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Leveraging specialty-contractor knowledge in design-build organizations

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Abstract Specialty contractors have knowledge to contribute to the early design of architecture, engineering, and construction (AEC) products. In current practice, however, they are seldom involved in early design, but evidence suggests that their early involvement is increasing. Lean construction theory advocates such involvement. The practice of involving suppliers in product development efforts and manufacturing has proven to be highly successful. The paper reports on empirical research that identified the contributions of specialty contractor (SC) knowledge to early design, which led to gains in process efficiency and improvements in product quality. These contributions are categorized and illustrated by means of examples that stem from current practice or present potential opportunities for improvement. Reasons are given why SC knowledge is often ignored in design. Changes in AEC practices nevertheless suggest that organizations are creating conditions to increase interaction between designers and SCs. Such interactions will help AEC organizations to retain and share the knowledge of individuals as well as learn to develop new knowledge.

Keywords collaboration, concurrent engineering, design-assist, design-build, design build contracting, knowledge, lean construction, partnering, product-process integration, specialty contractors (SC)

INTRODUCTION

Architecture, engineering, and construction (AEC) projects invoke complex processes for designing and building a product. These projects typically involve a client, a lead design firm and several design specialists, a general contractor, and an array of specialty contractor (SC) firms. Design firms typically are in charge of most of the design development process and they help to manage or supervise the management of the construction work. General contractors may execute some part of the construction work (e.g. cast concrete or erect steel). In turn, SCs competitively bid to perform different parts of the remaining construction work. This work is divided according to different specialties or trades, such as mechanical, electrical and process piping.

How to effectively co-ordinate the work of SCs in AEC projects has been an industry concern for long (Hinze & Tracey, 1994; Crichton, 1966). The work of SCs has evolved from requiring artisanship to sophisticated assembly of components (Bennett & Ferry, 1990). Specialty work, typically carried out on-site, has progressively extended to include off-site tasks, such as creating detailed fabrication and installation drawings, selecting vendors, procuring and expediting delivery of materials and equipment, building, starting-up, and maintaining building systems (Tommelein & Ballard, 1997). Inefficiencies during construction result from lack of interaction between contractors and designers (Tommelein & Ballard, 1997).

In contrast, other industries are increasingly involving suppliers in product development and manufacturing. Organizations with lean manufacturing practices have suppliers work closely together with their own personnel in order to streamline the production processes (Womack *et al.*, 1990; Clark & Fujimoto, 1991; Ward *et al.*, 1995). They share information on their production systems with the following goals: to reduce inventories, to deliver parts just in time, to increase reliability of supply lead times, and to cut cost. To achieve these goals, manufacturers have adopted different practices. They move their people to work at suppliers' facilities and they welcome supplier employees in their own manufacturing plants. In addition, they have established incentives for suppliers to get involved earlier in design: they have increased the size of orders and commit to longer-term contracts.

Similarly, computer manufacturers work with suppliers in early design to leverage available technology and increase process efficiency (Iansiti, 1995). Because market conditions are unpredictable and technology evolves rapidly, manufacturers overlap the concept development and the implementation stages to gain speed (Fig. 1).

Given these observations, the authors set out to study supplier involvement in the AEC industry. Design and construction overlap in fast-track projects, but knowledge is transferred in one direction mainly. Design is broken up in pieces, conservative assumptions are made regarding succeeding pieces, and completed design pieces are then handed off to construction. In contrast, product developers and manufacturers have found means to enable two-directional knowledge transfer (Iansiti, 1995). Assuming that SCs on AEC teams are one kind of supplier – the equivalent of suppliers in manufacturing – a key question therefore is: What knowledge can these suppliers bring to the table?

RESEARCH APPROACH

Research started in November 1998 and focused on developing an understanding of the knowledge SCs can contribute to the design of semiconductor facilities. These high-tech facilities are technologically complex and have to be built fast and economically, in intense conditions of uncertainty regarding design criteria and scope.

The research comprised three phases. The authors first interviewed people at a leading-edge design-build firm, then people at specialty contracting firms, and finally people at client organisations. All had worked on semiconductor facilities. The interviews lasted approximately 1–2 h. Frequently, we carried out follow-up interviews with the interviewees. No written questionnaires were used. All interviews were audio taped except for those carried out over the telephone.

First, the authors interviewed 18 experienced practitioners, including lead designers, design managers, and construction managers who worked at Industrial Design Corporation (IDC), in Portland, Oregon. The IDC is a leading design-construction firm, with a wealth of expertise in the development of high-tech facilities. The number of interviews approximately doubled with follow-up interviews. We questioned interviewees regarding the decisions they make in early design, the information they typically have on hand vs. what they wished they had before making decisions, and the hand-offs of information between design specialties. Next, we interviewed 12 people who worked for mechanical, electrical and piping (MEP) trade contractors, ranging from labour manager to vice-president. The interviews were helped to articulate the knowledge that SCs might contribute to early design. Finally, the authors interviewed seven people who worked for client organizations. These interviews aimed to capture the uncertainties that plague the definition of design criteria and project scope of semiconductor

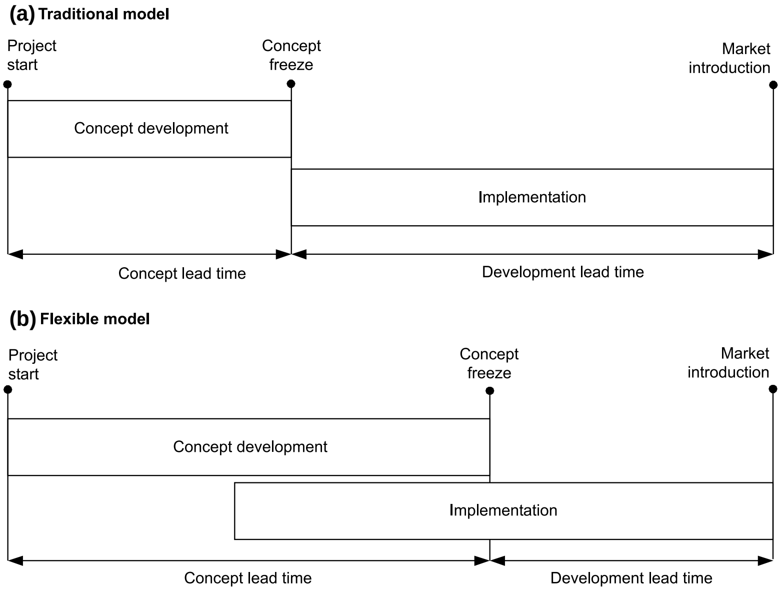

Figure 1 Two models of effective product development (Iansiti, 1995).

facilities. We also probed interviewees into innovative practices that could add value to design-build processes. Although we conducted a large number of one-on-one interviews in this empirical research, the questions and answers did not lend themselves to statistical analysis. Instead, we report anecdotal evidence of specialty-contractor contributions to early design and new ways to collaborate.

AVAILABILITY OF SPECIALTY CONTRACTOR KNOWLEDGE

Specialty-contractor knowledge can contribute to early design in multiple ways. Contributions fall in four categories.

Ability to develop creative solutions

Specialty-contractor knowledge can bring to early design creative solutions, which designers may not necessarily be aware of. On one hand, specialty-contractor creativity derives from 'cross-fertilization': it results from SC's involvement in projects owned by different clients and designed by different design firms. Such diversification and rotation of work exposes SCs to alternative ways of solving design problems and keeps them up-to-date on technological innovations. On the other hand, specialty-contractor creativity also reflects the SC's own pursuit of technological innovations and their knowledge of constraints affecting the construction process (Slaughter, 1993).

Admittedly, this is a double-edged sword. SCs who are involved early in design may try to impose the solutions they prefer because these are easier to develop, procure materials for, and build, i.e. they are more lucrative to the contractor. Nevertheless, designers face a similar condition when contractors do not get involved early. Should the design prove to be impossible to build, an added risk then is to have to redesign solutions.

Examples of creative solutions

1.A. In a recent semiconductor project, the original design of the air plenum body specified a steel structure to hang from the ceiling (the plenum is the space above the false ceiling of the cleanroom; the cleanroom houses the process tools). The structure was to be built on site. Once the mechanical SC was selected, based on his bid for the original design, the contractor developed and proposed jointly with the ceiling manufacturer an innovative system to build the plenum body. The system consisted of 560 modules to be fabricated in a shop and then assembled on site. These modules require pre-assembly of ventilation ductwork, light fixings, and ceiling grid. The client accepted the proposal and the plenum was built accordingly. This solution brought significant savings in labour hours, installation time and cost, and increased safety during installation. However, it led to redesigning the plenum body at a cost to the client and stripping off the electrical system that was already installed according to the original design. Savings in cost and time were largely associated with the efficiencies gained in the off-site shop fabrication of the modules and their ease of installation. The performance quality of this solution is higher because of better conditions available in the shop to carry out work such as welding. The solution has been patented and the client is presently exploring its applicability to future projects.

1.B. Offsets, rolled offsets and 45-degree fittings (as opposed to 90-degree fittings) are ways for changing the direction of pipes and ductwork (Fig. 2). They achieve shorter routings and can potentially lead to savings in terms of materials, labour, space, and number of welds, flanges and fittings. They also improve performance by

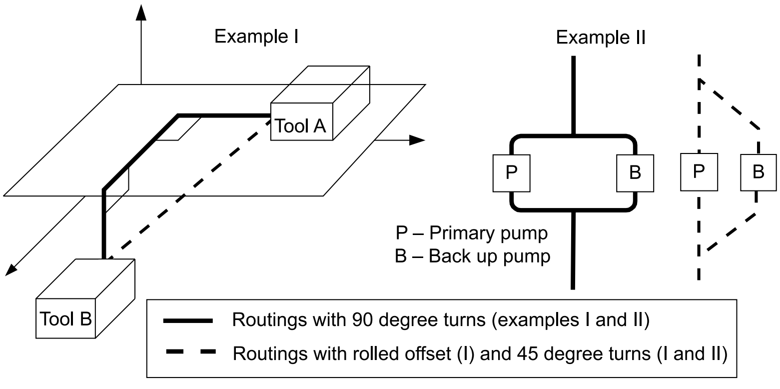

Figure 2 Examples of alternative design solutions.

restricting flow less. Yet, these alternatives are seldom used in design development. Apparently, their use is less intuitive for design detailers because designers are too used to drawing and viewing orthogonal and two-dimensional graphical representations of building systems. Moreover, in absence of knowledge about the skills of the construction labour force, 90-degree elbows are used throughout design because they are easier to build.

In contrast, sophisticated SCs create three-dimensional computer models to detail their work. Such models are easier to interpret than blueprints are. Their use by construction workers eases planning for the installation process on site and helps in identifying space constraints; it prevents errors during execution. SCs also know if they will have qualified labour on site and can thus choose to match labour skills with design detailing solutions. Involving SCs earlier in design would yield these benefits. Contractors could then also start looking for labour earlier, level their labour utilization over a longer look-ahead time frame, and be more certain regarding continuous employment of its best, hourly work force.

In addition, detailers working for SCs have a better sense for the use of alternative routing solutions than design detailers do. In a subfab, the piping contractor got involved early in design and took advantage of alternative routings to a great extent. This yielded savings in terms of shorter routings, fewer labour hours, and less material. Kim *et al.* (1997) and Zabelle & Fischer (1999) have reported similar instances where the early and concurrent use of three-dimensional models by SCs and designers brought significant gains to the design-build process.

Knowledge of space considerations for construction processes

Because SCs build the design, they have developed a sense for space needs that should be accounted for in early design in order to allow construction to proceed efficiently. Instances of such knowledge concern access paths to bring in equipment and materials, and clearances around routings so people have space to work in and move around. Involvement of SCs in early design can prevent designers from developing solutions that are inefficient or impossible to build.

Examples of space considerations

2.A. To install routing lines in the mains and laterals of a semiconductor subfab, piping and mechanical contractors typically follow a sequence of steps. First, they have to decide on the length of spools to order, according to the space conditions they anticipate will exist on site when the spools arrive. Once the spools arrive, contractors have to bring them separately into the building. They slide the spools up into the steel racks where they put them in rows ready to weld. To weld the spools around, they need 2–3 feet (0.5–1 m) of empty space sideways. Finally, to hoist the routing line into its final position, they need vertical clearance between the area where they welded the spools and their final location. If routings are stacked, contractors can install those on top only after installing those at the bottom. Yet, because contractors do not get involved in the design, they cannot contribute to the creation of alternative configurations that would add flexibility to the construction process. Because they are uncertain about the space constraints they will face when spools arrive, they order the shortest spools in anticipation of not being able to slide longer ones into place. Unfortunately, shorter spools increase the number of welds and may unnecessarily increase labour hours and time to install.

2.B. To weld stainless steel, fibreglass, and other materials on site, mechanical and piping contractors use equipment of significant dimensions, such as orbital welding machines. Contractors suggest, for instance, a minimum of 6 inches (15 cm) between adjacent lines to efficiently weld spools and valves. In addition, contractors need designers to consider access paths to reach work areas with welding tools. Lack of a consideration for such requirements may result in drawings of subfab cross-sections that specify welding operations hard – if not impossible – to perform. When this is the case, contractors may propose to replace welded- for bolted-connections. Yet, because some think bolted connections are more prone to leaking, such change orders may demand significant attention, effort, and co-operation from all parties involved.

2.C. Designers typically arrange cable trays in the mains of subfabs by stacking them (Fig. 3a). They graphically represent such an arrangement with cross-sections at regular distances. Stacking can be inefficient during cable-tray installation, if the design does not leave enough space between trays for the contractor to enter and leave with cables. Having a contractor check, during design, for ease of installation of cables could therefore benefit the process later. Staggering cable trays could potentially facilitate such tasks, according to one electrical contractor, but this configuration requires more lateral space (Fig. 3b).

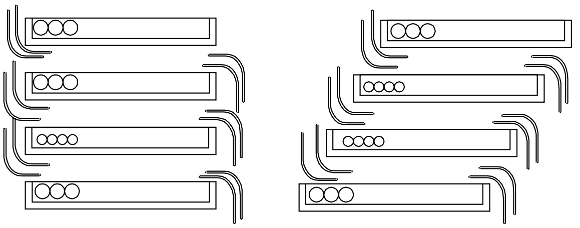
(a) Stacked cable trays **(b)** Staggered cable trays

Figure 3 Alternative arrangements for cable trays.

Knowledge of fabrication and construction capabilities

Capabilities of SCs reflect the qualifications of the labour force available at the time of construction, and of the equipment and tools used off- and on-site. For instance, mechanical contractors who know which labourers will fabricate ductwork in their shops and which machines those labourers will work on can detail their design for the most effective fabrication. Such process knowledge can enable designers to better match early design decisions and production choices with contractor capabilities without sacrificing design creativity or quality.

Examples of fabrication and construction capabilities

3.A. Welding stainless steel is a sophisticated operation. Welding on site takes longer than in the shop because of multiple reasons, such as safety concerns for people working on ladders or the time people spend bringing in specialized equipment and setting it up on site. These concerns also result in higher costs (especially insurance) for site work. Contractors estimate, for instance, that it takes approximately 2 h to weld a 24′ (60 cm) stainless steel pipe in the shop and 10–12 h to perform the same welding task on site. When procurement and shop fabrication are co-ordinated with ongoing site work, materials handling costs may even be reduced.

3.B. A lateral is a set of routings including pipe or ductwork that branch off the main routing. From the valves on laterals, other pipes and ducts branch off to connect with the process tools up in the cleanroom and with the process support tools down on the floor of the subfab. The location of tools in the cleanroom determines the valve spacing on the laterals. Designers, however, typically decide on the diameter and spacing of valves during early design development, when the tool layout is still prone to many changes. They do so because the client needs the design specified for contractors to bid it. Involving contractors early on in design would create understanding regarding which commitments on parameters to postpone, and thereby which sets of design alternatives to leave open (e.g. assuming different valve spacings or duct diameters) until the client has a more definite layout. Such a set-based design practice has been successfully adopted in manufacturing where design is subject to similar unpredictable environments (e.g.Ward *et al.*, 1995) and it has been explored in AEC computer-based applications (e.g. Lottaz *et al.*, 1999).

Because contractors and designers would be sharing information during design, contractors would then be able to order materials and execute the design more promptly once the client committed to a specific layout. Contractors would also know better what valves would be located in positions that are difficult to access and hook up to the process tools and support equipment. If given the opportunity, they could pre-assemble those valves in the shop before shipping spools to site. Besides, contractors could create points of connection using valves on Ts, so as to increase their accessibility once the pipe was installed, and thereby ease hook-up work.

Knowledge of supplier lead times and reliability

Specialty contractors can contribute in various ways to equipment and material selection in early design. Designers typically detail specifically the equipment and material that contractors have to procure. They do so in part because they worry that contractors might opt for low quality or cheap alternatives, if specifications were less precise. Design specifications are, however, not necessarily customized to the specific project at hand. Moreover, by making product choices, designers also make implicit process choices because chosen products have their respective lead times and installation requirements (Sadonio *et al.*, 1998). Once contractors start procuring what is specified, they may discover that these items are not readily available. Alternatives that are acceptable from a delivery performance perspective may not exactly conform to what was specified. Specifications then end up creating unnecessary delays. Further investigation of ‘or equal’ specifications is appropriate in this regard (De La Garza & Oralkan, 1993; Ganeshan *et al.*, 1991; Bernold & Treseler, 1991).

In contrast, SCs have a strong sense of urgency when procuring long lead items or available alternatives because they install such equipment and materials on a regular basis. Specialty contractors also have ongoing relationships with distributors and suppliers and know their reliability regarding shipping dates and product quality. If SCs and suppliers are involved earlier in design, they can inform designers of the lead times associated with different alternatives and make designers aware of the impact poor supplier selection may have on production. In addition, SCs frequently maintain the systems they build for a warranty period. They can therefore help designers and clients to differentiate between alternative equipment and system designs in terms of performance reliability and operations-and-maintenance needs. These issues as well as others pertaining to supply-chain management are becoming increasingly important in AEC product delivery.

Example of supplier lead time and reliability

4.A. Knowledge of material lead times is essential for SCs to develop and adhere to the most efficient construction sequence. In the case of mains and laterals in subfabs, experience recommends that contractors first install vertical lines, such as vacuum lines that hook up vacuum pumps to process tools, because of their length constraints. Installation should then proceed with drain lines and ductwork because they are part of large-diameter gravity systems that have to slope. Then, installation of process piping should follow. Finally, electrical cables should be installed as they offer flexibility to be routed around obstacles.

Material lead times affect in different ways the readiness of mechanical, electrical and piping (MEP) trades to start work. Electrical contractors are not constrained by long lead items for a number of items, so this enables them to promptly start work once space is available. Other trades, such as process piping and mechanical, often have lead items of 4–6 weeks if not longer, depending on the kinds of spools and fittings needed and the suppliers involved. Accordingly, electrical contractors may start their work while other contractors are still waiting for orders to arrive. Electrical systems may then end up blocking the access paths that other contractors had relied on. When this happens, either electrical systems have to be ripped out and built anew later, or piping and mechanical contractors have to find alternative ways to execute their work, using, for instance, shorter spools. In any event, time delays and additional labour expenditures are likely to result.

BEYOND AVAILABILITY OF SPECIALTY-CONTRACTOR KNOWLEDGE

Contractual agreements

Many more examples exist of specialty-contractor contributions to early design than those that have made it into practice. The examples in this paper characterize the nature of such contributions. Whether or not SCs have the opportunity to participate in design, often is a contractual issue. Figure 4 illustrates three different contractual agreements: (I) design-bid-build, (II) design-build with architectural/engineering firms-general contractors (A/E-GC) and (III) design-build with SC. Only the latter expressly accounts for specialty-contractor involvement in design. Furthermore, design firms may request SCs to provide design-assist services or clients may get specific contractors involved in a project – and potentially in design – by nominating them.

Design-bid-build and design-build by architect/engineer-general contractor (A/E-GC)

In design-bid-build and design-build projects, SCs are typically left out from the initial contractual agreements between the client and the architect/engineer, and the client and the general contractor (Fig. 4I), or the client and the design-build firm (Fig. 4II). Instead, the general contractor selects SCs primarily through competitive bidding after obtaining a set of drawings and specifications defining the AEC product. By involving SCs

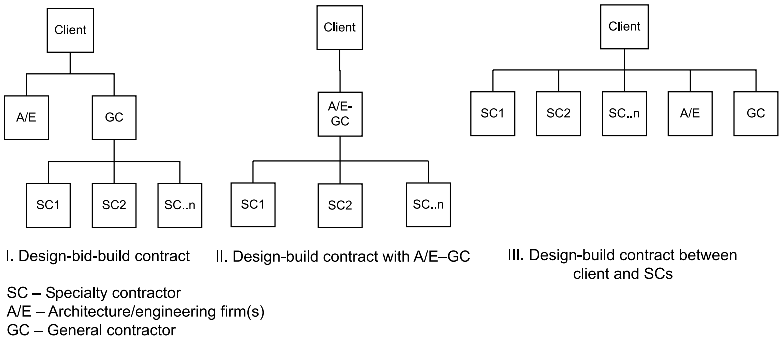

Figure 4 Alternative contractual agreements between client, general contractor, architecture/engineering firm(s) and specialty contractors.

earlier, design-build organizations may be able to not only leverage specialty-contractor knowledge but also to jointly create new knowledge. Such involvement implies that selecting contractors by competitive bid based on more-or-less completed drawings and specifications should be abandoned in favour of selecting contractors earlier in the process. In doing so, design-build organizations and clients must address other issues, such as establishing communication, means and incentives, and liability, which are discussed later in this paper.

Design-build by specialty contractor

The client or design-builder may contract directly with one or multiple SCs to develop the design and execute the work. This practice is becoming increasingly common, particularly with mechanical, electrical, and piping trades, as their work gets to be more specialized (ENR, 1997; Iskra *et al.*, 2000). Alternative contractual agreements to competitive bidding, such as unit pricing or cost plus contracts, enable clients to involve contractors earlier, with a less defined design, while they could still maintain a good sense of the expected cost of work. Still, design-build by SCs leads to other issues in terms of project-based operations management. It raises questions as to who should take the project lead and how to co-ordinate the work during design and construction. Recent publications have started to tackle these issues and present innovative tools to support new process designs, such as: (1) WorkPlan (Choo *et al.*, 1999) – a database program to support job-shop scheduling, (2) the 'Parade Game' (Tommelein *et al.*, 1999) – a game that illustrates the impact that work flow variability has on the performance of construction trades and (3) the '5 WHYs' (Tsao *et al.*, 2000) – a management method for problem solving still rarely applied in the AEC industry.

Nominated contractors

A client may identify and name a specific SC early on in the project, a so-called 'nominated contractor', who is to later engage in construction. When this is the case, the general contractor does not have the opportunity to choose any other contractor for that specialty.

The client may nominate a contractor because they already have a good working relationship, because the architect/engineer suggested that this contractor has significant knowledge and can help design a specific technology, or because of any other reason. However, nominated contractors get involved in early design decisions only when the client or the design-build organization explicitly asks them to. Contractors get compensated for early efforts in that nomination guarantees that they will do the work and it lets them save on bidding costs. In practice, nominating contractors essentially boils down to establishing a contractual relationship to formalize an early contractor selection (Higgin & Jessop, 1964, pp 44; Bennett & Ferry, 1990).

Design-assist

Design-assist is an informal arrangement between the architect/engineer and the SC. Design-assist has in recent years become common in the USA, but a description of this practice is surprisingly absent in the research literature. The objective of design-assist is to give SCs the opportunity to comment early on the design, based on their knowledge regarding design, procurement, and construction processes, but this does not mean that they will get the job. Specialty contractors may agree to assist designers because it gives them the opportunity to know more about the design, the designers and the expected builder team. Such knowledge helps them to assess better what the risks may be during the postaward submittal process and construction, so they may be able to bid the work more favourably.

Design-assist has, however, only limited effectiveness. Because the participating contractors are not contractually guaranteed they will get the job, they may not give much assistance because competitors who later bid the work will see their solutions. For instance, an electrical contractor told the authors that he often takes a priced one-line design diagram to design-assist meetings. However, whether or not he reveals that information depends on his assessment of the chances of getting the project, and how interested he is in getting it, given what he had learned during the meetings.

Communication systems

Communication is important for SCs to share knowledge in design-build organizations. Communication will enable SCs to better understand designers' intent, especially when designers insist on building in a way different from what they think would be the best solution. Confrontation often arises because of lack of understanding of other disciplines' concerns and rationale for making specific choices. For example, the valves welded on Ts in pipe, which allow for future access by contractors, is a lesser alternative to valves welded on the perimeter surface of the pipe. Designers prefer the latter because the absence of the T avoids stagnation of fluids and thus potential contamination by impurities.

Better communication will also enable contractors to discuss alternatives with designers. For instance, designers frequently complain how difficult it is to draw and specify their intentions regarding empty space they want to leave for future needs. As a result, such space may end up being invaded during construction. If designers insist on it being left free, contractors will have to rework their installation.

Communication between SCs and designers can also help to estimate more accurately the cost of design alternatives. In semiconductor projects, estimates at an early design stage frequently turn out later to have been too low. Design-build organizations and clients tend to let less realistic estimates proceed through design development – even if individuals may be sceptical – because costs and the likelihood of changes are not explicitly acknowledged. When contractors bid the project, especially under lump sum contracts, higher-than-expected costs may be revealed. Clients may then request value engineering. This frequently means changing the design to bring back costs within the initial budget. This causes rework and wastes time and resources. Greater accuracy in estimating would help design-build organizations and clients to better rationalize early design decisions and choices.

Various communication mechanisms are used in practice in the semiconductor industry. One mechanism is to promote meetings between SCs and designers during early design before design-build teams commit to design parameters and before designers start developing the design based on those parameters. Such was the case in a tool hook-up project where SCs, designers and client representatives worked together in small groups for two consecutive days during which they jointly agreed upon major design decisions and production choices (Miles, 1998).

Another mechanism is to co-locate detailers working for contractors in design offices side-by-side with detailers working for the design firm during the design detailing stage; or co-locate engineers and detailers working for design firms on site while construction progresses. The authors know of several SCs who co-locate their detailers in a single trailer with other specialty-contractor detailers on site, so that it would be easy and expedient for them to identify and resolve interference problems.

A third mechanism is to promote meetings between selected suppliers and SCs. Such was the case in a project, which consisted of hooking-up tools that were manufactured in Japan. The client arranged meetings in the USA between the tool manufacturers and the SCs before the tools arrived, and provided language translators to intermediate the meetings in which potential interface issues were addressed.

But providing the means for people to meet does not guarantee communication will happen. This is our critique on partnering efforts that lack an underlying formalism to streamline communication and fail to recognize explicitly what needs to be communicated and when. For instance, communication failed to occur on one project because people who work for SCs (such as labour managers) were brought to design co-ordination meetings without proper guidance. These meetings may involve 20 or 30 people, including designers and client representatives, and may be intimidating. It is then natural that someone, who intends to share what he knows, opts to remain silent.

Alternative means exist, however, for organizations to guarantee that available knowledge is shared effectively. In one project, a client representative used to meet periodically with specialty-contractor foremen to get their feedback on the design being developed concurrently. With that feedback in hand, the client representative then went to co-ordination meetings with design leads and authoritatively relayed the suggestions made by the foremen.

Tremendous organizational impediments need to be overcome for communication to be open and effective. Our work to date has focused on identifying what kinds of knowledge might be communicated, before the authors tackle organizational issues.

In addition to promoting organizational change, existing and emerging information technologies (IT) can also ease communication between AEC project participants. Today's web-based collaboration tools track design drawing submissions (e.g. as .pdf files in Portable Data Format) and changes (e.g. using digital, two-dimensional redlining features), but many still support a throw-it-over-the-wall mentality. Shared 3-dimensional CAD models and databases begin to be used but are far from common. A follow-on step is to share set-based models for concurrent design that are annotated with design intent and rationale. Early prototypes of such systems exist (e.g. Tommelein *et al.*, 1991; Ward *et al.*, 1995; Lottaz *et al.*, 1999). The AEC community is facing a long, yet exciting path forward in terms of developing practical IT applications for true collaboration!

Means and incentives to promote specialty-contractor involvement in design

Specialty contractors have little incentive to share knowledge and improve the design, especially when harsh contractual agreements are spelled out

(Pietroforte, 1997). To involve SCs in early design means to involve people with construction experience, such as labour managers and foremen, who typically are very busy and extremely valuable on site. Thus, although SCs may have the flexibility to pull one or two of their most experienced people from an on-going job so they can spend a couple of days with designers, they need to be assured that this is worth doing.

Other industries offer examples of incentives to get the right supplier representatives involved in product development. Specifically, manufacturers have fostered long-term relationships with suppliers, spelled out contracts that state those intentions, and increased the size of orders by reducing the number and proximity of suppliers they work with (Womack *et al.*, 1990; Dyer, 1997). Manufacturers and suppliers jointly may engage in target costing (e.g. Cooper & Slagmulder, 1997). Similarly, design-build organizations should try to foster long-term relationships with SCs, rethink their contracts, and reduce their pool of SCs so that the latter will recognize that their effort in early design will pay off with more construction work in future.

Observations of current practices confirm that AEC organizations are moving in this direction. In one case, a semiconductor client decided to reduce its pool of MEP trade contractors – traditionally selected by competitive bidding – to a steady few (two or three) for each specialty. In another case, a client selected a specific mechanical contractor early on and, to ensure the contractor and designer would communicate effectively, contractually agreed with the mechanical contractor that his detailers (pipefittter and sheetmetal workers by trade) would be located in the design firm's office for the duration of the design process. In a third case, a SC became involved in early design of tool-install work. The installation of tools inside a fab is performed mainly by MEP contractors. Due to the uncertainty regarding tool characteristics at the time installation design unfolds, clients frequently select SCs early on. Detailers working for contractors and designers may even form interdisciplinary teams to collect information from tool vendors and together decide on the best routings for the tool-install utilities.

Liability

Traditionally, designers have contractually assumed liability for design. The division of professional liability in current practice is far from being a trivial problem. Specialty contractors often propose changes to the original design that designers have to approve, but when designers approve such changes, they typically add the clause that such approval does not bind them to any professional liability. Such clause, however, may not be enforceable in practice.

If SCs participate in early design and contribute their knowledge to design definition, all on the AEC team have to jointly agree on how they will share professional liability. With increased involvement in design, the SC's liability naturally is likely to increase. In the aforementioned example of the plenum body, for instance, the SC assumed liability for the modular design. Other evidences that SCs are ready to assume professional liability are the recent acquisitions of design firms by SC firms. Such acquisitions grant contractors engineering capabilities as well as the professional competence to assume design liability.

CREATING EXPLICIT KNOWLEDGE IN AEC ORGANIZATIONS

Tacit knowledge consists of informal technical skills, intuitions, and insights of individual employees, etc., and is commonly captured in the term 'know-how'. Tacit knowledge is only implicit and people cannot easily articulate it (Nonaka, 1991; Nonaka & Ray, 1993; Bohn, 1994). In contrast, explicit knowledge exists in some kind of representation (e.g. books, guidelines and procedure manuals) that makes it more independent from individuals. Explicit knowledge is easier to share and communicate among people who work in the same organization than tacit knowledge is. Socialization and interaction among individuals are means to share tacit knowledge and such sharing contributes to company culture. By sharing tacit knowledge, individuals may find it easier to articulate and convert it into explicit knowledge. In turn, once new explicit knowledge is shared among individuals, it helps to extend each individual's own tacit knowledge base into new knowledge, which is what Nonaka (1991) defined as the 'spiral of knowledge'.

The AEC practitioners working for SCs or design-build organizations do not get enough opportunities to interact with each other. Efforts that aim to increase the level of interaction between them, such as partnering, have proven to be successful to some extent. Lack of interaction explains why potential contributions of specialty-contractor knowledge have not made it into design practice but there are numerous other explanations, including blue- vs. white-collar barriers.

The reluctance to interact is also fuelled by the perception that adversarial relationships must exist as they historically have between designers and contractors. Adversarial relationships arise when parties blame each other, even when it is impossible to assign blame to one party exclusively. On one hand, SCs noticing errors and omissions in bid documents may not inform the design firm thereof and bid according to the original design. Bidding on an alternate solution may put a contractor at a disadvantage against competitors or disqualify him altogether. In turn, the designer may consider an error or omission to be inconsequential and not worth spending time on. For instance, a SC reported a case where he noticed some valves were missing. These valves were needed to prevent equipment in the system from getting filled with the fluid used in the de-passivation of the piping before start-up. He let the error go unreported until he got the project. Because explicit communication between professionals from the two parties did not exist, there was no guarantee that designers who missed the valves could be informed of their usefulness.

On the other hand, contractors are said to not point out problems as soon as they notice them because changes after contract award are potentially lucrative. Which kinds of problems should one be expected to identify during bidding vs. is one likely to come across during detailed work planning? Whether or not these perceptions are valid in any specific circumstance is hard to evaluate. Consequently, contradictory views are bound to exist as long as communication between the parties remains poor. The AEC practitioners must learn to create win-win situations through increased interaction and collaboration, rather setting themselves up for the lose–lose situations that are so prevalent today.

Tsao *et al.* (2001), who also question the way boundaries are drawn for work to be divided among AEC participants, phrase the issues succinctly. ‘Trades do not necessarily complain about (design) problems (encountered during construction) because (1) contractually speaking, site problems may be considered theirs to resolve, (2) they may have more important problems to address such as developing bargaining tactics and determining which battles to fight and (3) complaining might reflect poorly on their trade skill and pride (‘tricks of the trade’) so they believe workarounds are what they are supposed to do. Such workarounds are costly and time consuming. However, they are an accepted way to perform work. Workers do not question the design because their contracts have already been signed and work must proceed according to the original design.’

A second example of how the lack of interaction impedes the process of building explicit knowledge in AEC organizations relates to ‘fitting-bound’ problems. Fitting-bound problems consist of insufficient height to install a certain number of fittings needed on a pipe so that it would perform the changes of direction as needed. Fitting-bound problems are an intrinsic subject in the education of pipe fitters. In subfabs, valves left on laterals and mains for later hook up to process tools in the cleanroom should be left at 45 degrees instead of horizontally. If these valves are designed horizontally, most certainly one additional fitting will be needed to turn the direction of the pipe and chances increase that installers will later run into fitting-bound problems. At present, designers consider this to be common knowledge, but because this knowledge mostly remains informal, not all designers necessarily know it. Besides, those who know it may have learned it in the hardest way, by repeatedly specifying solutions that were difficult or impossible to build.

A third example illustrates how the lack of interaction between SCs and designers may further delay the resolution of problems. In one project, two cable trays were designed one on top of the other, merging at one end into one cable tray. Installation of the cable trays had started. The contractor was aware that code officials might not approve the transition the way it was designed because, as such, it would probably lead to a density of cables above what regulation allows. The problem was apparently well known at that point among individuals involved in the project. But because individuals thought that resolving the problem would be time consuming and they were too short on time to develop an alternative, they kept postponing its resolution.

If AEC organizations do not make an effort to create explicit knowledge that results from individuals’ interaction, new recruits or employees not directly involved in the process are unlikely to share knowledge; there will be no common basis for understanding. Also, if people who have tacit knowledge leave, the organization loses that knowledge. Accordingly, mistakes will be made over and over again. By keeping knowledge tacit, the AEC industry forces itself to remain an experience-based industry and thereby loses a tremendous opportunity for theory-based learning (Koskela, 1992; Tommelein, 1999). Learning that is supported by theory – as opposed to learning based exclusively on experience – enables firms to more quickly integrate new recruits and get them to perform at higher levels of skill and competency. This should be a key concern in today’s construction industry, which is facing an increasingly ageing work force. Quicker integration may also lead to even higher mobility for employees (mobility already is high in construction), which is a good way to disseminate best practices and thereby advance performance in the industry as a whole. Higher performance levels lead to higher returns but demand higher wages or salaries. This too will help to attract new people into the industry.

Automated rule-based systems have offered a way for AEC organizations to leverage tacit knowledge and make it explicit (e.g. Hendrickson *et al.*, 1987; Kartam & Levitt, 1990; Winstanley & Hoshi, 1993; Dzeng, 1995; Fischer & Aalami, 1996; Dzeng & Tommelein, 1997; Aalami, 1998; Akinci & Fischer, 2000). These systems formalize tacit rules on best construction sequences and relationships between physical components to automatically generate construction layouts and schedules, given a specific design. Despite their potential, such automated systems still are not widely used in practice today.

As opposed to creating construction plans that suit a design, our work addresses a different question. Why not use knowledge that makes construction easier and adapt the design to suit it? Such adaptation processes should be carried out thoughtfully to ensure that construction convenience does not compromise the creativity and product quality of the design solution. Taking this thinking even further and questioning who should join an AEC organisation to be best positioned to take on what work, is called 'work structuring' in lean construction (Ballard, 1999; Howell & Ballard, 1999; Tsao *et al.* 2000, 2001).

In contrast, other organizations preserve tacit knowledge of employees by formalizing it in design rules or at least creating opportunities so colleagues can share their knowledge. For instance, some Japanese companies promote socialization among people from different parts of their organization. They make designers follow the execution of their design so they get exposed to other perspectives that they would normally not see (Nonaka, 1991). Similarly, Iansiti (1995) reports on the effort that organizations in the computer industry make for retaining, leveraging, and sharing the knowledge of experienced employees across the organization. The rotation of new recruits, from estimating and bidding to field engineering and project management, is common in larger construction firms but it tends not to bridge design-construction boundaries.

CONCLUSIONS

Current practice reveals that AEC organizations have few if any formal mechanisms in place to leverage the knowledge of SCs. Our empirical research and others' work has shown, however, that SC knowledge is available and may contribute significantly to the effectiveness of design-build processes and the quality of AEC products. The authors classified this knowledge in four categories and we provided examples from our observations of current practice and anecdotal evidence collected in interviews. Industry practices illustrate that SCs are increasingly getting involved in projects earlier.

The AEC practitioners must become more aware of the opportunities currently being lost and rethink some of their practices. The involvement of SCs in early design makes it possible for experienced design and construction people to share and leverage their knowledge.

One challenge for AEC organizations is to implement means and incentives for individuals to make their knowledge explicit and to share what they know within their organization as well as with individuals working for other firms. Not only the individual organization that succeeds in doing this, but also the industry as a whole, will benefit from such knowledge creation and sharing. This may become a key selling point for the construction industry to attract new blood.

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