DESIGN STRUCTURE MATRIX (DSM) IMPLEMENTATION ON A SEISMIC RETROFIT

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ABSTRACT

A void exists in the practical application and theoretical development of design theory methodologies within the structural engineering (SE) community. This void contributes to project performance deficiencies as characterized by, e.g., cost over-runs, rework, and sub-optimal design. In the manufacturing sector, product design and production improvements have resulted from implementation of the design structure matrix (DSM) methodology. DSM offers a means to represent, analyse, and decompose complex systems in order to improve their performance. DSM has been used within the architecture engineering construction (AEC) industry and is becoming more readily available thanks to recent developments of project specific DSM scheduling software. DSM helps design teams streamline their processes (so that process steps can be executed sequentially) vs. identify situations when iteration is to be expected or group meetings can be called for brainstorming and rapid feedback. This paper examines a case study where DSM-based planning software was used on a seismic retrofit project. It demonstrates how lean practitioners can use DSM to fill the gap when translating a sticky-note schedule showing hand-offs into an activity network with various types of dependencies, and how that, in turn, can be translated into a schedule.

KEY WORDS

design, design structure matrix, DSM, lean construction, structural engineering, scheduling, dependence, oba, oobeya, big room, building information modeling (BIM), laser scanning

INTRODUCTION

The concept of "production system" is defined by the lean community as the designing and making of a product (Ballard et al. 2001). Production is therefore understood as the process of value conceptualization through design and subsequent realization through physical transformation in construction. Production system design or "work structuring" means to develop a project's process design while trying to align engineering design, supply chain, resource allocation, and assembly efforts (Ballard 1999, Tsao et al. 2000). These concepts of production and system optimization are rooted in the manufacturing sector. As a result, the understanding of *temporary* production system theory as applied to projects is

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skewed toward a focus on realization rather than conceptualization.

Work structuring during design, also referred to as "work planning" in the architecture engineering construction (AEC) industry, focuses on arranging information flows (generation, synthesis, distribution and collection) throughout the design process. The goals of work planning are similar to those of work structuring, namely to maximize value and minimize waste throughout the production system (Ballard et al. 2001). Closely tied to work planning is an understanding that there will be iteration within the design process (Ballard 2000a). Maximizing value-adding positive iteration and minimizing wasteful negative iteration are goals that lead to overall process optimization. These goals are achieved through the timely synthesis of information as required to enable teams to make decisions and realize value. In this context, the Design Structure Matrix (DSM) is a useful methodology as it helps design teams streamline their processes (process steps can be executed sequentially) vs. identify situations when iteration is to be expected or group meetings can be called for brainstorming and rapid feedback. Work planning using DSM and can enhance project outcomes. We illustrate that in this paper, by presenting case study where DSM-based planning software was used on a seismic retrofit project.

DESIGN STRUCTURE MATRIX DEFINITION AND METHODOLOGY

The DSM is a representation and analysis tool for system modeling, especially to help with decomposition and integration. Project based DSM is a dynamic form of DSM characterized by the mapping of dependency relationships within process domains. Parameter based DSM is a related method that traces critical system parameters through the design process to identify the sequence that affords the greatest transparency and control. The subject of this paper, project based DSM, assists in understanding activity inter-relationships and dependencies. Its goal is to shed light on optimal activity sequence, so that designers can realize overall process efficiencies through work planning and minimize unnecessary rework (Browning 2001). http://www.dsm.web.org presents additional references and tutorials on the DSM method. DSM functions as a design process aid to analyze highly inter-dependant systems. It offers richer modeling capabilities than CPM and PERT scheduling offer, as it explicitly addresses the issues of inter-dependency between process tasks introduced by necessary design iteration. "The techniques (DSM) can be used to develop an effective engineering plan, showing where estimates are to be used, how design iterations and reviews are to be handled, and how information flows during the design work" (Steward 1981).

The DSM modeling process requires three basic steps. The first two generate the process representation matrix and the third is analytical, involving the manipulation of the matrix. Step one decomposes a design project into a process with discrete activities, while identifying the required inputs, outputs, and information dependencies. Step two arranges activities sequentially in a square matrix with identical row and column identifiers. Numeric or binomial marks at row and column intersections identify a dependency relationship between activities. Binomial marks, made with an X or a 1, indicate dependency. Weighted numerical marks, from 0 to 1, describe identified dependency strength. More advanced formulations deploy the Likert scale or similar comparative ranking system. Marks that are symmetrical relative to the matrix diagonal are non-directional and indicate mutual (reciprocal) dependency. Marks that are non-symmetrical are directional and imply a precedence relationship between activities, e.g., they read as: "The activity in row *i*, is dependant upon activity in column *j*" (some papers in the literature reverse this order). Figure 1 illustrates a conceptual DSM. Crawley and Colson (2007) describe the link between object oriented process mapping and DSM.

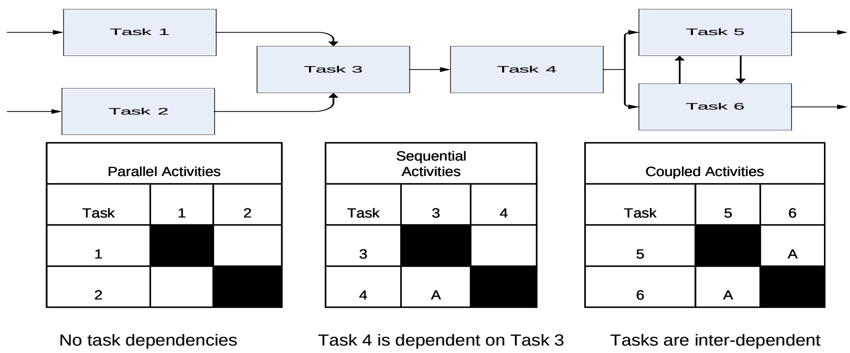

Figure 1: Representation of Schematic DSM

The last DSM step, referred to as triangularization or sequencing, involves analysis and manipulation of the assembled matrix. This can be done manually (e.g., Kusiak 1999) or in an automated fashion (e.g. Browning (2001). The activities located below and to the left of the diagonal are sequential and feed-forward information. The activities located above and to the right of the diagonal are out-of-sequence and require iteration and information feedback. The term "block" refers to a collection of activities bounded by feedback information. Three types of activity dependency are visually evident: (1) independent (concurrent/parallel or conditional), (2) dependant (sequential), and (3) inter-dependent (coupled) (adapted from Browning 2001). Kusiak (1999) further classifies dependencies by the nature of relationship including information, technology, commonsense, resource, preferential, or functional. The general sequential flow of information within the matrix is counter-clockwise based on dependency relationships between activities.

An additional step, referred to as tearing, involves breaking iterative loops. Tearing requires that dependencies be released and this can be done by making targeted design assumptions, and aggregating or decomposing activities.

DSM can be used to improve processes by properly sequencing activities, defining activity content, and introducing assumptions optimize information flow. Eppinger (2001) describes four information management opportunities in DSM, listed in optimal order of consideration. **(1) Rearrange task sequence.** Elimination of out-of-sequence work reduces iteration by rearranging activities to move marks to the feed-forward side of the diagonal. The activities are then further arranged to bring necessary feedback marks closer to the diagonal. This operation effectively reduces the number of activities impacted by iteration. **(2) Revisit task organization and definition.** The work content and clustering of feedback activities are modified in this step to eliminate the unnecessary work within iterative loops. Reorganization involves grouping a set of activities by internalizing an iterative sub-task or decomposing a larger activity into smaller parts to separate an iterative sub-task. Stand alone inter-dependent tasks with a large number of iterative activities are wasteful. **(3) Optimize (reduce or improve) knowledge flow between activities.** Information transfer is a necessary but potentially wasteful activity because it provides no value. It is analogous to material movement in production. Proper decomposition and redefinition of activities can reduce the need for information transfer. Design parameter assumptions allow for alternative activity definition and tearing of sub-cycles. Assumptions require validation following iteration. Activity clustering enables the collocation of teams, reducing information exchange. Institutional learning reduces repetitive information exchange. Effective information technology solutions, including Building Information Modeling (BIM) and web based project tracking software, optimize information transfer. To the extent possible, repositioning critical activities early increases the reliability of downstream flows. In cases, intermediate activity insertions allow for earlier information releases to down-stream activities. **(4) Identify and incorporate unplanned work.** Unplanned work counters optimization efforts. Comparison of observed vs. planned processes facilitates institutional learning and continuous improvement.

DEVELOPMENT OF DSM WITHIN THE AEC INDUSTRY

Huovilla et al. (1995) applied DSM to fast track construction and retroactively identified realized construction problems. The ADePT methodology marks the first use of DSM on conventional construction projects (Austin et al. 1997 and Austin 2000). Koskela et al. (1997) and Choo et al. (2004) propose constructs to couple DSM with the Last Planner™ system (Ballard 2000b). These proposals, now integral with ADePT, explore process efficiencies obtained by coupling DSM's ability to sequence work and the Last Planner™'s ability to increase plan reliability. The process parameter tool extends the flow of work (process) perspective developed by ADePT to consider the flow of information (information) perspective (Chua et al. 2003). Maheswari (2006) researched DSM based schedule collapse on an AEC project and reaffirmed that using DSM can positively impact AEC project outcomes.

CASE STUDY

The project studied is Building 511 (B511) at the Lawrence Livermore National Laboratory (LLNL) in

Livermore, California. B511 was built in 1942 and served as a Navy airplane assembly hanger throughout WWII. The Department of Energy converted the base to a research laboratory in 1950. Following several modifications, B511 now houses Plant Engineering, which supports infrastructure maintenance across.the LLNL. The structure, with a footprint of 79 m by 61 m (260 feet by 200 feet), was timber framed with long span wood trusses. Previous studies found the building's high bay seismically deficient. LLNL commissioned a conceptual seismic study in May of 2007. The seismic scheme of concentric steel braces on shallow mat footings was selected at a total project cost of $5 million. The basis of preference for this concept were cost, limited impact on building occupants, and reduced "collateral" impacts on mechanical, electrical, and plumbing (MEP) systems.

The seismic retrofit design development and construction documents contract was awarded to the prime design subcontractor Degenkolb Structural Engineers (Degenkolb) in August of 2007. The project delivery method chosen by LLNL was design-bid-build. Degenkolb assembled a multi-disciplinary design team including RBB Architects Inc. (architects), Affiliated Engineers Inc. (mechanical and electrical engineers), Optira (digital scanning consultants), and Davis Langdon, Inc. (cost estimators). LLNL provided design and project management. The objective goal of the project was to upgrade the facility to ASCE 41 life-safety performance criteria. The subjective goals included maximizing worker and occupant safety and minimizing project duration, cost, and non-structural facility impacts. The over-riding subjective goal was to limit impacts on building MEP systems due to new structural elements (footings, columns, braces, collectors, etc.).

The request for proposal for design services included a research component: it required the subcontractor to collaboratively implement DSM methodologies during work planning. Pre-award studies identified significant dependencies between structural retrofit sub-systems/details, MEP impacts, and total project cost. LLNL obtained permission from Adept Management Ltd. to experiment with their DSM software.

The design team produced an industry standard "baseline" Microsoft Project schedule (conventional CPM) and developed an activity-dependency spreadsheet. LLNL synthesized the schedule and spreadsheet for input into the ADePT software via a Microsoft Excel spreadsheet. Clustered by organization, the input file listed activities with related dependency. The team categorized dependencies by strength in descending order from A to C and set DSM algorithms to optimize the sequence around the type A and B only. ADePT generated the optimized DSM matrix (Figure 2) and CPM (Figures 3). Degenkolb cost loaded these activities based upon the original proposal, and then commenced design. LLNL prepared a cross functional (swim-lane) diagram of the design process (Figure 4) to gain additional insight into the relationship between iteration and organization information hand-offs. The team color-coded the DSM matrix, CPM schedule, and swim-lane diagram to highlight iterative blocks. Red, blue, and green respectively identified type A, B, and

C feedback loops while black identified feed-forward dependencies. When the team compared these representations with their conventional CPM, people recognized that iteration had not been made explicit but nevertheless existed in it.

OBSERVATIONS

Conventional Work Planning

CPM Scheduling: In the consultant proposal, the team correctly identified the iterative *nature* of the central design problem. Both Degenkolb and AEI recognized the inter-dependence of mechanical impacts with structural retrofit concepts and details. This understanding translated poorly into expectations of team interactions, however. The conventional CPM represented a linear process and focused on client deliverables. The team sequenced design activities start-to-finish, by phase (preliminary structural layout→MEPF impacts evaluation→details-finalized structural layout). Deliverables, i.e., 35% submittal drawings, were erroneously identified as activities on the conventional CPM. The general context of activities such as meetings replaced clear descriptions of design activities, i.e., coordination between seismic frames and MEP systems.

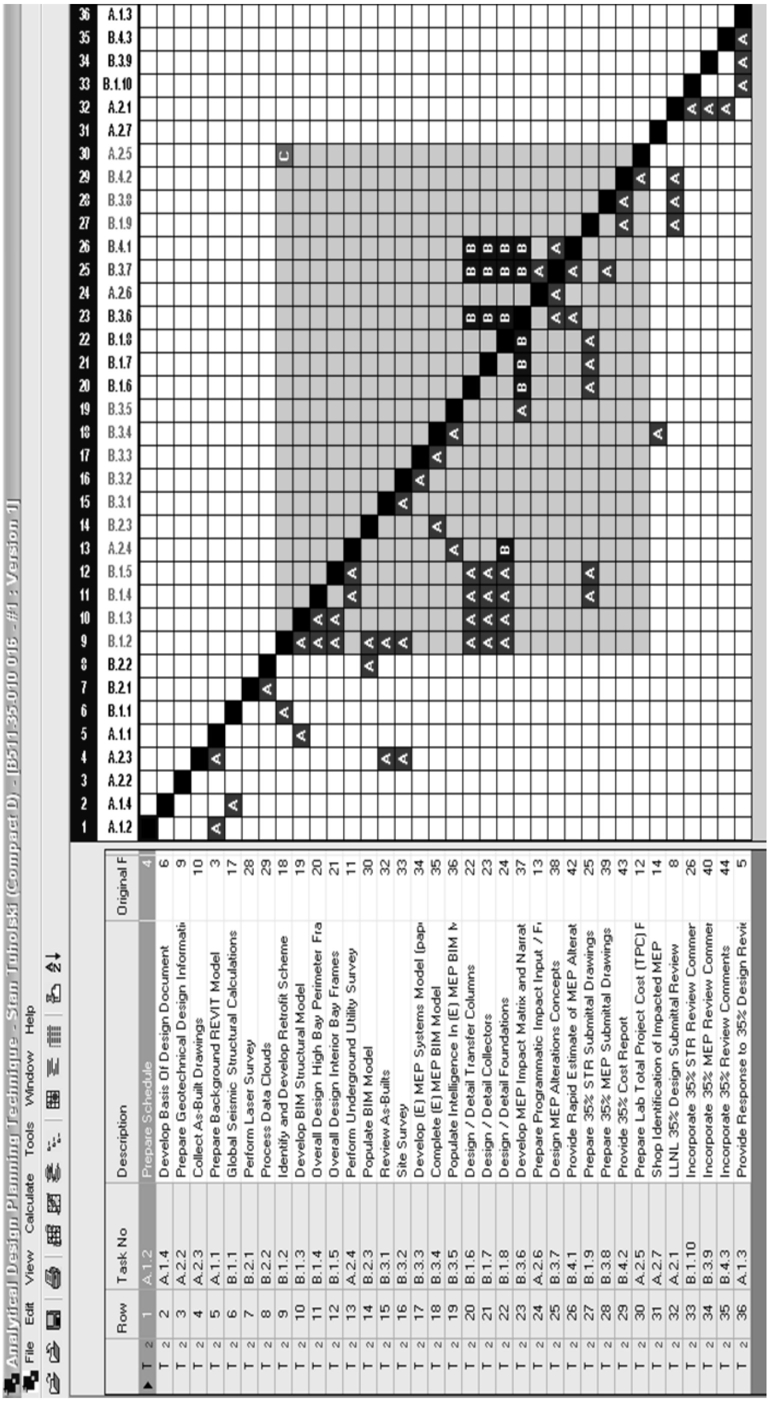

Figure 2: Design Process DSM

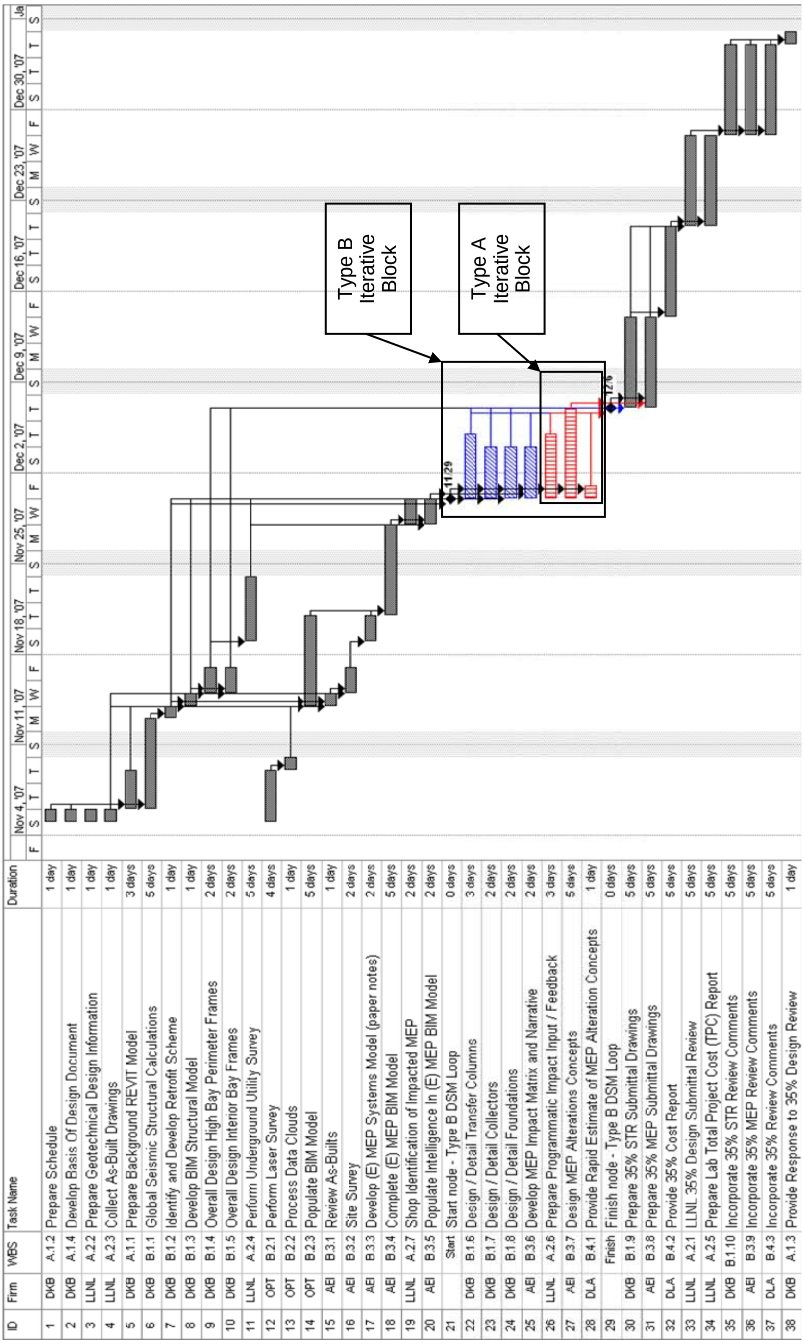

Figure 3: Design Process CPM Schedule

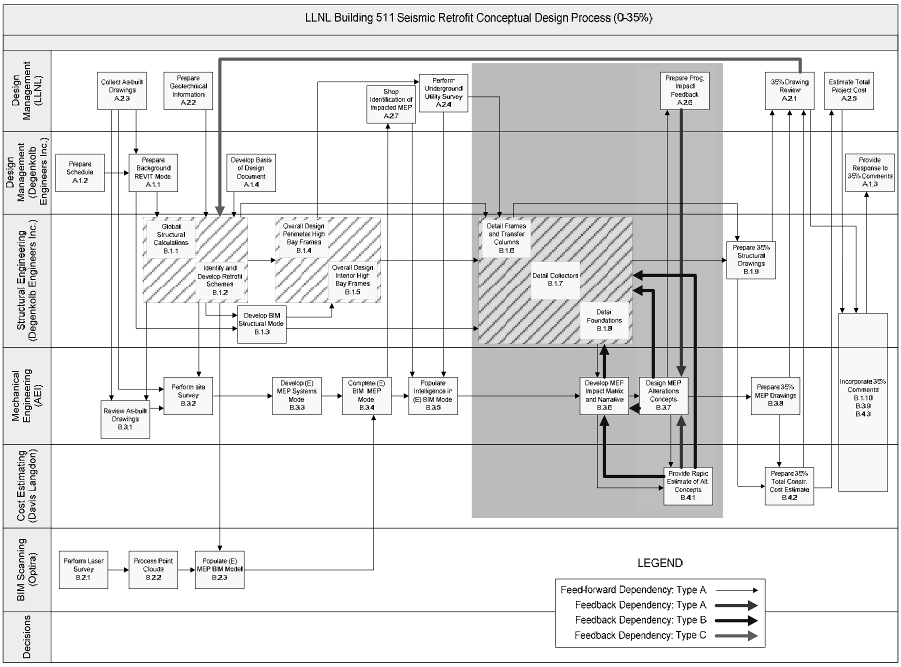

Figure 4: Design Process Cross-functional Swim-lane Diagram

Linearity: Little or no concurrent activities appeared on the conventional CPM. Expectations of linear processes surfaced during discussions surrounding finality and completeness of information hand-offs. For example, AEI initially requested a *finalized* structural frame layout from Degenkolb prior to performing a preliminary field visit to assess potential MEPF impacts. During this conversation, AEI described the potential for rework (negative iteration) if Degenkolb revised the frame layout. In general, the design team expressed the desire to limit iteration within the conventional process. Iteration carried a negative connotation because it implied corrective rework as the result of changes or corrections by others. The LLNL design manager summarized this impression by stating, "*more time, more cost, less profit*."

The conventional CPM addressed non-linearity implicitly through the inclusion of loop tearing activities such as rapid estimating. Degenkolb introduced rapid estimating, by experience, to provide cost input on mechanical alterations concepts prior to final estimate preparation. The introduction of intermediate cost input tore an iterative block relating final cost with specific MEPF details and reduced negative iterations of drawing production.

Activity Vocabulary: The team reinforced expectations of linearity within the conventional design process through the use of iteration masking language, i.e., *estimate, re-visit, revise, confirm, check, verify, finalize, and complete*. These terms defined discrete activities within the schedule, which is linear and sequential by nature, but the team later recognized that these activities actually described multiple iterations of the same activity with the differences attributed to process batch size, level of completion, and degree of integration.

DSM IMPLEMENTATION PROCESS

LLNL project managers, all first-time DSM users, documented their DSM implementation process (Figure 5) in an effort to understand how it differed from the conventional design process. Their observations, as documented, represent a starting point for improvement during additional trials. The resources required to implement DSM on this project included 60 hours of senior engineering effort split between LLNL and Degenkolb design managers. The process took approximately 3 weeks to complete. The implementation exhibited a high degree of iteration. Managers recorded 15 DSM runs, with the first 12 encompassing the block between input files and review of results. The remainder occurred to adjust intra-loop dependencies and the output schedule. Experienced project engineers appeared effective at manipulating the DSM matrix and at exploring solutions to highly inter-dependant details. Team interactions benefited from insights derived from the DSM implementation and during the review of optimized output.

Noteworthy comments on steps in Figure 5 include:

Brainstorm Activities: This activity involved exploring the DSM tool, dependencies, descriptions, and granularity. The team categorized dependencies as sequential, geometric/physical, and functional/operational.

Generate Activity Lists with Dependencies and CPM Schedule: The team narrowed activity lists to remove non-actions, milestones, deliverables, and meetings. The team clarified information exchange including content, level of completion, batch size and format. Information sources were identified as external to team, inter-firm, or intra-firm. Engineers initially lacked the tools necessary to identify dependencies and potential loop blocks as evident by the lack of dependency assigned to A.2.6 Prepare Programmatic Impact Input/Feedback.

Optimize DSM and Review Results: Algorithm sensitivity to dependency assignment resulted in multiple iterations with subsequent system adjustments. Algorithm control parameters required adjustment as well.

Adjust Intra-loop Dependencies and Finalize CPM Schedule: The CPM schedule output from the DSM program required resource availability screening within defined loops. The team repopulated milestones and deliverable designators.

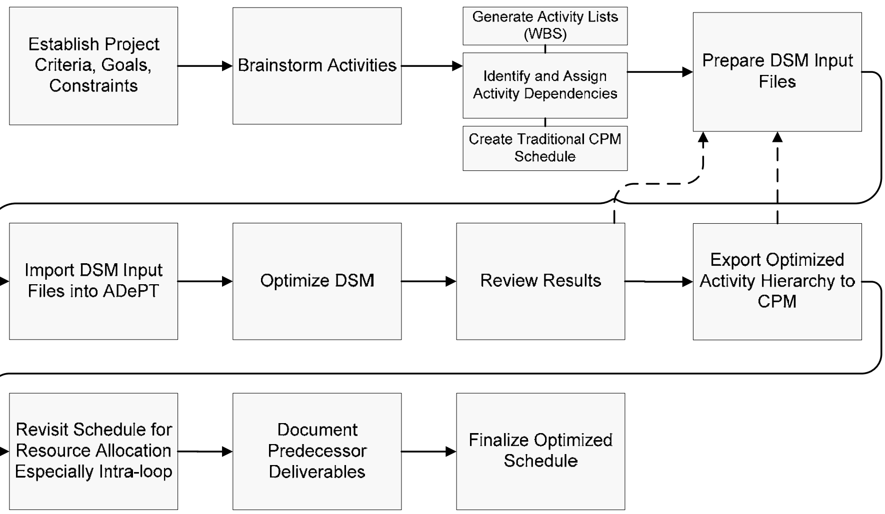

Figure 5: Observed DSM Implementation Process

OPTIMIZED DESIGN PROCESS

DSM identified interactions at system/sub-system/component levels. These relationships appeared transferable to similar SE design problems. Designers identified and removed wasteful activities such as paper deliverables and substituted BIM digital files. Block identification clarified the context of iteration, reducing associated negative connotations. DSM facilitated the conversation of partial information exchange and batch size as observed in the development of critical column connection details described below.

CPM Schedule - DSM increased activity concurrency: increased concurrency is evident, e.g., within the type A and B dependency loops shown in red and blue in Figure 2. The type A block encompassed activities A2.6 Prepare Programmatic Input/Feedback, B3.7 Design MEP Alterations Concepts, and B4.1 Provide Rapid Estimate of MEP Alterations. It nested within the type B loop, thus incorporating structural detailing. The optimized CPM schedule (Figure 3) shows these loop activities as taking place concurrently. Accordingly, team management planned a co-location design day (like a gathering in the 'big room' or 'oba' in lean production, e.g., Tanaka 2005) at B511 to complete the type A and B tasks concurrently.

During this exercise, type B activity B1.6 Detail Frames and Transfer Columns influenced type A activity B3.7 Design MEP Alterations Concepts more than the others within the type A block. DSM properly predicted iterative blocks, however failed to identify the specific activity most often repeated. Degenkolb generated 7 different transfer column connection details throughout the project, 2 with sketches, in collaboration with the collocated team. The team described this iteration as positive because each successive concept reduced the overall cost of the project by limiting costly MEP alterations. The compromises reached between structural and MEP systems through iteration provided overall project benefits, even though successive solutions appeared less efficient from the structural perspective. Collocation to address CPM concurrency proved beneficial because information exchange was facilitated by sketch and all team members were available when the specific activity requiring iteration shifted from that predicted.

Work Planning - DSM provided insights into activity definition and iteration. An early project decision required definition of activity B2.1 Perform Laser Survey to quantify data collection by Optira. Was the scan localized at structural impact locations or conducted across the entire building? Optira's contract called for localized scanning. The DSM (Figure 2) illustrated the interruption of a large iterative cycle by releasing the dependency of B2.1 Perform Laser Survey on B1.4/B1.5 Overall Design of High Bay Frames. A modest additional fee was paid to Optira to collect additional data and tear the dependency block.

The swim lane diagram (Figure 4) highlighted information hand-offs crossing organization and block boundaries. This assisted is making activity assignments. Both Optira and AEI had the ability to transform the scanned point cloud into a BIM model with mechanical components. Assignment of this activity to Optira implied they would be recalled to the project if additional data population were required due to SE changes. Management weighed cost trade-offs and assigned this data population activity to AEI because they could more easily perform re-work, if required.

CONCLUSIONS

This paper examined a case study where DSM-based planning software was used on a seismic retrofit project. It demonstrated how DSM filled the gap when translating a sticky-note schedule showing hand-offs into an activity network with various types of dependencies, and how that, in turn, was translated into a schedule. As shown, outstanding opportunities exist to apply DSM methodologies to SE design. The development of DSM tool requirements specific to this field promises increased proliferation. Interactive displays containing unique perspectives, coupled with DSM visualizations afford SEs greater work planning insights. These include cost loaded work breakdown summaries, CPM diagrams, cross-functional swim-lane diagrams, graph theory relational constructs, and value stream maps.

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