

CONTRIBUTION OF SPECIALTY CONTRACTOR KNOWLEDGE TO EARLY DESIGN

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ABSTRACT

This paper discusses what knowledge specialty contractors may contribute to the early design of architecture, engineering, and construction (AEC) products. In current practice, specialty contractors are seldom involved in the early design effort, but evidence suggests that their early involvement is increasing. Lean construction theory advocates this involvement. The paper reports on research that focused on the processes for designing and building semiconductor facilities. The research consisted of conducting a series of one-to-one interviews with experienced practitioners, ranging from labor managers to lead designers and owner representatives. Specifically, we unveil the contributions of specialty contractor knowledge to early design in terms of process efficiencies and improvements in product quality. We group such value in distinct categories and provide examples that stem from current practice or which present potential opportunities for improvement. We discuss reasons why specialty contractor knowledge often is ignored in practice. Examples from changes in the AEC environment nevertheless suggest that organizations are creating conditions to increase interaction between designers and specialty contractors. Such interactions may help AEC organizations to retain and share the knowledge of individuals as well as develop new knowledge.

KEY WORDS

Specialty contractors, knowledge, lean construction, early design, concurrent engineering

INTRODUCTION

Architecture, engineering, and construction (AEC) projects are complex processes aimed at designing and building a product. These projects involve at least a design or design-build firm and an array of specialty contractor firms. Design and/or design-build firms typically are in charge of most of the design development process and occasionally execute some parts of the construction work, such as the concrete or steel structure. In turn, specialty contractors most often competitively bid on different parts of the remaining construction work. This

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work is segmented according to the different specialties, such as mechanical, electrical, and process piping.

How to effectively coordinate the work of coordination of specialty contractors in AEC projects has for long been a research question (Crichton 1966, Hinze and Tracey 1994). The work of specialty contractors has evolved from artisan-ship to sophisticated assembly of components (Bennett and Ferry 1990). Their work, typically done on-site, has progressively extended to off-site tasks, creating detailed fabrication and installation drawings, selecting vendors, procuring and expediting delivery of materials and equipment, building, starting-up, and maintaining building systems (Tommelein and Ballard 1997).

Yet, specialty contractors are still seldom involved in early design. Design-build organizations primarily select specialty contractors once designers have produced a set of drawings and specifications defining the AEC product. Inefficiencies during construction thus result from such lack of interaction between contractors and designers (Tommelein and Ballard 1997). The AEC industry's persistent use of harsh contractual agreements between specialty and general contractors has also deserved criticism (Pietroforte 1997).

In contrast, other industries have progressed towards more involvement of suppliers in product development and manufacturing. In organizations that have adopted lean manufacturing practices, suppliers work closely together with manufacturers in order to streamline the production processes (Womack et al. 1990, Clark and Fujimoto 1991, Ward et al. 1995). Suppliers and manufacturers share information on their production systems in order to reduce inventories, perform just in time parts delivery, increase reliability of supply lead times, and cut cost. To achieve such goals, manufacturers have adopted different practices, such as move people from their organizations to work at suppliers' installations, and create conditions so people who work for suppliers can work in their assembly plants.

In addition, manufacturers have established incentives for suppliers to get involved earlier in design: they have increased the size of orders and commit to long term contracts. Suppliers' early involvement aims to: (1) avoid conflicts between suppliers and manufacturers in the assembly stage that stem from lack of understanding, (2) create conditions for more frequent innovation, (3) reduce meaningless changes in product development and manufacturing, (4) create conditions to start manufacturing without complete product information, (5) increase trust and mutual commitment among parties, (6) make upstream downstream-friendly solutions, and (7) make it possible to postpone decisions in design without sacrificing overall development and implementation time.

Similarly, in the computer industry, manufacturers work together with suppliers in early design to leverage available technology and achieve gains in 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. Moreover, manufacturers postpone the date when the design concept is frozen in order to gain flexibility to accommodate late changes, as Figure 1 illustrates.

Given these observations, we wondered to what extent these new practices regarding supplier involvement would be applicable to the AEC industry. Assuming contractors in AEC systems are the equivalent of suppliers in manufacturing, a key question of our research therefore is: What knowledge can these suppliers bring to the table?

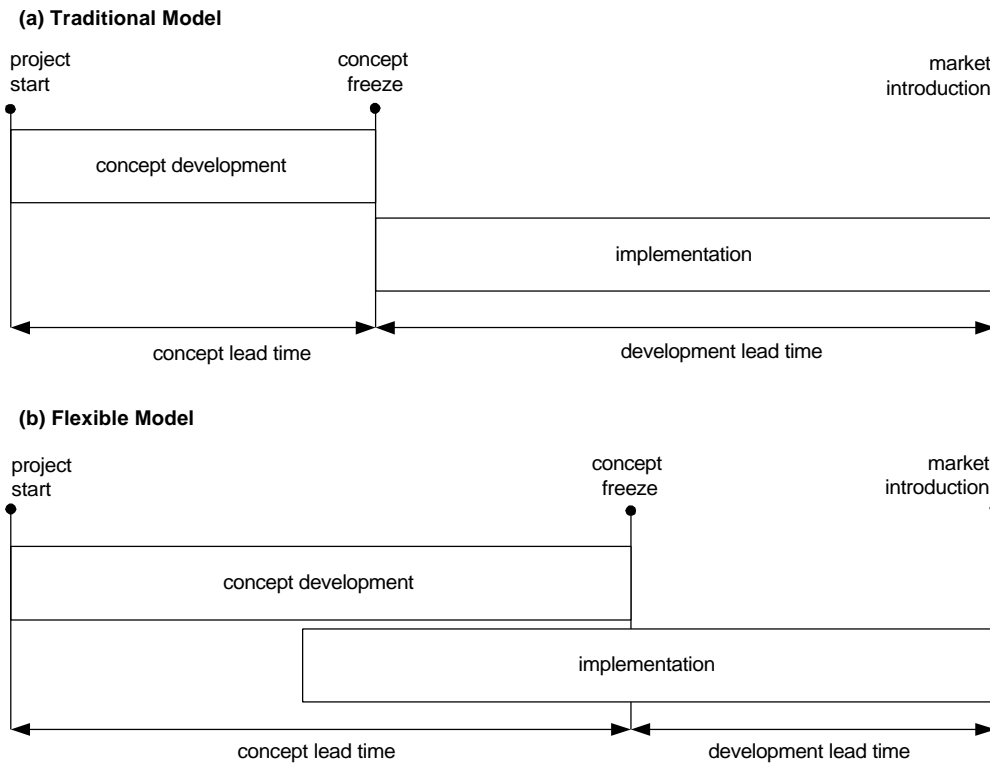


Figure 1 Two Models of Effective Product Development (Iansiti 1995)

RESEARCH APPROACH

Our research started in November 1998 and has focused on developing an understanding of the value specialty contractor knowledge can bring to early design. We chose as a research setting the design and building processes 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 approach consisted of three phases. We first interviewed people at a leading-edge design-build firm, then people at specialty contracting firms, and finally, people at owner organizations. All were experienced in the design and building processes of semiconductor facilities. The interviews lasted approximately one to two hours. Frequently, we carried out follow-up interviews with the interviewees. No written questionnaires were used. All interviews were audio taped except for those done over the telephone.

In the first phase, we interviewed 18 lead designers, design managers, and construction managers who work at Industrial Design Corporation (IDC), in Portland, Oregon. IDC is a leading design-construction firm, with a wealth of expertise in high-tech facilities. The total 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 and what they wished they knew before making decisions, and the hand-offs of information between design specialties. In the second phase, we interviewed 12 people who worked for specialty contractors, ranging from labor manager to vice-president. The interviews aimed to better understand the knowledge held by specialty contractors and

its contribution to early design. We limited the interview process to the mechanical, electrical, and piping (MEP) trade contractors. In the third phase, we interviewed 7 people who worked for owner organizations. The interviews aimed to better understand the uncertainties that plague the definition of design criteria and project scope of semiconductor facilities. We probed interviewees as well into innovative practices that could add value to design and building processes.

AVAILABILITY OF SPECIALTY CONTRACTOR KNOWLEDGE

The contributions of specialty contractor knowledge to early design can be multiple. We arranged these contributions in four categories.

1 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, part of their creativity results from their continuous involvement in projects of different owners and designed by different design firms. Such diversification and rotation of work exposes specialty contractors to multiple alternative ways of solving design problems and keeps them up to date on technological innovations. On the other hand, their creativity may also result from better knowledge of the constraints affecting the construction process.

We acknowledge however that the early involvement of specialty contractors creates conditions so they try to impose the solutions they prefer. Still, designers face a similar condition when contractors do not get early involved, with the additional risk of having to redesign the solutions when contractors later get on board.

Examples

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 specialty contractor 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 include in a pre-assembled fashion the ventilation ductwork, the light fixings, and the ceiling grid. The owner accepted the contractor's proposal and the plenum was built accordingly. The solution has reportedly brought significant savings in labor hours, installation time and cost, and increased safety of installation. However, it led to redesigning the plenum body at a cost to the owner 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 execution of the modules in the fab shop and their ease of installation. The performance quality of the solution is apparently higher because of better conditions available in the shop to carry out work such as, for instance, welding. The solution has been patented and the owner is presently exploring its applicability to future projects.

1.B Offsets, rolled offsets, and 45 degree fittings are ways for changing the direction of pipes and ductwork. These ways achieve shorter routings and can potentially lead to savings in terms of materials, labor, number of welds and flanges, fittings, and space. They are also

beneficial from a performance standpoint because they restrict flow less. Yet, these alternatives are seldom used in design development. Apparently, the use of such alternatives is less intuitive for design detailers because they frequently limit the graphical representation of building systems to two-dimensions. In contrast, specialty contractors typically detail three-dimensionally so as to ease the installation process on site and prevent errors during its execution, particularly if they expect workers not to be all equally qualified because of labor shortages. As a result, detailers working for specialty contractors have developed a better sense for the use of these alternative routing solutions than design detailers. We observed an example in a subfab where the piping specialty contractor got involved early in the design of the routing systems. The contractor took advantage of alternative routing to a great extent. Such involvement brought savings in terms of shorter routings, labor hours, and materials. Likewise, Kim et al. (1997) and Fisher and Zabelle (1999) report on comparable instances where the early and concurrent use of tri-dimensional models by specialty contractors and designers brought significant gains to the design-build process.

2 KNOWLEDGE OF SPACE NEEDS ASSOCIATED WITH CONSTRUCTION PROCESSES

Because specialty contractors build the design, they have developed a sense for the needs of space during construction that should be accounted for in early design in order to build it efficiently later on. Instances of such knowledge concern access paths to bring in equipment and materials, and clearances around routings so people have space to work and move around. Involvement of specialty contractors in early design can prevent designers from developing solutions that are inefficient to build or that cannot be built.

Example

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 expect to 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. Then, contractors weld the spools around, for which they need 2 to 3 feet of empty space sideways. Finally, they hoist the routing line into its final position, for which they need vertical clearance between the area where they welded the spools and their final location. If routings are stacked, contractors can only install those on top after they have installed 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. Besides, because contractors are seldom certain of space constraints they will face when spools arrive, they frequently decide to order the shortest spools in anticipation of not being able to slide longer spools into place. Consequently, shorter spools augment the number of welds, and may unnecessarily result in labor hours and time to install.

3 KNOWLEDGE OF FABRICATION AND CONSTRUCTION CAPABILITIES

Capabilities of specialty contractors are a function of the qualifications of the labor force available at the time of construction, and of the equipment maintained in fabrication shops. Mechanical contractors, for instance, fabricate ductwork in their shops with specific tools. Those tools dictate how they detail a design so they can most effectively fabricate ductwork.

Such knowledge can enable designers to better match early design decisions and production choices with available building capabilities without sacrificing design creativity and quality.

Examples

3.A Welding stainless steel is a sophisticated operation. Welding on site takes longer than in the shop due to multiple reasons, such as safety concerns for people working on top of ladders or the time people spend in bringing specialised equipment and setting it up on site. Contractors estimate, for instance, that it takes approximately 2 hours to weld a 24” stainless steel pipe in the shop and 10 to 12 hours to perform the same welding task on site.

4 KNOWLEDGE OF SUPPLIERS’ LEAD TIMES AND RELIABILITY

Specialty contractors can contribute in diverse ways to equipment and material selection in early design. Designers typically specify in detail the equipment and material contractors have to procure. Designers do so primarily because they worry that contractors would opt for low quality and cost alternatives, if specifications were less precise. Design specifications are, however, not necessarily customized to the projects. Once contractors start procuring the specified items, these items may not be available and existing alternatives, though may exist and be acceptable from a performance perspective, may not exactly conform to what was specified. Specifications then end up creating unnecessary needs for long lead items.

In contrast, specialty contractors have a better sense of urgency to procure long lead items and of available alternatives because they install the equipment and materials. Specialty contractors have gained experience and developed a better sense for the reliability of suppliers regarding shipping dates. If they are involved earlier in design, they can inform designers of the lead and delivery times associated with different alternatives. Moreover, contractors can inform designers of the less reliable suppliers and help to create awareness for the impacts of selecting those suppliers.

Moreover, specialty contractors frequently maintain the building systems for a warranty period. They can therefore help designers and owners to differentiate between alternative choices of equipment and system designs in terms of performance reliability and maintenance needs.

Example

4.A Knowledge of material lead times is of the essence to guarantee that specialty contractors can follow the most efficient construction sequence. In the particular 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 gravity systems that have to slope and have the biggest diameters. Then, installation of process piping should follow. Finally, electrical cables should be installed as they offer flexibility to move around obstacles in their routing. Material lead times affect in different ways the readiness of mechanical, electrical, and piping (MEP) trades to execute their work. Electrical contractors typically are not constrained by long lead items, which enables them to put promptly start work once space is available. Other trades however, like process piping and mechanical, have long lead items on the order of 4 to 6 weeks if not longer, depending on the kinds of spools and fittings needed and the suppliers involved. However, in current practice, it frequently happens that electrical contractors start executing their work while

other contractors are still waiting for their orders to arrive. Thus, electrical systems end up blocking the access paths other contractors had relied on. When this happens, either electrical systems have to be ripped out and build 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 labor expenditures result in most circumstances.

BEYOND AVAILABILITY OF SPECIALTY CONTRACTORS' KNOWLEDGE

Not all examples of available specialty contractor knowledge have made it into practice. In current practice, design-build organizations typically bring together design firms and general contractors but leave out specialty contractors. Some of the aforementioned examples therefore persist as potential contributions to early design. However, by involving specialty contractors earlier, design-build organizations will be creating conditions to leverage their knowledge. Such involvement implies that selecting contractors by competitive bid them based on specifications and drawings should be abandoned in favor of selecting them earlier in the process. In doing so, design-build organizations and owners will face other questions, the most relevant of which we discuss next.

COMMUNICATION SYSTEMS

Communication mechanisms are important so people in specialty contractors firms can share their knowledge with people in design-build organizations. Communication enables specialty contractors to better understand designers' intents. It will make it easier for contractors to understand why designers insist sometimes on building in a way different from what they think would be the best solution. Contractors will also have the opportunity to discuss alternatives with designers. For instance, designers frequently complain how difficult it is to communicate their intentions to specialty contractors in drawings and specifications regarding empty space they want to leave for future needs. As a result, such space occasionally ends up being invaded during construction. If designers stipulate such space should definitely be left free, contractors will have to rework the solution they installed.

In addition, communication between specialty contractors and designers can help designers and owners to accurately estimate the cost of design alternatives. In semiconductor projects, cost estimates at an early design stage frequently reveal later to have been undervalued. Design-build organizations and owners tend to let less realistic estimates proceed during design development because costs of changes are not explicitly assumed, even if individuals may disbelieve them. Only when contractors bid the project, will awareness for costs higher than expected become finally explicit. Owners may then impose new changes in design aimed at bringing back costs to the initial budget. Such changes cause rework and waste of time and resources. Accuracy in costs would help design-build organizations and owners to better rationalize their early design decisions and choices.

We have observed multiple examples of communication mechanisms set in practice in the semiconductor industry. Instances are:

- Promote meetings between specialty contractors and designers at the early design decision stage before design-build teams commit on design parameters and designers start developing the design based on those parameters. Likewise, such was the case in a hook-up project where specialty contractors, designers and owner representatives worked

together in small groups during two days in a row at early design. During those days, they jointly agreed upon major design decisions and production choices (Miles 1998).

- Co-locate people such as engineers and detailers working for design firms on sites while construction progresses. Co-locate detailers working for contractors in design offices side by side with detailers working for design firms during the design detailing stage.
- Promote meetings between selected suppliers and specialty contractors. Such was the case in a project, which consisted of hooking-up tools that were manufactured in Japan. The owner arranged meetings between the tool manufacturers and the suppliers before the selected tools arrive, and provided language translators to intermediate the meetings.

But providing the means so people can meet may not suffice to guarantee communication will effectively happen. Instances exist in which communication failed to occur because people who work for specialty contractors such as labor managers were brought to design coordination meetings without proper guidance. These meetings can however involve up to 20 or 30 people, among designers and owner representatives. It is then natural that people who would intend to share what they know, opt to remain silent.

Alternative means exist, however, for organizations to guarantee available knowledge is effectively shared. In one project we visited, for instance, one owner representative used to meet periodically with foremen who worked for the specialty contractors so as to get their feedback on the design being developed concurrently. With that feedback at hand, the owner representative would then go to coordination meetings with design leads in order to guarantee the suggestions from specialty contractors would be considered.

INCENTIVE SYSTEMS

To involve specialty contractors early means to involve people with construction experience, such as labor managers and foremen in the early design effort. Experienced labor managers and foremen are, however, valuable people on site so they typically are very busy. Thus, although specialty contractors may have the flexibility to pull one or two of their most experienced people from a current job so they can spend a couple of days with designers in early design, specialty contractors need to be assured that it is worth doing so.

Other industries offer multiple examples of incentives in order to get the right people from suppliers involved in product development. Specifically, manufacturers have fostered long term relationships with suppliers, spelled out contracts that explicitly reflect those intentions, and increased the size of orders by reducing the number of suppliers they work with (Womack et al. 1990). Similarly, design-build organizations should try to foster long term relationships with specialty contractors, rethink actual contractual practices, and reduce their pools of specialty contractors so that the latter will recognize that the effort they put in early design will grant them more work in future. Observation of current practices gives evidence that organizations are moving in this direction. As an example, an owner of semiconductor facilities has recently decided to reduce its pool of MEP trade contractors to a steady few for each specialty.

LIABILITY

Traditionally, designers have contractually assumed liability for design. The division of professional liabilities in current practice is far from being a trivial problem. Specialty

contractors often propose changes to the original design that designers have to approve. Designers approve changes but typically add the clause that such approval does not bind them to any professional liability. Such clause, however, may not be enforceable in practice.

But presupposing specialty contractors participate in early design and contribute with their knowledge to the design definition, practitioners have then to jointly agree on the way firms will assume professional liability. Specialty contractor liability naturally will have to increase. In the aforementioned example of the plenum body, for instance, the specialty contractor assumed liability for the modular design. Other evidences that specialty contractors are ready to assume professional liability are the recent acquisitions of design firms by specialty contractor firms. Such acquisitions grant contractors engineering capabilities as well as the professional competence to assume liability over design solutions.

CREATING EXPLICIT KNOWLEDGE IN AEC ORGANIZATIONS

Tacit knowledge partly consists of informal technical skills, intuitions, and insights of individual employees, often captured in the term “know-how”. Tacit knowledge seldom exists explicit and people often cannot easily articulate it (Nonaka 1991, Bohn 1994). In contrast, explicit knowledge exists in some kind of support 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. By sharing tacit knowledge individuals are then able to articulate and convert it into explicit knowledge. In turn, once new explicit knowledge is shared among individuals, it helps to extend each own’s tacit knowledge base into new knowledge, in what Nonaka (1991) defined as the “spiral of knowledge”.

In the AEC industry, people who work for specialty contractors and design-build organizations seldom have opportunities to interact with each other. Such lack of interaction helps to explain why potential contributions of specialty contractor knowledge have not made it into practice. One particular example is that of errors and omissions with design drawings and specifications. Specialty contractors may notice the errors and omissions before they bid the work. However, contractors frequently opt for not informing the design firm and bid according to the original design. Contractors do so because they worry that if they would bid according to the solution they presume will get built it would put them at disadvantage against competitors. A specialty contractor reported, for instance, one case where he noticed some valves were missing but let the error go unnoticed until he got the project (these valves were needed to block equipment in the system from getting filled with the fluid used in the depassivation of the piping before start-up). Besides, because explicit communication between professionals from the two parties did not exist explicitly, no guarantees exist that designers who missed the valves were informed of their usefulness.

A second example of the way such lack of interaction retards 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 it performs 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 to later hook up to process tools above 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 installers may later run into fitting bound problems. At present, designers perceive such procedure as common knowledge, but because this knowledge mostly remains informal, it is not sure all know the procedure. Besides, those who know it gained such understanding in the hardest way by specifying for repeated times solutions difficult or impossible to build.

A third example illustrates how the lack of interaction between specialty contractors and designers may negatively contribute to postpone the resolution of problems. In one project, two cable trays were designed one on top of the other. Installation of the cable trays has started. At their end, the two will merge into one. The contractor is aware that code officials may not approve such transition the way it is designed because, as such, it probably will lead to a density of cables above what regulation allows. The problem is apparently well known at this point among individuals involved in the project. But because individuals perceive the resolution of the problem as time consuming and they lack time to focus on an alternative, they have been postponing its resolution.

If AEC organizations do not make an effort to create explicit knowledge that results from individuals' interaction, nothing guarantees that novices or people not directly involved in the process will share the knowledge. Also, if people who have the tacit knowledge leave, the organization loses that knowledge. In contrast, other organizations care for preserving the tacit knowledge of its individuals by formalizing it in design rules and creating opportunities so individuals can share the knowledge between colleagues. These are the cases, for instance, of Japanese organizations that promote socialization among people from different parts of the organization. They make designers follow the execution of their design so they get exposed to other perspectives they would not normally be aware of (Nonaka 1993). 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.

CONCLUSIONS

Current practice reveals that AEC organizations have few if any mechanisms in place to leverage the knowledge of specialty contractors. Research reveals however that specialty contractor knowledge is available and may offer significant contributions to improve the effectiveness of the design and building processes and the quality of AEC products.

Management in owner and design-build organizations must therefore gain awareness of the opportunities currently being lost and rethink some of their practices. The involvement of specialty contractors in early design is of the essence so their experienced people can share knowledge with designers. Industry evidence suggests that specialty contractors are getting involved in projects earlier, which is a sign owner's awareness is increasing.

One challenge for AEC organizations will be to implement means and incentives so that individuals may share what they know within the organization as well as with individuals working for other firms. In addition, organizations must also create means so individuals can make new knowledge resulting from such interaction explicit to others in their firms.

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