REDUCING REWORK IN DESIGN BY COMPARING STRUCTURAL COMPLEXITY USING A MULTI DOMAIN MATRIX

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ABSTRACT

Complexity in design causes iteration which can be value-adding or wasteful. Wasteful iteration, called rework, may stem from inefficient information flow in design. This paper focuses on the structural complexity of information flow, and on the identification of root causes of the resulting rework. We propose that one can identify root causes for rework in the design phase of a project by (1) making actual information flow transparent and by (2) comparing actual information flow to planned information flow. After identifying misalignments between actual- and planned information flow, one can find their root causes, and then address those causes in order to reduce rework in design.

We use a Multi Domain Matrix to deduce actual ('As is') and planned ('Should') information flow and then apply the Delta-Design Structure Matrix to compare the structures of the 'Should-' with the 'As is' perspective. The proposed hypotheses, "Comparing structural complexity between the 'Should-' and the 'As is' perspective helps to identify misalignments" and "Reduction of misalignments between actual- and planned information flow reduces rework in design" were tested during the detailed design phase of a project. The Multi Domain Matrix and Design Structure Matrix were successfully applied: comparison of structural complexity aided in making actual information flow transparent and in reducing rework.

KEYWORDS

Structural Complexity, Design Structure Matrix (DSM), Multi Domain Matrix (MDM), Lean Design, Building Information Modeling (BIM), Virtual Design and Construction (VDC).

INTRODUCTION

Designing a building requires a number of different skills, typically provided by experts who work for different companies, and those skills may differ from project to project. Accordingly, participants on project teams tend to not have worked together

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before. Nevertheless, those experts must collaborate to generate as well as assess design criteria and design alternatives, so as to achieve a design that delivers value to project stakeholders. In the process of learning about criteria and alternatives, experts exchange information, i.e., information flows between those who are part of their project organization.

To plan information flow and to optimize the sequence of design tasks, one may use tools such as the process-based Design Structure Matrix (DSM) (Browning 2001). The quality of data used to build such a DSM is crucial for the success of DSM application. Therefore, we suggest checking the quality of planned information flow (as defined using the process-based DSM) by comparing it to actual information flow, in order to find root causes for differences between them. Our methodology, based on the Multi Domain Matrix, aims (1) to make actual information flow in a design organization transparent and (2) to ease identification of root causes for differences between actual and planned information flow.

The paper is structured as follows. First, we highlight some characteristics of design processes and the application of lean thinking in design. Second, we present the methodology (1) for making actual information flows transparent and (2) for comparing actual- to planned information flow in order to find root causes for differences. Third, we propose hypotheses and describe the research approach. Fourth, we expand on an action-research case study where we implemented the methodology, and last, we close with conclusions.

LITERATURE REVIEW

THE TASK OF DESIGN

Koskela and Kagioglou (2006) describe the task of design as oscillating between analysis of problems and synthesis of solutions. Through oscillation, designers gain knowledge about design criteria and alternatives. Albers and Meboldt (2007) argue from a Systems Engineering perspective that an efficient "operating system" defines design criteria continuously to realize a successful design alternative.

Designers often deal with 'wicked problems:' these are indeterminate problems, i.e., problems that have "no definite formulation" (Rittel and Webber 1973). Thus, while acquiring knowledge about design criteria and alternatives, the operating system is subject to complexity. Complexity surfaces in the design process through iteration between tasks.

LEAN IN DESIGN

'Designing' differs from 'making' in at least 3 ways: (1) The 'matter' of designers is information. While material flow in 'making' is mostly visible, information flow in 'designing' can be invisible. This makes it harder to trace the actual flow of information. (2) Complexity hinders the identification of waste in design, and it is often the case that necessary vs. non-value adding tasks can be differentiated only after the design has been completed (e.g., Browning 2003). (3) Iteration in 'making' represents waste, whereas iteration in 'designing' may offer an opportunity for designers to deepen their understanding of the task and explore alternatives, so that they can deliver an outcome of greater value to the customer. Value-adding iteration is to be encouraged. Iteration is called wasteful if it can be eliminated from the process without a loss of value or risking the success of the project; this so-called negative iteration (Ballard 2000) should be avoided.

Some information flows in design are wasteful. Several sources of waste have been named in design: These include the 7 sources as defined by Ohno (1988), and others such as ‘make do’ (Koskela 2004), and ‘not listening’ and ‘not speaking’ (Macomber and Howell 2004). This paper focuses on negative iteration, here called rework, due to wasteful information flow. Rework can be an effect of other sources of waste (Bauch 2004) and rework can be the cause for waiting time for information and extension of schedule and project cost (Tribelsky and Sacks 2010).

DESIGN STRUCTURE MATRIX AND MULTI DOMAIN MATRIX

The Design Structure Matrix (DSM) (Steward 1981) is a means to manage information flow. It has been successfully applied for mapping processes and optimizing the sequence of design tasks. Elements and dependencies between these elements in any given domain are represented by a DSM. Domain Mapping Matrices (DMM) (Danilovic and Browning 2004) then connect the DSMs. Together these matrices form the MDM (Maurer 2007). DSM and MDM have been successfully applied the Architecture-Engineering-Construction (AEC) industry (e.g., Huovila et al. 1995, Austin et al. 2000, Furtmeier et al. 2010).

Although DSM and MDM are relatively simple modeling tools, their ability to map iteration makes them powerful relative to, e.g., schedule networks used in the critical path method. The matrix format enables the use of algorithms to optimize the sequence of elements in the matrix, and it enables the deduction of dependencies and the comparison of relationships between elements through mathematical operations.

Increase quality of input information for Process-DSM formation

Ballard (2000) recommends using the DSM as a tool to reduce rework in design by finding an optimal sequence of tasks. Algorithms, e.g., as implemented in ADePT (Austin et al. 2000), aid design managers in finding the optimal sequence of tasks based on the process model. However, the optimal sequence of design tasks—as delivered by a DSM-sequencing algorithm—depends on the identified process model: If tasks or dependencies between tasks are missing from the DSM, enforcing the calculated sequence may cause waste and failure to deliver customer value. MDM application can increase the quality of the DSM process model (Elezi et al. 2010).

Learn from deviations from the planned process

Sosa et al. (2004) computed a Delta-DSM to find differences in the structure between two DSMs, specifically differences between product structure and actual team interaction. Kreimeyer et al. (2007) applied MDM and Delta-DSM to find differences between planned process structure and planned organizational structure.

Koskela (2000) names several factors that push the process away from the planned sequence. Deviations from the planned process can be found by comparing planned- to actual information flow. MDM and Delta-DSM in combination makes it easy to compare a large number of indicators for actual- and planned information flow, and thus to identify deviations.

IDENTIFY DEVIATIONS FROM PLANNED PROCESS WITH MDM

The goal of MDM application is to reveal actual information flow between design experts and then find deviations from the planned design process. Thus, we compare two perspectives: (1) Planned information flow called the ‘Should’ perspective and (2) actual information flow called the ‘As is’ perspective.

Documentation of actual information flow is time-consuming and sometimes even infeasible, because information flow in design can be invisible. We therefore propose the use of indicators to approximate information flow. Indicators can be:

- From the Process Domain: Process maps or documents in circulation,
- From the Product Domain: Modular product structure or error indications from the product model, e.g., BIM clashes,
- From the Organization Domain: Office layouts and seating plans, email lists, organizational structure charts, or surveys to characterize communication between designers.

Both the ‘Should-’ and the ‘As is’ perspective can consist of 1 or more datasets. These datasets are deduced using MDM methodology (Maurer 2007). Using MDMs, one can deduce indirect dependencies that connect elements of the domain in question through elements of other domains. Deduction is carried out by matrix multiplication: Indirect dependencies in the domain in question are calculated by multiplying the DSM of the indirect domain with DMMs.

All indicators for information flow are deduced to the organization domain: We work with the assumption that designers can relate better to their information exchange with other designers, than they can relate to the abstract exchange of information between tasks of a process map. Root cause analysis becomes more tangible for designers, when analyzing information flow between their peers. Thus, we define the organization domain as the base for comparison of information flow and DMMs that connect the organization domain can be interpreted as an affiliation matrix: They show the relation of a person to an element of the indicator domain.

Figure 1 shows in lines (1) and (2) examples of MDM deduction of the ‘Should-’ and ‘As is’ perspectives. The notation ‘X’ inside the matrices represents a dependency between the elements of the respective line and column of the matrix. In line (1) the DSM ‘Information flow, should’ (elements of the domain represented by capital letters) is deduced by multiplying the DSM of the indicator domain (elements represented by numbers) with the DMM and transposed DMM that connect both DSMs. In this example, the indicating domain could be, for example, a process map in which person C is responsible for completing tasks 3 and 4 (as shown in the DMMs). Since task 3 depends only on input from task 2, and task 4 depends only on input from task 3, the dependencies between tasks 2, 3, and 4 (in the DSM ‘Indicator, should’) can be aggregated into the indirect dependency between person B and person C in the DSM ‘Information flow, should’. Line (2) follows the same logic: Elements of the DSM ‘Information flow, as is’ are represented by lower-case letters. Line (3) shows the calculation of the Delta DSM between ‘Should-’ and ‘As is’ perspective. ‘M’ stands for matched-, ‘E’ for expected-, ‘A’ for additional information flow.

In case one of the domains consists of more than one data-set (when comparing 3 or more DSMs), the fields of Delta DSM show tuples. These tuples (in the case of 3 DSMs, e.g., [M;M;M]) show the relation between the ‘layers’ of the Delta-DSM.

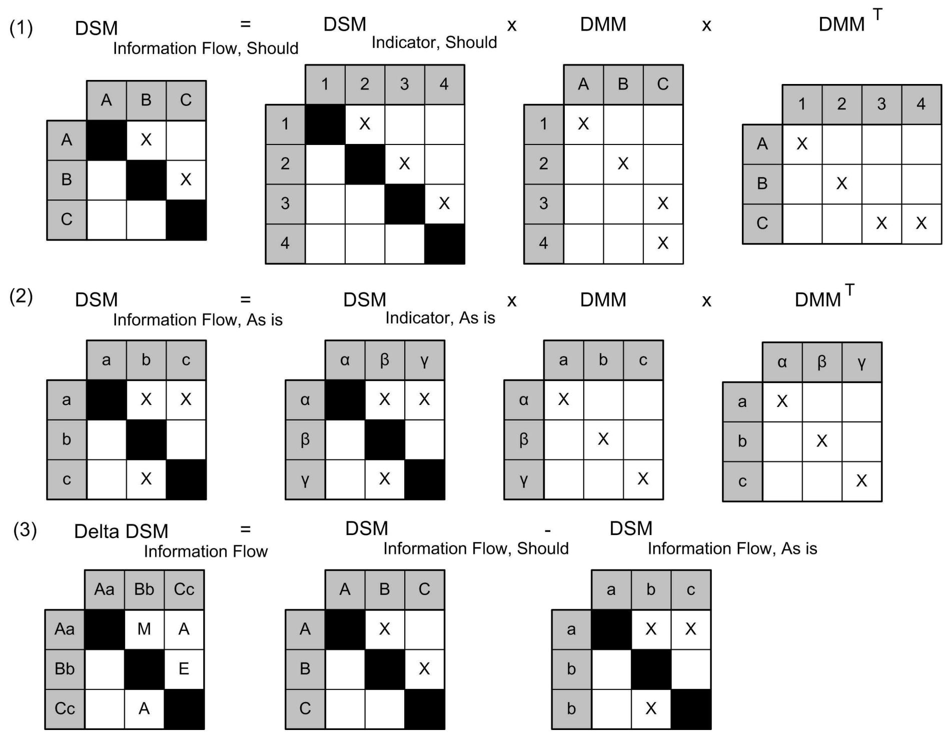

Figure 1: Formulas (1) and (2) for deduction of 'Should-' and 'As is' perspective of information flow, and formula (3) for calculation of Delta-DSM; based on (Maurer 2007, Sosa et al. 2004).

Occurrence of expected and additional information flow can give insights into differences between the 'Should-' and the 'As is' perspective; differences known as misalignments of information flow.

FRAMEWORK FOR PRACTICAL IMPLEMENTATION

Comparison of the 'Should-' with the 'As is' perspective is a collaborative effort for the design team. Reasons for misalignments can be manifold: Either people did not exchange information as they 'Should' have, the 'Should' perspective is wrongly defined, or both. Expert knowledge about the purposes of information flow is necessary to identify the root causes of misalignment.

Thus, we propose a workshop setting in which to conduct the comparison and analysis: Visualization of the 'Should-' and the 'As is' perspective with force-directed graphs (e.g., Figure 2) aids in identifying misalignment. Root-cause analysis, e.g., using 5 Whys (Ohno 1988), aids in finding reasons for misalignment.

The presented MDM approach makes the actual information flow transparent. This transparency may serve learning cycles by comparing actual- to planned information flow. Learning can improve the quality of the planned process and mitigate factors that tend to push to process away from the planned sequence. Thus, the workshop may be relates to the Check stage of a PDCA cycle (Deming 2000).

HYPOTHESES

To test the proposed methodology in a case study we define two hypotheses: (1) Comparing structural complexity between the 'Should-' and the 'As is' perspective helps to identify misalignments, and (2) Reduction of misalignments between actual- and planned information flow reduces rework in design.

RESEARCH METHOD

The first author joined the team involved in the detailed design phase of a project. During the first part of his action research, he documented the detailed design process through case-study research. He then led a workshop to implement the methodology. After completion of the workshop he again documented work on the project to compare the processes before- and after implementation of the presented methodology. We present the findings of this work next.

CASE STUDY: MDM AS A TOOL TO IMPROVE BIM DEVELOPMENT

The setting of this case study is the $1.7 billion Cathedral Hill Hospital (CHH) Project in San Francisco, California. In part due to seismic code regulations in this state, the design of hospitals is complex. In the detailing phase, designers created an integrated 3D-model of the building using BIM. BIM developers for different trade partners, here called 'detailers,' were collocated in one office among other experts so that they could communicate easily and solve conflicts quickly.

A challenge in the AEC industry is to fit highly interconnected systems into small spaces, while meeting numerous functional requirements yet maximizing open spaces (rooms) for operational building use. Design of these dense spaces can be critical for project success. A critical question of the detailed design phase is 'How will the model be built?'. The process of developing the BIM model needs to be designed according to the characteristics of the project and the capabilities of those involved.

INFORMATION FLOW IN BIM DEVELOPMENT

BIM users aim to achieve an error-free model during design in order to avoid costly rework during construction. They perform clash detection, that is, they use BIM to identify spatially conflicting building parts. 'Hard clashes' refer to parts occupying the same space. 'Soft clashes' refer to parts being within a certain distance of each other. To resolve clashes, BIM users must rework the contents of the model. Rather than doing such rework, lean BIM developers will want to avoid errors (including clashes) upfront. Clash avoidance needs a well-defined development process according to which to populate the BIM model. Exactly how to develop such a process, designed to the characteristics of the actual project, is still a research question. BIM users may find the Plan-Do-Check-Act (PDCA) cycle useful to continuously improve their BIM development process, so as to adapt it to the characteristics of the actual project as it unfolds.

MODELING APPROACH

BIM users will want to identify misalignments between the 'Should-' and the 'As is' perspective, and then find root causes for them, so they can begin to improve their processes. Conflicts in the BIM are an indicator of the quality of communication between model developers, because the resolution of each conflict will need communication between the developers who worked on the conflicting components and possibly others. The seating chart of members of the collocated project team can serve as an indicator of the quality of communication between developers, based on the observation that the probability of communication between developers decreases as the physical distance between them increases (Allen 1977).

Accordingly, an integrated model for BIM modelers to identify misalignments can build on input from at least three domains:

1. Process Domain: the BIM clash detection process is an indicator for the 'Should' perspective of information flow,
2. Product Domain: Conflicts between building systems are an indicator for the 'As is' perspective of information flow,
3. Organization Domain: The seating chart serves as a second indicator for the 'As is' perspective of information flow between developers.

Process and Product Domain are deduced into the Organization Domain for comparison of the 'As is-' with the 'Should' perspective. Clashes in the product model connect developers in the organization domain: BIM developer A, developing system α, and BIM developer B, developing system β, need to communicate with each other when their systems clash. The planned tasks in the BIM development process connect these developers similarly. The Process-Organization DMM (for deducing the 'Should' perspective) was derived from the developers' responsibilities for detailing tasks. The Product-Organization DMM (for deducing the 'As is' perspective) was derived from the developers' ownership of systems during detailing. Development of the Process DSM (DSM 'Indicator, should'), the Product DSM (DSM 'Indicator, as is'), and the two aforementioned DMMs completed the process of collecting the so-called 'native' dependencies. In the next step, two DSMs were deduced: (1) The DSM 'Information flow, should', which shows the planned information flow between detailers, and (2) the DSM 'Information flow, as is', which shows the actual communication between detailers regarding clash resolution activities.

PRACTICAL IMPLEMENTATION

Analysis started with formation of the Delta-DSM by subtracting DSM 'Information flow, as is' from DSM 'Information flow, should'. The Delta-DSM shows a high number of additional information flow marks (A).

CORRESPONDENCE TO PDCA CYCLE

A comparison of information flows between planned and actual will reveal differences between the perspectives. This corresponds to the Check (in the PDCA cycle) of the planned process, and can then be followed by Act to improve the process.

Check Misalignments

The analysis was augmented using data from a seating chart showing people at their desks, collocated in the project office in a 'big room.' Detailers compared the DSMs 'Information flow, as is' (Figure 2), 'Information flow, should' (Figure 3), and the seating chart (Figure 4) visually in a workshop. Visual comparison directly showed structural differences of the graphs. The roles of detailers J and O demanded attention during root cause analysis with the project team: Detailers J and O are not connected to the rest of the organization in the 'Should' perspective, but they are in the center of the organization when viewed in the 'As is' perspective. The seating chart of the 'big room' revealed that detailer J was seated about 15 m away from others on the detailing team. Detailer O does not work in the 'big room,' but in an office several 100 km away.

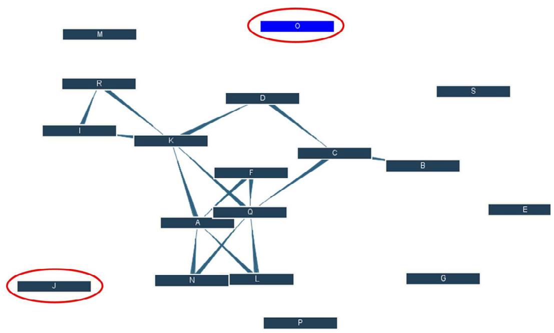

Figure 2: 'Should' perspective of information flow.

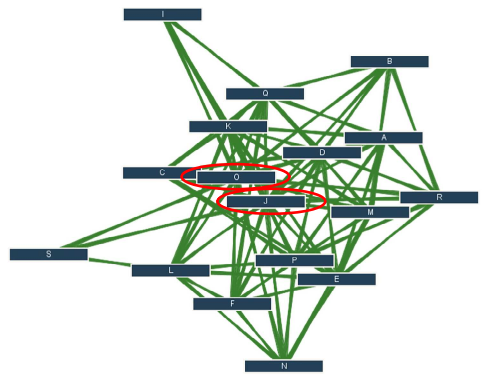

Figure 3: 'As is' perspective of information flow.

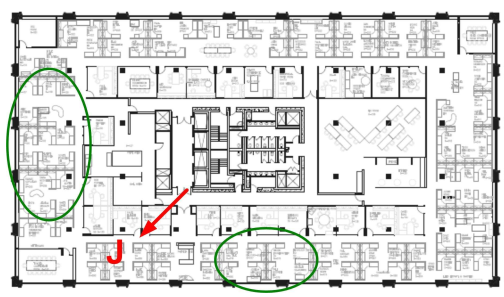

Figure 4: Seating chart of Collocated Project Team (circled areas indicate location of detailing team).

Both detailers worked on detailing space partitions (e.g., walls). Discussion with the project team revealed that critical framing (which is part of partitioning and includes, e.g., studs that cannot move due to corner positions) was usually disregarded by other trades during the detailing process. Root-cause analysis yielded three reasons for the disregard: (1) Critical framing was not part of the 'detailing' portion of the BIM development process at that time, (2) detailers did not load the partitioning layer into their 3D-modelling program even though the layer already existed, because the loading time of this layer is exceptionally long, and (3) the use of BIM for partitioning is a relatively recent development in the industry and other trades on the project were not used to integrate their work with that of partitioning BIMs.

Act to Improve

First, the 'Should' perspective (in this case: the BIM modeling process) was adjusted. The team agreed to integrate the task of modeling 'critical framing' into the detailing portion of the process. Second, the organizational structure was modified. A new standard process was developed to integrate detailer O with the rest of the team despite the physical distance of his office relative to the collocated office. Also, team members introduced actions to improve communication with Detailer J. Third, an A3 report was started to identify reasons for long loading times of BIM layers and remedial actions.

CONCLUSIONS

This paper presented a methodology for MDM application to align actual- and planned information flow, together with guidelines for analyzing the resulting Delta-DSM. It described a workshop approach for practical application of this methodology and implementation of PDCA learning cycles.

Regarding Hypothesis 1, we found that application of the methodology made the actual information flow transparent and directly helped the detailing team find root causes for misalignment. Regarding Hypothesis 2, we found that aligning the ‘Should-’ with the ‘As is’ perspective, through measures defined by project participants during Act of the PDCA cycle, reduced rework in the next repetitive application of the detailing process. Follow-up interviews revealed that detailers appreciated being confronted with the actual information flow: they wanted to see the causes for rework and the amount of rework due to avoidable clashes, and work towards clash avoidance within the team.

Identification of misalignment between actual and planned information flow improved the quality of the planned process and mitigated factors that tried to push the process away from its optimal sequence.

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