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Communicating Design Processes Effectively and Efficiently

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Communicating Design Processes Effectively and Efficiently[1]

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Abstract

Industry struggles to efficiently implement design process management methodologies aimed at improving communication of design processes. Meanwhile, project information management methodologies enable efficient communication of product information but do not communicate design process information. The lack of methods for effective and efficient design process communication manifests as a struggle to effectively and efficiently: (1) **collaborate** *within projects*, (2) **share** processes *between projects*, and (3) **understand** processes *across projects* to strategically invest in improvement. These struggles motivate the paper's first contribution: a set of metrics and accompanying test method for evaluating a design process management methodology's ability to effectively and efficiently communicate design processes. As a second contribution, this paper applies the metrics and the test method to validate the Design Process Communication Methodology (DPCM). DPCM specifies elements and methods for exchanging and organizing digital information in the context of the design

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process. Results demonstrate that designers employing DPCM accurately capture processes with little effort. When **collaborating**, process clarity and information consistency result in little rework, and positive iteration enables consideration of multi-disciplinary design trends. Designers **share** processes between project teams without committing process mistakes. DPCM enables the **understanding** of processes providing insights into the relationships between design integration and project performance; and opportunities for strategic investment in improved processes.

1 Introduction: The need for process communication methodologies

Design processes are often under-productive (Scofield 2002; Gallaher *et al.* 2004; Flager and Haymaker 2007; Young *et al.* 2007; Navarro 2009). The design process management research field addresses this lack of productivity through the design rationale (Moran and Carroll 1996) and design process improvement research (Clarkson and Eckert 2005). Researchers in these fields attempt to improve design processes by first validating descriptive and predictive process modelling methods using industry observation and case studies (Cross and Roozenburg 1992), which then lay the foundation for normative research proposing new methods aimed at directly improving industry design processes. These new methods frequently depend on process communication to improve design processes (Ford and Ford 1995).

While the design process management research field already developed methodologies for effectively communicating design processes, industry has not widely adopted these methodologies (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. It is not sufficient to have the methodology and tools to effectively communicate process. The act of process communication must also require little effort; it must be efficient.

Design processes consist of organizations exchanging information that lead to digital models of a product (Garcia *et al.* 2004). Communication is the “process of exchange of information between sender and receiver to equalize information on both sides” (Otter and Prins 2002). Combining the two definitions, designers communicate processes by exchanging information that describes how professionals exchange information. As digital files are the primary deliverable of design professionals, the authors intuit that maps of the dependencies between these files would be indicative of design processes and thus, lead to effective process communication. The intuition that visualizing digital information dependencies leads to process communication prompted the authors to investigate the project information management field, which aims to facilitate the efficient exchange of information.

While the design process management field effectively but not efficiently communicates design processes, the project information management field develops methods for efficient exchange of information, but not effective process communication. This gap between the two fields motivated both the practical and theoretical development of the Design Process Communication Methodology (DPCM) (Senescu *et al.* 2011b). 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. As a result of these elements and methods, DPCM can be characterized as computable, embedded, modular, personalized, scalable, shared, social, and transparent. Senescu et al. (2011b) described the operationalization of DPCM through the Process Integration Platform (PIP) web application (Figure 1). PIP is a combination between a file sharing tool and a process modelling tool that enables project teams to exchange and organize information as nodes in a process map in addition to a folder directory. It enables visualization of the dependencies between information as designers work and thus, provides the opportunity for both effective and efficient process communication. Senescu et al. provided both theoretical and practical justification for DPCM as a contribution to the design process management and project information management research fields, but stopped short of validating DPCM's impact via PIP.

In response to this shortfall, this paper first contributes a test method for validating the ability of methodologies like DPCM to effectively and efficiently

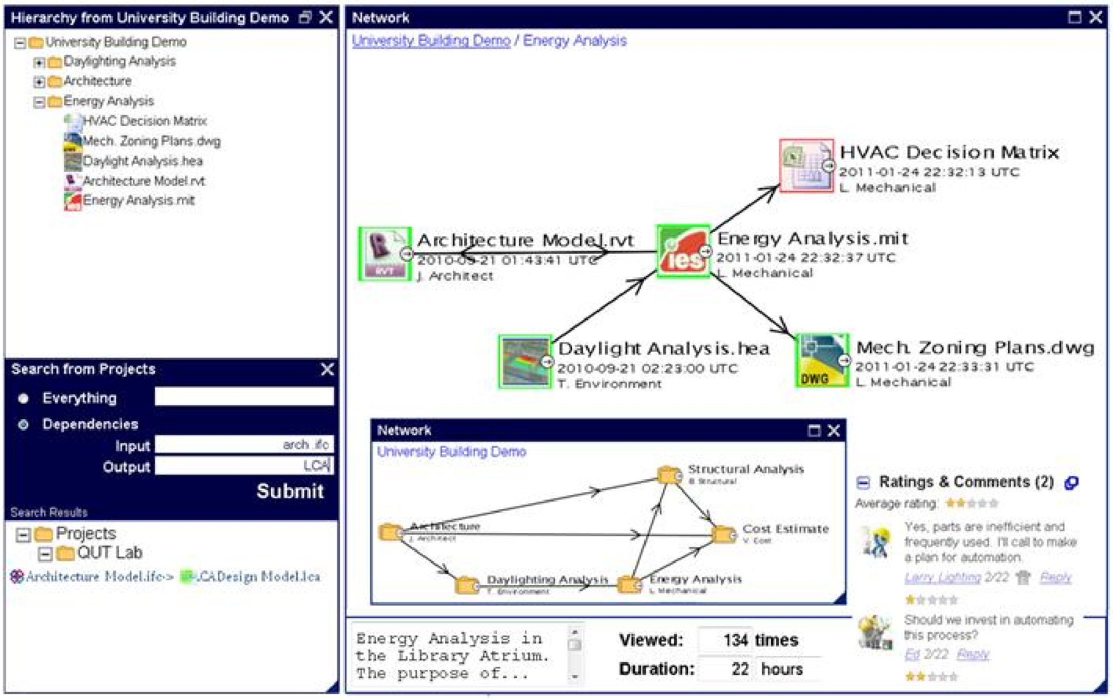

Figure 1. The Process Integration Platform. PIP is a web tool enabling project teams to organize and share files as nodes in an information dependency map that emerges as they work. Users navigate to the appropriate process level via the hierarchy view or by double clicking folder icons in a network view. Users create nodes, upload files to those nodes, and draw arrows to show dependencies 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. Users can also search dependency paths to find relevant historic processes from other projects. Each node contains an information ribbon providing

additional process information and the opportunity to rate process productivity or comment.
communicate process. Section 2 explains existing test methods and metrics, and proposes the Mock-Simulation Design Charrette (MSDC) and Ethnographic-Action methods as appropriate validation methods. Section 3 summarizes DPCM and its operationalization through the development of PIP. Section 4 uses the test methods and PIP to validate that DPCM effectively and efficiently communicates processes – the second contribution of this paper. The paper concludes with an explanation of how the test method and DPCM contribute to the design process management and project information management fields.

2 Metrics and Test Methods for Design Process Improvement Research

This section first describes three types of process communication necessary for process improvement. Based on the four steps required for each type of process communication, the section then proposes metrics for evaluating effectiveness and efficiency. Building on previous design process improvement work, the section then synthesizes two research methods appropriate for evaluation of design process communication methods: the Mock-Simulation Design Charrette (MSDC) method and the Ethnographic-Action method. After describing the test setup for each method, the section closes by explaining how the authors instrumented the tests to apply the metrics.

2.1 Four steps to enable three types of communication

Senescu et al. (2011a) argued that researchers can improve design processes through three types of process communication:

(1) The organization can **collaborate** more effectively and efficiently *within the project team*. In this case, the organization better executes processes 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 better software that they then implement on their project.

(3) A team may consciously develop an improved process. Developing improved design processes often requires strategic investment, which requires a claim that the return will be an improvement on the current state. Organizations must **understand** their current processes to invest in improvement *across projects*. For example, a team may understand that 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.

Each type of process communication challenge requires consideration of how designers: (1) capture, (2) structure, (3) retrieve, and (4) use processes. With respect to the first type of communication, Benkler (2002) describes these four steps as part of the information-production chain needed for **collaboration** when team members are not aligned by the goals and hierarchy set by a single firm. With respect to the second type of communication, knowledge management research describes these steps as needed for **sharing** of processes across projects (Kreiner 2002; Carrillo and Chinowsky 2006; Javernick-Will and Levitt 2010). Finally, with respect to the third type of communication, innovation literature cites these steps as required for companies to **understand** their processes to make strategic investments in process improvement (Hargadon and Sutton 2000). Thus, consensus exists on the necessary steps for all three types of process communication. This paper contributes a test method to evaluate methodologies with respect to the four steps necessary for the three types of communication. The paper subsequently contributes the validation of a unifying methodology, DPCM, which enables all three types of process communication.

2.2 Metrics for evaluating effective and efficient process communication

To evaluate design process improvement methodologies, Senescu et al. (2011b) proposed and justified metrics to evaluate the effectiveness and efficiency of the three types of communication: collaboration, sharing, and understanding. The authors proposed combining the four steps into simply *capturing* and *using* as these provide sufficient granularity for evaluation. This sub-section describes and justifies how the authors measured the effectiveness and efficiency of capturing and using processes.

For the first step, an effective and efficient methodology captures the design process accurately with little effort.

Once captured, the process can be used for collaboration, sharing, and understanding. Effective use of the processes for collaboration should result in a higher number of local iterations and increased discussion of design trends. An efficient use of processes within the team results in higher number of complete and accurate design options produced, internal consistency of design assumptions, and few expressions of confusion by designers.

Effective process sharing requires that the current project team use the most productive processes from previous projects. Thus, to measure a methodology's ability to enable effective process sharing, existing processes must be scored. Once a team selects a historical process to mimic, they must be able to implement the shared process efficiently. The efficiency of process sharing can thus be evaluated by counting the number of errors made implementing the shared process.

An effective process communication methodology enables organizations to effectively use their understanding of current processes to strategically invest in the future. Unlike the above communication types, the authors evaluate effective understanding qualitatively by investigating the possibility of drawing insights from use of the methodology. For example, what are the most important types of information on a project? What information flows between tools are most common and most inefficient? What is the relationship between information distribution on the team and project performance? Understanding efficiency is measured by the time required to achieve insights on the answers to these types of questions.

The next two sub-sections describe the development and application of test methods to obtain the metrics discussed above.

2.3 Synthesizing the test methods

To apply the quantitative metrics to evaluate the capture of design process and the use of the processes for collaboration and sharing, the authors looked for test methods where different communication methodologies could be easily compared. The first test method applied by the authors was primarily inspired by the Charrette Test Method, which combines the architectural notion of charrette (a short, intense design exercise) with the software usability testing common in the human computer interaction research field. Clayton et al. (1998) developed the charrette method “to provide empirical evidence for effectiveness of a design process to complement evidence derived from theory.” The method permits:

- multiple trials which increases reliability;

- repeatable experimental protocol;
- objective measurements;
- comparison of two processes to provide evidence for an innovative process.

Researchers can widely apply this method to design computing research questions, but they must customize the method to their particular question. For example, Clevenger et al. (2011) created a customized charrette called the Design Exploration Assessment Methodology, which enabled designers to use Energy Explorer (a Microsoft Excel spreadsheet) to quickly generate and record design alternatives to provide quantitative measurements of different design strategies.

The authors similarly customized the charrette method with additional inspiration from research outside of the architecture, engineering, and construction industry. For example, Heiser and Tversky (2006) performed A-B experiments with students and concluded that showing students diagrams with arrows caused the students to describe equipment with functional verbs as opposed to nouns and adjectives describing the equipment structure. Also, students with text descriptions containing functional verbs were more likely to draw arrows. Heiser and Tversky did not make normative claims about whether, for example, teams should use more arrows when collaborating with each other, but, unlike Clayton's implementation of the Charrette Test Method, they described a cognitive phenomenon by recording user language.

Another inspiration was GISMO – a method that aims to improve decision making by graphically displaying information dependencies. Pracht (1986) demonstrated that business students made decisions leading to higher net income for their mock companies when presented dependencies in graphical form. Though not applied to a design problem, the validation method for GISMO presented quick, quantitative results demonstrating that a new computer-aided process resulted in students making more effective decisions to achieve a clearly defined goal.

Inspired by these validation methods, the authors developed the Mock Simulation Design Charrette method, which customizes Clayton's method while still leaving it sufficiently general such that other researchers could use the method to validate their research and compare their results with DPCM.

However, MSDC alone was insufficient for evaluating all three types of communication. Design charrettes require that the design challenges studied must often be simpler and of shorter duration than actual design projects. Researchers also therefore employ ethnographic-action research methods using professional or student class projects, because compared to the charrettes, student class projects (1) work on a time scale more on par with professional projects; (2) have more freedom to choose processes and tools like in professional projects; (3) work at a level of product detail similar to scheme design in professional projects; (4) tackle more of the "wicked" and complex problems with more ambiguous design goals faced by professionals (Rittel and Webber 1973; Bachman 2008; Hartmann *et al.* 2009). These attributes of student design projects translate to more intertwined production and coordination work. This intertwining makes it difficult to isolate and measure impacts on coordination work, which inhibits the ability to use the method for validation of collaboration and sharing. However, these drawbacks do not inhibit the ability to draw insights about design processes to validate the impact on, for example, process understanding.

Thus, in this paper, the authors selected the MSDC to validate collaboration and sharing and the Ethnographic-Action method in class projects to validate understanding. The authors utilized the Ethnographic-Action method, because of its success in validating the development and implementation of information systems. In particular, Beylier et al. (2009) demonstrated how a research method nearly identical to Ethnographic-Action successfully validated the KALIS methodology, which, similar to DPCM, embedded process-sharing capabilities into an information management tool. Like the KALIS research method, both the MSDC and Ethnographic-Action research can be categorized as part of a comprehensive study in the Design Research Methodology's "Descriptive Study II stage to investigate the impact of the support and its ability to realize the desired situation" (Blessing and Chakrabarti 2009). Adopting the Center for Integrated Facility Engineering Horseshoe research framework (Fischer 2006), MSDC and Ethnographic-Action are specific research methods used in the testing task to validate the DPCM.

2.4 Application of the test methods

2.4.1 Mock-Simulation Design Charrette setup

The authors chose students as opposed to professionals for the charrettes, because it was easier to recruit student volunteers and previous charrettes found no correlation between professional experience and performance in another charrette (Clevenger 2010). The author incentivized students to participate with a pizza party and a prize to the team that completed an accurate design of a classroom with the highest Net Present Value (NPV).

Participants signed up for different sessions during a three month period without knowing whether the sessions were going to be control or experiment cases - a between-subject experiment design. Each session consisted of one team of five participants. The first author randomly assigned each participant to a design role: architect, environmental consultant, mechanical engineer, structural engineer, and cost estimator. The first author presented a summary of the information in the remainder of this section to the participants in each session via a PowerPoint presentation and a tutorial.

The teams were chosen to design the next generation of green classrooms and their goal was to collaborate to maximize the NPV. The teams calculated NPV using a subset of the 20 Microsoft Excel mock-simulation tools available.

The teams had access to the project folder of six historic projects (Figure 2a). Prior to the charrette, the first author completed the six different designs in each project folder using six different subsets of the 20 tools. Thus, the teams could choose what tools to use for their new classroom project by looking at the tools from the historic project folder, or they could choose the tools from a project folder containing all 20 tools. The teams did not need to use all the tools, and certain tools were not interoperable with other tools.

For example, the structural engineer could choose to use GreenStructuralAnalysis.xls, StructuralAnalysis.xls, GravityAnalysis.xls, SeismicAnalysis.xls, FoundationDesign.xls, and/or SuperStructuralAnalysis.xls. Many of these tools were redundant. SuperStructuralAnalysis.xls conducted both a gravity and seismic analysis, so using the Gravity, Seismic and SuperStructural tools would have been inefficient. On the other hand, only GreenStrucutralAnalysis.xls outputted the environmental cost of structural materials, so if the cost estimator depended on this value for the GreenNetPresentValueCalc.xls, the two participants would have had to collaborate to ensure they use these two interoperable tools. The various tools received different inputs and created different outputs. Some also used different units, allowed simulation of different types of designs, and took a different amount of time to analyze. The variety of tools simulated the real choices of professional designers and the interoperability problems of complex software applications.

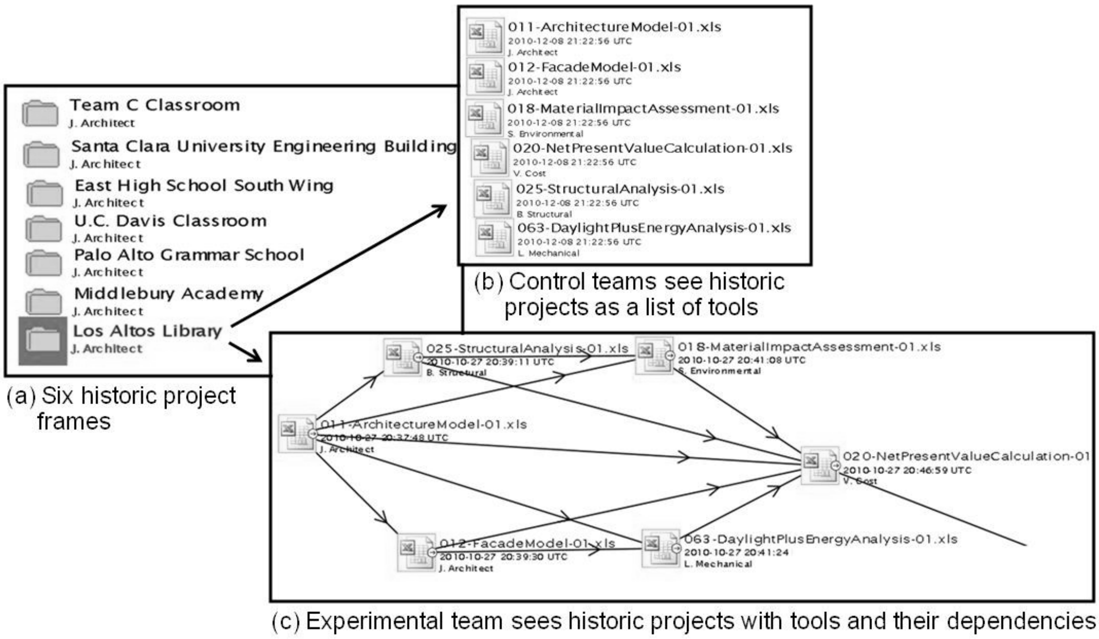

Figure 2. Mock-Simulation Design Charrette test setup. All teams opened up PIP to see the historic project folders (a). Control teams could open any of the six historic project folders to view the list of tools used to complete that project (b). Experimental teams saw the same list of tools used to complete the project and their dependencies (c). The teams worked in the "Team C Classroom" folder, which is initially blank, but then became populated with the tools used to design the classroom. The work of the control teams eventually resembled a list similar to (b) and the work of the experimental teams resembled the process in (c).

Each participant inputted independent variables into one or more of the mock-simulation tools. The mock-simulation tools then analyzed the input values to output performance values (Figure 3). The conversion of inputs to outputs did not correlate with first principle predictions of building performance but did follow general trends based on actual analysis. This lack of correlation was acceptable because the intent of MSDC was to model the coordination of design work; the work performed between simulations. The actual input and output values had little absolute significance, which was preferable to using real simulation tools because MSDC nullified the domain specific skills and experience of the participants and focused instead on the coordination design work impacted by the DPCM intervention.

Two differences existed between control and experiment groups. The control group could not draw arrows. They simply exchanged files with each other in a list similar to how most teams in professional practice save files in Windows Explorer. The first author instructed experimental groups to draw arrows to show the dependency between tool files. This difference measured the impact of DPCM on collaboration, but other implementations of this test method could test other interventions.

In addition, the control group could search and view information on historic projects, but not information dependencies (Figure 2b). The experimental group could search and view historic projects' information dependencies (Figure 2c). This difference enabled the measurement of the impact of DPCM on sharing.

The teams began the charrette with a ten minute meeting to plan their design process. Simulating the typical non-collocated, asynchronous project team, the participants dispersed and sat at different computers and communicated only via instant messaging and the communication methodologies being tested (i.e., PIP - the operationalized version of DPCM).

Energy Analysis Mock-Simulation Tool

Red	Input Independent Variable
Black	Input Variable Dependent on Other Document/Tool
Blue	Output Variable Dependent on this Analysis

INPUT

Variables	Metric Description	Value	Units
Building Width	-	10.00	m
Building Height	Floor to Floor Height	4.40	m
Window Length	-	1.50	m
Orientation	Clockwise From North	90.00	deg.
Lighting Energy	Energy required for artificial lighitng	38.00	Kw*Hr/m2
Equipment	Air Handling Unit	Xbg4U	-
Location	Site Location	San Diego, CA	-

Analyze

OUTPUT

Variables	Metric Description	Value	Units
Equipment	Air Handling Unit	Xbg4U	
Energy	Energy Consumption Per Year	78.70	KJ/m2
Comfort Index	Percentage of Inhabitants that are Comfortable	46	%

Figure 3. Example of a mock-simulation tool. All 20 mock-simulation tools resemble this Energy Analysis tool. In this case, the mechanical engineer finds dependent input values from the output values of other tools. He then chooses a design by selecting input independent variables. Clicking the "Analyze" button produces the output values, which become input to a subsequent tool.

2.4.2 Ethnographic-action research in design class projects

To implement the Ethnographic-action research method, the authors selected student projects as opposed to a professional project, because student projects: (1) do not require the usability, reliability, security, and legacy integration required by professionals; and (2) enable simultaneous comparison of multiple projects of similar scope within a three month period. Four professors chose to use PIP as the primary process capturing and file sharing web tool in five classes, but the results presented in this paper came from use in one multi-disciplinary design and analysis course taught in the winter of 2010. 32 student designers in this class worked on eight teams of three to five students over three months. The designers adopted specific roles similar to the charrettes and professional practice. Each team presented a design solution for a real project for which they received a grade.

2.4.3 Techniques for collecting data and measuring results

The authors instrumented PIP to measure the effectiveness and efficiency of (1) capturing, (2) structuring, (3) retrieving, and (4) using processes. This section describes how the authors measured and/or calculated results from applying the two test methods (the structure of this section follows the results presented in Table 1).

PIP logs most user actions in a MySQL database. Each Excel tool records design values every time a participant calculated output values. The participants used instant messaging to communicate with each other. The first author told students they could only exchange design values using PIP, so the vast majority of the work was recorded.

The authors calculated the *percentage of dependencies captured* with an algorithm programmed in Visual Basic (VB) that matched the input values of uploaded files with the output values of previously uploaded files. If there was a match and an arrow was drawn, then the dependency was captured. If a match existed and an arrow was not drawn, then the dependency was not captured. If no matches were found, the authors manually investigated the dependency. As the authors did not know what information influenced decision making, false-positives (i.e., cases where a participant draws an arrow without using information from the start node) could not be calculated.

Each tool contained a VB macro recording design options calculated in each tool. Another VB macro aggregated all the tools uploaded to PIP and calculated the total *number of local iterations per participant.*

The first author compiled all logs of instant messages and blind coded these messages for the *number of statements about trends* and *of confusion*. An example of a trend statement was “cement weight has a lot more environmental cost than steel.” A statement of confusion example was “sorry I was confused, hold on. Let me redo the structure calcs.”

Inconsistency occurred when an input value in one tool did not match the output value in a previous tool. A VB algorithm checked the consistency between dependent files. Occasionally, the algorithm incorrectly identified inconsistent variables, and so the first author manually checked the variables the algorithm identified as inconsistent. A high *percentage of inconsistent variables* could occur because the participants simply copied a number incorrectly or because they used the wrong precedent file to retrieve an output value

Whereas inconsistency looks at information transfer between any tools, the *number of complete and accurate designs* reflected a global iteration that includes an NPV calculation. The first author emphasized to students that they cannot simply fabricate values. For example, if a participant inputs total energy as 145 MJ/year into the NPV tool, a corresponding energy analysis tool must have an output of 145 MJ/year. Otherwise the NPV calculation was invalid and the global iteration was incomplete or inaccurate.

The effectiveness of sharing required an assessment of whether teams chose better historic projects to mimic. Before looking at what historic projects the teams mimicked, the authors developed an equation that calculated a score for the process employed in the historic projects. The score considered number of tools required, number of arrows, rating (1 to 5 stars), discussion posts, process duration, and times viewed. Looking at the tools used, teams frequently combined process modules from more than one previous project, so the authors calculated the *mean process score of projects mimicked.*

After evaluating the effectiveness of the teams' retrieval of historic projects, the authors measured the efficiency with which the teams applied these historic processes. The *number of missing tools* was calculated with respect to the tools required to complete the NPV calculation. Frequently, participants were confused and wasted time trying tools not necessary for their NPV calculation, which prompted the calculation of the *number of redundant tools used.* The *number of non-interoperable tools used* reflected pairs of tools that the participant attempted to use together, but that were incompatible, because the output format of one variable did not match the input format of the variable in the dependent tool.

Applying these metrics to the charrettes resulted in non-normally distributed data. Consequently, p-values of counts were calculated using the non-parametric permutation method (Hothorn *et al.* 2010). For binary calculations such as whether a global iteration was completed accurately or not, the authors used the binary two sample Fisher Test (R Development Core Team and contributors worldwide 2011). Neither method depended on an assumed distribution. The authors considered a p-value less than 0.10 as statistically significant; i.e., at least 90% confidence that DPCM caused the observed differences between control and experimental teams.

3 Design Process Communication Methodology

With the synthesis of the test methods and metric definitions complete, this section describes DPCM - the methodology being tested. Senescu et al. (2011b) developed DPCM to lay the foundation for commercial software that fosters effective and efficient process communication. DPCM consists of elements (Figure 4) that represent and contextualize processes and methods that describe how designers capture and use these processes by interacting with a computer. One example of an element is the *Dependency*, which represents information from one file being used to create information in another file. One example of a method is *Draw Arrow*, which is how the designer defines the *Dependency.* The elements and methods enable the characteristics derived from the points of departure as described in detail in Senescu et al. (2011b). For example, the element, *Dependency*, enables process *Transparency* (a characteristic). The method, *Draw Arrow*, enables the capturing of process to be *Embedded* (a characteristic) in minute-to-minute work as designers organize and exchange information in files.

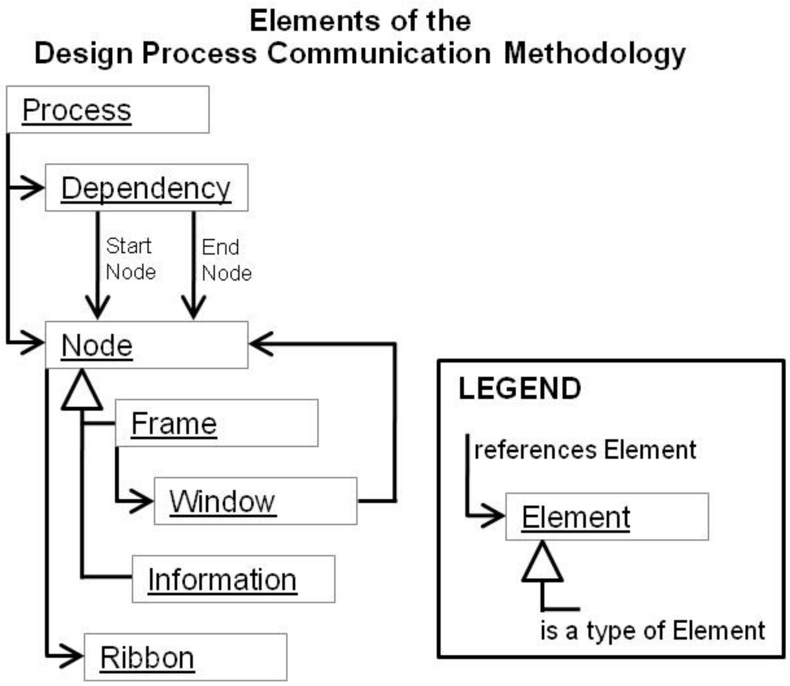

Figure 4. Summary of the Design Process Communication Methodology. DPCM consists of seven elements that enable design teams to represent and contextualize processes. Elements contain methods and attributes (not shown) described in more detail in Senescu et al. (2011b).

Senescu et al. (2011b) described the operationalization of DPCM through the Process Integration Platform (PIP) web application (Figure 1). PIP is a combination between a file sharing tool and a process modelling tool that enables project teams to exchange and organize information as nodes in a process map in addition to a folder directory. The next section validates DPCM's impact on process communication by exhibiting participants' ability to communicate processes using PIP compared to a traditional hierarchical information management application.

4 Results and Discussion

This section presents results (Table 1) according to the four steps required for communication: (1) capturing, (2) structuring, (3) retrieving, and (4) using processes. Capturing and structuring is combined into one activity validated by the charrettes to enable effective and efficient collaboration, sharing, and understanding. Retrieving and using is also combined and is evaluated within projects, between projects, and across multiple projects.

4.1 Design charrettes for collaboration and sharing

The time test participants worked on their classroom designs varied between 57 and 67 minutes, with just a one minute average difference between the four control and four experiment teams. PIP crashed for one of these eight teams and so that team's results are not reported.

4.1.1 Capturing processes effectively and efficiently

DPCM's ability to communicate relies on accurate process capturing. Participants employing DPCM captured 93% of the 132 actual information dependencies between the tools. Moreover, the same participant was responsible for seven of the nine missing arrows. The authors interpret this result as evidence for the power of DPCM to capture processes effectively. In conventional practice and in the design charrette teams without DPCM, designers simply list files without capturing the dependencies between the files.

As discussed in the introduction and extensively in Senescu et al. (2011b), many previous design process management research efforts demonstrate the ability to capture processes effectively. One of DPCM's unique contributions is the efficiency with which process capturing occurs. This efficiency is important since designers use the information exchange method requiring the least effort (Ostergaard and Summers 2009). After uploading a file to share with teammates, the participant quickly draws an arrow from the files containing information that the participant used for the newly shared file. By recording the time between file upload and arrow drawing, the authors confirm that capturing dependencies is efficient. Furthermore, no evidence exists that suggests a burden on the teams drawing arrows. Participants employing DPCM exchanged about the same number of files with others as participants without DPCM. Participants also considered more design options and discussed trends more frequently with DPCM. These results suggest that capturing processes did not reduce the time spent on value-adding production work and thus, DPCM enables not just effective but also efficient process capture.

4.1.2 Using processes effectively and efficiently to collaborate within teams

Capturing processes effectively and efficiently does not necessarily equate to usefulness. After all, other design process management research captures the rationale behind decision-making or dependency relationships at the variable level. DPCM only captures the dependencies between aggregated groups of variables (i.e., files) and does not require specification of the rationale behind the process nor the extent or type of dependency. Does DPCM's limited definition of process capture still enable effective and efficient use of process for collaboration within projects?

Effective collaboration entails consideration of multi-disciplinary design tradeoffs. Isolated in discipline-specific silos, designers will iterate to optimize designs only within their discipline as opposed to working collaboratively to optimize globally. The design charrette results provide evidence that DPCM positively impacts collaboration, because teams employing DPCM discussed trends 37% more frequently ($p=0.06$) and participants accordingly iterated 60% more ($p=0.02$). The authors interpret these statistically significant results to mean that DPCM enabled the participants to collaborate around their processes more effectively within the project team.

The teams with DPCM also collaborated more efficiently. The three teams employing DPCM completed four accurate classroom designs. The four teams without DPCM completed zero accurate designs. Both sets of teams worked for about one hour uploading and downloading files, discussing designs, etc., but the teams without DPCM never completed an accurate calculation of their classroom's NPV based on analysis performed in other tools. This result is analogous to a professional project team working for three months performing analysis and discussing designs, but never actually producing drawings that a construction team could use to build the design. Such a collaboration is inefficient, because it does not produce a design.

Two other results support the conclusion that teams with DPCM collaborated more efficiently. First, teams without DPCM inconsistently transferred information from one tool to another five times more frequently ($p \sim 0$). The authors conclude that DPCM enabled design teams to work more consistently with each other. Consistent with this result, participants without DPCM instant messaged each other expressions of confusion with three times more frequency (p=0.12). Frequently, these expressions of confusion were followed by rework. Both this confusion and the related information inconsistency provide additional evidence that teams collaborate more efficiently when employing DPCM.

4.1.3 Using processes effectively and efficiently to share between teams

Teams looked at previous projects' processes to choose tools to use or they chose tools from a separate folder containing all 20 tools. Effective use of shared processes should result in the selection of better processes to mimic with DPCM than without. Every time a team attempted a new NPV calculation (i.e., an attempted global iteration); the authors calculated the score of the processes they mimicked based on the historic processes. The authors normalized the scores, so exclusive use of the best historic process resulted in a score of one. The experimental teams on average chose precedent projects that scored 17% higher than the control teams. The variation of the experimental teams' was 0.17 versus 0.06 for the control. Thus, the teams with DPCM more consistently retrieved processes with higher scores (p=0.03).

Once the teams chose historic projects to mimic, they mixed and matched them and used them for their classroom design process more efficiently. For example, 20% of the time a team without DPCM used a tool, the tool performed a redundant calculation to a tool that the team had already uploaded. Teams with DPCM used redundant tools just 6% of the time, suggesting that DPCM made the processes from previous projects more transparent, so they did not waste time on tools they did not need. Also, teams with DPCM never missed a tool nor used a tool that was not interoperable with another tool. Teams without DPCM missed eight tools that were necessary for completing a design. For example, one team without DPCM never performed an energy analysis, suggesting that they had trouble learning from previous projects, which always included some type of energy analysis tool. 5% of the time, teams without DPCM chose tools that were not interoperable with another tool they had chosen. Choosing an inappropriate tool or missing a tool altogether is a process mistake that detrimentally impacts the efficiency with which the teams use historic processes. Teams with DPCM made eight times fewer process mistakes per tool used (p~0), which the authors interpret as evidence that DPCM enables teams to efficiently use processes shared between teams.

4.1.4 Using processes effectively and efficiently for understanding across projects

During the ten-week multi-disciplinary design and analysis class, 32 students on eight project teams used PIP to upload 1,222 files, and they downloaded files 1,939 times (an average of 60 downloads per designer). They drew 2,057 arrows to capture the dependencies between the files they created. This usage data provides evidence that students used PIP as a primary file sharing tool on their projects.

Table 1. Summary of results from the Mock-Simulation Design Charrette.

Process Communication Metrics			No DPCM	DPCM	*p*
Capturing Processes					
	Effectiveness	*n = # of true dependencies*	151	132	
		% of dependencies captured	0%	93%	-
	Efficiency	*n = # of participants*	20	15	
		# of files uploaded per participant	4.6	4.8	-
		# of local iterations per participant	26	43	0.02
		# of statements about trends per participant	3.3	4.5	0.17
Using Processes					
Collaboration within projects					
	Effectiveness	*n = number of teams*	4	3	
		# of statements about trends per team	16.3	22.7	0.06
		n = number of participants	20	15	
		# of local iterations per participant	27	43	0.02
	Efficiency	*n = completed global iterations*	8	8	
		# of complete & accurate designs	0	4	0.08
		n = total number of variables transferred	367	277	
		% of inconsistent variables	21%	4%	~0
		n = number of participants	20	15	
		# of statements of confusion per participant	0.45	0.13	0.12
Sharing processes between projects					
	Effectiveness	*n = attempted global iterations*	11	9	
		mean process score of projects mimicked	0.63	0.74	0.03
	Efficiency	*n = # of files uploaded*	92	72	
		# of redundant tools used	18	4	-
		# of missing tools	8	0	-
		# of non-interoperable tools used	5	0	-
		# of total process decision mistakes	31	4	~0
Understanding processes across multiple projects					
See Figure 5 and Figure 6 and related discussion in Section 4.1.4.					

DPCM enables effective and efficient understanding of design processes across the eight projects. Unlike the quantitative evidence provided for collaboration and sharing, this section provides qualitative evidence by demonstrating that employing DPCM provides insights into design processes. DPCM enables teams to visualize the degree of information distribution across a team (Figure 5). The darkness of a square in Figure 5 (see legend) indicates the number of arrows drawn between information created by e.g., Jones and information created by e.g., Smith. The relatively dark single band diagonal suggests that designers most frequently depend on information they created themselves. However, some teams depend on information distributed evenly across the team (top left) whereas others have information that is more fragmented or concentrated (bottom right). The former suggests that the teams in the top left have integrated their designs, because generally the designers created information dependent on other designers. The latter (bottom right) suggest the potential for fragmented designs, because designers created much information independent of information created by others on the team. It is important to interpret this graph as indicating only the *potential* of integration problems. That is, it is possible that the difference between the top left and bottom right reflects the teams on the bottom right prefer communicating verbally, using paper documents or that the tools they used or projects they work on did not require as much integration.

DPCM also enables understanding of how information flows across multiple projects. For example, three project teams worked on different train stations along the same rail line. Figure 5 shows that one primary liaison exchanged information between these teams. Though not shown in the figure, DPCM enables the overlay of average information latency between designers where information latency is the difference in time between uploads of dependent files. Graphing information latency revealed that Metro Station 3 used information from Metro Station 1, but that the Metro Station 1 team then updated that information. The Metro Station 3 team never used that updated information. Again, this situation just reveals a *potential* problem. Still professional designers frequently create spreadsheets that are then used on subsequent projects. Years later, construction of the building may reveal an error in a design calculation that has since propagated to other projects. DPCM enables understanding of the process by which this information propagates between projects.

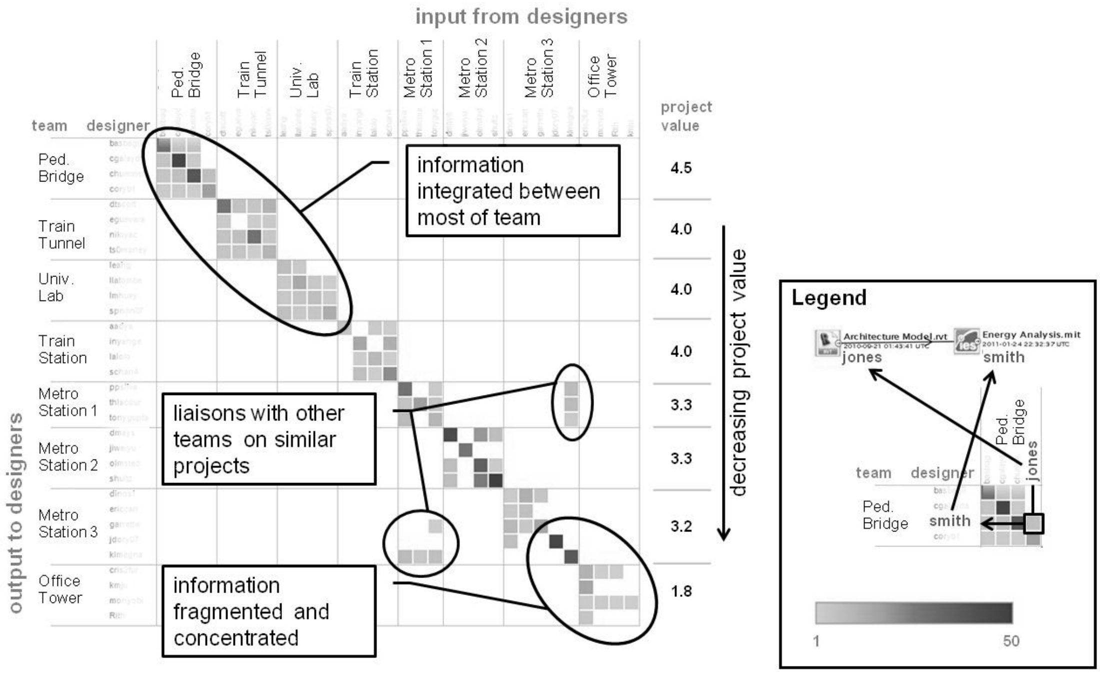

Figure 5. Information distribution across projects in a multi-disciplinary design and analysis class. The shade of each square represents the number of arrows (i.e., dependencies) from information created by a designer on the top (input) to information created by a designer on the left (output). Designer names are hidden and project names changed for anonymity. A strong single-band diagonal exists from top left to bottom right because designers depend mostly on information they created themselves. A wide-band diagonal exists because most designers only depend on information from within their own team. One exception is the three teams working on different train stations along the same metro line. The projects are ordered from highest to lowest project value, suggesting that teams with information distributed across the team delivered more value (top left) than teams with fragmented and concentrated information (bottom right).

As the teams are sorted by project value (normalized final presentation grades provided a proxy for project value), a trend exists between the degree of information distribution and the project value delivered. The authors make no claims about the statistical correlation between higher value and more distributed information in PIP. Rather, Figure 5 provides evidence for the power of DPCM to enable managers to answer questions such as: Does the amount of information distribution across projects correlate with client satisfaction, project profit, or change orders during the construction phase? Project managers can use Figure 5 as a live project dashboard enabling interpretation of large quantities of blank squares as potential integration problems. Employing DPCM thus provides effective understanding of the degree of design integration within one project for comparison across many different projects.

Just as Figure 5 shows the frequency of information flow between people, the shade of the squares in Figure 6 shows the frequency of information flow between tools. Insight on tool use is important, because companies in, for example, the architecture, engineering, and construction (AEC) industry consider IT investment 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). The AEC industry wastes $138 billion annually due to poor interoperability, but few companies have the tools to understand their detailed inefficiency problems (Young *et al.* 2007). At least one global building design firm uses over 200 tools to assess AEC project impact on the environment, so understanding the best tools to use together is not trivial (Ayaz 2009). From Figure 6, a manager can see that across the eight projects, designers frequently used an AutoCAD file to create a 3D Revit model and on average about 20 days passed between the uploading of the AutoCAD file and the uploading of the Revit file. This square represents the process of students frequently acquiring 2D plans from their professional project mentors, and then, building up 3D models in Revit that they could feed to other software for analysis. As this process was frequent and time consuming, a manager would want to invest in improving this process, perhaps by creating or buying a software script that automatically created 3D models from 2D plans. In practice, a manager could immediately decide against process investments involving information flows that are not time consuming or infrequent (small, light squares) and immediately focus attention on improving the information flows of common, time consuming processes (large, dark squares). Thus, DPCM enables effective understanding of the latency and frequency of information flows between tools across multiple projects.

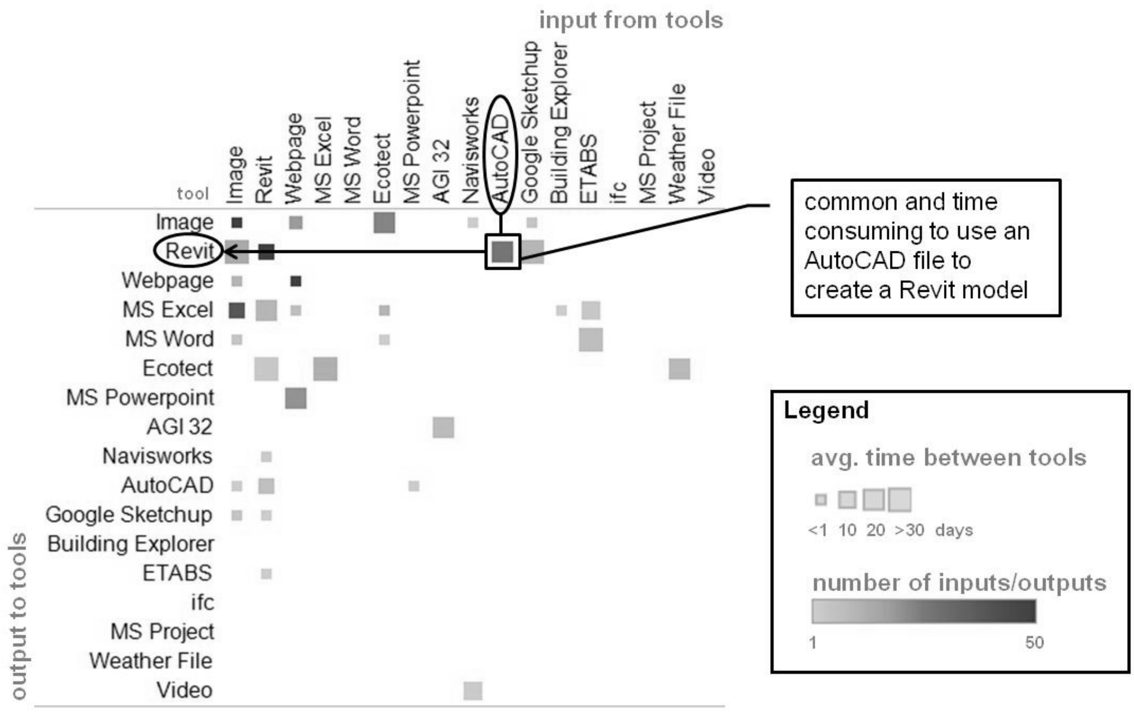

Figure 6. Frequency and upload latency of information flow between different tools across all projects in a multi-disciplinary design class. The shade of each square represents the number of arrows (i.e., dependencies) from information created by a tool on the top (input) to information created by a tool on the left (output). The size of the square represents the average latency between when an input file is uploaded and when an output file is uploaded. The visualization enables managers to understand potentially inefficient information flows, so they can invest in improved processes. For example, the large dark squares represent information flows that are both frequent and time consuming.

5 Discussion of Power and Generality

5.1 Internal Validity

Internal validity is the "extent to which the structure of a research design enables us to draw unambiguous conclusions from our results" (Vaus 2001). The ability to conclude that the research design validates DPCM is contingent on an acceptance that PIP accurately models the abstract DPCM. The features in PIP map directly to DPCM, but it is possible other researchers could develop different technical instantiations of DPCM. As discussed more thoroughly in Senescu et al. (2011b), the authors mapped DPCM to PIP using the Agile Software Development (Cohn 2004). After PIP became usable, the authors shifted away from the Agile Development method toward the Ethnographic-Action method (Hartmann *et al.* 2009). For example, at first the *Node* element in DPCM included an attribute containing an image of the information referenced by the node, but this feature was never requested by students, so the authors iterated and removed this attribute from DPCM. Also, students did not insist on automation between nodes, and so the *Computable* characteristic was deprioritized. Students did require the notion of a "home folder" where students could personalize their views onto different project folders. The authors iterated to find that this notion was consistent with human computer interaction literature emphasizing the importance of *personalizing* visualizations of information and so, the attribute is included in DPCM. This iterative research process bound the abstract methodology (DPCM) with the usable technological model (PIP) and ensured that test results from PIP apply to DPCM.

This PIP-DPCM coupling enables overall conclusions to be made about DPCM, but not granular conclusions about the relative importance of individual characteristics, elements, and methods. This paper does not provide evidence that PIP is transparent, social, scalable, embedded, shared, computable, and modular, nor that the elements and methods enable these characteristics. Rather, this paper provides evidence that collectively, the elements and methods aimed at enabling these characteristics results in effective and efficient communication. A more exhaustive literature review and application of the Ethnographic-Action method to practice would likely reveal more characteristics, elements, and methods that may result in even greater effectiveness and efficiency. And similarly, it is possible DPCM includes some components that contribute only marginally to effectiveness and efficiency. For example, few students utilized the method for searching dependencies, so the validation provides no evidence that this particular method is necessary for process communication. However, Senescu et al. (2011b) provide theoretical justification for DPCM in its entirety, and this paper validates that DPCM does enable effective and efficient communication – a theoretical contribution to project information management and design process management research and a practical contribution to industry.

Another potential limitation to the power of the results lies in the internal validity of the charrette method due to the limitations in eliminating "demand characteristics" – indications to participants about the researchers' hypothesis. It is possible that the control and experimental teams knew of each other and consequently tried to act like "good subjects" (Goodwin 2009). Previous attempts to change the charrette to a within-subject design failed both because participants were unwilling to design the classroom twice and it was difficult to nullify the impacts of learning. Though qualitative and subjective, observations of chats and the general morale of the teams suggest that the challenge of the design task and incentive to win the prize were sufficient to ameliorate the desire on the part of the students to appease the authors' expected outcome. This conclusion is consistent with the finding that the desire to perform well when evaluated by peers (it was clear to students that results would be made public) overpowers the desire to confirm the hypothesis of the researcher (Rosnow *et al.* 1973).

Experimenter bias may also have impacted results. The authors tried to minimize their impacts on the designers' performance by using a scripted presentation for each group. Furthermore, many of the results had p-values below 0.05 combined with differences between control and experiment groups of greater than 50%. It is unlikely that individuals desire to appease the researcher or experimenter bias could account for such dramatic differences. A claim for internal validity is further enhanced by the repeatability of the charrettes.[4]

5.2 External Validity

External validity is the "extent to which results from a study can be generalized beyond the particular study" (Vaus 2001). Two main features of the validation method limit the extent to which conclusions can be generalized. First, the charrettes and the class projects are merely models for the complexity of real project environments. Second, the participants are students as opposed to professionals. In both cases, the emphasis on coordination work reduces the limitations of the validation methods. While the production tasks performed individually differ greatly from practice, the patterns of information exchange in the class and in the charrette do not appear to differ from industry projects. Furthermore, a similar application of the charrette method by Clevenger (2010) showed that the experience and skills of professionals did not influence their ability to assess the relative impact of different variables on energy performance. In fact, the professionals in that study could not identify important variables for energy performance with any more accuracy than random guessing. Thus, it is not surprising that the authors found that improved collaboration and sharing did not lead to a building with higher NPV's. This lack of correlation between process effectiveness and product outcome is consistent with the findings from other researchers' charrettes. For example, when asked to select the type of variables (e.g., window area, building geometry, etc.) with the greatest impact on energy efficiency, professional responses approached random guessing immediately after they chose the

[4] Researchers can visit http://www.cafecollab.com, register, and view the class project and charrette results and download the charrette setup and repeat the experiments presented in this paper.

most impactful variable (Clevenger 2010). Similarly, a charrette involving structural designs found that student participants' ability to pick optimal designs drops from 96% of optimal when deciding between two variables to 76% for six variables (Flager 2011). The MSDC required decisions for several dozen variables (the amount varied with the process chosen), suggesting that any charrette results showing near optimal solutions were probably due to randomness and not skill. This suggestion does not imply that professional designers make random design decisions, but that the charrette isolates coordination work from production work, mitigating the relevance of design decisions. The charrette intends to measure how designers exchange information, not the quality of the information they exchange. Thus, the authors only claim that DPCM enables effective process communication, not necessarily improved product outcomes.

While the authors only measured collaboration in the charrettes and not the class projects, the students clearly adopted PIP for collaboration on their projects. This adoption demonstrates that the methodology could be applied in practice, even if the authors cannot claim that professional projects would see the same dramatic differences between conventional information management methods and DPCM. The class projects do not demonstrate adoption of DPCM for sharing processes across projects. Also, it was beyond the scope of this research to measure the impact of process understanding on investment decisions on process improvement.

5.3 Future Work

Despite the qualifications attached to the external validity, the power of the findings presents a strong case for future work to make more generalized conclusions about DPCM. Also, the repeatability of the MSDC contribution enables future researchers to compare DPCM with other design process management methods while the accessibility of PIP enables its application to future industry case studies to compare with other project information management research.

This research provides two additional opportunities. First, the application of DPCM to AEC education and research may enable students and researchers to learn more from each other when using PIP. Second, DPCM enables the replacement or supplementation of ethnographic research methods used to study the process of design. Just as social and professional networking sites have revolutionized the ability of organizational scientists to apply social network analysis to modern communities, a tool such as PIP enables design researchers to capture the social interactions and information relationships and apply social network analysis algorithms to these data. This paper presents a tiny fraction of the results from the 120,000 actions recorded by 387 different user names in PIP between April 2009 and April 2011. Much opportunity exists to use these and future data to study how teams exchange information.

6 Conclusion

Designers (1) struggle to **collaborate** *within projects*, (2) **share** better processes *between projects*, and (3) **understand** processes *across projects* to strategically invest in improvement. Overcoming each challenge requires communication of design processes. The Design Process Communication Methodology (DPCM) enables effective and efficient design process communication. To test DPCM, previous research mapped the methodology to software features in the Process Integration Platform (PIP). PIP is a web tool enabling project teams to organize and share files as nodes in an information dependency map that emerges as they work. This paper contributed a set of metrics and an accompanying test method to measure the impact of DPCM on the effectiveness and efficiency of four steps required for process communication: (1) capturing, (2) structuring, (3) retrieving, and (4) using processes. The authors measured effectiveness and efficiency using PIP and contrasted these measurements with results from a conventional information management method that does not show the dependencies between information.

Using PIP in the Mock-Simulation Design Charrette (MSDC), the authors conclude that DPCM captures and structures processes effectively, because the student designers captured 93% of the true information dependencies in the controlled design experiment. The capturing and structuring is efficient, because it places no measurable burden on the design teams

DPCM had a statistically significant impact on the number of iterations performed by designers and the frequency of discussion of multi-disciplinary trends. The design teams without DPCM did not complete any accurate designs, whereas teams with DPCM completed four accurate designs. These results provide evidence for the effectiveness and efficiency with which DPCM enables collaboration within teams.

To select a process, the student design teams viewed the information created by historic projects. When viewing historic projects employing DPCM, teams selected better projects to mimic. Once they selected a project, teams with DPCM used the newly shared processes more efficiently, because they committed few process mistakes. Teams with DPCM shared processes between teams effectively and efficiently.

DPCM enabled the understanding of processes across projects, which provide insights into the relationship between information distribution among designers and project performance; and DPCM also exposed opportunities for investment in improved information flows.

The collection of the results demonstrates the power of the MSDC method to validate design process improvement methodologies. The results themselves demonstrate the power of DPCM to effectively and efficiently communicate design processes within projects, between projects, and across projects. DPCM contributes to filling a gap between two research fields: (1) Project information management research enables the efficient exchange of information, but does not effectively communicate process; (2) Design process management research effectively communicates processes, but with methods too inefficient to be adopted in practice. 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.

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