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PROBLEMS IN THE INTERFACE BETWEEN MECHANICAL DESIGN AND CONSTRUCTION: A RESEARCH PROPOSAL

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ABSTRACT

As construction projects emerge from the traditional delivery processes to modern *fast-track* forms, stress has developed in the interface between the design professional's delivery process and effective construction production. This is no greater evidenced than at the specialty contractor level. The current attempts at fast-track team type projects remain largely a time-compressed form of the traditional processes with respect to the design-construct production flow. While many of these projects are comprised of a pre-selected "team" of design and construction firms, in most cases the role of the specialty contractor is limited to pricing exercises and perhaps some traditional "value engineering" suggestions during the design phases. Substantial improvements in production workflow, if any, have been generally limited to the area of cooperative construction activity sequencing and scheduling. Problems arising from this situation are illustrated and research is proposed for testing possible solutions.

KEY WORDS

Construction, fast-track, value chain, production process, pull, lean construction, delivery process

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INTRODUCTION

The real extent of design and construction integration is often revealed by looking at projects through the eyes of the specialty contractor, especially those, like mechanical contractors, who fabricate custom-designed components based on design information received from others. Design and construction are insufficiently integrated in all forms of project delivery currently on offer: design-bid-build, design-build, and hybrid forms that involve negotiated selection of specialty contractors prior to completion of design. These different organizational structures do not fundamentally change the work processes through which designing and constructing are actually done. Consequently, there is tremendous waste on projects; waste that is amplified and made more visible as projects are pushed toward the dynamic extreme of quicker, more complex, and less certain.

What is needed is a new form of project delivery designed to accomplish the lean objectives of maximizing value and minimizing waste. To further that cause, we provide a description of problems and waste in current practice, suggestions for improvement, and a proposal to experimentally test possible improvements.

ILLUSTRATIONS

To best illustrate the failures at the interface between design and construction, following are fictionalized, but realistic examples. They are far from all-inclusive, but will convey the "flavor" of some of the problems inherent in the current process.

EXAMPLE 1 – UPSIDE-DOWN PLUMBING [LACK OF WORK STRUCTURING]

Mechanical contractors do plumbing, piping, heating, ventilation, and air conditioning. The underground plumbing must be detailed by the mechanical contractor and in place immediately after excavation and while underground structural work is in progress. The design of the drainage systems is most logically performed working from the top of the building down, as the various drainage loads are accumulated. If the underground construction work must begin before the traditional sequential design process can complete, the underground plumbing and the entire project are delayed. There are ways to design from the bottom up, but they are more risky and costly to the designers[2]. The design professionals therefore resist this alternative process if imposed after they are contracted based upon a traditional approach. In this case failure to work package[3] the work at the very beginning of design precludes an alternative approach. There is no opportunity to recover from this failure after the design process has been set and has proceeded in the traditional design delivery process.

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[2] The method used is based upon what manufacturing calls "robust design". In robust design, analysis is performed as to the likely highest probable drainage load and then a design is selected that will accommodate that load. In many cases, this load may be within the envelope of capacity of a system that results in no, or limited, extra construction cost. Any extra cost may well be paid back (some times many fold) by the costs deferred by not delaying the project. The added risk to the designer is related to designing without "all the exact data". This may also require some additional analysis and design effort.

[3] Work Packaging is a process by which the required sequence of construction is used to determine (pull, in lean production terminology) the content of design document issue "packages" and the sequence and schedule in which they are produced to support construction. These work packages may be single trade or multi-trade related. In some cases, they will need to be produced in a sequence that is less optimal for design efficiency alone. If the design efficiency is optimized in this case, the project as a whole is suboptimized. Work packaging will be developed in more detail in a future paper.

EXAMPLE 2 – DUCTWORK "CONSTRUCTION" DOCUMENTS [NON VALUE ADDING DELIVERABLES]

Under the traditional design delivery process, the ductwork system is specified, sized, and drawn (usually double line in 2D CAD). The designer makes a reasonable[4] effort to properly draw constructable systems in the so-called construction documents. However, drawings at the level of detail achievable by the typical commercial/light industrial design firms' staff are of very limited use to the mechanical contractor for the following reasons, and are therefore non value adding to the project:

- They are created in 2D AutoCAD. The contractor must totally redraw the ductwork in a full 3D CADCAM software in order to be able to interference check with all other work in the space and in order to electronically download into the shop fabrication process.
- They are created under severe time constraints that result in drawings that are diagrammatic, at best. In fact the contract document specifications and drawing notes will almost always so stipulate and shift the responsibility to the contractor to modify the ductwork to fit the spatial limitations.
- They are seldom created by someone who has the specialized skill in mechanical detailing required to design a constructable system and to coordinate it with all other elements of the facility.

The design firm devotes considerable time creating these drawings, while the mechanical contractor loses precious time **waiting**. The design firm has created the waste of **over production**[5] by generating drawings that the mechanical contractor cannot use for fabrication or installation. Again, the failure to properly work structure based upon the **pull** of the project milestones, results in wasted time and effort. There are ways that the designer and contractor could reallocate the tasks to eliminate waste, but these are not addressed in traditional delivery systems. Given that ductwork is almost always on the project critical path, the impact is multiplied. The impact on the contractor's detailers of redrawing the design is further amplified by the delays in the traditional communications systems, as illustrated in Example 3, below.

EXAMPLE 3 – COMMUNICATIONS GRIDLOCK [EXCESS PROCESSING STEPS AND WAITING]

The traditional design-construction procedure for obtaining information, clarifications, and responses to questions by the contractor is the Request-For-Information process. Let's review the process in a fictional example:

The "construction" documents produced by the engineer are self-conflicting. The written specifications require the mechanical contractor to employ long-radius elbows in all ductwork. The drawings show a section of such ductwork. The designer's drawing (as is the typical case) shows only the ductwork and the architectural background. When

[4] "Reasonable" is based upon the allotted fee and time, and the skill of the designer. Most designers within design firms are not skilled in construction detailing, which requires craftsman level experience and training.

[5] See Womack & Jones (1990) for an account of the types of waste derived from the Toyota Production System.

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the mechanical detailers attempt to re-draw the ductwork in true fabrication quality 3D CADCAM that includes all the other trades' work in the area, it becomes apparent that it is impossible to fit the ductwork in the space using a long radius elbow for the change in direction. The detailer consults the specifications and finds no provision for alternative construction. He contacts the mechanical contractor's project manager who instructs him to draft the required written Request-For-Information to the design engineer. The detailer prepares the Request and forwards it to the mechanical contractor's project manager, who delivers it to the general contractor's project engineer. The engineer reviews the Request, prepares a cover transmittal and faxes it to the design architect, who then forwards it to the design engineer. The design engineer is overloaded responding to other Requests-For-Information and on other project tasks. He/she uses the full 10 working days allowed by contract to respond. The response reads:

> *"Reconfigure duct and coordinate with other trades as required to utilize the specified long-radius elbow per the contract documents."*

The project manager calls the design engineer directly (going around the formal process), requesting a face-to-face meeting. The engineer says they are too busy to meet right now. The engineer says "just find a fix and send us a drawing showing what you want to do". The project manager contacts the detailer, who develops that area of the drawing showing the interferences (coordinating it with all the other affected trades' work) and the use of a rectangular elbow with turning-vanes. The designer sends a plot of the drawing to the project manager, who has it rush delivered to the design engineer.

After a week of waiting, the project manager calls the design engineer. The engineer says he does not like rectangular elbows and asks if it would work using a short radius elbow with vanes. The project manager calls the detailer, who stops his other work again and re-draws the area with the short radius elbow. He finds that it does work, but only if the electrical contractor can move a conduit. The detailer calls the project manager back and so indicates and asks for direction. The project manager (or what is left of him) tells him to "hold" the effected area and send the rest of the drawing to the internal quality assurance reviewer (the internal step prior to formal coordination sign-off and fabrication), so as to move the process along at least a bit.

The project manager goes to the general contractor's project engineer and tells him that he is putting that part of the work on hold, and why. The project engineer then calls the design engineer and demands a face-to-face meeting with all effected parties. It takes another three days to find a time all can meet. At the meeting the electrician indicates that he cannot move the conduit. The design engineer agrees to allow the use of the originally proposed rectangular elbow with turning vanes. The project manager calls the detailer and tells him to revise the shop drawings again to put the rectangular elbow back in and then release the area for quality assurance re-review.

Likely total project impact:

- 5 weeks lost time in reaching final resolution
- Wasted labor by all parties to find a resolution: 20 man-hours.
- Work put in place by other trades during the delay requires that the late ductwork be installed out of sequence. Cost impact multiplier 1.5.
- Frustration factor: immeasurable.

There are multiple failures in this example including lack of proper work structuring and allocation to the most capable parties, and wasteful organizational boundaries and "chimneys." Evidence of cross-functional teams[6] is totally absent.

All the above examples illustrate "Failures at the Interface" that are present even on projects where the mechanical contractor is brought on board before design is complete. The problems are systemic and cannot be solved by simply "working harder." The following section will discuss some proposed solutions.

PROPOSED PROCESS MODIFICATIONS

While the ideal solution to the interface problems lies in a total restructuring of the delivery process around the creation of value and elimination of waste, the current state of the marketplace is such that radical restructuring is unlikely in the short term. This being the case, the contractor must look for opportunities to gradually change the interfaces with the goal of creating an environment that will accept the more radical changes needed in the total project delivery process. The following will describe opportunities for significant yet more gradual change.

The highest opportunity for leverage exists where the key specialty contractors can agree among themselves that implementation of these process modifications is to their mutual advantage. Where a limited number of contractors work together on project after project, this seems possible. It is proposed that the minimum contractor participants in this process would initially include mechanical, electrical, drywall, and perhaps steel/concrete Structure. This is due to the fact that this group incurs the greatest number of project coordination interfaces and workflow concurrence. Obviously, the leadership of the general contractor, and the cooperation of the design team and facility owner are needed at some level (the higher the level, the better).

EARLY PROJECT WORK STRUCTURING (WORK PACKAGE DEFINITION)

The team should define design work packaging before design progresses beyond concept level. Once the design team members venture into Design Development[7] level work, key design deliverables are set and it is difficult and expensive to restructure them. The initial exposure to the process of restructuring the design deliverables will be strange and threatening to the uninitiated designer. It is therefore imperative that the discussion begins much prior to Design Development to allow time to educate and win over the design team members. There will be a tradeoff between additional effort in delivering multiple packages on the design side and the handoff of sufficient "construction documents" to the constructors for legal permitting and for the contractor to fully detail

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[6] Cross Functional Teams are basic organizational units in lean manufacturing's product development processes, and would appear to be appropriate for construction as well. For more on the use of cross functional team sin construction, see Ballard & Zabelle (2000).

[7] The traditional phasing of architectural projects in the U.S. includes Predesign (sometimes called Project Definition), Schematic Design, Design Development, Construction Documents, and Construction Administration. These typically serve as payment milestones and, with the exception of construction administration, are defined in terms of documents to be delivered to clients. Figure 1 shows the primary deliverables.

into construction/fabrication documents. In addition, there will be a need for greater design firm involvement during the construction efforts. All this needs to be understood by all, and any necessary fee and staffing adjustments made up front.

The basic element of Lean Design delivery is the work package. This differs fundamentally from the traditional design delivery flow shown in Figure 1. The traditional design is sequential, based upon increasing level of detail uniformly across all elements of the design. The architect, civil engineer, and structural engineer lead the process, with the interiors, mechanical, and electrical following behind based upon release of prerequisite information from the former.

The traditional design process also follows the most logical sequence of design activities, from the viewpoint of the designer. For example, the plumbing designer would like to design the drainage systems from the top of the building down, as that is the way in which the flows accumulate and are totaled to size the piping systems. However, it is apparent that this is exactly opposite the way the building will be built. Herein lies the most fundamental problem with fast-track delivery: the designer's deliverables are largely sequenced in reverse of the construction sequence. Unless a non-traditional design approach is used, the result will be late and/or incomplete design information supplied to construction detailing and the downstream construction activities.

Figure 1 - Traditional Design Deliverables Production Flow

It has been proven possible to reverse the design deliverables development sequence. This is now standard practice on turnkey industrial projects and on the ultra-fast-track team projects for semiconductor fabrication plants[8]. In order to do so, the designer must develop "robust design" solutions that will allow reasonable assumptions to be made in the sizing of elements "downstream". The design is then delivered to construction in a sequence that supports the construction sequence. In this delivery system, design and construction is "work packaged" to support the project construction sequence.

The design work package sequence and level of content is established to meet the needs of the construction "pull" schedule[9]. This is then integrated into the construction work package structure and master schedule. Construction pull schedule content required for establishing the design work package structure need be as little as the <u>sequence</u> and content of design packages. This will set the priority sequence of design activities. Dates for the design work package release can then follow, as the construction schedule milestones are set.

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[8] See Miles (1996).

[9] A 'pull schedule' is one produced initially by representatives of those who are to do the work being scheduled, working backwards from a target completion date. See Ballard (2000a).

Work packages usually define multi-discipline design and multi-craft construction activities. For example, a work package might be created to describe the design and construction activities for the "Chilled Water System for Supply of Early Cooling to Level 1 through 11" of a 30 story building. This package would include all work specific to the delivery of the described work package. In this case it might include the following:

- All chilled water equipment set in place and operational by the mechanical contractor, which in turn requires
  - Equipment pads by the concrete contractor
  - Plant structure complete by the steel erector
  - Power to equipment by the electrical contractor
  - Controls operational by the automatic controls contractor

  and so forth . . .

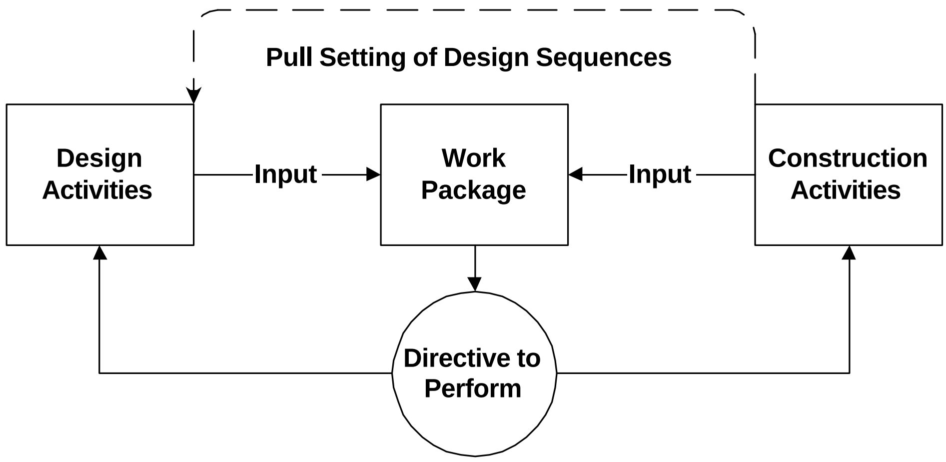

Figure 2 - Lean Design and Construction Deliverables Flow

As shown in Figure 2, work packages become the basic unit of assignment. They consist of the information necessary for doing some chunk of work, ultimately fabrication and assembly, with design work packages defined as needed to generate that information. Work packages should be structured around facility subsystems and functionalities. This differs from traditional forms of work structuring such as Work Breakdown Structure, that divides the project in accordance with customary contracting and craft divisions. This latter methodology is much at fault for the current project structuring and performance.

Facilities are comprised of subsystems and functionalities. These cross traditional contract and craft boundaries. For example, the facility roof's purpose is to keep the whims of mother-nature outside, and the contents and occupants inside safe, comfortable and dry. Roofs are not single craft or contract entities. The roof bears upon a structure. It is penetrated by numerous objects related to mechanical, electrical, communications, structural and other systems installed by various crafts. A failure at the interface between these elements can quickly result in a failure of the intent of the roof, or may reduce its long term value to the owner. It is a fiction of the current delivery process to treat the roof as a single element, the responsibility of a single contract. Successful performance of the roof design and construction involves a team of players. Yet the current delivery process and work breakdown structure ignores this when it comes to true production process performance.

In some cases the work package may be single-source related, such as in the case of equipment pre-purchase packages for long lead items in order to meet the project schedule. However, even in this case multiple parties will have input to the design specification of the equipment and in construction related issues such as rigging and setting accommodations.

Package Definition Documents contain such information as the list of and general content of the associated design documents, the names of all stakeholders and related team members and their respective roles, the related construction work that is released by this package, the schedule for start and completion, and the format and routing of the completed documents.

Work later identified (such as changes or added scope) that "add to" prior packages must build upon, not replace, the work of earlier packages. The Package Definition Document is the "Plan of Record " for the work to be performed and is therefore the road map for both design and construction. This guarantees that all parties are working from the same playbook. This also assures that workflow in the field is not subject to upstream variation and resultant loss in productivity.

It is essential to minimize or eliminate "late blooming brilliance." This occurs when someone comes up with a "better idea" late in the process with the result of waste in revisiting work already performed. Such changes should only be entertained is they add net value to the project as viewed by the Owner. Often this better idea was available earlier, but the process did not reinforce early revelation. The Package Definition Document serves to obtain input and sign-off of all stakeholders. This is based upon establishing a formal methodology for the "programming" of the project. This methodology drives decision making. Items of scope need to be ranked in order of highest downstream impact and delay of immediate downstream work, to lowest of the same. Vigorously working the resolutions in that order and documenting the scope of work in the Package Definition Document results in the Plan of Record for the design efforts.

REDEFINITION OF CONSTRUCTION DOCUMENTS AROUND VALUE ADDITION

It is readily apparent from the prior comments that the organization, packaging, and schedule of release of the design documents changes dramatically in the Lean Delivery process. It is essential that the mechanical contractor obtains *necessary* documents and information earlier in order to start detailing, fabrication, and installation earlier and in a more productive flow sequence. The use of multiple design work packages to release pre-purchase of equipment, pre-fabrication, and field work earlier is key to successful implementation.

The project team must therefore redefine and target design efforts with the objective of releasing downstream construction work, as opposed to following the traditional design flow of doing work in the simplest design sequence alone. In addition, the emphasis is to design-in value from the beginning with the more active participation of construction earlier, as opposed to traditional late "value engineering" with resultant design re-work, expense, and schedule impact.

Design work packages must be complete and before release to construction. This means either that releases must be made at the last responsible moment (to allow maximum time for developing the design) or that the design must sufficiently robust to accommodate future changes .

In order to free design to perform this redefined project role, it is imperative to eliminate non-value adding design activities. Design needs to allow construction detailing to "flesh out" and inter-craft coordinate. The mechanical contractor that utilizes 3D CADCAM for production of fabrication and installation drawings is re-creating the design layouts in any case. There is no value added for the designer to go beyond one-line conceptual drawings for this part of the design. However, it is then essential that the entire spatial concept be "doable." This means a much closer involvement of construction in the predesign and design processes. As discussed below, the key to this is some form of Cross-functional Teams.

In the specific case of mechanical design, there must be a reallocation of tasks between the specialty contractor and the design firm. It must be remembered that the goal is to free the design professional from tasks that add little or no value to the project so that they may use their resources to increase their involvement in value adding tasks for which they have the greatest expertise. These include the development of the best life-cycle efficiency of systems, and providing engineering expertise to solve problems during construction.

Current practice is for the mechanical design staff to produce "Construction Drawings" as the final phase of their work before commencement of construction. As related above, these drawings are qualified by the design professional as "diagrammatic" in nature. It is the responsibility of the contractor to detail the work, coordinate it with all other crafts, and fit the work into the space. However, the designer puts considerable effort into creating 2D CAD drawings depicting double-line representations of equipment, ductwork and piping.

The mechanical contractor must re-draw all of the mechanical drawings in true-to-measure 3D CADCAM shop drawings in order to coordinate them and send them to fabrication and installation. The specialty contractor uses the design drawings only as a design intent diagram.

The project specifications will generally require "as-built" drawings at the close of the project. The usual form is that of design's construction documents marked-up by the mechanical contractor to reflect the as-installed conditions.

While it is necessary for the design professional to reasonably assure that the design is "doable", the level of detail generally invested in the design construction documents is unnecessary. It would add value to the project to produce the minimum level of drawing so as to represent the design intent, and let the mechanical contractor detail from there. Less effort and cost would be invested in the construction documents. In turn, the construction shop drawings will be of greater value to the facility owner than marked-up design CD's for "as-builts", as they are more accurate to actual built conditions. In exchange, the design professional's staff would be freed to work directly with the mechanical contractor's detailing staff to produce the shop drawings and to process submittals and requests-for-information in a more timely manner.

The impact on the design firm to accommodate these changes must be appreciated. What is presented here will reduce labor hours in drafting, with an offsetting increase in design and engineering to support collaboration with the specialty contractor during detailing and construction. This may impact the staffing requirements and perhaps the fee structure of the design firm. It will however, also reduce some risk exposure as the design firm produces more diagrammatic documents and criteria, and allows the specialty contractor to address coordination and spatial fit. In turn, the specialty contractor's detailing effort may increase somewhat with the trade off of an earlier start and more flexibility in detailing to criteria, rather than trying to make the design firms' construction documents work as drawn or suffering the delays of the traditional request-for-information and submittal processes.

STREAMLINED COMMUNICATIONS CHANNELS

The organizational vehicle for making all of the above possible is the formation of project cross functional teams . The teams should ideally involve all stakeholders: Owner, Operator, Design, Construction, Major Suppliers, and Regulators. The input from all these parties is needed to properly construct the work packages and write the Package Definition Documents.

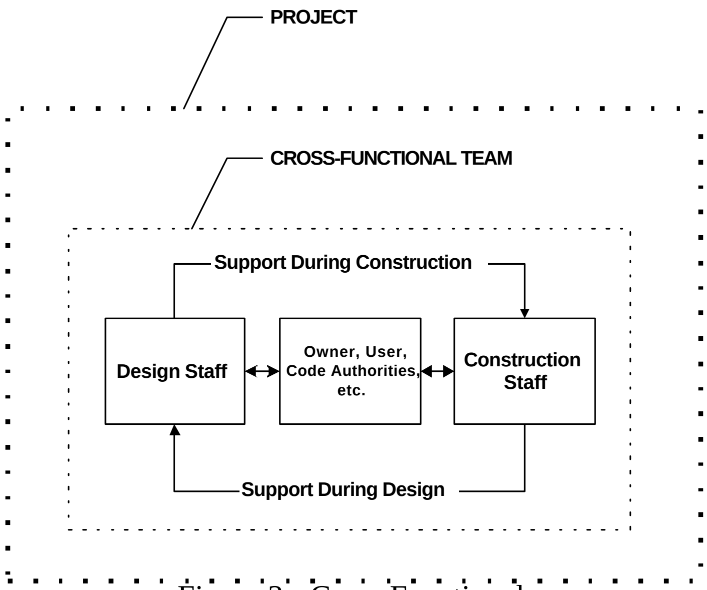

Figure 3 - Cross Functional Teams

Early in the project's life, design leads the team, with support by construction. Then as the first shovel moves dirt on the project, a transition begins so that construction leads with support by the appropriate design parties. In this delivery process, design plays a greater role during construction in providing immediate response to questions and resolution of design issues. This is an area where the reduced role of the designer in production of detailed design construction documents is traded for more expert engineering services during construction.

The ideal situation is to co-locate the design staff and the construction detailing staff during detailing. This is not always possible, but offers the highest level of instantaneous communication and coordination at this critical early time in the project. The next best option is streamlined electronic communications, coupled with key milestone face-to-face meetings. In any case, the head of the detailing team should have direct communications with the relevant design parties. Proper documentation of decisions-made is prepared cooperatively and issued by the team leader for project documentation. Where issues of cost or scope are involved, the related design and construction project managers must be included in the final decisions, and sign off on the change directive document. This directive document then becomes a formal change order (if necessary) to the Plan of Record documentation for the project.

RESEARCH PROPOSAL

Based upon the ideas presented in this paper, what might a Lean Delivery process look like from the specialty contractor's viewpoint? The organizational foundation upon which this process improvement is based is the cross functional team. It can be readily seen that this is a fundamental change from the hierarchical organization typical of construction projects. If projects are to achieve the promise of "Faster-Better-Cheaper", the rigid organizational chimneys must give way to cross functional teams. Quick response, high quality and effective operations require a team organization with the most fundamental element of the project, the work package, at the center. The old style top down command structure and the concept of the all knowing "spider at the center of the web, pulling all the strings" is not quick enough and cannot hold all the knowledge necessary for this new delivery process. In addition, communications must approach the ideal of instantaneous.

Research is proposed to implement and test these ideas. The 'experiments' will include the following key elements:

- Organizing in cross functional teams
- Structuring design work in work packages, based on the strategy for fabrication and assembly
- Shifting the production of fabrication and assembly drawings to the specialty contractor
- Matching compensation mechanisms with value generation capabilities (e.g., not paying architects and engineers by labor time)

Contractual and organizational restructuring will clearly be every bit as vital as the process redesign implicit in a work packaging approach. Consequently, while motivated immediately by the problem of design/construction interface, this research may contribute to developing understanding of implementation issues fundamental to any progress toward the lean ideal.

Regarded as a step in the direction of a full fledged lean delivery system, projects so structured are hypothesized to reduce the wastes identified in the illustrations provided earlier in this paper; specifically, the wastes of waiting and overprocessing. Within the context of fast track projects and the value they accord to speed, such waste reduction is expected to reduce both cost and time. Research findings will be reported in future papers.

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