CIFE CENTER FOR INTEGRATED FACILITY ENGINEERING

Relationships Between Project Complexity and Communication

By

Reid Senescu, Guillermo Aranda-Mena, and John Haymaker

CIFE Technical Report #TR196
January 2011

STANFORD UNIVERSITY

If you would like to contact the authors, please write to:

c/o CIFE, Civil and Environmental Engineering Dept.,
Stanford University
The Jerry Yang & Akiko Yamazaki Environment & Energy Building
473 Via Ortega, Room 292, Mail Code: 4020
Stanford, CA 94305-4020

Relationships Between Project Complexity and Communication[1]

Reid Robert Senescu, P.E.[2]; Guillermo Aranda-Mena, PhD[3]; and John Riker Haymaker, AIA, PhD, LEED ap[4]

Abstract

The Architecture Engineering Construction (AEC) industry delivers increasingly complex projects to maximize project value. This complexity requires communication, but the AEC industry struggles to leverage information technology to facilitate communication. Also, theory lacks methods to evaluate communication, complexity, and their relationships. First, the authors apply complexity and virtual design and construction research to develop a method for evaluating product, organization, and process (POP) complexity. Second, through project team interviews, the authors develop a communication evaluation method. The method evaluates (1) collaboration within projects, (2) sharing between projects, and (3) strategic understanding across the firm or industry. Applying these two evaluation methods to the case studies, the authors validate the usefulness of the methods and establish a trend between increased POP complexity and increased communication challenges. The two evaluation methods provide the opportunity for teams to learn from and improve upon their communication strategies. By increasing the awareness of the relationship between complexity and communication, the paper aims to motivate and provide foundation for the development of more efficient and effective communication tools.

[1] Submitted for Publication to the *ASCE Journal of Management in Engineering*, January 14, 2011.
[2] PhD Candidate, Stanford University, Center for Integrated Facility Engineering, Jerry Yang & Akiko Yamazaki Environment & Energy Building, 473 Via Ortega, Room 292, MC:4020
Stanford, CA 94305 (corresponding author). E-mail: rsenescu@stanford.edu
[3] Senior Lecturer, School of Property, Construction and Project Management, RMIT University, GPO Box 2476, Melbourne, VIC , Australia. E-mail: guillermo.aranda-mena@rmit.edu.au
[4]Founder, Design Process Innovation, 477 Vermont St., San Francisco, CA 94107. E-mail: johnrhaymaker@gmail.com

Subject Headings: Communication, Information Management, Organizations, Project Management, Technology and Innovation Management

1 Introduction

The Architecture Engineering Construction (AEC) industry delivers increasingly complex projects to meet the financial, social, and environmental goals of stakeholders. Ideally, project teams would continue to efficiently and effectively communicate despite this complexity. Yet, even with the increased availability and pervasiveness of Information Technology (IT), project teams still struggle to communicate (Eckert and Clarkson 2004; Haymaker and Chachere 2011; Luiten and Tolman 1997; Senescu and Haymaker 2008; Senescu et al. 2010). These struggles limit the ability of project teams to manager complexity to achieve stakeholder goals.

The authors adopt the information processing view of a company to elucidate the AEC project as a network of information exchanges (Weber 1947). AEC Projects consist of an organization implementing a process to deliver a product, such as a building (Garcia et al. 2004). This product, organization, process (POP) ontology provides a useful lens for looking at the network of information exchanges on a project. Complexity theory helps quantify the challenge of representing these projects (Homer-Dixon 2000). Communication research provides guidance as to how people must exchange these representations by (1) collaborating within projects, (2) sharing between projects, and (3) understanding across the entire firm/industry (Senescu and Haymaker 2009). Despite the importance of efficient and effective communication in managing POP complexity, theory lacks a method to evaluate the relationship between complexity and communication.

This paper reviews this POP, complexity, and communication research and synthesizes a method for measuring projects along these dimensions (Figure 1). To develop a communication evaluation method, the authors collected empirical data through interviews with AEC professionals. In contrast, the authors base the POP complexity evaluation method on complexity literature, and the interviews simply confirm the relevance of this literature to AEC projects.

This paper contributes a method for measuring project complexity and a method for measuring the efficiency and effectiveness of communication. The two evaluation methods provide the opportunity for teams to learn from and improve upon their communication strategies. Application of the two evaluation methods to the interviews results in the second contribution: evidence of a trend between increased complexity and increased communication challenges. By establishing this trend, the authors aim to motivate and provide foundation for the development of more efficient and effective communication tools.

2 Points of Departure in Project Information, Complexity, and Communication

2.1 Product Organization Process – an ontology for project information

Using a "POP ontology" to define the project comes from research on Virtual Design and Construction. Project teams manage POP models to achieve project goals. Product represents "the physical and abstract concepts that describe the artifact itself, such as the columns and electrical system of a building." Organization "is the agency and agents responsible for design and construction of the artifact." Process is the design and construction tasks that the organization carries out to build the artifact (Garcia et al. 2004). In application, the POP model generally only lists POP objects without explicitly defining the relationships between the objects. For example, the entire project team rarely uses parametric product models because of the opacity of the relationships between product objects (Gane and Haymaker 2010). Also, the relationships (i.e. knowledge sharing networks, decision-making authority, complementary skills, etc.) between professionals in AEC are rarely transparent (Haymaker et al. 2010). And finally, professionals are rarely aware of the relationships between their own tasks, let alone how their tasks interrelate with the entire project team (Eckert and Clarkson 2004; Senescu and Haymaker 2009). Simply listing objects is conveniently simple, but this lack of communicating POP relationships is limiting, because the true value of a model comes from the relationships between the objects (Rechtin 1991).

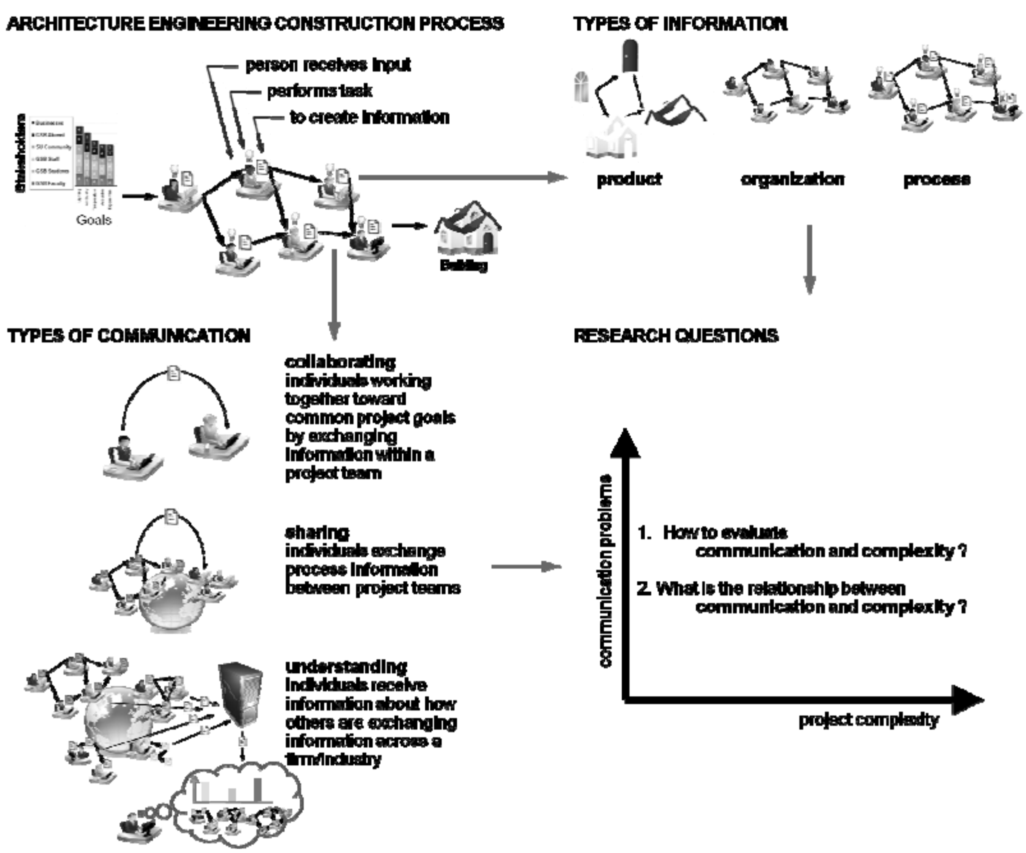

Figure 1: This diagram of the key concepts in the paper shows three types of information (product, organization, and process) and three types of communication (collaborating, sharing, and understanding).

The original intent of POP models was to develop increasingly detailed relational models to "elucidate and eventually mitigate potential risks to project success" (Garcia et al. 2004). As project complexity increases, developing relational POP models becomes increasingly difficult. Developing a method for evaluating the POP complexity provides a first step toward implementing this relational POP model.

2.2 Complexity – evaluating the challenge in project model development

Managing project complexity is a critical factor impacting project success and the application of conventional management systems to complex projects is inappropriate (Allen 2008; Baccarini 1996). Complexity can be measured according to the following criteria (Homer-Dixon 2000):

1. Multiplicity – number of components
2. Causal Connections – number of links between components (to the extreme, there is causal feedback where a change in one component loops back to affect the original)
3. Interdependence – the larger the module that can be removed from the complex system without affecting the overall system's behavior, the more resilient and less complex the system
4. Openness – to outside environments, not self-contained, difficult to locate boundary
5. Synergy – the degree to which the entire system is more than the sum of the parts
6. Nonlinear behavior – the effect on the system is not proportional to the size of the change on a component

This definition is consistent, though more specific than other applications to AEC (Allen 2008; Allen et al. 1985; Baccarini 1996). Others view complexity with respect to organization, technology, environment, information, decision making, and systems (Baccarini 1996). Baccarini, for example, focuses on organizational and technical complexity, but calls for work on determining the correlation between project complexity and the degree of integration, which can also be assessed by evaluating communication. Maier et al (2008) considers complex product development outside AEC, but while many communication factors such as "autonomy of task execution" are indicative of the project's complexity, complexity itself is never explicitly defined and the relationship between communication and complexity is not investigated. Otter and Emmitt (2008) also discuss communication in the context of process complexity, but never explicitly define the latter. The previous methods of assessing a project's complexity do not consider P, O, and P explicitly, and a need exists to establish the relationship between project complexity and communication within the AEC context.

2.3 Communication – exchanging information to create valuable facilities

People can exchange information about Product (e.g. a reinforced concrete beam), Organization (e.g. Acme Structural Engineering firm), and/or Process (e.g. the steps outlined in the reinforced concrete building code for designing a beam). Exchanging information about a specific process is itself a process. The "process of exchange of information between sender and receiver to equalize information on both sides" is called *communication* (Otter and Prins 2002). This definition is consistent with "sharing of meaning to reach a mutual understanding" (Otter and Emmitt 2008) and as a "cognitive and social process by which messages are transmitted and meaning is generated" (Maier et al. 2008), but places less emphasis on others' requirement that communication must intend "to gain a response" (Otter and Emmitt 2008).

AEC literature frequently distinguishes knowledge from information and data (Otter and Prins 2002). This distinction is also common throughout the knowledge management field of which Foss et al. (2010) provides an overview. The evaluation of communication does not require this distinction, because people must exchange all three types. Furthermore, the distinction is not useful, because the definitions of each are relative both personally and temporally. For example, a person may possess information (aware of the data's relevance and purpose), but the rest of the project team, ignorant of the relevance and purpose, may consider the data merely data. Also, people forget the relevance and purpose of data quickly, therefore relegating current information to future data. Consequently, this paper calls data, information, and knowledge simply *information*. Exchange of any information is called *communication* (Luiten and Tolman 1997).

The "Communication Grid Method" evaluates communication on projects (Maier et al. 2008). The majority of the Method's categories apply to communication within the team (e.g. decision making transparency, collaboration, and comprehension of the project's overall sequence of tasks). The Method also asks surveyees about communication between teams, (e.g. capturing best practices for future application and consideration of lessons learned). And finally, the Method also considers the availability of information about the surveyee's company and standard procedures. Yet, the Communication Grid Method does not categorize AEC communication by (1) within project, (2) between projects, nor (3) across firm/industry information exchanges.

Considering all three modes of information exchange explicitly 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 company (Dossick and Neff 2010). Thus, distinguishing between three categories of communication is useful: 1. People exchange information within project teams in order to *collaborate*; 2. People exchange information between project teams with the intent to *share*. 3. People gather information from projects across the firm or industry to aggregate and visualize with the intent of strategic *understanding*. Including these three types in the evaluation method encourages a holistic approach to improving communication. The following paragraphs explain the challenges and opportunities for improvement of each type of communication and relate each type to POP complexity.

2.3.1 Collaboration within projects

First, there is exchange of information on a project, which is found in collaboration literature (Kvan 2000) and project information management literature (Froese and Han 2009). Laufer et al. (2008) and Otter and Emmitt (2008) provide an overview of literature on within-project communication in AEC, and Laufer claims, but does not provide evidence for a link between communication challenges and complexity on construction projects.

Recently, product communication has improved as firms more deeply adopt Building Information Modeling (BIM) and increasingly exchange BIM between companies on a project. However, firms have difficulty using BIM for anything more than geometric coordination (Taylor and Bernstein 2009). While BIM may precipitate more tightly coupled technology within the project, decision making is often divided between different companies on the project (Dossick and Neff 2010). Collaboration research does not examine whether complexity has a negative impact on the type of information exchange that would enable BIM's use beyond geometric coordination (e.g. design decision making informed by BIM-supported performance analysis). Taylor and Bernstein call for more research on the impact of project complexity on the evolution of BIM. As BIM is fundamentally a product communication method, a need exists to contextualize Taylor and Bernstein's work by explaining the relationship between complexity and product communication.

2.3.2 Sharing between projects

In addition to the challenges of exchanging information within projects, knowledge management literature focuses on the exchange of information between projects (Carrillo and Chinowsky 2006; Javernick-Will and Levitt 2010; Kivrak et al. 2008). Carrillo and Chinowsky suggest knowledge managers identify their firm's most important knowledge assets; choose a people- or an IT-centric strategy; learn from others; identify the firm's unique barriers; and identify metrics. They also find barriers to implementing knowledge management systems (e.g. not enough time, cautious approach to new management ideas, not enough money, "not invented here" culture, and "knowledge is power" culture) but do not examine the impact of project complexity on the ability of teams to share information across projects.

Outside of AEC, 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." Once this system enables knowledge acquisition, the management strategy must structure the knowledge. Hansen et al. (1999) describe two aspects of knowledge structuring: codification and personalization. Codification relies on IT tools to connect people to reusable explicit knowledge (Javernick-Will et al. 2008). Personalization relies on socialization techniques to link people so they can share tacit knowledge. IT can provide the general context of knowledge and point to individuals or communities that can provide more in depth knowledge. Knowledge management is not just acquisition and structuring (Kreiner 2002). Will and Levitt (2008) address the additional importance of the future ability of others to retrieve the collected knowledge. Despite focus on the critical aspects of knowledge management, research lacks a method for evaluating the impact of project complexity on this information sharing.

2.3.3 Understanding across the firm/industry for innovation

Finally, exchange of information from the project level to the corporate or industry level is called understanding. Although construction companies consider IT investment to be costly and risky, investments proceed based on "gut feel" without understanding current processes and how the specific investment will improve them (Marsh and Flanagan 2000). Innovation literature commonly discusses understanding to describe how companies make strategic investments to innovate. For example, innovation requires a "knowledge-brokering cycle" consisting of 1. capturing good information 2.

keeping information alive, 3. imagining new uses for old information and 4. testing these new uses (Hargadon and Sutton 2000). Research lacks a method for evaluating a firm/industry's ability to understand its current POP information at the firm/industry level. Consequently, industry struggles to strategically invest in improvement.

2.3.4 Collaboration, Sharing, Understanding: one for all, all for one

Research and industry address these different types of communication independently. For example, companies have different systems (both technically and socially) for project team collaboration, knowledge management, and research and development. However, at the same time one is exchanging information to collaborate within a project, that person can also contribute to sharing across projects and to strategic understanding across the firm/industry. The authors intuit that an opportunity for this convergence exists, but that with current IT, POP complexity stifles the achievement of convergence. Before implementing an IT solution that combines the three types of communication, project information management research requires a communication evaluation method, a complexity evaluation method, and a comprehension of their relationship.

3 Research Method: Case Studies

3.1 Interviewee Selection and Agenda

To gather empirical observations on project complexity and communication, the authors undertook a qualitative approach based on interviews and observations of the selected case studies. Using the criteria described by Yin (2003), the authors selected case study projects and professionals within the selected projects, and prepared an interview agenda. The validity and reliability of the collected empirical data lies within a constructivist, not a positivist, paradigm (Crotty 1998). Thus, results are not deterministic but still insightful due to careful selection of projects and interviewees. Interviews occurred at eight offices in three Australian cities (Table 1). Two of the offices are part of the same firm. At each office, questions focused on one project, though the authors also interviewed people unassociated with the project, but possessing relevant information about general office practice. Also, some of the interviewees worked on the project at the office but represented, for example, the owner representative. Interviewees' roles included architect, structural engineer, drafter, project manager, BIM coordinator, quantity surveyor, and design technology director.

The authors formulated open-ended questions related to technology, business processes, knowledge management, information management, communication, and decision making. Interviews were semi-structured and focused on topics of interest to interviewers and interviewees rather than on prepared questions. Generally, the authors focused on a particular process employed by the interviewee on the project. This process focus then spring boarded to other topics addressing other questions.

Table 1: Interview summary

Company Type	Geographic Distribution	Project Type	Interviewees
Multi-Disciplinary Engineering Firm	Global	University Building	6
Multi-Disciplinary Engineering Firm	Global	Commercial and Residential High-Rise	7
Architecture and Multi-Disciplinary Engineering Government Office	Multiple offices in state	Call Center and Offices	8
Architecture Firm	A few offices in Oceana	Commercial High-Rise	2
Construction General Contractor	Global	Stadium	9
Architecture Firm	One office	High School	1
Architecture Firm	Global	Apartment Building	3

3.2 Criteria Development

3.2.1 Complexity

Viewing the interviews from a Product Organization Process lens, projects differ independently along these three axes. That is, the two high-rise products are similar, but the processes for achieving that product vary in terms of rigidity and standardization. Similarly, the organization designing the Low-Rise Residential and University Building has similar structures, but the end product and processes are different. The interviews reveal that the definition of complexity given in Section 2.2 can be applied individually to product, organization, and process to develop the evaluation method.

3.2.2 Communication

To develop a communication evaluation method, the authors repeatedly and randomly choose two interviews and brainstorm ways the two interviews differ. This cross-case searching tactic prompts the development of new unanticipated categories (Eisenhardt 1989). By repeatedly comparing random pairs of interviews, the authors assemble a list of communication categories. Aggregating the list, the types of communication fall into three categories. Professionals communicate product, organization, or process: (1) within project teams to collaborate, (2) between project teams to share, (3) across the firm/industry to understand. The authors thus develop the method for evaluating the interviews with respect to these three communication types.

3.3 Project Assessment

3.3.1 Measurement Scale

Requiring a method for evaluating interviews with respect to both complexity and communication, the authors develop a one to five scale. A “five” represents the most complex instance encountered in the interviews and a “one” the simplest. Similarly, a “five” represents the worst communication encountered and a “one” represents the best communication. The scale is relative to the interviews conducted. That is, if interviews included a villager building his own grass hut, a “one” would have represented a much simpler P, O, or P than the simplest project in this research effort. The intent of quantifying this measurement scale is to identify trends, not absolute levels of complexity and communication, nor mathematically defined correlations.

3.3.2 Scope

The authors assess complexity at the project level within the scope of the interviewee’s responsibility. For example, when talking to five people about one project, the authors averaged findings across five people. If one interviewee’s scope involved a small product at a low level of detail (low product multiplicity) and one a large product at a high level of detail (high product multiplicity), the two would be averaged and the project would be assigned medium multiplicity (e.g. “three”). Interviewing many interviewees with small simple scope on a large and complex project would result in a project assessment of simple (e.g. “one”).

The authors assess the interviewee’s collaboration on the project, but ignore statements made about collaboration between others. Thus, an engineer may have small scope and interact simply and collaborate effectively with one other person, even though the overall project may have high complexity and horrible communication. Sharing is evaluated with respect to how the team learns from other project teams or vice versa. In assessing understanding, the authors assume that understanding of the project and investment related to the project is indicative of the entire firm. In some cases, interviewees not specifically involved in a project contributed to the assessment of sharing and understanding.

3.3.3 Intuitive estimation

After reviewing the notes, the first author, who attended all interviews, assessed each project with respect to each criterion on a one to five scale. This method is subjective but provides a check for the detailed analysis method to ensure significant issues are not missed or skewed by the detailed analysis.

3.3.4 Analytical assessment

The first author coded the interview using the methods applied by Erdogan (2008). If the statements related to the Complexity and Communication Criterion were deemed useful, the author measured the statement on the one to five scale. Some statements applied to multiple criteria.

To be considered in trend analysis, projects needed on average at least one useful statement for every two criterion for both complexity and communication. The authors made this decision, because one project lacked sufficient data for meaningful measurement. For example, the high school project lacked sufficient description to identify project complexity. Thus, the authors did not use the project for evaluating a trend, but did use this project's data for validation of the evaluation method.

4 Complexity and Communication Evaluation Methods

4.1 Product Organization Process Complexity Criteria

The criteria for assessing complexity come from the aggregation performed by Homer-Dixon (2000). These criteria provide a useful method for addressing the project information management needs of AEC (Froese and Han 2009). Extending Froese's application, this paper disaggregates complexity assessment further by applying it individually to a project's product, organization, and process. Table 2 provides a definition for each criterion and an example from interviewee statements.

Table 2: Criteria for measuring a project's product organization and process complexity

-	Complexity Criteria	Very Simple =1. *Interview Example*[i]	Very Complex = 5. *Interview Example*[i]

Product	Multiplicity	not many components, low level of detail. *We model a diffuse sky, one floor, one façade, varying only height.*	many components, high level of detail. *We performed energy analysis within a mm of detail.*
	Causal Connections	one component has no impact on others. *We focus collaboration on a few crunch points, e.g. floor-to-floor height.*	one component impacts many others. *Choosing controls and sensors is not trivial: on/off vs. dimming, sensor locations, etc. [all have many impacts on performance].*
	Interdependencies	functions independently, resilient, separable. *We use packaged systems for HVAC and electrical.*	does not function independently, not resilient, integrated. *As so many things are highly sensitive to it, they know they need to look at solar load more carefully.*
	Openness	not sensitive to environments beyond product scope or control. *To design the elevator, all I need is building height and how much space I have.*	sensitive to environment beyond product scope or control. *Our design goal is to come in 2nd or 3rd in tendering.*
	Synergy	building is simply the sum of its parts. *We have an assembly code parameter and/or data set for each element in the model.*	Need to assess everything together. *The bits between disciplines are where the real innovation occurs.*
	Nonlinear	linear, easy to predict whether stakeholder goals will be met, even with precedence-based design. *We use back-of-hand calcs to approximate ducts and shaft sizes.*	emergent/non-linear, requires intense performance-based design and even then, still difficult to predict. *It was hard to predict how long it would take to do roof construction, [because there are so many factors and it's unprecedented].*
Organization	Multiplicity	single discipline, few people. *For Scheme Design, there were no models, design was generic, no participation of engineers.*	multiple firms, hundreds of people. *We are doing design of all services to Detailed Design [and then sub-contractors take over].*
	Causal Connections	hierarchical chain of command, one person affects only the person above. *[He didn't know about the construction sequence or why his supervisor prioritized certain areas over others; he just responded to requests.]*	highly networked, one person impacts multiple other people. *MEP, facades, ESD, acoustics, and building physics [all participated in design decisions].*
	Interdependencies	people can work independently. *The Senior Engineer decides [by himself] and considers [options] based on experience*	people need each other to work. *In Design Development, we ditched our own model of slabs and instead, used the architect's model [because we couldn't work independently].*
	Openness	independent self-contained group. *The developer gave us a spreadsheet showing their value function for the return on the apartments [there was just one stakeholder with a clear delineation of the organizational extent of the project].*	project group is ill-defined, because of heavy government and/or citizen involvement. *[Contractor] gives 80% of what the [government owner representatives] are expecting and we need to make sure it's ok with [the government's facility] operator.*
	Synergy	team with distinct and separated responsibilities. *It's my job to figure out how to arrange and stack panels on site [he then went into details of exactly his job versus other people's responsibilities]*	a team working together is more than the sum of its parts. *There is a fine line between deciding what the discipline should take responsibility for versus what I should handle.*

	Nonlinear	one person does not have a huge impact on everyone else. *The QA sheet gives a sense of ownership to the crew so they take the quality of the panels seriously [a large check and balance system existed, so a failure by one person would not be catastrophic].*	everyone is on the critical path, no one is easily replaceable. *[Specific other engineer] could probably find it quickly, but she is out.*
Process	Multiplicity	few tasks. *We decided ahead of time what options to consider [so, the process was straightforward]*	many tasks. *MEP, facades, ESD, acoustics, and building physics [all participated in design decisions].*
	Causal Connections	non-iterative. *We [architects] work the services into the building and then hold [the engineers] to it. We don't let [the engineers] change their mind.*	iterative (necessarily, positive). *Cost planning is iterative with the architect.*
	Interdependencies	tasks can be performed independently and broken up into smaller and smaller tasks. *We established zones in underfloor space for each discipline "so we could work independently and speed up iterations."*	tasks need to be performed all at once and cannot be broken up. *Models were needed for constructability, because we're building from top down (not typical), so we need to work out geometry and construction together.*
	Openness	easy to scope the tasks and predict the tasks in advanced. *[It seemed to them unconscionable that they would miss these deadlines, that nothing would prevent them from meeting the deadlines, and I saw the date on the drawing sets had the same day as the scheduled delivery.]*	unknown factors make it difficult to know in advance what tasks will be required. *75% of the rooms randomly vanished in Revit, requiring 5 days work to replace.*
	Synergy	two tasks sum as two (e.g. interface between the two tasks are seamless). *We knew thermal performance was ok for 100% glazing so then, we just find glazing that works for daylighting [as opposed to a process that considered interactions between thermal and daylighting]*	two tasks sum as greater that the whole (e.g. due to transactions between the two). *Then, the fire consultants said they needed huge fans. Working out with the architect how to accommodate [geometrically] the new fans took 7-10 man days and put us over budget.*
	Nonlinear	each task is more or less isolated, errors are not cumulative. *The process is that everyone fills out a field for each object they create in the Revit model.*	unforeseen large repercussions, a small error in a small task can have huge repercussions on future tasks. *It's intense to make changes. You move wall and have to check all drawings.*

[i] brackets [] represent explanation or description by interviewer. Otherwise, examples are paraphrased words of the interviewee, unless quoted.

4.2 Communication Efficiency and Effectiveness Criteria

The authors developed the communication criteria from the literature review (Section 2.3) and by categorizing differences between interviews. Table 3 provides definitions for each criterion and examples from interview statements. Different criterion evaluates collaboration, sharing and understanding differently. First, some criteria evaluate communication directly and others indirectly by evaluation of some trend indicative of communication. Second, the criterion may measure the efficiency and/or effectiveness of the communication. For example, the criterion, *speed*, directly evaluates relative efficiency of collaboration. On the other hand, the criterion, *info pull*, evaluates how often the organization asks for information they need. The *info pull* criterion is indirectly indicative of collaboration *effectiveness,* because not asking for information (i.e. remaining ignorant of others information) takes zero time, but is indicative of ineffective exchange of information (unless the other people know to give you the information they require). Aggregated, the criteria provide a direct and indirect evaluation of project collaboration, sharing, and understanding efficiency and effectiveness.

Unlike previous studies outlined by (Maier et al. 2008), the criteria avoid measuring communication purely on quantity of information exchanged. Instead, consistent with Maier, the criteria aim at assessing efficiency and effectiveness. By talking to multiple people directly, as opposed to relying on the survey method employed by Maier (2008), the interview method reveals communication problems unknown to the project teams. For example, in one interview, the manager complained, the consultants give us Navisworks files, but they are "useless to us." In the same office, an engineer said she is using Navisworks on the same project. By interviewing the team, as opposed to surveying, the authors could assess that the team struggled to collaborate effectively, because they were not *connected* even though they were collocated. Thus, the *Connection* criterion permitted evaluation of their struggle to communicate their processes and organizational skills.

Table 3: Criteria for assessing a project's communication

	Communication Criteria	**Great Communication = 1.** ***Interview Example***[i]	**Poor Communication = 5.** ***Interview Example***[i]
Collabor ation	Speed	fast information exchanges. *[With these three semi-automated steps] overall scheme design takes 3-5 man days.*	time consuming information exchange. *Takes about 100 days to get coordinates of every piece of steel out of the model.*

	Clarity	explain product, organization, or process clearly. *Sketchup allows clients to connect with what we design.*	unclear product, organization or process explanation. *The documentation is "appalling." The industry relies more and more on shop drawings. The designer just creates schematics and relies on detailing and coordination after design.*
	Consistency	consistent information between team members. *There was consistency between discipline assumptions.*	inconsistent information between team members. *Sometimes the .dwg is revised or people e-mail files [instead of saving the file correctly] and that screws things up.*
	Integrated Decisions	considers multiple disciplines in decision making. *Multi-disciplinary workshops really help to integrate ideas.*	decision making silos. *The architect was not concerned about anything but aesthetics.*
	Common Process Knowledge	the entire team knows the processes within each discipline. *The architect is using ArchiCAD to IFC, but we haven't really used it [i.e. Engineer knows the architect's processes even if disconnected from their own process].*	no knowledge of people's processes outside discipline. *We purposefully delete [permanently] annotations [showing design rationale] after submitting the drawings.*
	Standardized	well defined standard for digital information exchange. *We created a BIM process manual.*	no standard, all different formats. *The modelers are not consistent, so it's difficult to extract information for cost.*
	Planned	planned coordination. *At the beginning of the project, we ask what are the key things that should be coordinated.*	reactive coordination. *Fire consultants weren't on board early even though we knew the building would need performance based smoke ventilation, [this caused problems].*
	Incentivized	incentivize to consider multi-disciplinary tradeoffs and strive toward a global optimum. *Acoustician says [engineer] wants to expose ceiling for thermal mass, even though acoustics is not good [but acoustician recognized other goal was more important]*	incentivized to optimize within discipline silos. *Structural engineer had no incentive to make all the panels similar, so constructability was difficult.*
	Options	considers many options. *We costed about 30 different options for [the building].*	considers only one option. *They produce 3D renderings of the selected option …for verification…[but the owner representative wasn't happy with results].*
	Connected	team is well-connected. *We hold workshops regularly to integrate ideas.*	few connections between the team. *[The manager complained], the consultants give us Navisworks files, but they are "useless to us." [In the same office, an engineer said she is using Navisworks on the same project.]*
	Info Pull	proactively explain what information is needed from other people. *The mechanical engineer knows what he needs and lets others know via conversations or e-mail.*	rarely requests information from others. *We changed shop detailers and they didn't give us the ProSteel model, only the Navisworks file…in the future we need to get the detailers to give us the information we needed [in the format we need].*
Sharing	Transparency	all information created is organized transparently in a single location and the information is linked to the process and organizations that created it. *We have a directory of [interoperability] scripts that are reusable.*	all information created is temporary, the process is never documented. *We highlighted the potential problem verbally….and then, later, we got blamed for it (we didn't have a record of us warning about it).*

	Awareness	exchange processes with global community. *[The engineer] presented at [the research institute] about Grasshopper, so the company shares processes via community talks.*	little awareness of processes outside the project, company, and city. *I am predicting actual performance within 3%. "No way they could use more energy than predicted." [either the engineer is unaware of the huge differences between prediction and actual performance common in industry, or the industry is unaware of the extremely advanced technique employed by this engineer].*
	Dissemination	disseminate processes so other teams can adopt them. *Wiki helps explain how to use the server.*	don't disseminate processes. *The truth is we have no idea how we transfer knowledge to the organization as it went from 4 to 18 architects*
	Externally Connected	well connected with communities outside project. *We are working with a [professor in Brisbane] and with the IAI in Scandinavia*	little personal contact with communities outside project. *"BIM is a software product" so everything needs to be compatible between all disciplines [contrasting with general view of BIM as a method and general acceptance that BIM is useful without complete compatibility, suggesting he is not well connected with the global BIM community.]*
	Standardized Processes	when possible, processes are standardized. *Now, we're running our own scripts on servers, solidifying our basic processes.*	processes that could be standardized are not. *Setting full procedures [for standard parametric modeling techniques] is very expensive….but it's scary because students [or newly graduated] create geometric messes that would kill a project.*
Understanding	Measurable Success	easy to measure process success. *Profit measures success.*	difficult to measure process success. *[The person managing investment in new design process technology, when asked about how they will know if their latest investment is successful] "Yes, it would be a good idea to have a measure of success" [they didn't have any].*
	Measured Time	measured time spent on tasks. *Before coordinating penetrations took 2 days [in Navisworks], now we have a customized process that takes half a day.*	did not measure time spent on tasks. *We can't quantify the cost of running BIM, nor the benefit of BIM…nor the cost of "appalling" documentation*
	Process Documentation	documented some aspect of the process. *The government is investing in reducing energy, so our mechanical spec will be used in many schools, so that is why we could spend the time to document our mechanical design process.*	no documentation and no knowledge of the process. *We start with an image of how the building should be, and then the process should just make that a reality. All the creation happens in the mind [the process is just producing what's in the mind at the beginning].*
	Categorization	categorized projects for comparison of process. *We looked at the ten best and ten worst projects [in terms of profit and then evaluated which ones used BIM]*	no categorization, so impossible to compare. *[Some companies simply had no formal way of categorizing projects]*

Incentivized To Innovate	incentivized to innovate. *We have a new revenue stream where our modelers go into sub's offices and model for them.*	no incentives to innovate. *It's our traditional policy to keep paper, so we just do that. Besides, it's [her] job [implying she would not have anything to do without paper].*
Process Language	formal computable language for describing the process. *I set up facade configurations. Then, Radcalc is a perl code that reads xml. The code parses the xml and feeds it into Radiance, and it analyzes all the options in the servers in Melbourne.*	informal, non-computable method for describing process. no language or grammar. process description is likely interpreted differently by different people. *[When asked about a particular energy analysis process, the engineer tried to find the answer in the project folder, but frustrated, said] This folder is "such a disaster. Someone deleted the presentation folder….This is such a mess…I can't remember what we did."*
Vertical Understanding	vertical understanding of process throughout the organizational hierarchy and buy in to the importance of process improvement. *64 bit computers is not a big deal. We just upgrade.*	process is not understood at different levels of the organizational hierarchy. *PM viewed BIM as only a software product and didn't want to upgrade until it was compatible with all disciplines.*
Investing	methodical about investment decisions. *We analyze when we need to upgrade and investigate options for computers in detail.*	investing in new technology is random. *We make decisions about investing in software or script development to go between them "somewhat randomly."*

[i] brackets [] represent explanation or description by interviewer. Otherwise, examples are paraphrased words of the interviewee, unless quoted.

5 Results

5.1 Validating the Evaluation Methods

5.1.1 A Calibrated Evaluation Scale

A useful evaluation method accurately reveals insightful differences between projects (Yin 2003). If all criteria score the same or are highly skewed to one end of the evaluation scale, the method does not reveal insights into the differences between projects. Across all seven projects, the authors apply 42 criteria (18 complexity criteria and 24 communication criteria) 398 times to interview statements. Figure 2(a) shows the number of interview statements considered useful to evaluating the project with respect to each criterion. For each criterion, the authors measure the mean and standard deviation of scores across the seven projects (Figure 2(b)). The mean score of all the criteria is 2.9 with a standard deviation of 0.6. This calculation reveals that each criterion was well balanced with about as many statements scoring higher and lower than three. The average standard deviation within each criterion is 1.2,

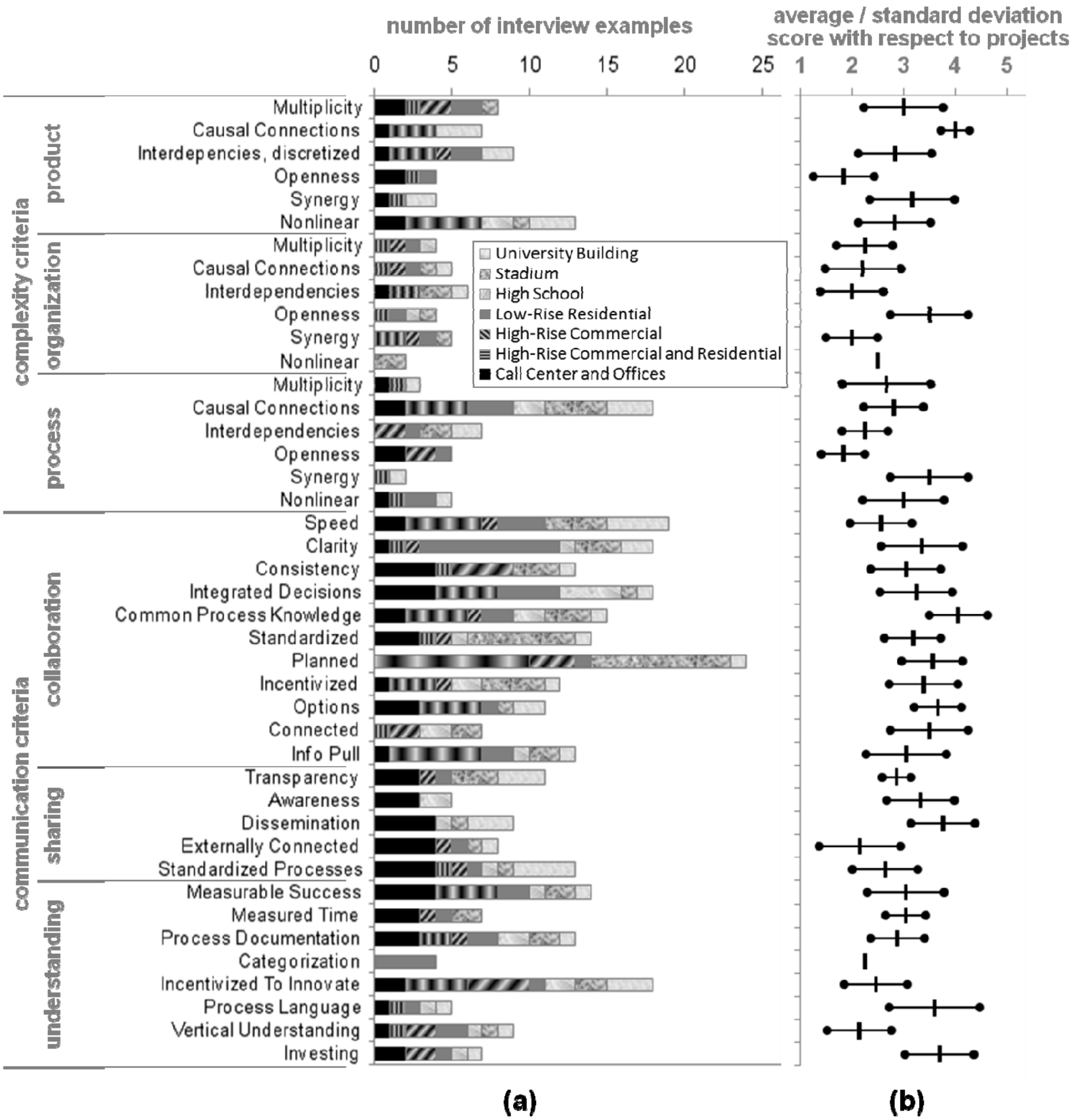

Figure 2: Assessment of the Distribution of Complexity and Communication Criteria. The number of statements relevant to each criterion varied from 2 to 24. The one to five scale was defined based on the interviews, so expectedly close to three; the average score across all criteria is 2.9. The average of the standard deviations across all projects is 1.2. This deviation across projects suggests that the evaluation criteria are sufficiently granular to differentiate trends between projects.

revealing that in general each criterion is sufficiently detailed such that variation exists between projects. However, two exceptions exist. There are only two examples of Nonlinear Organization and four examples of Categorization. For both criteria, the examples come from a single project, so the standard deviation is zero. This exception probably arose from insufficiently thorough interviews that failed to explore these criteria, rather than a problem with the criteria themselves. Since in general Figure 2 reveals that the evaluation method is balanced around three and varied away from three, the evaluation method is well calibrated and useful in discovering trends.

5.1.2 Alignment Between Intuitive Estimations and Analyzed Evaluations

Another way to verify the evaluation method is to compare the analytical results to the intuitive estimations. The analytical method should simply produce more precise results, so large deviations between what is expected intuitively would reveal potential problems with the analytical method or the intuitive estimations. Plotting each project's complexity on the x-axis and communication on the y-axis (Figure 3), the difference between the analytical assessment (large data points) and the intuitive estimate (small data points) for each project is the distance between the two points on the graph. The average difference was only 0.72, demonstrating reasonable alignment between the intuitive estimations and the analytical assessments.

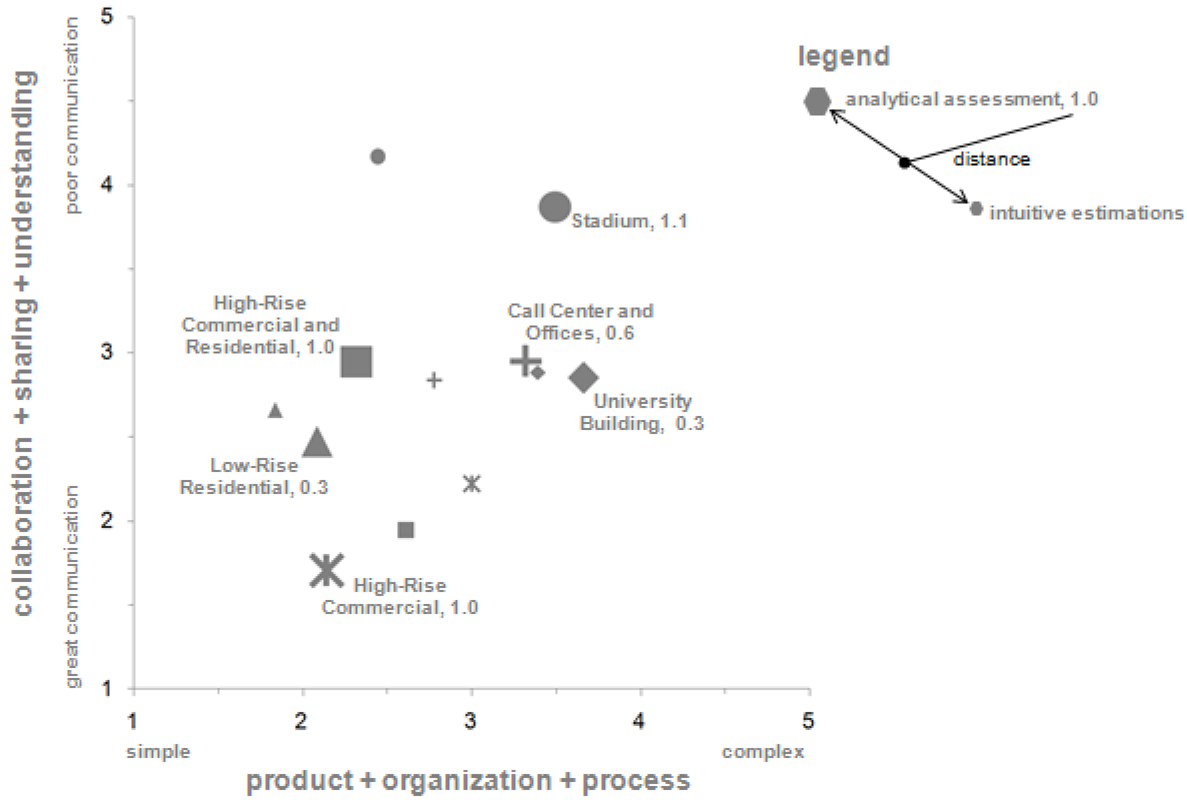

Figure 3: Assessment of the Intuitiveness of Results. For each project, the plot shows a comparison of complexity and communication evaluation methods. In general the analytical assessments (large data points) are relatively close to the intuitive estimations (small data points). The largest differences occur for the High-Rise Commercial and Residential, High-Rise Commercial, and Stadium projects (estimates are 1.0 to 1.1 distance away from analytical assessment). On the other hand, the University Building and Low-Rise Commercial were close (0.3).

5.1.3 Comprehensive interviews

It is important to ensure that each project covered both project complexity and communication comprehensively. A higher number of statements per criterion signified a more comprehensive interview. An evaluation method for which it is too difficult to comprehensively acquire data is not useful for assessing complexity and communication. Averaged across all projects, there were 0.9 statements per project complexity criterion and 1.6 statements per project communication criterion. That is, on average each project had just less than one statement for each project complexity criterion. As there were 18 complexity criteria, each project had on average 16 statements related to complexity.

For the High School project, there were only 0.3 statements per project complexity criterion (Figure 3). As this value was below 0.5, interviews on this project did not offer a comprehensive view of the project complexity, increasing the potential inaccuracy of the project's complexity assessment. Further supporting this potential inaccuracy, the intuitive estimate for complexity was 0.8 points higher than the analytical evaluation (the third largest difference). Also, this was the only project where only one person was interviewed. Consequently, the authors disregarded this project's complexity and communication evaluation, and it is not shown in the trend analysis.

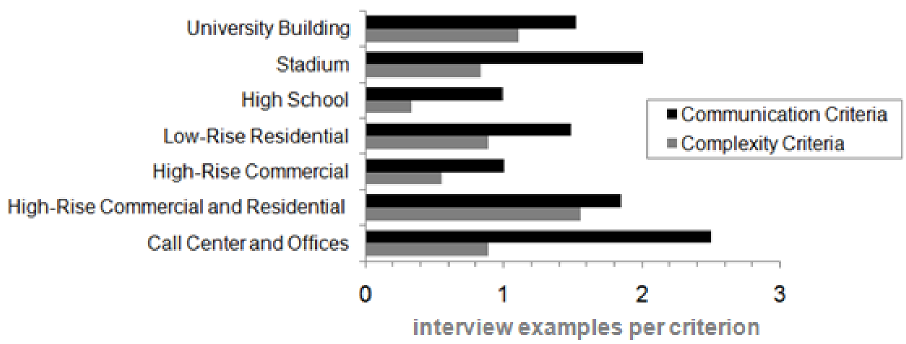

Figure 4: Assessment of the Comprehensiveness of Interviews. The figure shows that there were in general more interview examples related to project communication criteria than complexity criteria. In fact, the High School project had so few examples of complexity criteria that it is not considered in the trend analysis.

5.2 Observations of a POP Complexity and Communication Trend

After demonstrating the validity of the evaluation method, the authors investigated trends revealed by the analytical assessment. Figure 5 reveals a trend between increased POP complexity and increased communication problems. The authors do not claim a particular linear (or exponential) correlation, because there are just six points and the graph is translating qualitative information to scores. However, the graph shows an upward trend. The next two sections provide a few representative examples from two projects at the extremes of this graph to contextualize differences resulting in their two positions.

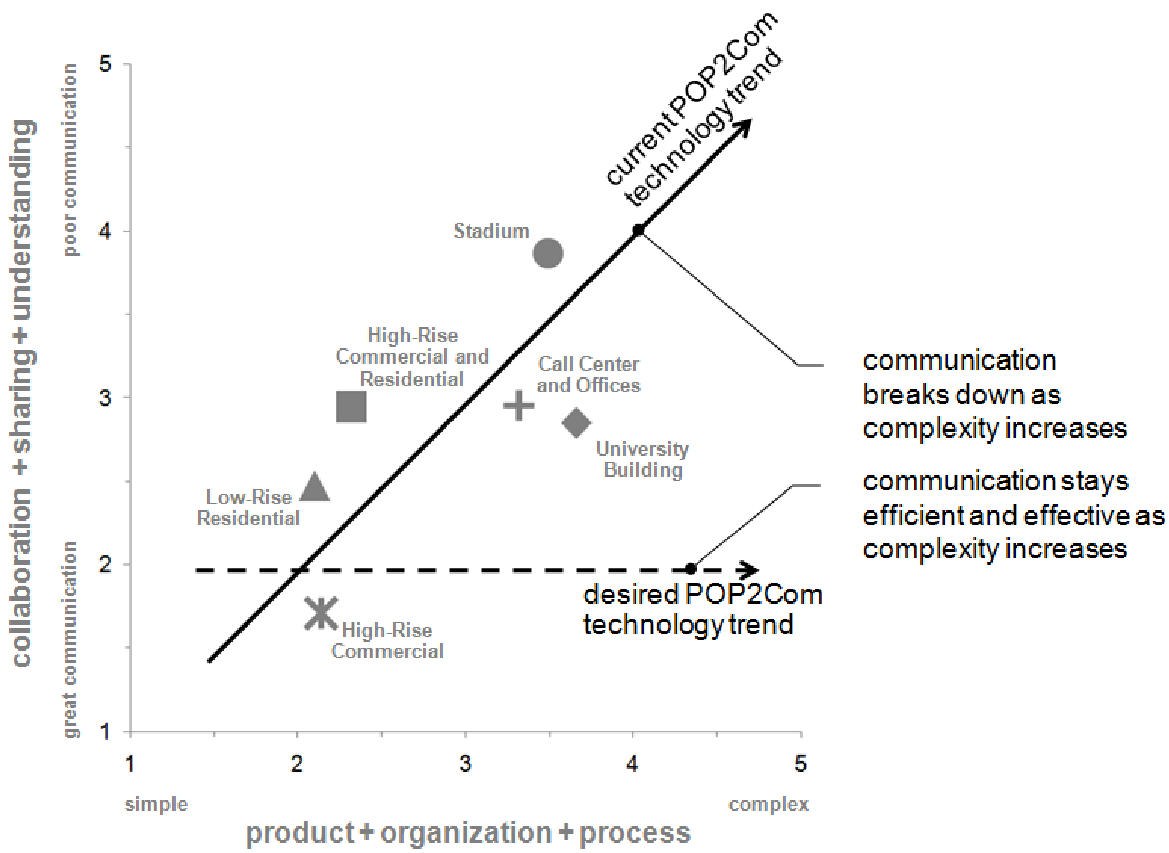

Figure 5: The Relationship Between Project Complexity and Communication. Based on the six AEC projects evaluated, product, organization, and process complexity increase with communication problems. This current POP2Com technology trend is unsustainable, because delivering projects of increased environmentally, financially, and socially sustainable value requires increased complexity. AEC requires information IT solutions with horizontal POP2Com technology trends that allow great communication with high complexity.

5.2.1 Stadium Project in Depth

The stadium project was a complex product because of its size and geometrical non-uniformity (product multiplicity). Interviewees stated repeatedly that every panel in the stadium was unique.

Organizationally, the project was complex in some respects and simple in others (see top middle plot in Figure 6). The project involved government representatives, many sub-contractors and fabricators, and many different designers (organizational multiplicity). Also, it was vulnerable to a wide variety of public organizations outside the immediate project team (organizational openness). However, the organization was simple since team members had delineated roles (organizational synergy) with clear lines of hierarchy (organizational causal connections). The process was complex, because design was influenced by constructability, making it difficult to separate contractor and designer tasks (process interdependence). Because decision makers were unclear, frequent iteration occurred (process causal connections).

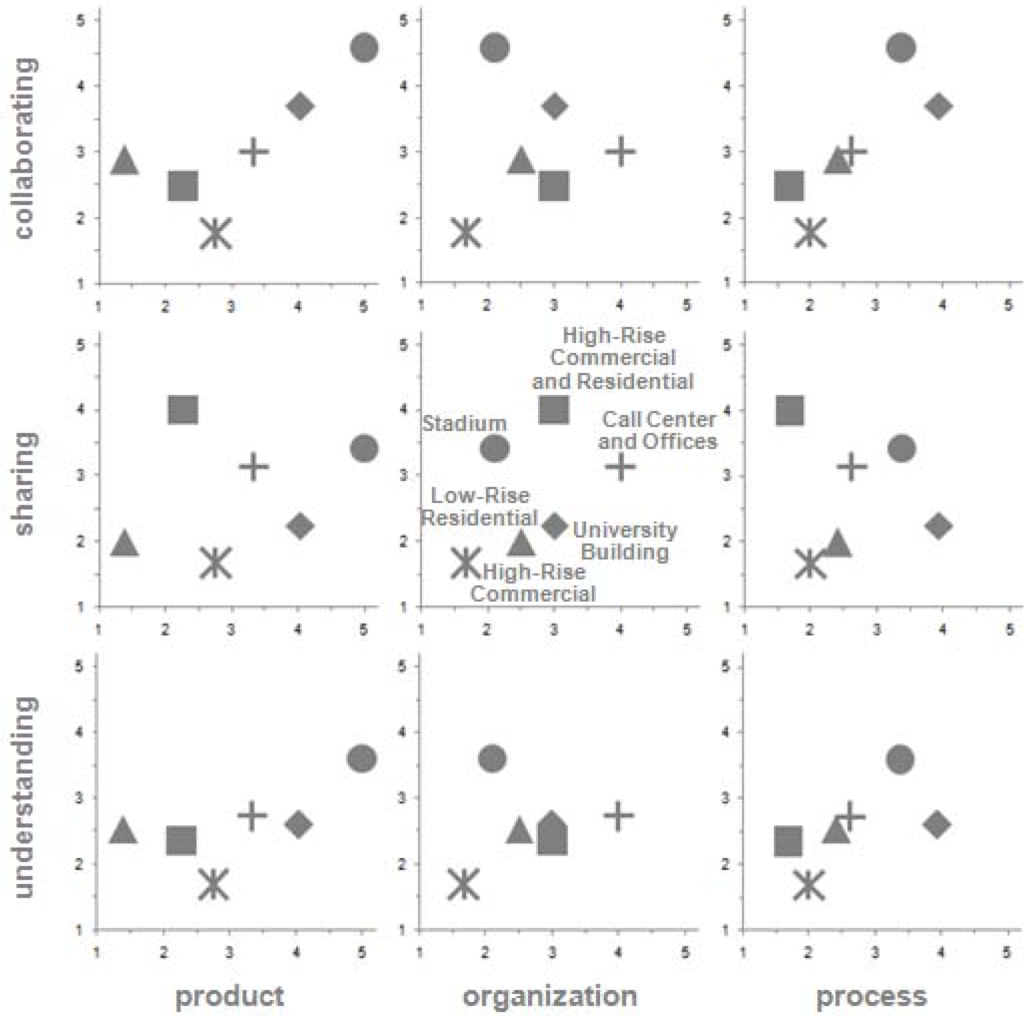

Figure 6: Disaggregated POP Complexity and Communication Trends. The strongest trends exist between product and process complexity and collaborating. Little evidence exists that sharing across projects is impacted by complexity. A less sensitive trend exists between product and process complexity and a company's ability to understand the project.

This complexity corresponded with many communication problems. For example, the organizational complexity inhibited team members from collaborating across discipline silos to make decisions. In one case, the contractor submitted an interior design option to an owner representative for approval. Neither the owner representative nor other stakeholders participated in the decision making, and the contractor lacked incentive to consider multi-disciplinary tradeoffs (collaboration – incentivized). At the same time, the team considered just one design option (collaboration – options) in one month (collaboration – speed). The project complexity also stifled efforts to maintain consistency (collaboration – consistency) in information management systems (the author observed a request to find an AutoCAD file that took 30 minutes to fulfill).

Sharing process information across projects was difficult, because the process is not documented. A Design Manager for the Contractor stated, 'he would like to link memos to build a story of what happened' (share – transparent). In one case, the Drafter explained how he needed to come up with a system for managing information from scratch. This example demonstrated that the company does not disseminate processes across projects (share-dissemination), perhaps because of organizational and process complexity. On the other hand, for information more easily standardized, such as material costs, and productivity rates, the company has a database shared across projects (share-standardized processes).

The ability of the contractor to understand the project to invest in improvement lagged only slightly behind the other projects. During a discussion about the cumbersome process of finding paper documents, the interviewee explained paper was both tradition and policy and many jobs were solely dedicated to managing the paper (understand-incentivized to innovate). It is more difficult for a large complex organization to quickly migrate to digital systems. Also, according to the project manager, 'we can't quantify the cost of running BIM nor the benefit of BIM so it's difficult to make a value proposition for introducing new technologies' (understand-measured time). Measuring complex and unique processes is more difficult than measuring simple frequently repeated processes. On the other hand, a quality assurance professional clearly strived toward ensuring no roof leakage and to provide traceability if leakage occurred (understand-measurable success). This definition of success and documentation of its achievement allows the company to compare different project processes and outcomes. Of course, while this professional had a well-scoped and measurable goal, the complexity of the project made many other goals more difficult to measure.

5.2.2 Low-Rise Residential Project in Depth

The low-rise residential project was relatively simple and communication excellent. The low-rise residential project contained many pre-packaged HVAC and electrical systems common across all the apartments, but also functioning independently (product interdependence). Also, the client was a real estate developer, contrasting with the many stakeholders on the stadium project. The client measured project success based on the number of apartments built on the site. This product goal was relatively unaffected by the outside environment (product openness) and clear to the entire team making collaboration easier (collaboration – clarity). Also, the site was highly constrained. Few feasible layout options existed and so, iteration was unnecessary (process causal connections). Also, the organization was hierarchical. For example, the geotechnical consultant gave a report to the architect and then, the architect gave the same report to the structural engineer (organization causal connections). The report did not have implications for the entire project, nor did the structural engineer have to work closely with the geotechnical engineer to develop a sophisticated foundation strategy. The process was also relatively simple since it seemed unimaginable to the team that they would miss drawing submission deadlines; all previous deadlines were met. This confidence and consistency suggests that it was easy to scope and predict tasks (process openness).

The team used Google Sketchup to communicate and reported that the tool effectively allowed the owner to connect with their designs (collaboration – clarity). It is easier for architects to use tools such as Sketchup to communicate designs of simpler buildings than complex buildings (Figure 6 top left).

They reported taking a week to create apartment layouts, because they worked closely with the structural engineers and developed an integrated design together (collaboration – integrated decisions).

The interview focused less on sharing, but some examples existed where the company created standardized processes for going between for example, parametric modeling tools and Microsoft Excel (share - standardized processes). Also, a senior associate in the office provided ample evidence that he was aware of global technology trends in the industry (share-awareness).

Relative to other projects, the architecture firm understood their current processes and invested in improvement. For example, the company categorized BIM projects and non-BIM projects (understanding - categorization). They considered tangible BIM investment costs such as hardware, software, human resource costs (understanding – measured time), and even when including these costs, measured increased profit on BIM projects. The company also invested in BIM technology at the corporate level (understanding – vertical understanding), though the investments themselves were not especially methodical (understanding-investing).

5.2.3 Disaggregating the larger trend

A trend exists when aggregating P, O, and P complexity into project complexity and collaboration, sharing, and understanding into communication (Figure 5). However, considering each component separately reveals a more nuanced relationship (Figure 6).

A trend exists between product and process complexity and collaboration problems (top left and top right). However, the middle column of Figure 6 reveals little insight into the impact of organization complexity on communication. Also, the middle row reveals little trend between POP complexity and sharing, suggesting that the complexity of one project is not indicative of how companies share information across projects. For example, the architecture firm that designed the low-rise apartment is a large global firm that works on many complex projects. Discovering a relationship between project complexity and sharing would require interviewing multiple project teams within the firm.

A trend exists between how product and process complexity impacts a company's ability to understand a project and invest in improvement, but this trend is less steep than the collaborating trend. For the stadium project, this trend is reasonable. The project was so complex that it was both difficult and there was little incentive to understand the project. But for the low-rise apartment building, the project's simplicity and the ability of the firm to understand the project strategically may have been circumstantial. More thorough investigation of complex projects by the same firm would be needed to confirm understanding increases with project complexity.

6 Conclusion

This paper describes two contributions to project information management literature. First, the paper describes a project complexity evaluation method and a communication evaluation method. The paper develops the first method by extending others definition of complexity to apply to products, organizations, and processes. The authors develop the communication evaluation method by revealing differences from interview statements. In both cases, the breadth of project types and measurement values demonstrate the method is both generalizable and powerful in its evaluative abilities. Second, the paper contributes evidence of a trend between a project's Product Organization and Process (POP) complexity and communication, defined as the POP2Com Technology Trend.

This trend between increased project complexity and poor process communication is unsustainable as the AEC industry must resort to more complex solutions to provide more financial, social, and environmental value to stakeholders. With current IT, the industry cannot continue to increase complexity (and corresponding project value) without increasing communication problems. Project teams need IT solutions with horizontal POP2Com curves insensitive to POP complexity. The authors hypothesize that this insensitivity requires IT solutions that make the relationships between product organization and process transparent. Such transparency will allow professionals to better communicate the value created by the complex interdependencies, and thus, deliver that value.

7 Discussion and Future Research

The paper applies inductive logic and does not seek to be hypothetico-deductive (i.e. the paper does not generalize results via correlation and causality analyses). For this reason, future work should focus on a quantitative study with statistical significance to accept or reject the described corollaries. For example, future studies could determine the steepness of the POP2Comcurve. Once determined, future researchers should also correlate results with existing methods of evaluating projects.

While this study did not evaluate the maturity of IT on the different projects, interviews provided insight on the state of IT. Many interviewees described how BIM enabled them to better communicate the building product. While communicating information about the organization may be challenging, interviewees infrequently cited this challenge as a major problem. On the other hand, many interviewees cited how their daily work was negatively impacted by poor process communication technology.

BIM may allow the communication of increasingly complex products and social networking tools may improve the ability to communicate information about organizations. However, throughout the interviews, the authors saw no technology that enabled process communication. More research is required to develop process communication methodologies that consider the (1) within project, (2) between project, and (3) across firm/industry requirements for efficient and effective exchange of process information.

8 Acknowledgements

The authors would like to thank the sponsors of this research including the Center for Integrated Facilities Engineering [CIFE] at Stanford University, California, USA; the School of Property, Construction and Project Management [PCPM] at RMIT University, Melbourne, Australia; and Arup.

The authors are also grateful for the openness and time generosity from each of the interviewees

9 References

Allen, P. M. (2008). "The importance of complexity for the research agenda in the built environment." *Archit. Eng. Des. Manage.*, 4(1), 5-14.

Allen, P. M., Sanglier, M., Engelen, G., and Boon, F. (1985). "Towards a new synthesis in the modeling of evolving complex systems." *Environ. and Planning B: Planning and Des.*, 12(1), 65-84.

Baccarini, D. (1996). "The concept of project complexity--a review." *Int. J. Project Manage.*, 14(4), 201-204.

Carrillo, P., and Chinowsky, P. (2006). "Exploiting knowledge management: The engineering and construction perspective." *J. Manage. Eng.*, 22(1), 2-10.

Conklin, J. (1996). *Designing organizational memory: Preserving intellectual assets in a knowledge economy*, CogNexus Institute, Glebe Creek, MD.

Crotty, M. (1998). *The foundations of social research: Meaning and perspective in the research process*, Sage Publications, London, UK.

Dossick, C. S., and Neff, G. (2010). "Organizational divisions in BIM-enabled commercial construction." *J. Const. Eng. Manage.*, 136(4), 459-467.

Eckert, C. M., and Clarkson, P. J. (2004). "If only i knew what you were going to do: Communication and planning in large organisations." *Methods and tools for co-operative and integrated design*, S. Tichkiewitch and D. Brissaud, eds., Kluwer Academic Publishers, Dordrecht, Netherlands, 375-384.

Eckert, C. M., Clarkson, P. J., and Stacey, M. K. (2001). "Information flow in engineering companies - problems and their causes." *Int. Conf. on Eng. Des.*, Professional Engineering Publishing, Suffolk, UK, 43-50.

Eisenhardt, K. M. (1989). "Building theories from case study research." *Acad. of Manage. Rev.*, 14(4), 532-550.

Erdogan, B., Anumba, C. J., Bouchlaghem, D., and Nielsen, Y. (2008). "Collaboration environments for construction: Implementation case studies." *J. Manage. Eng.*, 24(4), 234-244.

Foss, N. J., Husted, K., and Michailova, S. (2010). "Governing knowledge sharing in organizations: Levels of analysis, governance mechanisms, and research directions." *J. Manage. Stud.*, 47(3), 455-482.

Froese, T., and Han, Z. (2009). "Project information management and complexity in the construction industry." 26th Int. Conf. Managing IT in Constr., CIB W078, Istanbul, Turkey, 1-10.

Gane, V., and Haymaker, J. (2010). "Benchmarking current conceptual high-rise design processes." *J. Arch. Eng.*, 16(3), 100-111.

Garcia, A. C. B., Kunz, J., Ekstrom, M., and Kiviniemi, A. (2004). "Building a project ontology with extreme collaboration and virtual design and construction." *Adv. Eng. Inf.*, 18(2), 71-83.

Hansen, M. T., Nohria, N., and Tierney, T. (1999). "What's your strategy for managing knowledge?" *Harvard Bus. Rev.*, 77(2), 106-116.

Hargadon, A., and Sutton, R. I. (2000). "Building an innovation factory." *Harvard Bus. Rev.*, 78(3), 157-166.

Haymaker, J., Riker, and Chachere, J., Marvin. (2011). "Framework for measuring the rationale clarity of AEC design decisions." *J. Arch. Eng.*, in press.

Haymaker, J. R., Chachere, J. M., and Senescu, R. R. (2011). "Measuring and improving rationale clarity in a university office building design process." *J. Arch. Eng.*, in press.

Homer-Dixon, T., F. (2000). *The ingenuity gap: Facing the economic, environmental, and other challenges of an increasingly complex and unpredictable world*, Knopf, New York, NY.

Javernick-Will, A., Levitt, R., and Scott, W. R. (2008). "Mobilizing knowledge for international projects." *Proc. of the 2008 ASCE LEED Conf.*

Javernick-Will, A., and Levitt, R. E. (2010). "Mobilizing institutional knowledge for international projects." *J. Const. Eng. Manage.*, 136(4), 430-441.

Kivrak, S., Arslan, G., Dikmen, I., and Birgonul, M. T. (2008). "Capturing knowledge in construction projects: Knowledge platform for contractors." *J. Manage. Eng.*, 24(2), 87-95.

Kreiner, K. (2002). "Tacit knowledge management: The role of artifacts." *J. Knowledge Manage.*, 6(2), 112-123.

Kvan, T. (2000). "Collaborative design: What is it?" *Autom. Constr.*, 9(4), 409-415.

Laufer, A., Shapira, A., and Telem, D. (2008). "Communicating in dynamic conditions: How do on-site construction project managers do it?" *J. Manage. Eng.*, 24(2), 75-86.

Luiten, G. T., and Tolman, F. P. (1997). "Automating communication in civil engineering." *J. Const. Eng. Manage.*, 123(2), 113-120.

Maier, A. M., Kreimeyer, M., Hepperle, C., Eckert, C. M., Lindemann, U., and Clarkson, P. J. (2008). "Exploration of correlations between factors influencing communication in complex product development." *Concurrent Eng.*, 16(1), 37-59.

Marsh, L., and Flanagan, R. (2000). "Measuring the costs and benefits of information technology in construction." *Eng. Constr. Archit. Manage.*, 7(4), 423-435.

Otter, A. d., and Emmitt, S. (2008). "Design team communication and design task complexity: The preference for dialogues." *Archit. Eng. Des. Manage.*, 4(2), 121-129.

Otter, A. F. d., and Prins, M. (2002). "Architectural design management within the digital design team." *Eng. Const. Archit. Manage.*, 9(3), 162-173.

Rechtin, E. (1991). *Systems architecting: Creating and building complex systems*, Prentice Hall, Englewood Cliffs, NJ.

Senescu, R., and Haymaker, J. (2008). "Requirements for a process integration platform." *7th Int. Workshop on Social Intelligence Design: Designing Socially Aware Interactions*, Universidad de Puerto Rico, San Juan, Puerto Rico.

Senescu, R. R., and Haymaker, J. R. (2009). "Specifications for a social and technical environment for improving design process communication." *Proc. of the 26th Int. Conf. on IT in Constr.*, Istanbul Technical University, Istanbul, Turkey, 227-237.

Senescu, R. R., Haymaker, J. R., and Anderson, D. J. (2010). "PIP: A process communication web tool." *Modelling and Manage. of Eng. Processes*, Cambridge Univ., Cambridge, UK.

Taylor, J. E., and Bernstein, P. G. (2009). "Paradigm trajectories of building information modeling practice in project networks." *J. Manage. Eng.*, 25(2), 69-76.

Weber, M. (1947). *The theory of social and economic organization*, The Free Press, Glencoe, IL.

Yin, R. K. (2003). *Case study research: Design and methods*, Sage Publications, Thousand Oaks, CA.