

THE RELATIONSHIP BETWEEN INFORMATION FLOW AND PROJECT SUCCESS IN MULTI-DISCIPLINARY CIVIL ENGINEERING DESIGN

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ABSTRACT

Civil engineering projects are characterized by complex products developed by teams of consultants who have been selected for their individual unique skills and knowledge. One of the central difficulties in the work of a design team is to achieve smooth and continuous flow of information. Phenomena such as bottlenecks, rework, large batches and long cycle times are common. We hypothesize that these adversely impact the teamwork and reduce the quality of their work.

Tools developed to visualize the flows of information in the design process and a set of computed analytical measures designed to quantify the flows were applied to a sample set of 14 civil engineering projects that were part of a major airport construction project. The measures indicate the presence or absence of bottlenecks, rework, large batches and long cycle times. The degree of success of each of the design processes of the sample projects was recorded independently through a series of interviews with the various participants and stakeholders in the projects. Comparison between the occurrences of phenomena associated with poor information flow, on the one hand, and the degree of success of the detailed design phase of the projects, on the other, revealed a high degree of correlation.

KEY WORDS

Case studies, Design management, Information flow, Project management.

INTRODUCTION

Building and infrastructure projects require a variety of engineering and architectural skills. The need for multi-disciplinary expertise is a significant root cause of waste in the design process, because design teams are composed of multiple designers, are commonly composed ad-hoc for individual projects, and must produce a single coherent design through collaborative effort. The difficulty is exacerbated by the fact that the designers do not co-locate for the project, and tend to shift focus from project to project within their own design offices. While the behavior of commercially independent design consultants within collaborative teams is generally governed by the design contracts signed by each party with the client, the day-to-day functioning of such teams rests heavily on informal relationships and tacit understandings between the team members (Ford and Sterman 2003; Love et al. 2002).

While clients derive value from the facility that is eventually built, designers do not build per se, they produce information. Ideas, principles, rules and skills are applied to generate an abstract description (a building model or a set of drawings and specifications) that defines how a physical facility is to be formed. Information is also designers' raw material. Information must flow between designers, and that flow is a

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critical determinant of their ability to perform their work effectively and efficiently (Eckert et al. 2001; Gray and Hughes 2001; Moreau and Back 2000; Prasad et al. 1993). Inefficient flows of information result in numerous forms of waste:

- Rework follows wherever design has proceeded on the basis of outdated versions of other designers' drawings because newer information was not forthcoming (Ashford 1989; Love et al. 2000).
- Waiting for information leads designers to shift their attention to other projects, incurring the waste of renewed 'setup' times for familiarization with what was done earlier when work on a project is resumed;
- Overall project durations are extended and overhead and financing costs grow as local cycles of iteration are delayed or repeated due to negative iteration (Ballard 1998).

Unfortunately, the flow of information in dispersed design teams is not well understood, partly due to lack of theory and partly due to lack of measures (Tribelsky and Sacks 2007), and so it is frequently not managed well. Baldwin et al. (1999) found that understanding the process by which information flows between project participants is essential to improvement of design management.

We hypothesize that the phenomena that characterize poor flow in generic production systems, such as large batch sizes, long cycle times, flow bottlenecks and others, can be identified in flows of information in the detailed phase of civil engineering design, and that they are predictors of design process outcomes. If this could be shown to be true, then it would support the notion that project teams can improve the value they deliver by taking conscious steps to improve the information flows within their design teams. More specifically, it would indicate that the principles that guide flow improvement in production, such as single piece flow, cell production and pull control, might have a similar positive effect when applied to the detailed design process considered here (although of course their mode of application is different, comprising – in the same order – small batch sizes for information transfer, multi-skilling or co-location, and reverse phase scheduling).

INFORMATION FLOW IN DETAILED DESIGN

In current civil engineering practice, design information is still most commonly communicated in documents, whether electronic or paper. The information itself is intangible, and measurement of information flow in a design process must be based on a conceptual model of the information flow. A variety of conceptual models have been proposed. Fyall (2002) suggested analyzing information flow in organizations using concepts of fluid mechanics and proposed a measure of turbulence in information flow based on the 'Reynold's Number'. Krovi et al. (2003) also used the fluid mechanics metaphor, proposing fluid flow dynamics measures such as velocity, viscosity and volatility. Ostergaard and Summers (2007) modeled collaborative design and information flow using concepts of electrical current, including calculation of a resistance value for each task through which information must flow. Ballard (2000) considered the detailed design process to be similar to production processes in as far as inputs are transformed into outputs at various processing stations, making the distinction that while in the typical production process machines and workers produce tangible products, in the detailed design process consultants transform requirements and ideas into product design documents. Huovila et al. (1997) extended

the production process analogy to include conceptualization of the flow of information between activities in addition to the transformation at each workstation.

The production process flow analogy is widely accepted implicitly, in that numerous researchers and practitioners have advocated and explored application of design management techniques derived from techniques that were developed in production contexts. Examples include the Design Structure Matrix (DSM) approach (Steward 1981), the Toyota Product Development System (Morgan and Liker 2006), Theory of Constraints (Goldratt 1997), and Lean Design in the context of Lean Construction (Freire and Alarcon 2002). Most of the literature recognizes the principle difference between production and design concerning perception of waste: in production, variance among products and rework are considered waste, whereas design relies on iteration of some steps. Design comprises cycles of synthesis and analysis (Alexander 1964). In design, 'straw' values must often be set for some parameters to enable analysis, on which deeper understanding is gained, which generates value even if the design set proved unworkable (Ballard 1998).

Lean construction design research has identified a number of prescriptive actions, some of which relate to management of information flows. Formoso and Tzortzopoulos (Formoso et al. 1998) suggested value stream analysis to remove non-value adding tasks, strong focus on acquiring client requirements, stabilization of tasks with high variability, reduction of design cycle times, simplification of the process, increasing the transparency of the process itself to its participants, emphasis on completion of design stages before commencing subsequent steps, and definition of performance measures and monitoring of them through the design process. A set of guiding principles for lean design listed by Ballard and Zabelle (Ballard and Zabelle 2000) include: a) small information batches, i.e. sharing even partial information with all of the team, b) multi-disciplinary design teams that also include end user representatives, c) design within fixed distinct modules within a building, d) simultaneous engineering (product) design and construction (process) design, e) transfer of detailed design of specialized items to fabricators, and f) use of pull flow control. Principles a) and f) relate directly to the flow of information.

RESEARCH METHOD AND RESULTS

The research method consisted of:

- monitoring the information flows in fourteen sample projects,
- analysis of the data including computation of measures of information flow and flow interruption phenomena,
- elicit and compute independent subjective and objective measures of the success of the design process in each project, and finally;
- comparison of the flow measures with the design process success measures and examination for possible correlations.

The 14 projects in the sample, listed in Table 1, were all part of a major airport relocation whose total cost was estimated at \$250m and included 85 individual sub-projects. The subset was selected randomly from the larger and mid-size projects of three types (civil works, building construction and infrastructure systems). The first author's affiliation to the client's project team provided him a unique degree of access to the projects and their design teams, which included open access to all project files

and communications on the project extranet and to all other documents, unobtrusive participation in project design meetings, and interviews with all the designers.

Since all the projects were procured by a single client, they had similar profiles, making it easier to compare them. However, each project had a different set of subcontracted design firms (14 on average) and a different subcontracted project manager.

Table 1: Profiles of the projects examined.

Project type	Built area (m²)	Budget (Million \$)	Number of file transactions	Time span (days)	Number of design firms/disciplines
A Residential buildings	5,000	4.5	4,870	182	14
B Runway	230,000	26.5	3,650	545	16
C Airplane park	250,000	20.7	13,355	188	15
D Sewage pumping station	320	1.4	2,457	456	12
E Control tower	800	4.2	6,515	303	16
F Communication centre	1,300	3.0	5,627	365	16
G Infrastructure facilities	NA	22.4	6,879	527	11
H Office building	1320	4.2	4,409	226	13
I Workshops	2,500	2.8	3,232	430	16
J Office building	340	1.1	3,488	487	14
K Airplane hangar	7,300	8.5	4,734	462	16
L Fuel delivery pipeline	NA	2.5	4,114	466	11
M Office building	1,900	3.9	2,470	282	15
N Residential building	1,700	1.5	4,248	182	11

Empirical data was collected for each project from the communication and file transfer data log compiled automatically by the commercial project management extranet application used to manage the projects. The application used the internet for centralized management of all project information, including CAD files, meeting summaries, presentations, time tables, task assignments and additional information. For each transaction, the log recorded the time at which it was performed, the name of the actor and the file names where relevant. The journal logs provided a large sample of documented, detailed and reliable information over extended periods for all the 14 projects; a total of 70,048 transactions were recorded and used.

In addition, selected drawings from each project were analyzed for changes to provide the data necessary for evaluating design information development. This was necessary because the transaction records provided no information about the content of the files. All the versions of every drawing uploaded to the system throughout the life of the projects were available. By comparing a drawing version to its predecessor and by tracking the changes in the drawings using automated review and compare software (Autovue, Cimmetry Systems 2006), the nature and quality of the changes made from version to version in sample drawing sets can be examined.

MONITORING INFORMATION FLOWS – OBSERVATIONS

Structured observations were made of 86 design progress meetings. The researcher observing the meetings prepared a detailed protocol of the discussions, examined the documents that were used, and recorded each participant’s behavior in terms of

sharing the information they held. The occurrence of five specific phenomena of interest, from the point of view of design information flow based on the lean production flow conceptualization described above, was monitored. The phenomena are flow bottlenecks, rework, large batch sizes, high levels of work in progress (WIP) and failure to meet client needs (Hopp and Spearman 1996; Koskela 2000).

These observations enabled collection of complementary information concerning design contents and contexts, the dynamics of the participants and their activities and the general progress of each project. These were important in assessing the impact of the background conditions that influenced the quality of the information flow and the success of the projects.

ANALYSIS OF INFORMATION FLOWS

In this step, a specialized technique for measuring information flows including seven numerical indices of flow characteristics were used to independently identify and verify the presence and intensity of the five characteristics of process flow outlined above. The basic numerical indices were developed by Tribelsky and Sacks (Tribelsky and Sacks 2010) to assist in quantifying and characterizing design project information flows. They measure rates and patterns of generation of design information, dissemination, batching, and other features. They are listed in Table . Detailed definitions can be found in (Tribelsky and Sacks 2010). The results from their analysis are shown in Table 3.

Table 2. Information Flow Indices

Index	Description	Symbols	Units
Action rate	The rate at which information is transferred	AR	Actions/time
Package size	Quantifies the level of detail of information packages	PS	Information attributes
Work in Process	The number of available but unused information packages	WIP	Information packages
Batch size	The batch volume of information transferred	BS	Information attributes
Development velocity	The velocity of information development as represented by accumulation of detail	DV	Information attributes/ time
Bottlenecks	Identifies possible bottleneck partners in the process at any given time	BN	
Rework	Quantify the rework included in information packages.	RW	Information attributes

INDEPENDENT MEASURES OF DESIGN PROCESS SUCCESS

Measuring the success of a design process is neither simple nor definitive. Some define project success according to the extent to which the project fulfils the clients' needs, while others consider the extent to which the project budget and design schedule targets are met. The quality of the design documents (assessed in terms of design errors and inconsistencies in the models, drawings or other documents) is another possible measure. Three independent assessment methods were employed:

1. Analysis of the design documents produced using a method developed by Chang and Ibbs (1999). The method assesses the design products using a

weighted scale of eleven attributes, classified into groups for constructability, usability and accuracy. Each attribute was evaluated on a three point scale. The results are shown in Table 4.

2. Interviews with the client representative and with the project manager of each project, in which they were asked to rate their degree of satisfaction with the results of the design process itself. The scale ranged from 'very dissatisfied' (1) to 'fully satisfied' (5). The client representatives each dealt with some 40 projects within the overall project, and the project managers with some 10 each, so that they were able to provide a broad perspective on the few projects from the sample of 14 concerning which they were interviewed. The lead researcher, who participated in the design review meetings and examined the documents produced, provided a third opinion for each project (see Table).
3. Finally, the ratio of the final design estimate of the construction cost to the initial project budget, and the ratio of the actual to the planned design phase duration, were computed for all projects (see Table). The effects of client-initiated design changes on cost and design duration were taken into account.

Table 3. Waste phenomena identified from information flow indices

Phenomena Observed Project	Bottle-necks	Rework	Large batch sizes	High levels of work in Progress	Failure to meet client needs	Frequency of waste phenomena
A	-	○	●	●	○	6
B	-	●	-	○	○	4
C	-	●	○	○	-	4
D	●	-	○	○	-	4
E	○	●	○	○	○	6
F	-	-	☒	☒	-	0
G	-	-	☒	☒	-	0
H	-	-	○	○	-	2
I	●	●	●	○	●	9
J	○	-	●	○	○	5
K	●	○	-	-	○	4
L	●	●	-	○	-	5
M	○	●	○	○	○	6
N	-	-	○	●	-	3

- Strong (2): the phenomenon appears consistently throughout the project duration.
- Weak (1): the phenomenon appears clearly, but with low intensity.
- None (0): the phenomenon was not observed in the data.
- ☒ Opposite: the inverse phenomenon occurred (i.e. small batch sizes, low WIP).

ANALYSIS AND DISCUSSION

The different measures relate to conceptually different aspects of the projects. The standards for determining success in each aspect differ widely, and they differ too for different clients according to their contexts. Any single aggregated measure of project success would be too abstract to be useful. It is therefore neither practical nor meaningful to attempt to compile a single parameter, made up of some weighted average of the various measures, to rate the degree of success of the design processes of the projects. Instead, comparisons between the project flow measures and the outcome measures were made separately for the different outcome measures.

Table 4. Effectiveness of design documents using Chang and Ibbs (1999) method.

Project	Constructability			Usability			Accuracy			Weighted and normalised effectiveness		
	Adaptability	Maintainability	Construction Knowledge	Const' Method and Time	Format	Conformance	Clarity	Completeness	Impacts of Error		No Errors and no Omissions	Consistency
A	-	○	○	-	○	-	○	○	●	○	●	57
B	●	○	-	●	-	●	○	-	-	-	○	51
C	-	○	●	○	○	○	○	●	-	○	○	63
D	-	●	●	-	●	-	●	●	○	●	●	86
E	-	●	●	○	●	○	●	○	-	○	○	74
F	○	●	●	-	●	○	○	●	○	●	●	91
G	●	●	○	●	○	○	○	○	○	○	○	80
H	●	●	○	○	●	○	○	●	-	○	○	80
I	○	○	○	-	●	○	○	○	●	-	○	63
J	○	-	○	○	○	●	○	○	○	○	○	63
K	-	●	●	○	●	○	●	●	○	○	○	86
L	-	-	●	○	●	○	●	●	-	○	-	63
M	○	○	○	○	●	○	○	○	○	○	-	63
N	○	○	○	-	●	○	●	●	-	●	●	80

Legend: ● Strong; ○ Medium; - Weak or none.

Table 5. Independent measures of the design process.

Project	Satisfaction with the design process				
	Project manager	Client rep.	Researcher	Budget overrun (%)	Schedule overrun (%)
A	2	-	3	-2.3	-47.6
B	4	-	3	-34.3	124.1
C	4	-	3	5.8	-5.4
D	3	2	1	13.7	-21.5
E	4	4	1	-2.0	22.0
F	2	2	3	1.4	-18.6
G	2	-	2	-20.3	2.0
H	3	4	1	-16.4	0.00
I	4	4	1	-29.1	10.4
J	4	5	1	-10.0	117.7
K	4	4	2	-10.7	127.0
L	4	3	3	-6.9	181.6
M	4	3	3	-3.0	-23.2
N	3	-	4	2.1	37.3
Average/ Median	3.3/4	3.2/3.5	3.1/3.5	-3.1/-2.7	36.1/6.21

Furthermore, each project had a rich history that cannot be fully captured in the quantitative or even the qualitative measures. First-hand observation of the project meetings and interviews with various participants provided the researcher with a comprehensive picture of the projects that extends beyond the measures. Thus while the discussion below builds primarily on the data collected and computed, it is also influenced by the researchers' subjective impressions.

In Fig. 1, the frequency of flow interruption phenomena data from Table are plotted against the design document measure results calculated using Chang and Ibbs'

method and listed in Table 4. The absolute value of the correlation co-efficient of the two sets of numbers is 0.61. This indicates that the more information flow waste phenomena are observed (where information flow is impeded), the design documents produced by the team tended to be of lower quality than for the projects where information flowed freely. The trend line computed for the data clearly shows the relationship between the two.

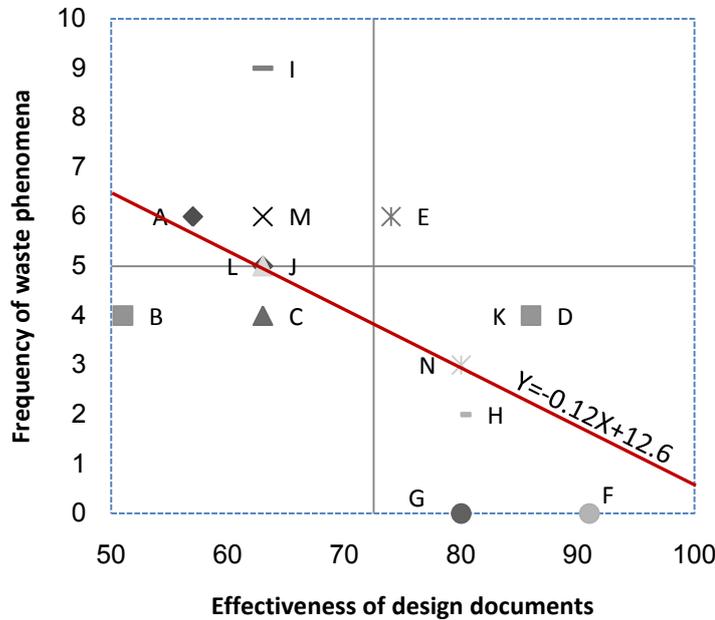


Fig. 1. Relationship between Chang & Ibbs' measure of the effectiveness of design documents and the frequency of occurrence of information flow waste phenomena.

The charts in Fig. 2 plot the data for the information flow waste phenomena against the degree to which each project met its budget and schedule targets. As the quality of the information flow worsens from project to project, the spread of the deviations for both budget and schedule grows. In other words, projects with smooth information flows appear more stable than those with interrupted or inefficient information flows. The projects with poorer information flows are less predictable, both in terms of their duration and the degree to which they meet their initial budget targets.

No clear correlation was found between the process flow interruption phenomena and the subjective reviews of design process on the part of the client and the project managers (see Fig. 3). Small positive correlation was found between the phenomena and the researcher's subjective review. The distinct lack of correlation between the project managers' subjective assessments of the design processes they managed and the actual nature of their information flows suggests that the managers were either unaware of the negative impact of poor information flows on their projects, or unwilling to admit the effect.

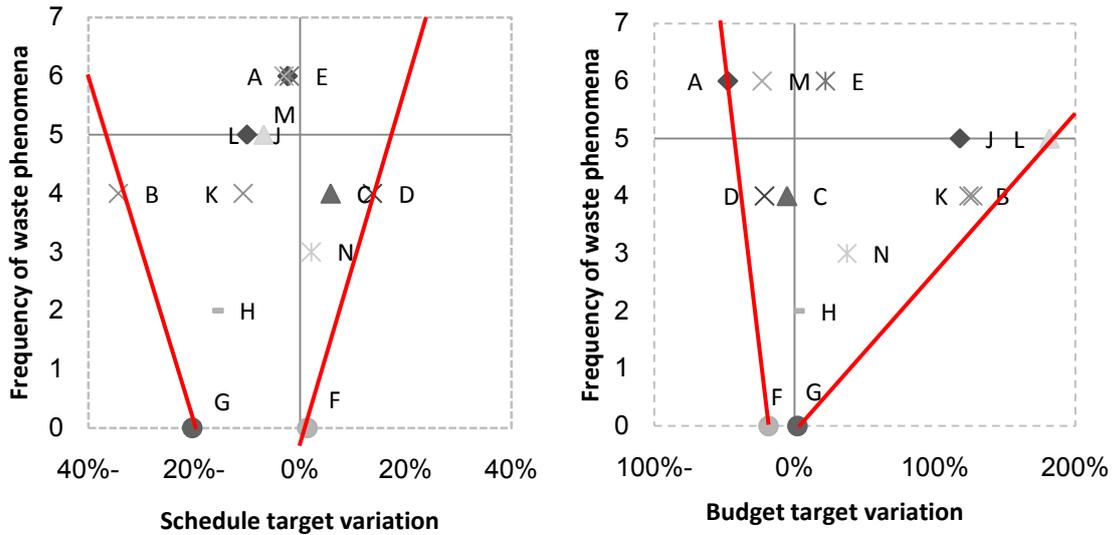


Fig. 2. Relationships between variation in meeting schedule and budget targets and the frequency of information flow waste phenomena.

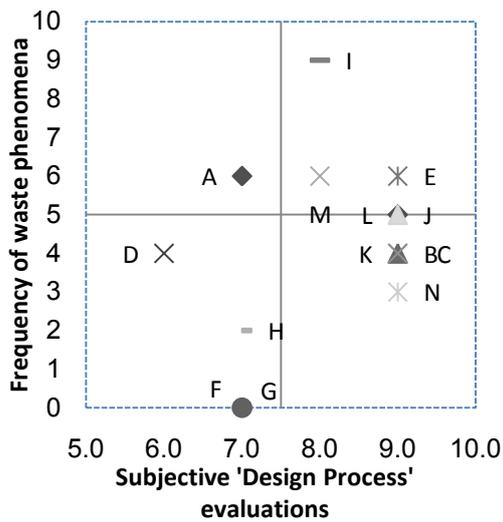


Fig. 3. Relationship between subjective evaluations of design process quality and the frequency of information flow waste phenomena.

CONCLUSIONS

This study sought evidence of possible correlation between the characteristics of information flow between design team members and the degree of success achieved in the detailed design phase of civil engineering projects. A case study research method was used, with a unique sample of fourteen independent projects. All of the projects had the same client and design procurement methods, and all used the same information technologies, but they had different project managers and design team members. The primary differences between them were therefore limited to their management style, group dynamics, and the behaviors of design team members.

The information flows were characterized in terms of measures drawn from the concepts of lean thinking, such as flow bottlenecks, rework, large batches and cycle time, which were monitored and computed analytically using a set of five information flow indices. These were supplemented with detailed observations of background factors (such as degree of cooperation, design program maturity, leadership style, team spirit, geographical dispersion, meeting frequency and intensity of design

review). The degree of success was measured in terms of the effectiveness of the design documents that were produced, the projects' success or failure in meeting targets of budget, schedule and client expectations, and supplemented by subjective assessments collected in interviews with key personnel from all the projects.

The results show a direct empirical relationship between the objective measures of information flow and the measures of the effectiveness of design documents. As can be seen in Fig. 1, stable information flow with lower occurrence of flow interruption phenomena correlated reasonably well with higher quality design documents. Similarly, the degree to which projects vary in terms of meeting budget and schedule targets appears to correlate with the frequency of occurrence of phenomena that indicate disruption of smooth information flows.

However, correlation between subjective impressions of a project's success on the part of its participants, including the client, and the quality of information flows, could not be proven. This was true both for their assessments of the final product and of the design process itself (Fig. 3). Interestingly, there was similarly no clear correlation between the design teams' evaluations of their own successes and the degree to which they succeeded in meeting budget or schedule targets.

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