Incorporating BIM into Architectural Precast Concrete Fabrication

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Abstract

Digital models have many benefits for construction; for example, clash detection prior to approval, ability to confirm assembly sequencing, verification of as-built dimensions, and more. Customizing and preparing such models for project delivery takes a large amount of time and, unfortunately, cannot guarantee that the physical building or part can be built as modeled; a disconnect between design intent and constructability can often occur. One reason for this is that design team is unaware of certain details that are involved in fabricating and assembling building components; an understanding that craftsmen take for granted.

This paper presents the process of incorporating Autodesk Revit into the workflow of an architectural precast concrete manufacturer, tracking a real-world project from design intent model through the incorporation of industry-specific fabrication details. Methods used to generate a novel digital model, as well as to produce shop drawings and shop tickets from that model are documented. Three approaches to creating custom Revit models are described: using parametric Revit families; through Dynamo scripting; and via Excel spreadsheet input. Future potential workflows which could extend the findings even further are discussed, setting the groundwork for "Design-Assist", an emerging project delivery approach wherein subcontractors are engaged early in project development to provide advice to the design team, allowing for more informed decisions, conversations, and digital models for construction.

Keywords

Building Information Modeling, BIM-based workflow; Precast concrete; Parametric modeling; Fabrication; Computer Aided Design

1 Introduction

Building Information Modeling (BIM), the process, and Building Information Models (BIM), the document, have become such a fundamental part of the building of buildings that owners are now requiring BIM processes and BIM documents as part of their contractors' contract. BIM "support[s] design through its phases, allowing better analysis and control than manual process." [1] This modeling approach "contain[s] precise geometry and data needed to support the construction, fabrication, and procurement activities through which the building is realized." [2] The benefits for construction schedule and budget are varied and vast – clash detection prior to approval, ability to confirm assembly sequencing, verification of as-built dimensions, and more. Not too long ago, contractors who took on the additional software and technical personnel expenses that BIM incorporation requires had a competitive advantage to those who could or would not. "Concerns that impede [a more] widespread implementations of BIM are…primarily [due to] a perceived inability of subcontractors to adopt or work with…technology." [3] However, "resistance disappears once the efficiencies accruing to the bottom line are evident." [4] Indeed, over time, the Architectural Engineering and Construction (AEC) industry as well as the perspective of the owners funding their buildings have converted to accept BIM so widely that those contractors who can't or won't evolve their "traditional" processes are in danger of being left behind.

1.1 Precast/Prestressed Concrete Industry

The Precast/Prestressed Concrete Industry (PCI) is one group that has consistently tried to stay ahead of advancing technology. The PCI was "founded in 1954 to advance the design, manufacture and use of precast and prestressed concrete." [5] Initially producing a series of graphic standards for use in hand drafting, and then computer aided drafting, "CADD drawings [were] only readable as graphics, so that information transfers for

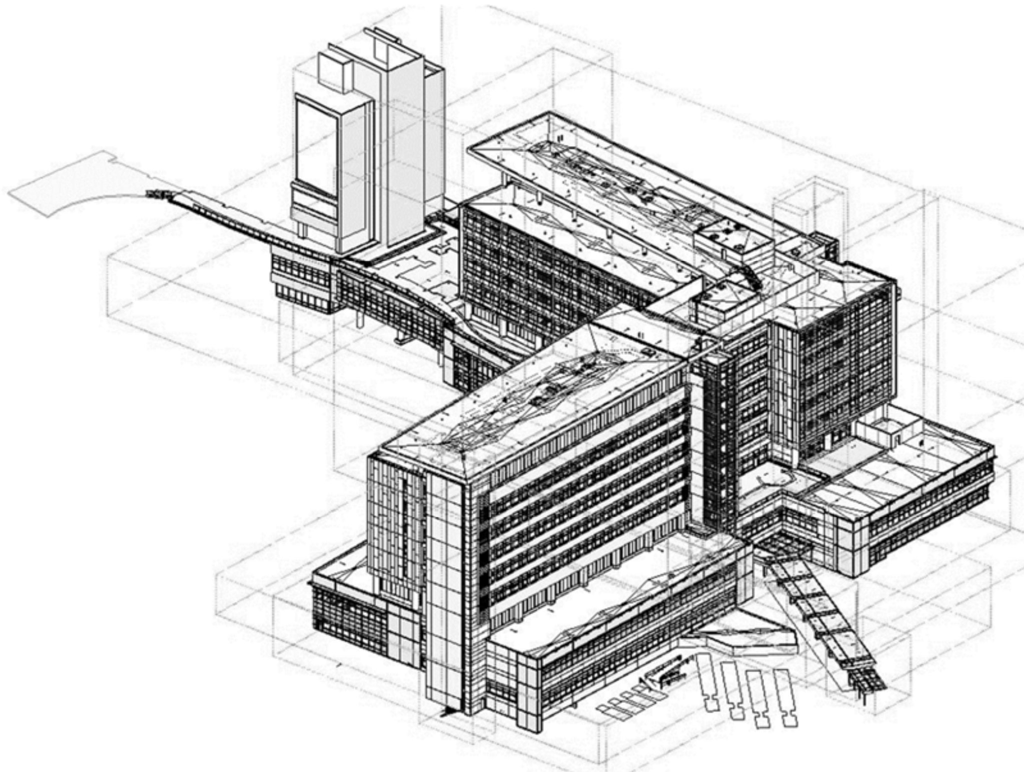

Figure 1. Shands digital model from the design team

process activities such as structural analysis, bills of material, coordination between building systems, quality control, rebar fabrication and piece production, [had to] be done by people.” [6] A desire for a common language, procedures, and automation appears to have been the PCI’s aim for some time.

Advances in digital technology led to research in parametric definitions of precast pieces [7], developing solution to concerns of software interoperability and data exchanges [8, 9], and improvements in process modeling. [10] Today, BIM software has now developed wherein achieving many goals, from the point of view of many stakeholders, including the precast concrete industry, is within reach.

1.2 Architectural Precast Concrete

Precast concrete, though rather specific in material and method, still includes an enormous catalog of building products. Just look around our built environment every day. Precast concrete is everywhere, used for many purposes, and specified by many professions – structural, civil engineers, architects, and more. One specific category of precast concrete called “architectural precast concrete” is defined by the PCI as “any precast concrete unit employed as an element of architectural design.” [11] More particularly, it is assumed that such pieces are critical components of a building skin – they have a high-quality finish and are integral to the overall aesthetic of the design.

Advantages of architectural precast concrete listed in the Architectural Precast Concrete Design Manual include: design freedom, quality control, plasticity (unlimited shape and configuration), economical erection and rapid enclosure, and trade scheduling.

1.3 Castone Corporation

Castone Corporation (Castone), an architectural precast concrete manufacturer, was founded in Opelika, Alabama in 1962 by David M. James, Sr. Mr. James’ three sons, David Jr, Michael, and Cooper now lead the company. They carry on their fathers’ “deep commitment for serving [their] customers, employees, and communities.” [12] Castone manufactures two products: cast stone, or “dry tamp” concrete and architectural precast concrete, or “wet pour” concrete. The focus of this paper is wet pour. Castone has an in-house engineer that provides specifications regarding the structural capacity of their architectural precast panels, including concrete mix, panel thickness, rebar sizing and spacing, and embed and other associated steel hardware design.

The facility in Opelika is housed in two main buildings; one for administration and the other for manufacturing. Administration manages a project from initial RFQ, estimating, contract negotiation, shop drawings, engineering, and through shop tickets production. It is only when shop tickets are completed that the manufacture of pieces required for a project will begin. The manufacturing facility handles each piece from the construction of formwork, assembly of rebar, concrete pouring, curing, and finishing. In addition to the building proper, the facility also has an extensive “yard” for the storage, staging, and loading of pieces onto trucks for shipping to job sites.

A more recent development in the history of the firm is that Castone is a General Contractor for building envelopes, certified by the Architectural Precast Association. This allows the company to offer “pre-construction design consulting, drafting and engineering, custom precast manufacture, in-house testing and Quality Control, masonry, installation, cleaning, and waterproofing of…building skin[s].” [13] One potential implementation of these services, “Design Assist,” will be discussed.

In 2014, Castone contacted Georgia Tech’s Digital Building Lab to start a conversation about the possibilities of incorporating digital modeling software into their existing workflow. That conversation developed into research of methods of incorporating BIM into architectural precast concrete fabrication. A report of the processes, current state, and results of this ongoing research follows.

2 Project Description and Goals

The building that serves as the case study for this project is a hospital designed by Flad Architects which expands the University of Florida Health Shands complex, located in Gainesville, Florida. The General Contractor for the 500,000 square foot building is Skanska. Construction began in 2014 and is expected to be completed in the fall of 2017. [14, 15]

The primary goal for this project is to aid Castone in building a digital model of the architectural precast concrete pieces to be fabricated for the new Shands building, specifically through the use of the software program Autodesk Revit. Submitting this model is a contractual obligation. On previous projects, Castone had been fulfilling such obligations by paying for the model to be built out of house. While this method fulfills the letter of the contract, other benefits of creating a digital model are squandered. Creating the model in-house with

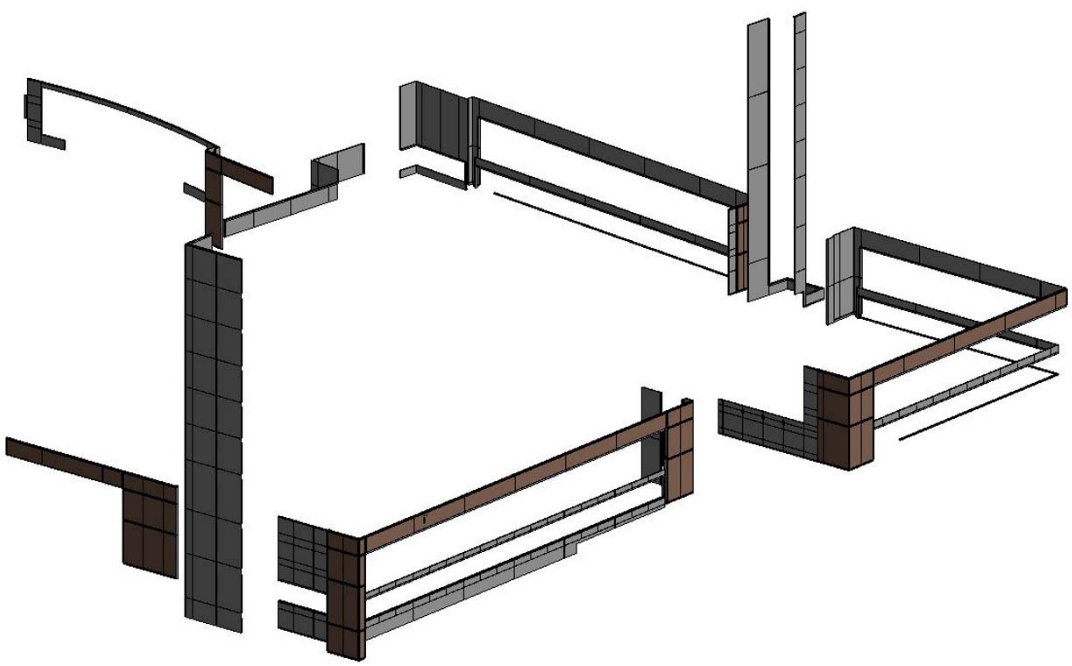

Figure 2. Compiled model of all architectural precast concrete pieces

this project, Castone hopes to be able to use the model for these additional goals:

- Clash detection with building superstructure and other exterior wall assembly trades – during the shop drawing phase, Skanska held weekly virtual coordination meetings
- Use the model to create shop drawings and shotickets – track time savings of production compared to current processes, access the process for potential future application and expansion
- Incorporate BIM into existing process – compare existing and future processes
- Generate families of panels for future use – create a limited set of model families that can capture as many variations of architectural precast concrete pieces as possible
- Use model for material take-offs currently done by hand – all accountable on spreadsheets, time-consuming and error-prone

3 Methods

The first step before starting to build any models or model families is an assessment of the whole building. The design team shared a Revit model with the project manager, Figure 1. Along with printed Construction Documents, the drawings and model are examined by Castone to determine quantity and variety of architectural precast concrete pieces and what parameters or alternatives for each piece will need to be obtainable. Based on the size of their facility, transportations costs, and scheduling, Castone determines that the completed building will require 313 individual pieces of architectural precast concrete.

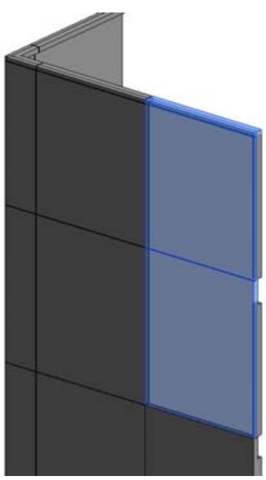

Figure 3. Piece generated using Revit parameters

3.1 Revit

Each of the piece types is modeled in Revit as a *Family* with parameters. For example, the piece shown in Figure 3 belongs to the “W Family” (W for wall) of models and has a long list of parameters controlled its form. Modeling in this manner allows many different variations and saves modeling time; each time a similar piece with a slight variation is needed one does not need to model completely from scratch, but use the Family model and make adjustments. Each adjusted model can be saved as a “Type” and a catalogue of piece varieties is soon collected. For the Shands project, Castone developed 56 Families.

As each piece is completed, they are assembled together in the *Project File*, Figure 2. When all pieces are present, this compiled model is federated into the General Contractor file for coordination with the building superstructure and other exterior components and materials. Models from Castone and the intended building superstructure are brought together in Navisworks for clash detection and other details of coordination. In one particular example, viewing the federated model revealed a clash of panel embeds with a column. During the coordination phase, the embed could easily be moved. Without the use of the digital model in this way, it would have been far less likely to catch this conflict, leading to costly adjustments in the field long after the pieces had already been manufactured.

The compiled model is also used to generate shop drawings sheets. Shop drawings are “detailed plans prepared by a fabricator.” [16] They are based on the Construction Documents – drawings, specifications, and digital model supplied by the design team and construction manager – but are produced by the fabricator to validate the design intent through the additional details required by each specific trade. The shop drawing process anticipates the potential of revisions to the drawings as pieces are coordinated to model the design intent and coordinate with related components and other trades.

On the shop drawing sheets, Castone notes the following timeline as the history of submissions, changes, and approvals:

1.	For approval	4/14/15
2.	Revised for approval	4/27/15
3.	Revised for approval	6/10/15
4.	Embeds for field use	6/24/15
5.	Revised for approval	7/10/15
5.	For field use	10/7/15

Because the shop drawings where generated from a digital model of assembled parametric *Family Types*, adjustments can easily be made to individual pieces through each of these drawing iterations and the shop drawing sheets update automatically.

Following the approval of the July 10, 2015 set of shop drawings, shop ticket production can commence for each of the panels. Shop tickets are different from shop drawings in specificity and detail. Each sheet will show one piece of architectural precast concrete only, as opposed to the shop drawings sheets which show an entire façade composed of many pieces. Shop drawings show the big picture. Shop tickets detail and dimension every single aspect of each architectural precast concrete piece that the fabrication team will need to produce it – the shape, details, rebar, locations and types of various embeds and lift points, and any other requirements.

Castone uses the same Revit model, updated through the coordination and shop drawing approval phase, to generate the shop tickets. This assures consistency of the fabricated panels and the approved design.

5.2 Dynamo

Parallel to the effort Castone made to model the architectural precast concrete pieces in Revit, the author extended the logic which developed the model parameters into Dynamo, an open-source graphical algorithm editor. [17] Dynamo models can be instantiated directly into Revit, thereby also capturing the beneficial abilities of Revit models including ease of coordination and drawing sheet production. Described below, similar parametric qualities of the above Revit models are coded into Dynamo. Five types of parametric features are modeled: Top cap, Turn back, Reveal (front), Notch (back), and Embed locations.

As with the Revit process, the model begins as a rectangular prism (*Cubiod.ByLengths*) to which additional features are successively added.

3.2.1 Top cap

Panels at the tops of walls at Shands have a cap detail. Another *Cuboid.ByLength* is added to the front face of the original rectangular prism. *Integer Sliders* allow flexibility of the cap's height and depth. *Solid.Union* joins the pieces together.

3.2.2 Turn back

A "turn back" is an extension of a wall panel perpendicular and away from the face of the building. This detail allows adjacent materials to be attached to or sealed to the panel. Assuming a rectangular panel, the turn back could occur on any of the four sides (top, bottom, right, or left) or any combination of the four sides. Again, *Cuboid.ByLength* is used to add a rectangular prism, though here additional scripting is required to allow the turnback to be able to occur on any side. *Integer Sliders* allow flexibility of the turn backs thickness and depth. *Solid.Union* joins the pieces together.

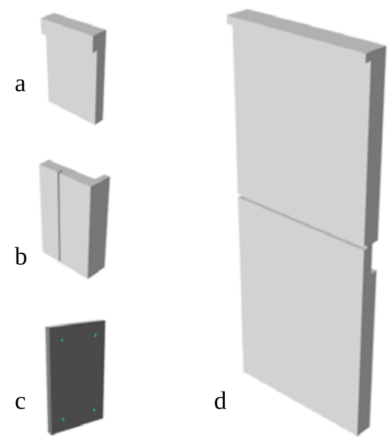

Figure 4. Pieces generated using Dynamo script

3.2.3 Reveal (front)

Perhaps the most "architectural" for its effect on the aesthetic of the overall façade, reveals are linear voids in the surface of a piece. Cuboid.ByLength and Integer Sliders control the thickness and depth of the reveals and Solid.Difference removes that part of the model. An added Dynamo node, Geometry.Translate, is used to allow adjustability of the location of the reveal.

3.2.4 Notch (back)

A back notch would be used to coordinate with the building superstructure, for example, the edge of a structural floor slab or beam. Node scripting is similar to the "Reveal" logic, just selecting the back face instead of the front. Again, thickness, depth, and location of the notch are parametric.

3.2.5 Embed locations

Points can be defined on the panel which serve later as insertion points for other related models, such as embed plates. *Curve.Offset* to offset each of the edges of the panels by a certain distance, thus locating each *Curve.EndPoint*. If more or less than four embeds where required or the offset distance on the sides differed from that at the top or bottom, alternate script logic could be used.

Each of the above described parameters can be combined with one another, used multiple times in each model instance, or not at all. The example shown in Figure 4d shows one possible combination. This model instance is intended to replicate the piece generated in Revit by Castone in Figure 1. This example is shown to demonstrate that the Dynamo model can create any and all of the panels that the previous Revit model could.

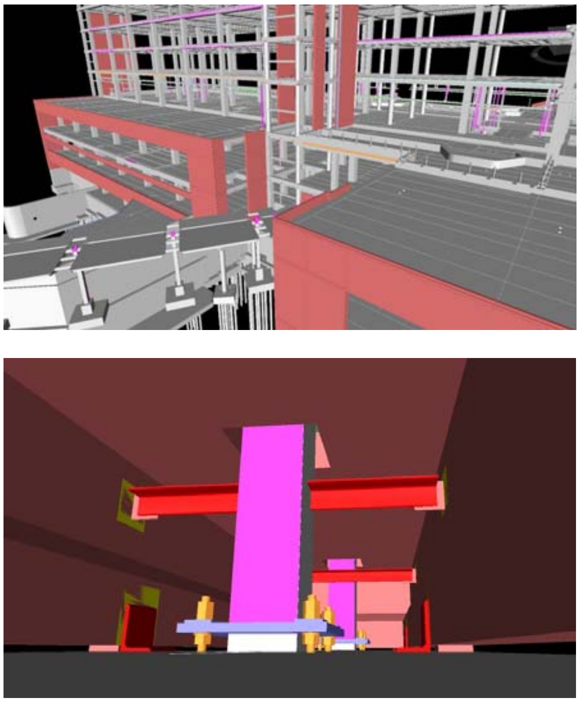

Figure 5. Navisworks views of coordination model

3.3 Excel

Many of the above Dynamo nodes work on the premise of (1) defining a parameter and (2) applying a value to that parameter. Once the scripting of nodes has been defined, the model can be flexed by simply adjusting the values. Taken a step further, just as Revit writes spreadsheets of numerical information, Dynamo can read the same from Microsoft Excel. Each Excel "cell" can represent one parametric value of the Dynamo model. When the files are linked, numbers in the spreadsheet can be modified and the Dynamo model updates accordingly. The node *ImportInstance.ByGeometries* can then instantiate the geometry into Revit.

Dynamo reads the Excel file as a list of lists – each column of information is a list of the items in each row of that column. Through successive *List.GetItemAtIndex*, one is able to connect the value in each specific cell to the appropriate Dynamo node that it is meant to control. This process of controlling Revit geometry through Excel and Dynamo is comparable to the process of manipulating the parameters set in Castone's Revit model.

This strategy of "modeling" through Excel, once scripting and actuated, is much quicker and potentially more user-friendly for novice software users. However, creating models this way does not yet offer the continual updating that is described in the Shop Drawing process above. Using Excel and Dynamo, once a model is placed into Revit, it must always be linked to that file if future changes are desired and a copied instance will no longer be parametric.

On the other hand, once a catalog of architectural precast model families is established and organized (discussed below in Section 4.2), these models could easily be linked into and through an Excel file.

4 Results

4.1 Previous work flow

The traditional work flow of architectural precast concrete manufacture, from receipt of Contract Documents through completion of pieces ready for shipping to the construction site, is described here in four stages: Estimating, Shop Drawings, Shop Tickets, and Production.

The estimating stage sets the road map for future stages of the project. The first task is interpreting the design intent and identifying architectural precast parts in the received Contract Documents that will be a part of the completed building. The more involved and critical aspect is translating this list of pieces into a bid. This time consuming process requires experience and knowledge regarding fabrication details, installation sequencing and strategy, production man-hours, and material unit costs. Furthermore, the assumptions made during this stage have lasting implications to the outcome of the completed project, not to mention profitability for the business.

Moreover, all of the work put into the estimating stage does not guarantee that the fabricator will be awarded the contract. If they do move forward with the project, the next stage is shop drawings, discussed in Section 3.1. The shop drawing stages involves implementing all of the assumptions made during the estimate (and related negotiation) phase, based on the described design intent, into drawings for approval by the design team. This iterative process can take several attempts; recall the Shands shop drawing process described previously.

Upon approval of shop drawing, the next stage is generation of shop tickets. This stage translates design intent drawings into drawing for production. Each individual architectural precast piece is carefully planned, considering, to name a few constraints: control joint locations, the maximum bed size in the production facility, the maximum truck size allowed on the roads from the production facility to the construction site, site limitations in terms of installation each panels' internal structural capabilities and weight, which side will be "up" during the concrete pour, whether formwork will be built traditionally or digitally, and more. Completed shop tickets are taken to the production facility for the production of each architectural precast piece.

4.2 Results relative to Castone goals

As described above, Castone was able to use Autodesk Revit to develop a novel digital model for a real-world project and to use that digital model to:

- Coordinate with other exterior wall assembly trades and components
- Explore construction sequencing
- Generate updatable shop drawings
- Generate updatable shop tickets
- Calculate material quantities, for example; concrete volume, number and type of embeds

These factors alone characterize this project as a success for Castone. As this is the first time that Castone is fully incorporating BIM into their work flow, time savings benefits were not yet achieved; there is a large learning curve when integrating any new software. Nath et al [18] describe a similar process of incorporating BIM into a "technologically-enhanced workflow." Their results show "overall productivity improvement …of approximately 36% for processing time and 38% for total time." *The Rosewood Experiment* [19], submits even more positive results – "production of the same set of general arrangement drawings and shop tickets that required 830 [man hours] in the 2D CAD process was accomplished within 358 [man hours], representing a productivity gain of 57%." Future Castone projects will no doubt capitalize on the teams' experience, improving productivity and efficiency and realizing similar productivity results. Furthermore, as more projects successfully incorporate and profit from BIM, Castone hopes to be able to expand incorporation of digital modeling to other phases such as estimating. If a digital model could be made very quickly, it could be used to improve accuracy in estimates before projects are even contracted. One method for this is to create a limited set of model families for future use that capture as many variations of architectural precast pieces as possible.

4.3 Advanced operability

It is worth noting that the building and, consequently, the architectural precast concrete pieces created for the case study described in this paper are somewhat standard in form. The digital modeling practices and processes described here are intended to be extensible to more complex forms. The overall shape, flatness, or verticality of the panels, texture of the formwork, and incorporation of voids through panels are all aspects of architectural precast concrete currently being explored by various design teams. Future research will explore how these features can be incorporated into the modeling process described above. Discussed below, it is particular interest to study how fabrication details from industry experts like Castone can be incorporated into the design process in order to make such features constructible.

5 Discussion

Project delivery in AEC refers to the handing over of a set of building descriptions from the designers to those who will construct the building. Procedures for how exactly to do this are fast evolving. Furthermore, as modes of designing and modes of representing designs increasingly utilize and rely upon digital technology, the boundary line between who designs and who builds is becoming blurred.

Regardless of the project type or size, "a building…is a complex venture encompassing many tasks and involving many different persons, firms, and organizations in these tasks. These tasks, roles, and responsibilities can be put together in numerous ways to deliver a building project." [20] For example:

> One… way is for the owner to contract with an architect for design and construction documents; when these documents are fully completed they become the basis for soliciting contractor proposals and awarding construction contracts. The architect administers the contract between owner and contractor and, when the work is completed and certified to, the project is occupied and closed out Although there are many options and variations… it is basic and widespread, and over the years, standard contract forms and procedures have evolved to guide its use. [21]

While this Design-Bid-Build process removes much liability from the design team and emphasizes competitive pricing, it does not allow any feedback to the design team on the proposals' feasibility, budget, or schedule. This process does not guarantee that the physical building or part can be built as designed; a disconnect between design intent and constructability can easily occur. One reason for this is that the designer is simply unaware of certain design details that are involved to fabricate building components; an understanding that craftsmen take for granted. This is in part due to above-referenced "standard contract forms and procedures" of the profession; the designer is not required to provide the means and methods of the fabrication, but a general direction for the design intent at which point various contractors fill in the gaps.

"Design intent has to do with the desired outcome, not the means by which it is achieved, however, as any designer knows, the design process can heavily influence that outcome." [22] Coordinating the various contractors, and therefore the built outcome, is the role of the Construction Manager (CM). The CM "use[s] the interaction of their design and construction staff to generate cost effective construction details (constructability)." [23] Though, as George Heery wrote in *Time, Cost, and Architecture*, "many would point out, and with some validity, that the evolution of construction management as a profession, or definable professional service, has taken place within and because of a management void left by the architectural and engineering professions." [24]

The filling of the "management void" by "these [new CM] specialists – often trained as architects or professional engineers themselves – was meant to streamline the building process by making others accountable for aspects of construction, changing costs of materials, managing leads times for materials or equipment and making substitutions, or even challenging design decisions made in the construction documents, but it did little to increase trust between owner, architect and contractor – in fact often it made the building process more contentious." [25]

Heery was aware of this downside as well as the potential effect, or perceived effect, on the design outcome, pondering:

> "[C]an something so intimately related to a building's design as the control of its cost and time of delivery be successfully separated from the design approach? It would seem clear that the two cannot be separated if that control is to be as effective as it can be…Still another view it that when there is strong control of cost and time, the design must suffer…What, then, is the relationship between architectural design and construction management, and what should it be? That relationship would seem to be, basically, that both are indigenous parts of the process that creates architecture, and that they both have to be carried out well and thoroughly intertwined to produce truly successful architecture. [26]

Furthermore, he knew that "the greatest savings in time and cost… can be achieved during the design phase. It is during the design phase that the quantity and quality of the building are established, the systems which will affect construction procedures are selected, and the start time for construction is determined. These activities almost invariably have more control over time and cost than management activities not initiated until bid/award or construction phases." [27] Shown in graphic form, this phenomenon has become known as the "MacLeamy Curve", named after Patrick MacLeamy, HOK's chairman and CEO, who invented it. [28] The graph shows that as design phases progress, teams are decreasingly able to impact cost and functional capabilities through changes to the design because the potential cost of such changes increases. The MacLeary curve depicts a scenario of the "traditional design process" wherein "by the end of Construction Documents, the only option to control cost is to degrade finishes – a terrible option." [29, 30] MacLeamy proposes shifting to an earlier "preferred design process," focusing "more effort to develop and test design alternatives" sooner.

In order to bolster the design teams' confidence in their proposals' proposals' feasibility, budget, and schedule, consultation with construction experts during this "preferred design process" time period is necessary. Several project delivery methods employ this approach, namely; Fast Track (also called Accelerated Scheduling), Design-Build, and Integrated Project Delivery (IPD).

Yet another emerging technique in which design teams and owners are supplementing the design phase with industry knowledge is called "Design Assist," defined by the AIA as "the procurement method by which, prior to completion of design… a contractor provides design assistance to the architect or engineer." [31] Design Assist offers a method for designers to have a similar amount of building control – of the design as well as the construction feasibility, budget, and schedule. Further, while Design Assist is not dependent on BIM, there does appear to be something in the way that BIM has been developed and is used that facilitates Design Assist – "innovation in construction delivery methodology is clearly trending toward collaborative, teamwork approaches." [32] Cavieres et al [33] provide an overview of these and other early conceptual design strategies and develop a case study of parametric templates based on rules and requirements from the concrete masonry industry. Future research will aim towards similar goals for based on industry knowledge of architectural precast concrete.

6 Conclusion

Advances in digital technology have led to a revolution in the way that buildings are documented and constructed. For some time, many AEC teams have been organizing their processes so that the transfer of design documents to contract documents occurs online and via

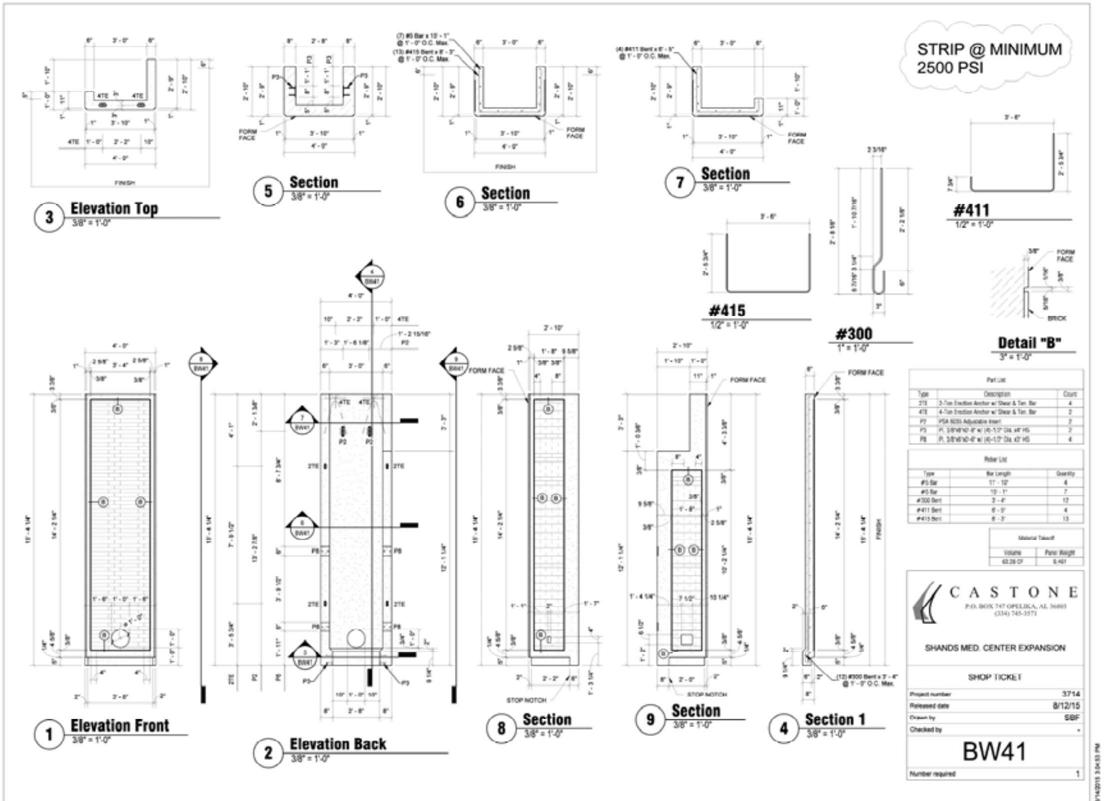

Figure 6. Example Shands shop ticket

digital model. This revolution has huge benefits for construction; for example, clash detection prior to approval, ability to confirm assembly sequencing, verification of as-built dimensions, and more. Castone was able to achieve all of these benefits through their Revit model described in Section 3. Design teams also find many advantages to digital modeling, particularly in the sharing and documenting of architectural representations. Various software programs propagate changes to designs to relevant model views and drawing sheets automatically, reducing the likelihood of errors. Further, digital models can be shared among team members for quicker, easier, and more accurate coordination. However, manipulating and customizing a digital model takes a large amount of time; perhaps equivalent to the time that goes into conceiving the design itself. Furthermore, such manipulation of the digital model does not guarantee that the physical building or part can be built as modeled. Many other factors – constructability, budget, and schedule commitments – may force changes to the design, resulting in time consuming re-modeling.

The potential need to remodel highlights the disconnect between design intent and industry knowledge. BIM offers the opportunity for AEC teams to work across disciplines and through various phases, allowing for more informed design decisions. This is true for "standard" designs such as the Shands buiding, and for more complex designs eluded to in Section 4.3. Engaging trades in conversation early in the design phases gives the design team access to industry knowledge regarding – to use Castone's work as an example – parameters effecting shop tickets, and therefore the outcome of the architectural precast pieces, during the design phases. Working together through emerging project delivery approaches such as Design Assist could imbed design intent models with fabrication knowledge that allows them to mature directly into models for construction, expediting much of the back and forth of traditional work flows discussed in Section 4.1. These steps work in concert to unleash further benefits of BIM, the process and the document.

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