Impacts of CAD on design realization

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Abstract

Complete and accurate design is critical for construction project success. Manifesting design intent in the constructed facility depends on coordinated design documents that are developed through design realization. This process evolves design intent from architects and engineers to contractors, through the production and review of shop drawings and other submittals. Information technology has been promoted as a tool to improve this process, but is not being fully utilized for this purpose. A case study investigates the impacts of computed aided design (CAD) on design realization. Comparative analysis between shop drawings prepared by hand and those done with CAD quantify notes, corrections and information transfer errors. Results support the hypothesis that utilizing CAD can improve design accuracy and lower project costs. Barriers to wider adoption, implications for practice and further research are discussed.

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Introduction

The complete and accurate realization of design intent is critical for construction project success. The transition from the designer's vision, as manifested in the contract documents (CDs), through the realization process, into the constructed facility, builds and integrates design information to supplement CDs. The process iteratively develops information among the designers (architects and engineers), the general contractor (GC) and subcontractors. Design realization is a deliberate and necessary part of the building design and production process. As a part of this process the GC and subcontractors detail and extend the picture of the final product developed by architects and engineers (what to build) to accommodate and facilitate construction methods (how to build). This additional information is documented in submittals, which include shop drawings, material samples, product specifications and certifications of performance. Shop drawings in particular have become the main interface between the end product described in the CDs, and the physical realization of the CDs in the constructed facility (Pietroforte, 1997). Producing shop drawings that accurately reflect the designer's intent through the contractor's construction methods requires the integration of very different and often divergent objectives and perspectives. Therefore, integrating CDs and submittals is critical but difficult.

The utilization of information technology can potentially increase the efficiency, accuracy and coordination of design realization. Computer integrated manufacture of steelwork (CIMsteel) an early application of an integrated computer software system in the construction industry, illustrates the opportunities. The American Institute of Steel Construction endorsed CIMsteel in 2000 as a means to eliminate paper design and improve the coordination of structural steel design and fabrication. CIMsteel is a complete software system that has demonstrated the integration of the design process from outline design through manufacturing details via the seamless transfer of data from one computer system to another. The intent is to go from design to specific details in less than 2 h with fully compatible data and no data corruption (Khanzode and Fischer, 2000). Although CIMsteel has advantages, advances in the ability to share files online via the Internet may provide additional benefits.

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Utilizing Internet-based technologies allows communication between remote users with the ability to share files, comment on changes and post requests for information. However, as will be described, even less advanced information technologies to assist design realization are not being fully utilized today.

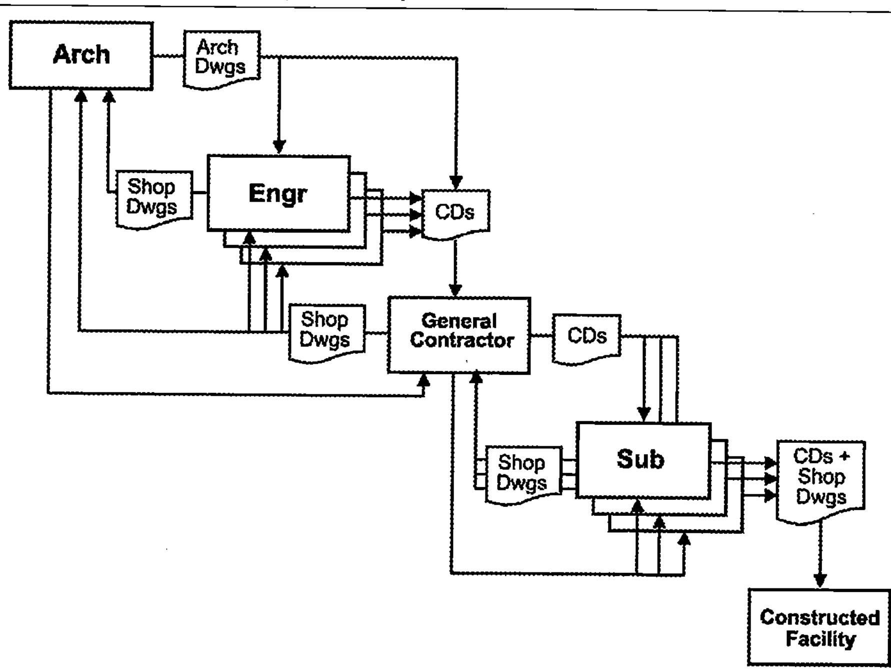
The challenges of design realization

Coordination between the architectural and engineering CDs and the installation of a particular trade's work is based on design realization, a process of drawing, detailing and checking that is organized to catch mistakes before they are installed on site (Master Builder, 2003). Integrating the construction expertise of contractors into the design is a primary objective of design realization. Figure 1 shows the information flows in a typical design realization process for shop drawings. The architects and engineers create a set of CDs and pass them on to the GC. The GC reviews the CDs and passes them on to the subcontractors, where submittals are produced for each trade [1]. Submittals pass back through the GC for review for constructability and coordination across trades. Changes and reviews are made necessary in an iterative loop between the GC and subcontractors. Submittals are then transmitted to the architects and engineers for review for consistency with design intent.
If approved, submittals are sent back to the GC who then releases them to subcontractors for procurement, fabrication and installation. Submittals that are not approved are returned to the GC and then to the subcontractors for revision and resubmittal. The process is repeated, if required, until submittals are approved. Traditionally, submittals have been paper-based, with shop drawings being drawn by hand. In this process, CDs are interpreted at each level to determine design intent and redrawn by subcontractors to prepare shop drawings. During interpretation, the process is susceptible to human error in transferring design information and reflecting the designer's intent.

Several common characteristics of CDs can cause the traditional design realization process to be slower and less accurate than necessary, including the following.

- *Missing information.* Missing information requires contractors to generate requests for information to specify and clarify design intent. This slows design realization and increases the opportunity for miscommunication and errors. Post (2000) observed significant amounts of missing information in fast-track construction, which often produces drawings out of sequence.
- *Uncoordinated information across disciplines.* Without explicit coordination by designers different systems may interfere or not work together. This typically results in change orders, and if not caught early enough, is compounded during design realization.

Figure 1 Information flows through the design realization process



- *Duplicate information.* According to Pollalis (1997), "It is the norm rather than the exception to duplicate information at the different stages of the design process, from programming all the way to producing the building". Specifications often repeat information in working drawings. Therefore, changes made to drawings or specifications may require additional changes in other documents to keep CDs consistent.
- *Inconsistent information.* Contradictory information and divergent design intent in the CDs that is not discovered until design realization generate requests for information, additional documents and iteration. This increases project duration and costs.
- *Additional information.* CDs can contain details, specification sections and other information that is not needed for construction. Patterson (2002) attributed this practice to the desire to "fill" drawing sheets and attempts to include as much information as possible in CDs to address as many possible project conditions as possible. This creates additional drawings and unnecessarily large documents, confuses contractors and adds costs.

These problems confuse project participants, increase the time required for design realization and ultimately create additional cost to owners. How can project teams efficiently create documents that integrate all required design information and accurately reflect how buildings should be constructed?

Possible improvements to the design realization process

The development, iteration and final approval and use of shop drawing information are critical steps in design realization. Several potential improvements to design realization processes have been suggested. Two helpful but insufficient approaches that apply to shop drawings are briefly described before computer aided design (CAD), the focus of this paper, is introduced.

Alternative delivery methods, such as design-build, have become a popular method of construction. This delivery process is intended to improve coordination and better integrate project participants from design through construction (Peck, 2001). In design-build development processes, designers and contractors work in a single organization. Coordination between design and construction can be more complete, accurate and effective, potentially saving time and money. But design-build teams are often organizational "marriages of convenience", created primarily to obtain work, but do not change design processes in ways that significantly improve design realization and projects.

Charles Thomsen's recommendations reduced "the silly wasted duplication" between the CDs and shop drawings because, "If we develop a process where the trades are selected either by bid or negotiation, during the development of construction document, we can integrate their knowledge and their drawings into the process" (Post, 2000). Therefore, early definition of the roles of project participants by integrating the GC and the major subcontractors during schematic or conceptual design can facilitate more integrated design information (Post, 2000). Even if used outside a design-build context, this early definition of roles and coordination can lead to improved design realization processes and integration of technical requirements to produce quality project designs. This can also be facilitated by establishing a plan for how documents will be prepared (Hart, 1994). Such a plan would explicitly identify those responsible for coordinating and integrating all the information produced by various trades (Glavinich, 1995). This can improve teamwork among the owner, designers and contractors thereby generating more effective designs by avoiding redundant and extraneous information (Construction Industry Institute, 1987). However, early selection and effective integration of the entire project team is rare and difficult to manage. Therefore, this is not currently an effective tool for improving design realization.

The use of CAD is one of the most potentially promising solutions to integrate design information into shop drawings, limiting iteration in the submittal process and thereby, improving design realization. A variety of terms and abbreviations (e.g. CAE, CADD, CAM, etc.) are used to describe tools that include the electronic development and transfer of construction documents addressed here. As used here, CAD applies computers and software in preparing drawings for construction. Using CAD does not change the basic information flows in the design realization process (Figure 1). Using CAD changes the format used to create and transfer the drawings by substituting electronic files for paper-based drawings. As envisioned, CAD can improve design realization by reducing the number of iterations and accelerating shop drawing development and improvement. CAD can reduce the number of iterations by eliminating errors in the redrawing of design information shared by architects, engineers and contractors (e.g. building shapes and column locations) and by reducing contractor-generated errors caused by those

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redrawing errors. The case study in the current work is used to test and quantify these potential benefits. CAD can accelerate shop drawing development and improvement by speeding up drawing, error identification (e.g. utility location conflicts) and information transfers.

During the production of shop drawings, subcontractors and material fabricators who use CAD, often request electronic drawing files so that they can prepare their shop drawings more economically (Middlebrook, 1991). Patterson (2002) illustrated that having the architect provided CAD files of the building shell to the various trades at no cost, could substantially reduce redundant drawing and project costs. An example of the design of a sprinkler system could save $3,500, depending on the size of a building. The case study in the current work is used to test this claim. Using CAD allows subcontractors to plot drawings at any requested size for review by the GC, architect or engineer. CAD drawings are also reusable; so future changes to the design documents can be made more readily.

CAD provides an array of features that can potentially improve design realization. The large efforts to develop CAD systems commercially and their use by some parts of project teams suggest large potential benefits. But the characteristics and size of the benefits of using CAD have not been objectively observed and documented. CAD cannot be fully and effectively implemented without an understanding of how and to what extent CAD improves design realization. This research investigates the impacts of CAD on the design realization process by conducting a comparative analysis of the hand and CAD produced shop drawings for a project. The results are used to draw conclusions about the impacts of information technology on design realization; and in particular, the impacts of CAD on shop drawing processes.

Research methodology

A case study of a project which utilized both traditional hand drawings and CAD was used to investigate how project teams create shop drawings that integrate design information, describe how a building is to be constructed and reflect design intent. The West Campus Training and Dressing Room Facility project is comprised of several support buildings for a sports complex located on the campus of Texas A&M University in College Station, Texas. The complex includes 27,347 square feet with the main athletic training facility building containing 16,062 square feet. All buildings have concrete floors, steel frames, masonry exteriors and mechanical and electrical systems. The project started on 2 November 2001 and was scheduled for completion on 2 November 2002, but weather and change orders delayed completion until 23 December 2002. The initial cost estimate of $4,317,133 was 5 per cent less than the actual cost of $4,630,002. The client (Texas A&M University) was well informed about the construction processes, and had substantial resources to manage construction projects. A traditional design-bid-build development process was used with a negotiated lump sum contract. The design firms and the GC had both worked for the Texas A&M University system prior to the project.

All pertinent information was collected about the project's design realization process. This information included a complete set of the working drawings, specifications with addendums, copies of all submittals, the submittal log and the change order log. The submittals were categorized as shop drawings, manufacturer data specification sheets, colour approvals, customized vendor drawings and all other types. The shop drawings were analyzed to determine which drawings were drawn by hand or CAD, the numbers of drawing sheets produced in each submittal and how many sheets were produced by each subcontractor. The sizes of the drawing sheets were measured, and the total number of square feet of drawing space per submittal was calculated. As described earlier, several project participants reviewed the drawings during the shop drawing review process. After the shop drawings were submitted, they were reviewed by the GC, then the engineer and finally, by the architect. At any point in this review process reviewers could make corrections, identify errors or make notes to subcontractors on the drawings. This process was repeated for some shop drawings, until the drawings met the approval of all parties. For the purpose of the current work, each comment on a shop drawing was classified as one of three types: correction, transfer error or note, with the following meanings.

- *Correction.* A change made by a reviewer to the shop drawings because of some type of detailing or design development error. Typically, a wrong calculation in sizing, placement or other correction.
- *Information transfer error.* Errors in the translation of the CDs when redrawing the background information for the shop drawings, such as the location of a column grid or dimensions.
- *Note.* A reference made by a reviewer to refer a subcontractor to the CDS, verification of a request for information by the subcontractor or other general note.

The shop drawings were analyzed to see how many notes and corrections were made by reviewers of shop drawings, and how many errors were made during the transfer of background information. The number of notes, corrections and errors in background information transfer were disaggregated by the different drawing formats (hand or CAD-based). To gain a better understanding of how the iterative process of shop drawing production and review was executed, additional information was gathered by conducting personal interviews with the architect, engineer and four subcontractors. During the interviews participants were asked questions to initiate a dialogue about their preferences for using CAD to complete shop drawings and the impacts on the project.

Results

One hundred and eighty two submittals were developed for review. As shown in Figure 2, 52 per cent of the submittals (95 of 182) were copies of the manufacturer's data specification sheets. These submittals typically confirmed the use of materials and products specified by the architect or engineer, and required no information to be developed by the subcontractors. Shop drawings represented 27 per cent (46 of 182) of all submittals.

Of the 46 shop drawing submittals 34 were analyzed. Shop drawings produced for metal roofing, toilet partitions, walkway covers and lockers were not included in the analysis because a manufacturer and not a subcontractor produced the shop drawings as a part of their service or product. The 34 shop drawing submittals addressed the structural steel, concrete reinforcing, mechanical and electrical trades. Forty-five per cent (15 of 34) were approved the first time they were reviewed without any corrections, errors or notes. Forty-two per cent (14 of 34) were approved with some type of note. Eight per cent (3 of 34) required revision and resubmission. Five per cent (2 of 34) were rejected. Only the revise and resubmit, and the rejected shop drawings had to go through the review process a second time (Figure 3). All shop drawings not initially approved were approved in their first resubmission.

The number of drawings produced by each subcontractor varied significantly. The number of drawings was normalized to 24″ × 36″ sheets because the sheet sizes varied across subcontractors and CAD drawings can be plotted at many sizes. Table I shows the quantification of project shop drawings.

The six photographic sheets prepared by the concrete reinforcing subcontractor were a single submittal that was rejected without corrections or notes because the subcontractor submitted a photographically reproduced copy of the engineer's CDs as shop drawings. This directly violates the project specifications, which state, "Do not submit Contract Drawings for shop drawings." (Specifications, §01340-5 [1.05] [A] [1]).

Comment frequency in hand versus CAD-based shop drawings

Notes or corrections made by reviewers and errors made in transferring background information were quantified (Table II). The densities of comments were found by normalizing the number of standard drawings drawn by hand or with CAD. Densities of comments in the hand- and CAD-prepared drawings were then compared for each of the three types of comments and for all comments. Hand-prepared drawings contained more of each type of comment and almost an order of magnitude (9.67) of more comments per standard sheet for all comments. The comparison of comment densities identify improvement (reduction) in comments with CAD use of 50-100 per cent, with an average improvement of 89.7 per cent.

Figure 2 Project submittals by type

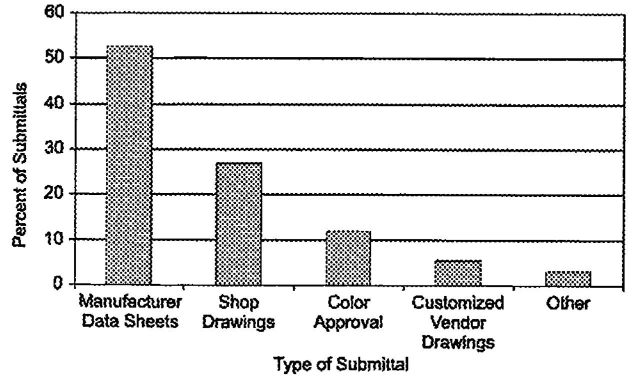

Figure 3 Shop drawing submittal review status

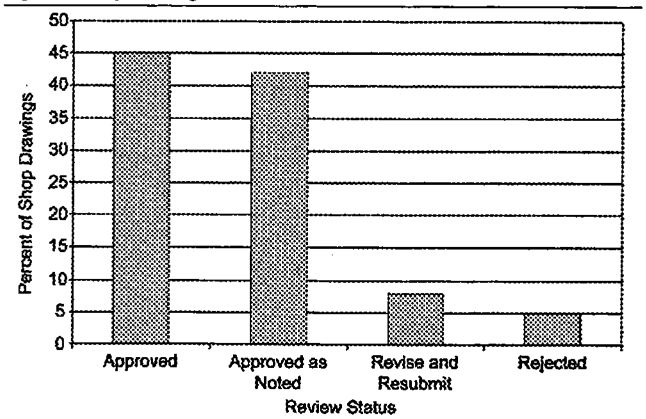

Table I Shop drawing quantification and type

Trade	Drawing size (in.)	Number of sheets	Drawing area (sf)	Drawing type	Equivalent standard sheets
Structural	24 × 36	80	480.0	Hand	80.0
	30 × 42	4	35.0	Hand	5.8
Concrete reinforcing	24 × 36	16	96.0	Hand	16.0
	24 × 36	6	36.0	Photo	6.0
Mechanical	30 × 42	16	140.0	CAD	23.3
	11 × 17	1	1.3	CAD	0.2
Electrical	24 × 36	9	54.0	CAD	9.0
Total		132	842.3		140.3

Table II Comparison of hand- and CAD-produced drawings

	Number of occurrences	Number of standard sheets	Occurrence per sheet	Improvement with CAD (per cent)
CAD				
Note by reviewer	8		0.25	83.6
Correction by reviewer	0		0.00	100.0
Information transfer error	1		0.03	50.0
Total	9	32.5	0.28	89.7
Hand				
Note by reviewer	155		1.52	N/A
Correction by reviewer	115		1.13	N/A
Information transfer error	6		0.06	N/A
Total	276	101.8	2.71	N/A

Cost impacts

Using CAD can reduce costs if used to transfer design information developed by one discipline (e.g. column locations by architecture) for use as backgrounds by other disciplines in developing drawings (e.g. HVAC duct locations by mechanical designers). These potential cost savings were estimated. As the collection of information and interviews with the project, participants progressed, it became evident that specific cost data were not available. This was primarily because the shop drawings were produced by draftsmen who were paid hourly and did not maintain records of the hours worked on specific parts of the project or in redrawing background information. In the interviews with subcontractors, all expressed that having the background CAD files would have saved them time in producing shop drawings. All subcontractors also said that whenever the backgrounds were available, they would be used unless the original CD drawings were of particularly poor quality. Despite the potential benefits of designers providing background drawings to the GC and subcontractors, this was not done on the West Campus Training and Dressing Room Facility project. The design firm gave no explanation as to why the backgrounds were not passed to the GC and on to the subcontractors for this project. However, the interviews indicate that this was because the GC never requested them.

To obtain cost data associated with producing shop drawings, the subcontractors estimated their cost of redrawing background information (Table III). Three subcontractors stated that the savings would have been "around a couple of thousand dollars". The fourth stated that he would spend approximately $200 per drawing sheet to transfer the background information. Original bid prices and final actual payments to subcontractors were used to normalize potential cost savings (Table III). Estimated potential savings by sharing CAD backgrounds for this project based on final payments ranged from 0.43 (electrical) to 2.92 per cent (concrete reinforcing) and averaged $9,200, slightly over 0.5 per cent of the project's subcontracted costs.

Discussion

Differences in the frequency of comments in shop drawings prepared by CAD versus hand, in this case study (Table II), are all positive and consistent in direction across comment types (notes, corrections and information transfers). This suggests that CAD can increase the accuracy and efficiency of design realization by improving shop drawing content. CAD could do this by facilitating the use of standardized drawings and

Table III Estimated cost savings by using CAD

Trade/subcontractor	Shop drawing method	Bid and (final) cost	Estimated savings by using CAD backgrounds	Per cent savings (per cent)
Structural steel	Hand	\$183,680 (\$191,908)	±\$2,000	1.08 (1.04)
Concrete reinforcing	Hand/CAD	\$68,300 (\$68,420)	±\$2,000	2.92 (2.92)
Mechanical	CAD	\$950,562 (\$950,546)	±\$3,200	0.34 (0.34)
Electrical	CAD	\$409,805 (\$469,076)	±\$2,000	0.48 (0.43)
Total		\$1,612,347 (\$1,679,950)	±\$9,200	0.57 (0.55)

eliminating the human errors in some information transfers. This explanation is espoused by proponents of CAD. However, other factors could account for a portion of the apparent benefit of adopting CAD in design realization or suggest different results. Some CAD- and hand-based drawings could have the same number of features requiring comments. If reviewers assume that shop drawings prepared with CAD are more accurate and therefore review them with less scrutiny that the CAD-based drawings would appear (but not actually be) more accurate. A second possible explanation is that certain trades or subcontractors (e.g. mechanical and electrical) are more sophisticated, careful, or both. These subcontractors would be expected to generate fewer features requiring comments and use CAD. In this case, fewer comments and CAD use are correlated but CAD use does not actually improve design realization through improved shop drawing content. Finally, the electronic media may impact comment frequency. More comments might be expected on CAD-based shop drawings if making changes appeared to be or actually was easier in CAD drawings than drawings prepared by hand.

This case study also suggests that project costs can be reduced through CAD use. The estimated potential cost savings in this project ranged from approximately 0.5-3.0 per cent of subcontractor prices. Profits for subcontractors can be 5 per cent or less, making these savings an important part of a firm's profit on some projects. Interviews suggest that, in addition to the elimination of background information transfer errors, savings can occur due to faster changes and reduced printing costs.

Many construction projects, including the one in this case study, do not fully utilize CAD in design realization despite evidence supporting the use of this information technology. The interviews of the participants indicated that a major cause is the lack of an industry-wide system to standardize transferring CAD file backgrounds from design firms to GCs and subcontractors. Currently, firms that invest in CAD technology are not guaranteed to benefit on any given project because of the potential incompatibility of CAD systems across project participants.

But CAD may not be adopted even when available due to the threats it poses to the integrity of the design realization process and the viability of project participants. Some designers are reluctant to share electronic files with contractors because of possible increases in their liability (Singer, 2003). Designers have at least two related concerns:

(1) the use of their CAD drawings as the basis for submittals facilitates the elimination of critical constructability reviews by contractors; and
(2) designers may incur increased liability for shop drawing and construction defects if their CAD drawings are used to prepare shop drawings.

The case study described here supports the first concern by finding that one subcontractor submitted the engineer's drawings as shop drawings, presumably without review or the detailed design required for construction. Perceptions held by some contractors that costs can be reduced by eliminating constructability reviews may tempt them to circumvent this portion of the design realization process and thereby threaten the integrity of the design. The ease with which CAD files can be shared has rejuvenated liability concerns about sharing design documents. The American Institute of Architects address the issue of liability by defining where liability should be placed in shop drawing production and review (AIA, 1997). In *General Conditions of the Contract for Construction* (A201-1997) and *Standard Form of Agreement Between Owner and Architect* (AIA B141-1997), it states that shop drawings are not a part of the CDs, and that the contractor shall not be relieved of the responsibility for deviation from requirements of the CDs by the architect's approval of the shop drawings (American Institute of Architects, 1997). This language attempts to relieve designers of responsibility for shop drawings. Suggesting action that would make this more explicit, Victor O. Schinnerer & Company, Inc. (2002), a large insurer of design professionals, says design professionals should reserve the right to remove their professional seals and title blocks from CAD files when they are provided for use in preparing shop drawings to limit future claims. Alternatively, some firms require a separate agreement requiring indemnity for the time and costs to a firm involved in a dispute over CAD information if a transfer of electronic data occurs. The resolution, or at least clarification, of liability issues concerning the transfer of CAD documents is needed to expand the use of this information technology in design realization.

Conclusions

A comparative analysis of a case study that utilized both hand- and CAD-drawn shop drawings in design realization investigated the integration of design intent and construction knowledge into shop drawings and the iterative nature of the process. Categorized and quantified submittals were analyzed for the number of notes, corrections and background information transfer errors between hand- and CAD-based shop drawings. Hand-produced drawings were found to have much higher occurrences of notes, corrections and transfer errors, suggesting that utilizing CAD to produce shop drawings can improve shop drawing content. Potential cost savings by utilizing CAD were estimated to be 0.5-3.0 per cent.

This work supports the use of CAD to produce shop drawings and share electronic copies of drawings between design firms and contractors in design realization. Several other potential contributors to the results that support CAD use were also suggested. An improved understanding of the underlying causes of differences between design realization with and without CAD will enable project managers to better utilize CAD. Compatibility across CAD systems and liability issues were identified as major impediments to the expanded use of CAD in design realization.

These results suggest that project mangers should attempt to use CAD in design realization if information technology systems are compatible, design realization processes can rigorously fulfil their purpose of integrating design intent and construction knowledge into the final constructed facility, and project participant responsibilities remain clear. The current work also identifies these three issues as important areas needing improvement that currently limit the application of CAD and information technology in general in construction project management. Future research can strengthen and improve the conclusions by repeating the analysis of the impact of CAD use on other projects and improving estimates of CAD cost savings. Project managers can improve their use of CAD and project performance by developing a deep understanding of how CAD impacts design realization.

Note

1 For the purposes of design realization, construction trades performed by the general contractor are treated as subcontractors.

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