

THE LAST DESIGNER'S CAD- DATABASE FOR SOURCING, PROCUREMENT, AND PLANNING

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ABSTRACT

Architects and engineers participate early in an architecture/engineering/construction project as they generate the design. This design is, however, seldom 100% complete. Presumably, specialty contractors will subsequently specify missing details and produce fabrication and erection drawings. They thus play the role of the Last Designer, completing design prior to construction.

The Last Designer's knowledge is highly specialized. It reflects trade-specific know-how in addition to regional and company specifics. Application of this knowledge may yield alternatives that are better than those generated by architects or engineers. Accordingly, a database system was integrated with CAD to support the Last Designer's value-adding contribution to the AEC process. The system, called CADSaPPlan (Computer Aided Design, Sourcing and Procurement Planning), focuses on materials sourcing and procurement because these have a major impact on the ultimate design and fall within the specialty contractor's responsibilities.

The Last Designer's wealth of knowledge could be applied early in the design process. Though this is not common practice, specialty contractors should be included at the time of formation of design-build teams, as undiminished AEC participants.

INTRODUCTION

Architects and engineers (AEs) participate early in an architecture/engineering/construction (AEC) project as they conceptualize the owner's requirements and generate the facility's design. They present their design in drawings and specifications that are, however, seldom 100% complete. They focus on the function and structure

of the facility and express concern for aesthetic relationships between parts of the design and the design as a whole. Presumably, the specialty contractor who will construct a specific set of components or system of the facility will subsequently specify missing details and produce materials submittals, fabrication, and erection drawings as deliverables to the previous designers. In this detailing process, design ambiguities, omissions, or errors are often revealed. The specialty contractor will then issue RFIs in order to get the AEs to complete their design and/or may engage in value engineering and propose alternative designs for their approval. The specialty contractor thus plays the role of the Last Designer, and is responsible for completing the design prior to construction.

The fragmented nature of the AEC process (e.g., see Howard et al. 1989) results in poor coordination between the design, procurement, and construction functions. This is especially true in the case of design-bid-build projects where the design function is performed by one firm, separate from the other two functions, with contracts linking them together. This traditional contracting approach often generates solutions that fail to optimize project cost and performance, as designers seldom have the means or incentives, for instance, to verify regional materials availability, consider installation difficulties, or know construction worker skills and equipment availability. Knowing that the design will be detailed later, designers do not want to over-specify it either. The resulting leeway enables contractors together with their fabricators and suppliers who bid on the project to apply their know-how in order to be competitive, yet profitable.

In contrast, other contracting approaches encourage coordination. Engineering-procure-construct (EPC) contracts make the entity responsible for the design also responsible for procuring materials and construction. Such contracts are commonly used on industrial projects. Many materials for industrial facilities are engineered. It is therefore easier to have those design engineers, rather than a contractor, follow-up with the fabricator. When engineering-procurement (EP) and construction (C) are split up, as may be the case, coordination problems arise again, this time stemming, e.g., from inadequacies in determining materials delivery quantities and timing.

Design-build contracts aim specifically at avoiding disputes by making a single entity responsible towards the owner and in charge of the project in its entirety. In principle at least, material selection, procurement, and installation are performed by the same entity. Consequently, the contractor can disclose procurement and construction means-and-methods sooner than is commonly the case and thereby enable the design team to '*design for procurability*' (DFP) and to '*design for constructability*' (DFC). DFP means that choices must be made throughout the design process while considering expediency of procurement. Selected materials must be available when needed for the project, and provided with favorable purchase terms and conditions as well as certainty regarding timing of their delivery. DFC means that choices must be made throughout the design process while considering ease and quality of construction. This mind-set differs from the one that drives constructability reviews today. Many are conducted—possibly by a third party—only after the design has been completed so that recommended changes constitute design rework. Several companies now offer pre-bid value engineering as a separate service.

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In practice, the design-build organization that contracts with the owner has been created opportunistically. The organizations comprised by it, including architects, engineers, and contractors, still tend to coordinate work in the traditional fashion and thereby forego the opportunity to really work as a team and optimize project performance. The pressure is on to establish truly collaborative teams (e.g., CPI 1998).

WHO IS THE LAST DESIGNER?

Irrespective of the contracting method, someone needs to fill the role of the Last Designer. DFP and DFC are necessary and valuable tasks and they require the highest level of attention to detail and accuracy. The ultimate design function must result in a set of documents where even the nuts-and-bolts are specified.

It is the specialty contractor (mechanical, electrical, glazing, i.e., the firm that procures materials and executes the work on site) that usually ends up performing this final step in the design process. This firm has the knowledge based on specialization and expertise acquired on previous projects that is needed to fulfill this role in the best way possible. Accordingly, it is in a better position than, e.g., a general contractor to create the best, last design. Moreover, it stands to benefit the most from performing this work well as it affects their work down stream. Therefore, by performing this ultimate design function, the specialty-contracting firm is the Last Designer.

EXAMPLE LAST DESIGNER: A ROOFING SPECIALTY CONTRACTOR

Pacific Contracting, Inc. (PC) is a specialty contractor that builds roofing systems for commercial and industrial construction projects. It is an exceptionally progressive company, practicing lean construction. As part of their operating procedure, PC creates its detailed design in the form of three-dimensional computer-aided design (3D CAD) models using AutoCAD R14 (Autodesk 1997). Using the 3D model, two-dimensional drawings are plotted on paper and then submitted as deliverables to the general contractor for AE approval. While PC could submit its 3D CAD models, this is not current practice. Contractors and AEs do not necessarily have the needed computer infrastructure and submittal procedures in place to enable this to happen.

PC's 3D CAD models show even the smallest details that reflect installation work to be done during construction. Knowledge about the materials that will be used to build the designed product and knowledge about construction procedures are used to spell out those details. Materials are explicitly defined in terms of product and manufacturer. Exact dimensions and locations are shown, including those for individual fasteners, sealant and filler materials, etc. Procedures describe the steps and their sequencing for PC's skilled trades to take in order to install materials according to manufacturer specification or to meet contractual performance requirements. This demands a lot of work from the CAD engineer. It also challenges the CAD computer program because the resulting models have numerous parts.

PC concentrates its efforts on detailed design and production-level planning in order to optimize productivity during construction. They now spend more time engineering their products in-house than assembling the constituent parts on site. They have learned that investment in such up-front work is more than offset by savings on site. Additionally, PC spends a considerable amount of effort in value engineering. It studies the use of alternative technologies and detailed designs in

order to improve constructability. Based on their experience, it is often that case that what has been specified in the contract documents and the AE's design is hard if not impossible to construct. To support PC in this role of Last Designer-Builder, a comprehensive database was developed for sourcing, procurement, and the creation of production drawings.

RELATED WORK

Lean production theory advocates that one (1) specify value by product, (2) identify the value stream, (3) make the product flow, and do so (4) at the pull of the customer, (5) in pursuit of perfection (Womack and Jones 1996). Translated to the AEC industry, lean construction focuses on 'the pull of facility owner' and one step up from there in the value stream, 'the pull of the contractor'. Pull means that activities upstream should be geared towards meeting downstream demand, not merely keep busy for the sake of keeping production rates high as the latter results in unnecessarily large work-in-progress inventories.

Tommelein (1997) describes the benefits of pull- over push-driven scheduling when uncertainties manifest themselves during project execution. Pull-driven techniques are part of the lean construction theory that has been under development in the last few years (e.g., Koskela 1992, Alarcon 1997). The Last Designer concept as articulated in this paper and the role the Last Designer plays in the AEC process fit within the development of this theory.

Activities at the start in the value stream should be performed at the pull of those downstream. This means that design efforts should be aimed at meeting not only the owner but also the site's needs. The CADSaPPlan (Computer Aided Design, Sourcing, and Procurement Planning) model presented in this paper adopts a pull-driven approach, where fabrication and construction needs are recognized and allowed play a major role in all activities upstream, and specifically design decision making. In contrast, the conventional approach is push driven. Design documents are pushed downstream and forced upon fabricators and contractors. Knowledgeable fabricators and contractors then do not get the opportunity to suggest alternatives early on, and of course, changes to the design become more costly as one moves further down the value stream and change orders are necessary.

At the heart of the CADSaPPlan system is a database and CAD graphics are provided as an auxiliary function. This system architecture has been advocated by many, including Smithers (1989) who attacked 'decorated geometries' (drawings overloaded with data) and Voeller (1996). Elzarke and Bell (1995) developed an entire piping design and materials management system within their database, with no apparent need to support CAD. Though our implementation environment is not object-oriented, some of our modeling concepts are based on those developed for shared product models (e.g., Fischer and Froese 1996) and integrated project, product, and process models (e.g., Tommelein et al. 1994, Stumpf et al. 1996).

Proof of concept of a pull-driven approach is delivered in the CADSaPPlan system. DFP and DFC are achieved by providing designers access to complete, timely, and accurate procurement information. Industry advances lend further support to this approach. In recent years, the construction industry has progressed considerably in providing data for design. Manufacturers and vendors now make lists of materials, technical data and specifications, performance standards, and CAD

objects available for computer access and manipulation. This information can be accessed electronically through the Internet using commercial software packages. In addition, a wide set of information and communication technologies enables collaborative working within the industry (e.g., Anumba and Evboumwan 1997). The Last Designer thus is not expected to work in isolation, using a private, static database. Instead, the CADSaPPlan database should be linked to numerous outside sources of data and be updated on a regular basis (though we have not yet implemented this capability.)

CAD-DATABASE SYSTEM FOR THE LAST DESIGNER

SYSTEM OBJECTIVES

The CADSaPPlan CAD-database system provides comprehensive support for all materials management functions at PC. These functions include sourcing, procurement, and planning, so we use the term 'materials management' in its broadest sense possible. The availability of procurement information results in design solutions that optimize construction cost, duration, and quality, and reduce their variability. Two premises support this idea:

- ✓ *Procurement activities are conditioned by design.* Once the designer has selected a material and inserted the corresponding CAD object in the three-dimensional CAD model, some procurement activities can be performed without requiring further decision making. In other words, once the material was included in the drawing, its cost has been committed to. For instance, it is common for vendor selection to be immediate, since there may be only a single one for a particular item. Consequently, the request for quotation (RFQ) can be addressed automatically and sent off to that vendor right away. Material selection by the designer also impacts construction sequence and schedule completion. This impact may be felt the most, e.g., when the material is not readily available on the market or delivery is likely to be delayed.
- ✓ *Construction activities are conditioned by design, procurement, and planning.* Design and procurement dictate which items will come delivered in prefabricated units vs. what assembly remains to be done on site. The break down of the project into work packages, the choice of construction technology and methods, and the projection of the schedule all affect project performance.

Consequently, designers should take advantage of the most complete information regarding cost, availability, and substitutability of materials, as well as vendor capacity and reliability. Making this information available is the main objective of the sourcing functions, where sourcing means "determining qualified sources of supplies" (Stukhart 1995). Sourcing may take place after materials have been selected, but it is important to recognize that material selection itself has a major impact on the determination of the optimal source in terms of cost (including installation cost), quality, availability, substitutes and delivery time. We therefore include activities such as providing information to designers and planners in sourcing.

The innovation in our system's conception is that The Last Designer is able to see the implications on procurement and construction *at the time a material is chosen for inclusion in a design*. If one fabricator's lead times and delivery performance are likely to compromise project deadlines or easier-to-install substitutes can reduce

construction time, then The Last Designer must be alerted of those alternatives. Similarly, when materials are assembled from components, those components' availability on site must be synchronized, and selective expediting or delaying may reduce unnecessary on-site materials handling and storage costs. In short, the system augments knowledge that is generally available with proprietary, local knowledge in order to help generate alternatives that are better, cheaper, and faster to build. It includes vendor-specific knowledge, as well as knowledge that is company-, project-, and trade-specific (e.g., contractor-specific means for doing work, crew skills and available equipment and tools, preferred materials to work with).

OVERALL ARCHITECTURE OF CADSaPPLAN

From the implementation point of view, CADSaPPlan takes advantage of Active X Automation. This programming interface enables AutoCAD to expose programmable objects that, in this case, a database application can create and manipulate. Thus, AutoCAD models representing the project geometry and a database application for sourcing and procurement share their design and procurement information. A Visual Basic for Applications (VBA) program that is part of the database application produces this link at the level of each individual material. The program creates 3D CAD objects called Material Blocks that represent a single piece of material whose procurement data resides in the database. Since 3D models are built as assemblies of Material Blocks, CADSaPPlan can retrieve each piece of material included in the CAD model and relate it with its own procurement data, then use this data to create a bill of materials and sourcing.

The elements of the system are a database application, CAD modeling procedures, and a CAD-database interface. The requirements and features of this system are created based on PC's operating procedures. However, they exemplify those used by many other specialty contracting firms that also act as Last Designers for their trade.

The database application produces reports that mimic those currently in use at PC. They are used to list materials, request price quotes, or purchase a set of items. The forms of this database are the screens that PC needs to display data or input new data. The modeling procedures mimic PC's methods to generate of 3D CAD models for detailed design and to support routines for automating quantity take off and material cost estimating.

SYSTEM SPECIFICATIONS

A product database should comprise information about materials to be included in the design. This information must be collected and regularly updated in order to assist designers in the selection of the optimal material and associated construction methods. It also must be represented in a format that is easy to incorporate during 3D model development so that it helps keep design time to a minimum. Every material is associated with:

- ✓ A part number or commodity code that makes the material identifiable in take off and procurement
- ✓ Manufacturers and fabricators that produce it and generate technical and commercial information about it
- ✓ Vendors from whom it can be procured

- ✓ Packaging alternatives to assist designers and buyers in selecting materials and determining commercial quantities to order
- ✓ A 3D CAD object that can be directly inserted in a project or work package's 3D model, thereby reducing design effort and increasing model accuracy
- ✓ A text document specifying characteristics, requirements, and installation procedures (technical specifications and standards)
- ✓ Specifications (graphical or text document) ready to be transmitted (e.g., by fax or e-mail) to the fabricator or supplier
- ✓ Historical cost and time data for different packaging sizes, purchase quantities, and delivery locations to allow designers to assess vendor performance, estimate material costs and gauge schedule impact, then search for better solutions
- ✓ Substitutes and associated information to help the designer identify alternatives

CADSAPPLAN SYSTEM FUNCTIONALITY

Support for the Last Designer is provided by means of several functions that are classified as follows.

1. **CAD modeling procedures** establish how PC:
 - ✓ Generates 3D objects representing materials or assemblies of materials (e.g., fabrics, insulation boards, sealants, fasteners)
 - ✓ Identifies and stores 3D CAD objects in a way that facilitates their manipulation using CAD and databases
 - ✓ Generates 3D models representing projects or work packages, which are sections of the whole project with controllable units of work, created for design, planning, and assignment purposes.
2. An **interface between CAD and the databases** establishes the methods to:
 - ✓ Associate 3D CAD representing materials with non-graphical information contained in the database
 - ✓ Insert 3D objects representing materials in the 3D CAD models
 - ✓ Identify, take off, and report the materials that have been included in a 3D CAD model
3. A **Database application** stores the procurement information and implements the following functions:
 - ✓ Report information about material and sources, duration of fabrication, timing of deliveries (lead times) by material or by vendor. Include material usage based on application, prices, quality, and standards.
 - ✓ Present vendor capacity and reliability
 - ✓ Consolidate the bill of materials on a single or multiple projects
 - ✓ Estimate material costs and fabrication plus delivery time
 - ✓ Suggest vendors from whom to request quotations
 - ✓ Group materials based on location, work package, schedule, or vendor
 - ✓ Generate requests for quotation (RFQ)
 - ✓ Analyze quotations
 - ✓ Generate and follow up on purchase orders (POs)
 - ✓ Report actual cost information
 - ✓ Export cost information to the accounting system

DATA MODELING

AutoCAD 14 is commercial software used by many designers to generate 3D CAD models of their projects. CADSaPPlan takes advantage of the AutoCAD object model and its support for Active X Automation. The AutoCAD object model conceptually defines CAD objects, their methods, properties, and hierarchical organization. Active X Automation exposes these objects and makes them accessible by other applications called Automation Controllers. CADSaPPlan is an Access application that controls AutoCAD objects.

CADSaPPlan uses the AutoCAD's Document Object to build the 3D model that represents the project. Since most computers can manage only limited-size CAD files, designers should create 3D models on a work package basis. They can also include several work packages in the same 3D model, if they indicate what materials belong to each.

CADSaPPlan uses AutoCAD Block Objects to represent materials. The program creates, stores, and manipulates Material Blocks, allowing designers to directly insert them into the 3D model.

CADSaPPlan's program module called Block Generator, written in VBA, adds block attributes using a standardized Tag, Prompt, and Text containing materials information each related to a specific record on the database. This results in an object called Material Block. It is a 3D CAD object that represents the material's geometry (modeled by the CAD Block), its identification as a material, the amount of material that is included in the block, and the identification and quantities of additional materials attached to the block. A material's information is originally created and stored in the database, so it is related to the rest of the procurement data stored in the database. Then, Block Generator attaches this information to the CAD block as standardized Block Attributes.

3D CAD models are, consequently, assemblies of Material Blocks, which in combination represent one or various work packages. Models are built in ModelSpace. Designers can derive two types of deliverables from the model. First, through PaperSpace they can present 2D views of the model, that, enriched with text, dimensions, and specifications, takes the form of blueprints. Second, through CADSaPPlan they can identify each material block in the model and retrieve the information associated with them, creating the Bill of Materials.

'Wrapped around' AutoCAD is an Access 97 relational database that stores the information about materials, projects, suppliers, procurement transactions, and documents. Each material in the database is associated with a Material Block in AutoCAD. In turn, the selected Material Block data can be stored in the database.

IMPLEMENTATION

CADSaPPlan is implemented through an Access 97 database application that models the Last Designer's sourcing knowledge, supports performance of procurement task and contains the Visual Basic programs that implement the CAD-Database interface. The system runs under the Windows NT environment. The hardware and software requirements for the system to run are modest. They were chosen so that this work could support the needs of one of numerous small contracting firms that make up a very large percentage of companies in our industry.

Figure 1 shows how object-oriented CAD and database applications enable The Last Designer to store and manipulate procurement information. Feedback loops are necessary to provide The Last Designer with timely input as the system is dynamic. Sourcing data is generated by The Last Designer through its own procurement history and supplemented by new data provided by suppliers and vendors. By having a library of Material Blocks, designers can save time by not having to create new drawings from scratch. Once a project has been broken down in work packages, their 3D models will be composed of a set of objects, each representing a material, and inserted using the CAD application. Designers can also access procurement information before selecting a material, in order to verify its cost and availability, and to find out about substitutes. Materials are taken off by identifying the objects that were included in the CAD model and determining their quantities. This information is exported to the database so that the successive procurement steps (vendor selection, request-for-quotation issuing, purchase order generation and follow up) can be performed by the database application. The documents required for these procurement tasks are created and can be faxed using the same application. Finally, the procurement process generates new information that will be used by designers and buyers in subsequent projects.

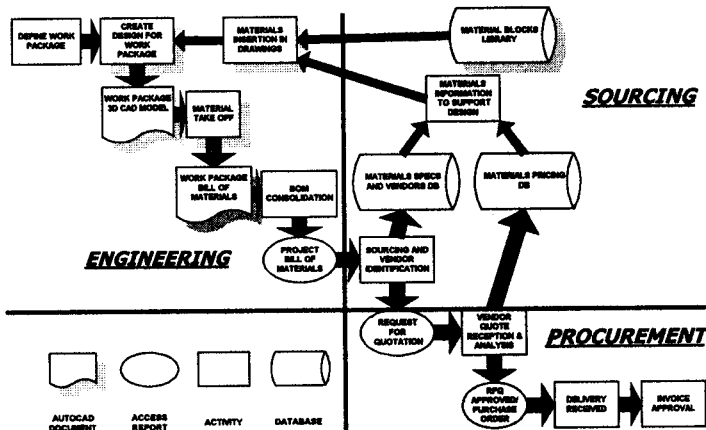


Figure 1: Information Flow

The CAD-Database interface constitutes the core of the system. It takes advantage of the aforementioned Data Model for providing the means to link Material Blocks with database records and to retrieve lists of materials from 3D models.

Figure 2 illustrates the interface design, which consists of three VBA modules that run on top of the CADSaPPlan database application. These modules are activated through a customized Access form.

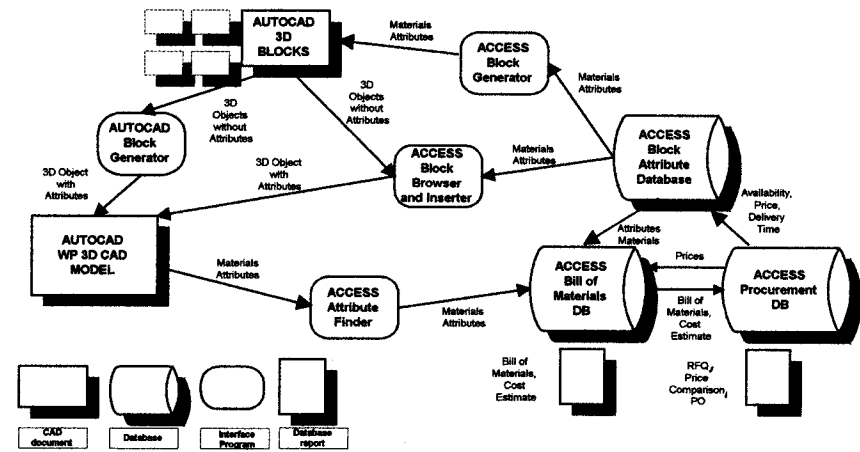


Figure 2: CAD-Database Interface Design

1. **Block Generator** creates a Material Block by attaching a block's attributes to a CAD block that was drafted previously. The Block Generation menu, which was incorporated into AutoCAD, enables the user to create, edit, and modify Material Blocks without exiting the CAD environment.
2. **Block Browser and Inserter** enables designers to search previously created Material Blocks by family of material or by the material's description criteria. In other words, when designers have to include a material in the 3D model, the program allows them to search among the various alternative materials that fulfil the search criteria. Since each block is related to the material's procurement data, designers can evaluate this information before inserting the material in the model, that is, before selecting the material for the project. Once the material is selected, the program inserts the Material Block in the 3D model, prompting the designer to select the insertion point.
3. **Attribute Finder** finally reads the attributes of all the Material Blocks included in the 3D model. By doing this, CADSaPPlan identifies the materials chosen for the projects and imports their quantities. That is, it performs the materials take-off. Total quantities are calculated after importing the Unit and Quantity attributes attached to each block (they represent the amount of materials included in the block) and then adding the quantities for blocks with similar identification. Material Blocks may contain information about additional materials that are associated with them but that have no CAD representation (e.g., gallons of glue attached to insulation boards, but not drawn in the model). Attribute Finder can also import quantities of these additional materials.

Note that the CADSaPPlan user can create materials of any 3D shape and add them to the block library. Some 2D CAD blocks already are commercially available, but it will take some time before the AEC industry commits to 3D. While we are awaiting industry standardization and vendor production of 3D libraries of the parts they sell,

there will always be a need for special shapes (e.g., to accommodate as-built dimensions).

The user needs to decide which properties to store with the block and then perform a take-off as needed. In contrast, some commercially available systems are based on standardized parts and rely on those to automate the take-off.

Once Attribute Finder has retrieved materials and quantities, this information is stored in the database. This then serves as the starting point for the procurement functions performed by the system. CADSaPPlan generates the Bill of Materials on a work package and project basis, and prints these out as a report. Note that the take off done material-by-material (as opposed to system-by-system or assembly-by-assembly) so this data can serve not only in procurement but also installation.

Based on the Bill of Materials, buyers can create packing lists to determine the commercially available units of materials to procure, identify items with pre-selected vendors, select vendors to request price quotes, receive and analyze quotations, and then issue purchase orders.

CONTRIBUTIONS AND SUMMARY

This paper clarified the work done by the Last Designer. The Last Designer's role typically is played by a specialty-contracting firm, which performs only a part of the work to construct a facility. The Last Designer's knowledge is highly specialized. It reflects trade-specific know-how in terms of the regional availability and application of a multitude of materials, skills and productivity of its workers, and state-of-the-art tools and equipment available to do the work. Application of this knowledge may lead to the selection of easier-to-build, cheaper, faster, safer, and better alternatives.

To aid in this effort, we developed a database system integrated with CAD to support the Last Designer's value-adding contribution to the AEC process. The paper presented the CADSaPPlan system for Computer-Aided Design, Sourcing, and Procurement Planning. The focus thus far has been on sourcing, and procurement of materials, because these have a major impact on the ultimate design and fall within the specialty contractor's responsibilities. We plan to extend this system so it can be used for work package scheduling, assignment, and field release. Knowledge about construction methods will be incorporated as well in order to facilitate work planning and help estimate activity durations.

The presented database-CAD system provides a framework for representing specialized company knowledge, including 3D CAD objects; manufacturer data; vendor information; automated take-off knowledge; historic experience of the contractor with vendors, materials, and designs. In addition, the system supports company functions, including automated take-off, and generation of and follow-up on RFQs, purchase orders, and field receiving reports. Because these administrative functions have been streamlined, the Last Designer can now focus on design and planning, which are truly value adding activities.

The contribution of the Last Designer to the AEC process is significant. The wealth of knowledge available in the Last Designer could be applied earlier on in the design process. Though this is not common practice, we recommend that specialty contractors be included at the time of formation of design build teams, as undiminished AEC participants. This will help to reduce duplication in and avoid ambiguity of the design effort, which currently is not clearly split up between

architects/engineers and the Last Designer and consequently results in numerous RFIs being passed from one to the other.

ACKNOWLEDGMENT

This research was funded by grant CMS-9622308 from the National Science Foundation (NSF) whose support is gratefully acknowledged. Any opinions, findings, conclusions, or recommendations expressed in this paper are those of the authors and do not necessarily reflect the views of NSF.

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