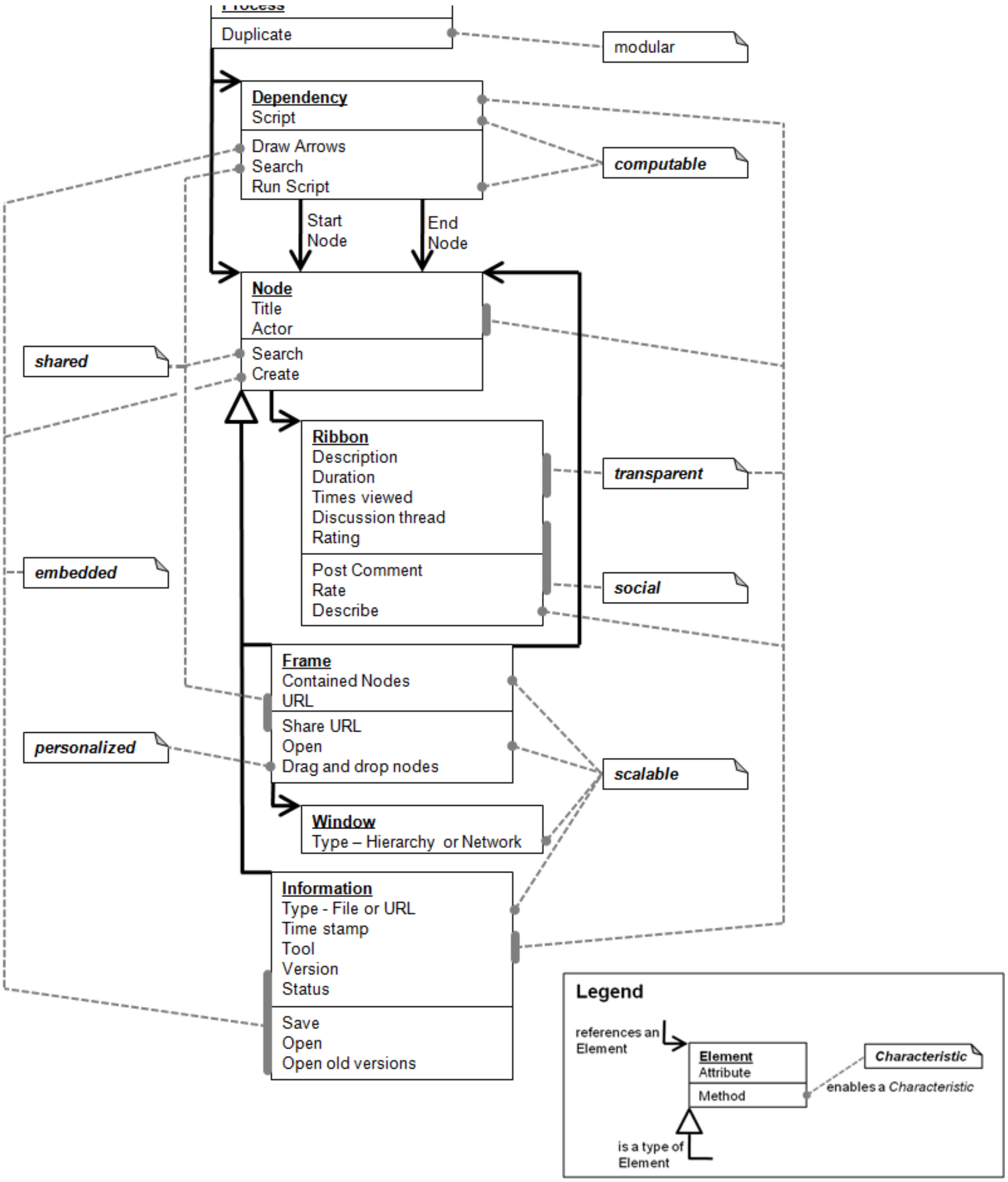


Figure 3-2. The Design Process Communication Methodology. Elements represent and contextualize a process and methods enable designers to capture and use the process model. These elements and methods enable the Characteristics.

7 DPCM Applied to Observed Problems

This section demonstrates how by operationalizing DPCM as the process-based file sharing tool, the Process Integration Platform, DPCM addresses the three types of communication challenges described in Section 3.

7.1 Collaboration with PIP

If PIP had been available to the mechanical engineering team on the university building project, they could have used PIP to *collaborate* around their digital files. After logging in, the user sees two personalized home page *Windows*: a *hierarchy* view on the left of the screen and a *network* view on the right (Figure 3-3). 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 frames enables the process to be ***scaled*** to many files. He *drags and drops* the *Information* Nodes containing the Architecture Model file and the Daylighting Analysis file into his Energy Analysis frame. The Frames are thus ***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 his desktop. The ability to *Open* and *Save* files directly in PIP *Information* *Nodes* enables process capturing to be ***embedded*** in the design process. He imports the Revit model into his energy analysis tool. Looking at the daylighting analysis results, he manually enters the energy required for artificial lighting into the energy analysis tool. After completing the energy analysis, he double clicks in the graph view to *Create* an *Information* *Node* and *Saves* the energy analysis file to that node. As he used the architecture model and daylighting analysis as input to the energy analysis, he also *Draws Arrows* from those two nodes to the new energy analysis node to represent this *Dependency* and make the *Process* ***transparent***. Now that the energy analysis is complete, he uses the results to create a decision matrix in Microsoft Excel. He uploads the Excel file to a new node and draws an arrow 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), because it was created based on an out-dated energy analysis file. If based on this new energy analysis, the mechanical engineers decide on a displacement ventilation system and create an AutoCAD file dependent on the new energy analysis, the rest of the project teams now know to integrate their designs with the AutoCAD file and not the out-dated decision matrix. Using PIP makes the mechanical design process transparent to the entire project team, so they can comprehend information relationships, consider tradeoffs, and make related information consistent.

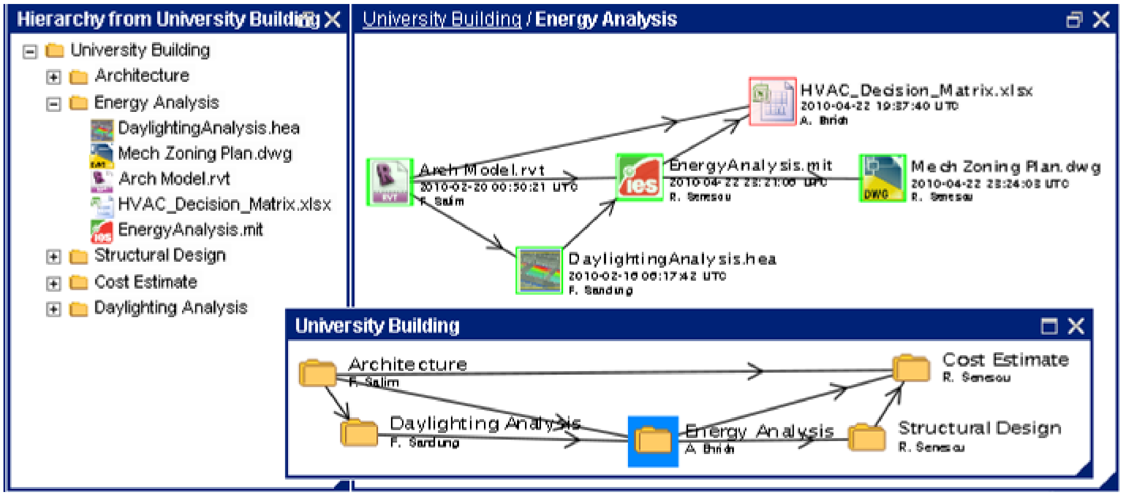
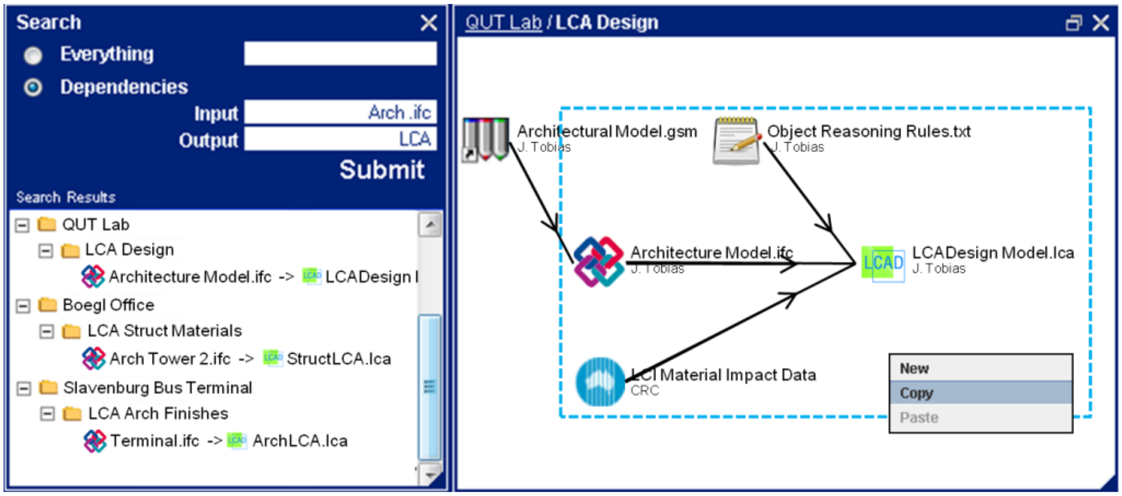


Figure 3-3. Collaboration in the Process Integration Platform. Users navigate to the appropriate process level via the hierarchy view (left) or by double clicking folder icons (right). Users create nodes, upload files to those nodes, and draw arrows to show relationships between the nodes. Green highlights indicate the node is up-to-date, and red indicates an upstream file has changed since the node was uploaded.

7.2 Sharing Processes with 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. Since PIP is web-based, ***sharing*** is enabled by the structural engineer *searching* for a *<u>Process</u>* where a project team started with input "Arch .ifc" to denote an architecture model with an Industry Foundation Class file format and produced "LCA," life cycle assessment (Figure 3-4). The results display three projects and the engineer browses to find the most relevant process. The engineer can *Duplicate* the relevant *<u>Process</u>* ***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.

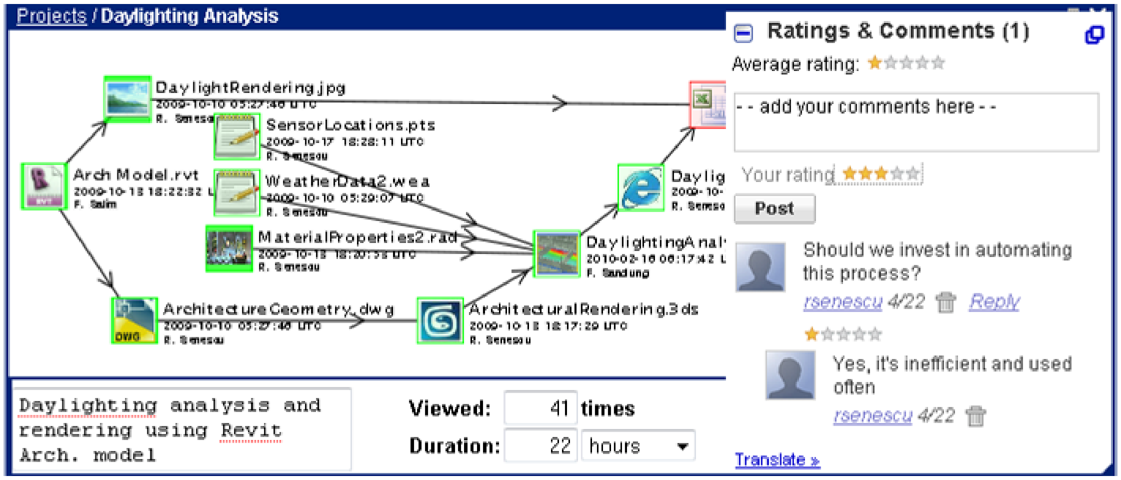


○ Everything
● Dependencies
Input: Arch.ifc
Output: LCA

Figure 3-4. Sharing processes in the Process Integration Platform. Users search information dependency paths to find processes with the input available and the output desired. Users can then copy processes to new projects.

7.3 Understanding Processes with PIP

With PIP, professionals can *understand* the processes across the firm or industry, so they can identify popular inefficient processes and strategically invest in improvement. Each <u>*Node*</u> has a <u>*Ribbon*</u> containing information that describes the process within the frame or the information contained within the node. PIP offers a process-centric discussion forum for users to *Post Comments* and *Rate* process productivity (Figure 3-5). 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, 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 PIP and drive ***computable*** information flows automatically.



- - add your comments here - -

Should we invest in automating this process?
rsenescu 4/22

Yes, it's inefficient and used often
rsenescu 4/22

Daylighting analysis and rendering using Revit Arch. model

Viewed: 41 times

Duration: 22 hours

Figure 3-5. Understanding processes in the Process Integration Platform. PIP tracks some process metrics automatically, so users can evaluate the most popular and time-consuming processes. Discussion threads are associated with each node, so project teams can discuss individual files or entire processes.

8 Validation Metrics

8.1 Motivation for the Metrics

Validating DPCM requires measuring the efficiency and effectiveness for each type of communication. Process communication requires (1) Capturing, (2) Structuring, (3) Retrieving, and (4) Using processes. Benkler (2002) describes these steps as part of the information-production chain needed for collaboration in the peer-production model (Section 5.1.2). Knowledge management research describes these steps as needed for sharing of processes across projects (Section 5.1.4) (Carrillo and Chinowsky 2006; Javernick-Will and Levitt 2010; Kreiner 2002). Finally, innovation literature cites these steps as required for companies to understand 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. Yet 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 strategic understanding of processes across the firm or industry. Thus, Section 8.2 measures capturing and structuring of processes and Section 8.3 measures 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, because capturing and using provides sufficient granularity for assessment.

8.2 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:

(1.1.1) Percentage of true dependencies captured by the process model.

A communication method that captures a high number of dependencies in a controlled environment should also capture a relatively high number of the dependencies on an industry project.

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 method for communicating process will not decrease the amount of time spent on production work nor increase the amount of 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:

(1.1.2) Frequency of value-adding information transfer between designers;
(1.1.3) Number of 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 process resulting in the capture of zero information dependencies. The authors hypothesize that applying DPCM would capture a much larger percentage of dependencies without the burden caused by previous methods which required hours of effort invested early in the project (Austin et al. 1999).

8.3 Effectiveness and Efficiency of Using Processes

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

8.3.1 Using processes for Collaboration within projects

The ability of a team to collaborate effectively around a process can be measured by the:

(2.1.1) Number of local iterations;
(2.1.2) Number of statements about design trends.

These two metrics both indicate multi-disciplinary collaboration effectiveness. Without collaboration, teams will optimize locally within their discipline silos. Successful design solutions require global consideration of multi-disciplinary tradeoffs and the resulting iteration that enables the best solutions to be found (Akin 2001; Ïpek et al. 2006).

Inefficient project teams perform negative rework without ever completing an internally consistent and complete design (Ballard 2000). The lack of up-front collaboration means most problems are resolved during construction when the cost of resolution is highest. Thus, the efficiency of collaboration around a process can be measured by:

(2.1.3) Number of complete and accurate design options produced.

Throughout the design process, 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:

(2.1.4) Internal consistency of design assumptions.

For example, in the mechanical engineering problem, the structural engineer may have assumed no underfloor air distribution in his structural design based on the HVAC Decision Matrix file, while the electrical engineer may have assumed he could place all his wires 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 (See Section 3.1), so collaboration effectiveness can also be assessed by the:

2.1.5 Number of expressions of confusion.

Together these metrics allow researchers to assess the relative ability of different communication methodologies to impact the efficiency and effectiveness of collaboration within projects.

8.3.2 Using processes for Sharing between projects

Effective use of other projects' processes requires retrieving productive processes. Researchers need a scoring system to evaluate processes. The actual scoring system used may vary depending on the goals of the project. Clevenger and Haymaker (2011) provide one method for evaluating design processes, though the actual scoring method used can vary as long as the same method is used to evaluate the comparison of the process communication methodologies employed. The ability of a methodology to enable the effective sharing of processes between project teams is indicated by the:

(2.2.1) Score of projects selected to imitate.

For example, many processes for leveraging building information models to perform life cycle assessments of structural systems may exist. An effective communication methodology will enable project teams to effectively retrieve and use the best processes. However, 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:

(2.2.2) Number of errors made 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 Figure 3-4, but if the structural engineer forgets a critical part of the process, then the methodology does not enable efficient sharing of processes.

8.3.3 Using processes for Understanding across the firm or industry

AEC companies consider IT investments to be costly and risky, yet 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 above communication types, the authors evaluate effective understanding qualitatively by investigating the ability of a communication methodology to answer the following questions:

1. What are the most important types of information on projects?
2. Who are the most critical individuals on 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?

Of course, some insights require case studies or ethnographic research, and other insights can be derived more efficiently through IT-based communication methods embedded in projects. The authors measure understanding efficiency as the time required to achieve the insights. The time is trivial for DPCM as data visualization tools provide nearly instantaneous access to the process information.

Table 3-1. Metrics to assess process communication.

Process Communication Steps		**Effectiveness**		**Efficiency**	
Capturing		(1.1)	Percentage of dependencies captured	(1.2)	Frequency of value-adding information transfer between designers
				(1.3)	Number of local iterations
Using	**within projects**	(2.1.1)	Number of local iterations	(2.1.3)	Number of complete and accurate design options
		(2.1.2)	Number of statements about design trends	(2.1.4)	Internal consistency
				(2.1.5)	Number of expressions of confusion
	between projects	(2.2.1)	Score of projects selected to imitate	(2.2.2)	Number of errors made implementing a shared process
	across firm or industry	Time required to gain insight		Insights provided by process information	

9 Conclusion

The DPCM contributes to PIM and DPM research fields by laying the foundation for the development of commercial software that communicates design processes to increase the value generated per man-hour expended by the AEC industry. The paper makes a case for 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 DPCM by synthesizing concepts from organizational science, human computer interaction, and process modeling research to conclude that a communication environment should be ***Computable, Embedded, Modular, Personalized, Scalable, Shared, Social***, and ***Transparent***. However, current research efforts do not exhibit these characteristics and thus, industry lacks a method for effectively and efficiently communicating process. In particular, prior research focuses insufficiently on *embedding* process communication in minute-to-minute work, fostering a *social* community around processes, *personalizing* process views, and *sharing* processes. Elements that represent and contextualize process and methods for capture and using of process enable these eight characteristics.

The paper validates the legitimacy of the DPCM theory by proposing metrics for comparing it with other communication methods. Also, PIP shows that developers can implement the theory, and that such an implementation addresses the three types of communication struggles observed in practice. Providing additional evidence of the testability of DPCM, over 200 students used PIP in class projects, design charrettes, and on graduate student research projects (
Figure **3-6**). This adoption of the tool demonstrates both the perceived usefulness of DPCM and the ability of future research to measure the impact of DPCM on communication effectiveness and efficiency. This future research will provide further evidence that DPCM can lay the foundation for commercial software that shifts focus away from incremental and

fragmented process improvement toward a platform that nurtures emergence of (1) improved multi-disciplinary collaboration, (2) process knowledge sharing, and (3) innovation-enabling understanding of existing processes.

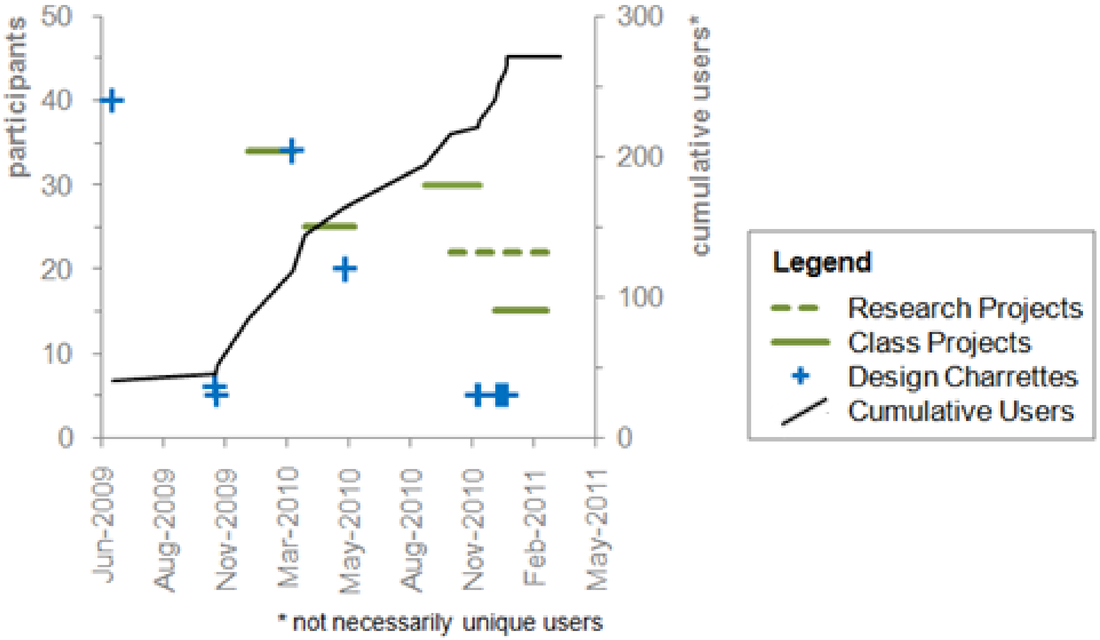


Figure 3-6. Use of the Process Integration Platform (PIP) by students at Stanford University. PIP is a process-based file sharing web tool that acts as a model for DPCM. Its use demonstrates that DPCM can be practically applied and tested.

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