Opportunities for Computer-Aided Design for Construction

by

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Opportunities for Computer-Aided Design for Construction

By Gijsbertus T. (Bart) Luiten¹ and Martin A. Fischer², Assoc. Member, ASCE

ABSTRACT: The demand for better integration of design and construction, also called Design for Construction (DfC), is growing. Clients demand faster delivery and higher quality, and building companies want to rationalize the building process. Many organizational approaches and technological opportunities are available or under development to improve integration of design and construction. Opportunities offered by information technology (IT) are especially promising. Only few projects, however, combine organizational approaches with state-of-the-art technologies in a systematic manner to derive the full benefits of computer-aided DfC. This paper describes a framework that helps organizations approach computer-aided DfC systematically. The framework identifies six interactions between design and construction and is based on frameworks for Design for Manufacture (DfM) and on an analysis of current building practice. DfM has proven most effective when integrated into a cyclical product development process. Our framework serves as a road map for the building industry to formalize its information flows and to integrate DfC into its linear facility delivery process and to approach a more cyclical delivery process.

INTRODUCTION

While most industries have faced a growing demand for quality of their products and speed of their production processes for decades, now also the Architecture, Engineering, and Construction (AEC) industry is under growing pressure to increase quality and speed of its production processes. For example, realization of production facilities is a major bottleneck for the successful introduction of a new chip by semiconductor producers (Wood 1994). The traditional, fragmented process of realizing buildings (e.g., by throwing drawings over the wall) does not support firms in meeting these challenges. In literature on this subject, the magic word seems to be integration, preferably using computers (e.g., Sriram et al. 1989; Björk 1991; Tolman 1991; Teicholz and Fischer 1994). Let us briefly examine what is meant by (computer-aided) integration.

No generally accepted definition exists of the word integration in the context of the building industry. Researchers at the Center for Integrated Facility Engineering (CIFE) at Stanford University have defined integration as “the continuous interdisciplinary sharing of data, knowledge, and goals among project participants” (Fischer 1989). This is obviously a very general definition, but it can be tailored to specific circumstances in a company by using the formula “sharing something <What?> by somebody <Who?> using some approach <When?> for some purpose <Why>.” Table 1 (Fischer et al. 1993) shows this generic definition and proposes five levels of integration for each dimension. This flexible definition

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of integration helps firms map their current level of integration and develop strategies to increase integration.

Table 1. Dimensions and levels of integration (Fischer et al. 1993).

<table>
<thead>
<tr>
<th>Level of integration Dimension</th>
<th>(1) -&gt; Low</th>
<th>(2) -&gt;</th>
<th>(3) -&gt;</th>
<th>(4) -&gt;</th>
<th>(5) -&gt; High</th>
</tr>
</thead>
<tbody>
<tr>
<td>Who?</td>
<td>individuals</td>
<td>departments</td>
<td>entire organization, firm</td>
<td>whole project life-cycle</td>
<td>entire industry</td>
</tr>
<tr>
<td>What?</td>
<td>data</td>
<td>information</td>
<td>knowledge</td>
<td>goals</td>
<td>all project information</td>
</tr>
<tr>
<td>When?</td>
<td>islands of automation</td>
<td>multiple applications in one discipline or phase</td>
<td>multiple applications from several disciplines in one phase</td>
<td>multiple applications from several disciplines and phases</td>
<td>all applications in facility delivery process</td>
</tr>
<tr>
<td>Why?</td>
<td>survive, stay in business</td>
<td>increase profit</td>
<td>increase market share</td>
<td>enter new market</td>
<td>create new market</td>
</tr>
</tbody>
</table>

The need for integration in daily practice is illustrated by the often troublesome interaction between design and construction. The classic construction problem is that early design decisions have a large impact on cost of construction, but these decisions have to be made in a phase in which it is still unknown how and by whom the building will be constructed (Ahuja and Walsh 1983; Ferry and Brandon 1992). Another problem is that, to control the whole realization process, designers often prescribe the building in all details, leaving no or little space for contractors to adapt the design to construction methods they prefer. Moreover, goals of owners, designers, contractors, and construction managers often conflict. Design for Construction (DfC) is a methodology that addresses these issues.

Researchers have studied organizational approaches to improve constructibility and have shown their effectiveness (Tatum 1987; Russell and Gugel 1993; O’Connor and Miller 1994). However, many building projects don’t take advantage of these organizational approaches and miss opportunities for improved constructibility. Along with other researchers (e.g., Finn 1989; Werkman et al. 1990; Adams 1993; Suckarieh et al. 1993), we have focused much of our research on developing information technology (IT) to support DfC (Fischer 1991; Luiten 1994). We hope that with increased IT support, organizations will find it easier to implement constructibility improvement programs. To help organizations combine organizational approaches and technological opportunities, we present a framework that identifies six interactions between design and construction. We argue that increased IT support for each of these interactions requires formalization of the information flows specified by the framework.

In this paper, we discuss the origin and motivation for this framework and classify and relate DfC technologies based on the six interactions. We defined this framework by studying similar frameworks in the manufacturing industry and by adapting them to the building industry. For each interaction, we give an overview of the state-of-the-art of DfC and identify current problems, available opportunities, and on-going research. From the framework, we then derive the technological and organizational hurdles the building industry has to take to fully benefit from DfC. Finally, we assess the future of DfC and discuss implications for practice and research.
FRAMEWORK TO RELATE DFC TECHNOLOGIES

To give direction to our computer-aided DfC research, we developed a framework that puts DfC technologies into the context of the facility delivery process. We based our framework on observation of current practice and study of on-going research in manufacturing and construction. We found inspiration in two frameworks defined for the manufacturing industry. The first framework describes a typical DfM process and relates DfM methodologies to this new process. The second framework identifies DfM opportunities in the traditional product development process. Our framework reflects current building practice and acknowledges the importance of information flows for the integration of design and construction.

Typical Design for Manufacturing process

In many manufacturing enterprises, Design for Manufacture (DfM) has become an integral part of the product development process and has increased product quality, saved cost, and reduced time to market (Swift 1987). We studied DfM and manufacturers’ approach to its introduction to provide inspiration for DfC and its introduction to construction.

Stoll (1988) outlines a typical DfM process in manufacturing (see Fig. 1). First, manufacturers (1) optimize the proposed product concept and process plan, then (2) they simplify the product design and (3) try to ensure conformance between the product and the production process. Finally, they (4) optimize the product function. This cycle is repeated until the product development goals are met. The imperatives for this process are a team approach or simultaneous engineering, an attitude to resist making irreversible design decisions as long as possible, and a commitment to continuous optimization of product and process. The results of the DfM process are a part list, part and assembly drawings, and a process plan.

Stoll uses the four main activities in this DfM process model as a framework to classify and relate ten often used DfM methodologies (see italic text in Fig. 1). The main lesson from this DfM framework is that manufacturers had to depart from their often fragmented and linear product delivery processes to reap the benefits of the cyclical DfM process. In Thompson's words (1967), DfM changes the traditional sequential process to a process where design and manufacturing are reciprocally dependent and changes the traditional coordination by plans to coordination by mutual adjustment.

The basic goal of DfM, i.e., improving the manufacturability of a product, translates directly to DfC, i.e., improving the constructibility of a facility. However, it is unclear how to superimpose this cyclical DfM model onto the typical facility delivery process. Usually, every building project is delivered by a new team of specialists from various firms. In addition, contractual arrangements often fragment the building process and make it linear, i.e., few facilities are developed by one organization that is vertically and horizontally integrated. This higher degree of fragmentation in construction (compared to manufacturing) makes it significantly more difficult to move towards integrated cycles of facility/process development. Furthermore, these organizational characteristics of the facility delivery process hinder the efficient information exchange necessary to support DfC cycles.

Therefore, to outline opportunities for DfC and to approach cyclical and integrated product and process design, we first need a DfC framework that relates to current practice.
**DfM/DfC opportunities: design-communication matrix**

Based on observation of manufacturing practice, Adler (1988) developed a matrix that relates DfM opportunities to product development phases. Fischer (1991) adapted this matrix for construction (see Table 2). The matrix classifies nine DfM/DfC opportunities with respect to broad project phases and the nature of communication. It breaks up product development into the phases: pre-design, design, and post-design, and it classifies communication as: one-way, formal two-way, and interactive.

When only one-way communication is available, no feedback from construction is possible. Firms either develop and use constructibility knowledge or make construction methods flexible enough to cope with any design. Formal two-way communication enables feedback from construction to design, either through constructibility rules that should be followed during design, through design reviews by a contractor, or through engineering change orders issued by contractors. Interactive communication requires organizational changes, such as sharing of goals between design and construction before design, establishment of cross-functional design teams, or location of designers in transition teams on site.

<table>
<thead>
<tr>
<th>Phase</th>
<th>Pre-Design</th>
<th>Design</th>
<th>Post-Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>One-way</td>
<td>Develop implicit constructibility knowledge (A)</td>
<td>Use (A) or (B) for design</td>
<td>Construction flexibility</td>
</tr>
<tr>
<td>Formal two-way</td>
<td>Develop constructibility design rules (B)</td>
<td>Design reviews</td>
<td>Engineering change orders</td>
</tr>
<tr>
<td>Interactive</td>
<td>Share goals between design and construction</td>
<td>Cross-functional design teams</td>
<td>Transition team</td>
</tr>
</tbody>
</table>

Adler's matrix reflects current practice and acknowledges the importance of communication between design and construction for the overall success of DfC. It also highlights the importance of combining organizational approaches and technological opportunities to improve constructibility. Adler (1992) has since extended his framework to relate DfM to Thompson's categories of interdependence and coordination. Thompson (1967) argues that moving from sequential to reciprocal interdependence "places increasingly heavy burdens on communication". To support this more complex communication with IT, we need to identify and formalize the specific information flows between design and construction.

Process model of current practice

To develop a DfC framework that relates to current practice and formalizes information flows, we modeled the facility delivery process and identified the interactions between design and construction. We then classified DfC technologies with respect to the interactions they support.

Luiten (1994) modeled the interactions between design and construction as observed in the Dutch building industry using the IDEF0 methodology (SoTec 1981) (see Fig. 2). The model is the result of an analysis of the most prevalent practice of delivering building projects. Because of the very general level of the model and its specific focus on design and construction, we believe that this model is also valid for building projects in other countries.

The traditional building process is characterized by its sequential processes. Designers produce a design which is input for construction managers, who produce schedules that are then used during construction. When compared to the DfM process shown in Fig. 1, the building process is linear and has only few, rather long feedback loops.

The process model reveals six interactions between design and construction.

1. forward exchange of design information,
2. feedback on building design from construction,
3. backward exchange of construction information,
4. backward exchange of constructibility knowledge,
5. upstream shift of construction management tasks, and
6. downstream shift of design tasks.

Interactions 3, 5, and 6 are only sporadically observed in current practice. In Fig. 2, these interactions are indicated with a dotted line. Interactions 1, 2, and 3 require sharing of information, interaction 4 requires sharing of knowledge, and interactions 5 and 6 require sharing of goals between designers and contractors.

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Because the six interactions reflect current practice and the importance of the information flows for computer-aided DfC, we will use them in the following section as a framework to classify and relate DfC opportunities. The framework, in combination with the generic definition of integration and Table 1, helps companies and researchers alike identify desirable DfC strategies and technologies. By modeling their own facility delivery process, companies can easily identify which interaction (or interactions) between design and construction could utilize IT support. They can use the generic definition of integration to determine the current and the desired level of integration. They can use the framework to identify what DfC opportunities are available to raise the level of integration for a specific interaction.

INTERACTIONS BETWEEN DESIGN AND CONSTRUCTION

For each of the six interactions between design and construction we investigated current practice and state-of-the-art research. In this section we summarize our findings for each interaction and illustrate current problems with a practical example. We also identify organizational approaches and technological opportunities available or under development. For the DfC opportunities we look at Stoll’s DiM methodologies, Adler’s opportunities for integration, current building practice, and research. At the end of the section, a table summarizes the DfC technologies.

The reader will notice that many projects already utilize some of these approaches and opportunities. However, few projects combine organizational approaches with state-of-the-art technologies in a systematic manner to derive the full benefits of computer-aided DfC.

Interaction 1: forward exchange of design information

During and after design, information about the designed building must be transferred from designers to constructors. Traditionally, this is done with paper drawings and paper
specifications. Nowadays, more and more of these drawings are available in electronic format. While electronic drawings make electronic communication possible, they don't change the communication content. Constructors still have to interpret the text and lines on the drawing to derive the input for project management applications. Often, these reinterpretations of designs are incomplete and inconsistent with the original intent. Furthermore, the original design drawings might be incomplete or inconsistent (e.g., architectural and structural drawings might conflict). Such problems are often discovered only late in the design and construction process.

Incomplete 2D-drawings of a roof detail illustrate this type of miscommunication (see Fig. 3). As construction of the roof eaves was about to start, it was noticed that a C-channel was missing. This C-channel was necessary for structural reasons (i.e., to connect the gutter to the roof assembly) and for constructibility reasons (i.e., to align the roof panels with the roof edge and to adjust for the undulation of the steel deck). The solution of this problem required a rapid redesign of the detail and a re-sequencing of the sheet metal, stucco, and roofing subcontractors. It led to delays in the completion of the roof and caused productivity losses for all involved parties.

![Fig. 3](image)

**Fig. 3** 2D CAD drawing of roof eaves detail.

The main cause of this kind of miscommunication is that different professionals interpret 2D-drawings differently and therefore do not necessarily discover inconsistencies. Several technologies exist or are under development to improve the speed and quality of this type of communication. The ultimate goal of these technologies is to reduce human involvement in processing (design) information. Examples are: Electronic Data Interchange (EDI), Product Data Interchange (PDI), classification of project components (Ray-Jones and McCann 1971), 3D-CAD, and product modeling. The manufacturing industry uses similar techniques, e.g., group technology and feature modeling, to raise the level of information exchange. These techniques represent design information in an open, high-level, computer-interpretable format (Froese 1992; Teicholz and Fischer 1994; Luiten and Tolman 1995). “Open” means that data is represented independently of the participants and their computer systems, “high-level” means that humans do not need to interpret the information, and “computer-interpretable” means that humans do not need to process the data. It is the major goal of the STEP product-modeling approach (ISO/TC184 1993) to provide a standard for such an exchange format. An organizational issue that has to be solved with the emergence of electronic information sharing is the willingness of companies to share information that is easily reusable. Legal issues, such as liability for incorrect information and protection of copyrights of design
concepts, need to be addressed. The prescription—in many situations—of stamped and signed paper documents as the legally binding documents is another hurdle.

Interaction 2: feedback on building design from construction

After receiving the design information, constructors often have comments on the designed building. They might, for example, not agree with the proposed or implied construction method or propose alternative designs that are cheaper or faster to construct or provide better value. Traditionally this feedback is done rather ad hoc—by telephone, fax, or meetings—and often under great time pressure.

The precast concrete element industry, for example, often faces the problem of ad hoc and late feedback. In the Netherlands, architects and their structural engineers generally design the building structures for in-situ concrete. To take advantage of the cost and time savings with precast concrete elements, their designs have to be changed substantially. In the case of an extension of Schiphol airport in Amsterdam, the structure was designed for in-situ concrete with fixed connections between beams and columns. For precast concrete, however, hinge connections are much faster and easier to build because the elements can just be placed on top of each other without temporary structures. Also, the details for precast fixed connections are more difficult to fabricate in the factory and to assemble on site. The architect did not want to change the design and as a result the project was not very successful for the precast element supplier.

Many of these problems are caused by the traditional way of working together which strictly separates design and construction responsibilities. Some facility owners require scheduled constructibility design reviews at specific stages of design completion (Kirby et al. 1988). Concurrent engineering (Prasad et al. 1993) and partnering bring design and construction closer together and might help introduce construction feedback earlier in the project than in traditional projects. Furthermore, organizational integration of design and construction facilitates formalization of feedback. As for interaction 1, formalization of communication enables open, high-level computer-interpretable communication. A technology that helps constructors give feedback to designers is 4D-CAD (Collier and Fischer 1995). 4D CAD links a 3D-CAD design with a schedule to visualize the construction process. Such a visualization elucidates constructibility implications of design decisions to designers. 4D-CAD is already supported with commercially available software, but still requires significant manual input.

Interaction 3: backward exchange of construction information

Instead of giving feedback after design decisions have been made, constructors could also inform designers of their preferences before the decisions are made. This would mean that constructors tell designers what resources they have available and which construction methods they prefer. Designers could then take that information into account when making design decisions. By doing so, they will increase the constructibility of their design and decrease the use of interaction 2, i.e., giving construction feedback only after design decisions have been made.

The relevance of exchanging construction preferences from the start of a project is well shown by two competing engineering contractors in Japan who had to build two adjacent warehouses with similar accessibility problems (see Fig 4). Because access was limited to the South side, lifting the commonly used steel elements to the North side of the building was problematic. The West contractor took this construction information into account during design and used in-situ concrete instead of steel. It was able to lift concrete buckets with a crane positioned on the South side of the building all the way to the North side and completed construction in one, continuous flow. The East contractor on the other hand designed a steel structure like they have done on other projects without accessibility constraints. During
construction planning they found out that they had to place the crane inside the building to lift the heavy steel columns and beams to the North side of the building. Removing the inside crane and filling in the slab later disrupted the construction flow and delayed project completion by one month.

**Fig. 4** Two warehouses with similar accessibility problems.

The West contractor could deliver its project faster and cheaper because its designers and construction managers were willing and able to share and consider project-specific construction information from the beginning of the project. Just as for interaction 2, backward exchange of construction information can only be accomplished if designers and constructors work together. The traditional process in which constructors offer a price to build a completed design does not benefit from these two interactions. Again, organizational changes, such as concurrent engineering or partnering, coupled with information sharing techniques are needed. To automate this interaction, contractors should be able to exchange information on available resources and preferred construction methods electronically. However, for the representation of resources and methods, an electronic, neutral format is currently not available.

**Interaction 4: backward exchange of constructibility knowledge**

Besides construction information from the constructors in the current project, designers could also use general constructibility knowledge to improve the constructibility of their designs. Constructibility knowledge originates from experiences in previous projects and therefore requires a long feedback loop that often even crosses company borders. Currently, there is no generally accepted method to formalize this constructibility knowledge on a large scale. As a consequence, the knowledge only exists in the minds of experienced designers, and when they leave a company, their knowledge leaves with them.

It is common practice for design firms to formalize this constructibility knowledge in heuristic rules, such as: “do not vary the concrete strength on one floor of a building” or “keep dimensions of similar elements constant.” These rules are often learned the hard way: every engineer knows an anecdotal story in which an exception to the heuristic rules was overlooked during construction and had to be repaired at large cost. For example, all columns in a building in the Netherlands for an American client had the same dimensions except two columns that had to carry some heavy equipment on a higher floor. As Murphy’s law would have predicted, the dimensions of the columns were mixed up in the basement and the supposedly stronger columns had to be reworked before the equipment could be placed.

A major issue in computer-aided DfM is to formalize constructibility rules. When formalized, such rules can be used interactively during design with computers, and constructibility knowledge can be shared between firms and within a firm. This formalization is also a main focus of DfM methodologies (Stoll 1988). DfM methodologies, such as design
axioms, DfM guidelines, Design for Assembly, manufacturing process design rules, and designer's toolkit, capture general manufacturability knowledge in rules and guidelines. Other DfM methodologies, such as the Taguchi method, the failure mode and effects analysis (FMEA), and value engineering, evaluate manufacturability of a design. Some of these methodologies are supported with computer applications. Fischer (1991) developed a similar approach for the building industry, in which he defined general constructibility rules for concrete structures and used these rules to evaluate structural designs. If these constructibility rules are to be defined and used to evaluate a design easily, design and construction management information have to be represented and exchanged on a high-level. When, for example, the design of a concrete structure is only represented with lines and text in a drawing, it is not easy to define a rule that reasons about the sequence of construction of components. On the other hand, when designs are represented as symbolic models of beams, columns, and supported-by relationships, it is straightforward to define a rule that formalizes that supporting components have to be built first. An important organizational issue is that not all companies are willing to formalize and to share their knowledge. This reluctance has legal backgrounds, such as the uncertainty about liability and copyrights, and historical backgrounds, such as the traditional mistrust between partners that might be competitors in future projects. Again, these kinds of problems can be eliminated partly by organizational approaches, such as partnering and concurrent engineering.

**Interaction 5: upstream shift of construction management tasks**

Another common problem for the integration of design and construction is the large time lag between design decisions and the elucidation of their consequences. To shorten this gap, designers could take part in the construction management process. Even in the early design phases when it is not always clear who will construct the building, planning, scheduling, and cost estimating would give designers insight into time and cost consequences of their decisions. However, designers are not always willing to spend time on construction management and are often not specialized in it.

The realization of the Storebaelt West Bridge in Denmark is an illustrative case in which designers successfully took part in construction planning. The engineering department of the leading contractor was responsible for designing the bridge so that is was easy to build. They chose to precast the elements of the bridge on a dock and transport the large elements by ship. They realized that design of the bridge and construction, i.e., precasting, shipping and hoisting the elements, affected each other to a large extent. Therefore, they chose to plan and visualize the construction process throughout design. As a result they were able to identify and address some of the effects design and construction had on each other.

Whether designers are willing to participate in construction management depends on whether goals for the project are shared between designers and constructors. Do they agree on and benefit from the priorities of the time to design, time to construct, overall project duration, cost of design, cost of construction, cost of material, optimal use of construction resources, and so on? If not, designers will not put extra effort in construction management. O'Brien (1995) addresses the issue of defining incentives for firms that go beyond partnering and establish a rationale for sharing the profits resulting from sharing project goals. Today, most designers are not necessarily experts in construction management nor do they have time or budget to perform construction management tasks. Parts of construction management, such as scheduling and cost estimating, are already supported with commercial computer applications, but planning (i.e., defining the required activities) and its link with the designed product are not yet supported by software. Several ongoing research projects aim at tackling these issues (Luiten and Fischer 1995; Törmä and Syrjänens 1995). These efforts might eventually lead to the emergence of desktop engineering (Kunz et al. 1994) which allows
engineers to perform multi-disciplinary evaluations of proposed designs and construction plans on one computer.

**Interaction 6: downstream shift of design tasks**

Likewise, it is possible to shift design tasks to constructors. In that case, design choices are made by constructors who have better insight into constructibility consequences. This implies that designers prescribe requirements and limitations, within which the constructors can develop a design of the part they are responsible for. The designers then have to approve and coordinate the designs proposed by the constructors.

Especially in heavy construction, constructors often design their part of the structure. In the case of a major bridge in Rhode Island, the original design specified a continuous box girder for the approach spans over open water. The construction of this design would have required the installation of falsework over several spans. The contractor elected to redesign the approach spans to accommodate precast box girders and to utilize the heavy lifting expertise of the company. This eliminated the costly falsework and allowed construction of the girders in a controlled environment on shore. This redesign required in-house design expertise from the contractor.

A problem often encountered when constructors design their part of the product is how to communicate project requirements and measure performance. Currently, most communication focuses on the final solution: drawings normally contain the proposed form of the building, the design intent is only implicit. Changes are on the way with the introduction of performance contracts between contractors and suppliers. This gives suppliers of parts of a building much more influence on design. Another change is the growing number of Design-Build contracts (Design-Build Institute of America 1994) in which one contractor or project manager is responsible for design and construction of a facility. Design-Build contracts only specify the users' requirements (i.e., the performance of a facility, a time schedule for realization, and a budget) and the conditions (such as the building site and the environment). The contractor that fulfills the requirements and conditions the best will get the contract. A major challenge when writing such a contract is to find a balance between being comprehensive enough to assure compliance by the contractors and avoiding overly restrictive requirements that would inhibit creative solutions.

**Summary**

Table 3 summarizes the main organizational approaches and technological opportunities that can be used to improve the six interactions between design and construction. It classifies the status of each DfC technology as either (1) worked out in enough detail and tested enough so that it is available for use in practice now, or (2) worked out theoretically but not yet tested fully in practice, or (3) an area that needs further research before it is ready for testing and use in the future.
<table>
<thead>
<tr>
<th>Interaction</th>
<th>Status</th>
<th>Organizational approaches</th>
<th>Technological opportunities</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 forward exchange of design information</td>
<td>Now</td>
<td></td>
<td>3D-CAD</td>
</tr>
<tr>
<td></td>
<td>Test</td>
<td>willingness to share information</td>
<td>classification</td>
</tr>
<tr>
<td></td>
<td></td>
<td>legalization electronic communication</td>
<td>group technology</td>
</tr>
<tr>
<td></td>
<td>Future</td>
<td>liability, copyrights</td>
<td>designing with product models</td>
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<td></td>
<td></td>
<td></td>
<td>industry-wide standards</td>
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<td></td>
<td></td>
<td></td>
<td>EDI, PDI</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>feature modeling</td>
</tr>
<tr>
<td>2 feedback on building design from construction</td>
<td>Now</td>
<td>partnering</td>
<td>integrating product and process information</td>
</tr>
<tr>
<td></td>
<td>Test</td>
<td>concurrent engineering</td>
<td>4D-CAD</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>PDI</td>
</tr>
<tr>
<td></td>
<td>Future</td>
<td></td>
<td>formalizing feedback</td>
</tr>
<tr>
<td>3 backward exchange of construction information</td>
<td>Now</td>
<td>partnering</td>
<td>modeling resources</td>
</tr>
<tr>
<td></td>
<td>Test</td>
<td>concurrent engineering</td>
<td>modeling construction methods</td>
</tr>
<tr>
<td></td>
<td></td>
<td>liability, copyrights</td>
<td></td>
</tr>
<tr>
<td>4 backward exchange of constructibility knowledge</td>
<td>Now</td>
<td>partnering</td>
<td>expert systems</td>
</tr>
<tr>
<td></td>
<td>Test</td>
<td>concurrent engineering</td>
<td>formalizing knowledge</td>
</tr>
<tr>
<td></td>
<td></td>
<td>liability, copyrights</td>
<td>DfM methods</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>PDI</td>
</tr>
<tr>
<td>5 upstream shift of construction management tasks</td>
<td>Now</td>
<td>partnering</td>
<td>scheduling tools</td>
</tr>
<tr>
<td></td>
<td>Test</td>
<td>sharing goals</td>
<td>cost estimating tools</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>integrating product and process information</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>planning tools</td>
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<td>4D-CAD</td>
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<td>6 downstream shift of design tasks</td>
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<td>Design-Build contracts</td>
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<td>Future</td>
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CONCLUSIONS

Based on the framework discussed in the previous section, this section discusses the main technological and organizational hurdles the building industry has to take to benefit fully from DfC. We then assess the future of computer-aided DfC and discuss implications for practice and research.

Hurdles for computer-aided DfC

To reap benefits from DfC, the building industry has to overcome both technological and organizational hurdles. As shown above, the technological hurdles originate from the traditional (low-tech) means of communication which hinder the sharing of information and knowledge. They also hinder high-level automation because new computer applications still have to produce paper documents as specified in contracts. To support integration of facility design and construction electronically, software applications must represent information and knowledge in an open, high-level, computer-interpretable format. The building industry should work on developing a standard for such a format. This will open the way for the integration of product and process, and therefore of design and construction. It will also be an incentive to develop advanced computer applications, such as construction management tools and 4D-CAD generators.

Organizations will not realize the full benefits from the technological opportunities, unless they shift tasks and reengineer the process. For example, constructors have to become more involved in the design process (interaction 6 in Fig. 2), or construction management has to parallel design and become an integral part of the evaluation of a proposed design (interaction 5 in Fig. 2). Such reorganizations will require different contractual structures and lead to new power relationships among project participants. Furthermore, to become comfortable in using computer-aided DfC technologies, AEC professionals (engineers and managers) will require significant training (Earl 1989). In despite of the legal climate, and even though current partners might be future competitors, firms will have to overcome the reluctance to share information and knowledge.

Assessment and outlook

Software (prototype) systems exist that show that computer-aided DfC is technically possible today. However, wide-spread use of these systems is limited because of the low-level, paper-based communication paradigm and the currently available computer applications that necessarily focus on the generation of paper-based documents. As a result, integration is still largely dependent on human interpretation. Because project organizations are customized for each project, computer-aided DfC requires an industry-wide, open, high-level, computer-interpretable representation of the information and knowledge used and generated by designers and constructors. At the same time, computer applications should be developed that understand such a standardized format and reason about products and processes at a high semantic level.

Maybe, more difficult to realize are the organizational changes that are needed to benefit fully from the new technologies. Fortunately, building companies already have many options available. Organizational structures can be established that ensure the sharing of goals. This can be accomplished by putting design and construction in one hand, e.g., by using Design-Build contracts or suppliers and subcontractors that both design and construct their part of a building. Lessons learned from manufacturing imply that to improve the realization process firms should eliminate unnecessary communications, make decisions as late as possible, make intent explicit, and let the right partner make the appropriate decisions. Design intent can be exchanged using performance contracts. Feedback loops can be shortened with concurrent design and construction management.
With these technological and organizational opportunities, building firms should be able to change their current fragmented and linear product delivery processes to adopt a cyclical DfC process, like manufacturing firms have already done (Stoll 1988). The difference with manufacturing is that most building products and their project organizations are one-of-a-kind. This implies that the design-management-construction cycles have to be done in a virtual (or computer) world. In a virtual world, product, construction process, and organization can be optimized concurrently before construction starts.

Implications for practice and research
Both practitioners and researchers can help bring about these changes. Practitioners could start using the technological opportunities that are ready for use and commercially available, such as 3D-CAD, exchanging 3D-CAD models, and integrated scheduling and cost estimating applications. They could also start using new organizational approaches, such as performance contracts, partnering, and design-build contracts. Practitioners and researchers could work together on bringing emerging technologies into practice to test and elaborate them further. Examples are product modeling, EDI, PDI, concurrent engineering, 4D-CAD, and expert systems or object-oriented environments that formalize constructibility knowledge. They should also collaborate on an industry-wide standard for communication, e.g., by contributing to the STEP effort. Researchers could work on technologies that need to be developed further before they are ready for introduction in practice. Examples of these new technologies are automated planning including construction methods; the integration of goals, product, process, and organization; and the integration of function, form, and behavior.

Computer-aided Design for Construction is within reach of the building industry. The DfC framework introduced in this paper puts several currently available and emerging organizational approaches and technological opportunities into perspective. We hope that it helps building firms implement successful DfC strategies.

ACKNOWLEDGMENTS

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APPENDIX 1. REFERENCES


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