Automation in Construction 91 (2018) 62–82

Contents lists available at ScienceDirect

Automation in Construction

journal homepage: www.elsevier.com/locate/autcon

BIM semantics for digital fabrication: A knowledge-based approach

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ARTICLE INFO

Keywords:
Building Information Modelling
Knowledge-Based BIM
Parametric object behaviour
Building Object Models
CNC fabrication
Machining features
Process re-engineering
Action research

ABSTRACT

This research investigates how a Knowledge-Based approach to developing BIM objects of Engineered-To-Order (ETO) components could facilitate the workflow between designers and fabricators. The work reported in this paper represents the findings of a 16 month action research project undertaken with an ETO woodwork component fabrication company with both conventional and Computer Numerically Controlled (CNC) machining capabilities. The goal of this paper is to demonstrate a way for how BIM objects could first be embedded with fabrication semantics, and then used to support the workflow between designers and fabricators, specifically where CNC machines are used. To demonstrate the idea, the methodology is outlined in the context of a developed BIM object for a base cabinet from the domain of custom cabinetry. The BIM object was validated by fabricating the actual component via a simulated workflow between design and fabrication disciplines in a real setting. The main contribution is that the research clarifies some of the ambiguity relating to BIM and CNC technologies working in tandem. The discussed results explain the benefits and challenges observed through the use of this method as well as provide avenues for further investigation.

1. Introduction

Currently, with the rising use of BIM applications worldwide, the role of component manufacturers has augmented as they provide designers with digital objects that represent their actual components in production [1,2]. These BIM objects (also known as Building Object Models) potentially assist designers in selecting the most appropriate component that aligns with design intent; facilitate product procurement; and in turn, improve the workflow between design and production disciplines.

Despite these advocated benefits, commonly available BIM objects fall under specific categories of component production: Made-to-Stock (MTS) and Made-to-Order (MTO) components [3]. In this sense they restrict the designer to a fixed set from their manufacturer's catalogues. This is rarely the case with all building components, as some necessitate a degree of customisation to fit specific requirements for the project at hand. Such components align to another category: Engineered-to-Order (ETO) components [4].

ETO components typically involve a more complex working process than their MTS or MTO counterparts. Through the use of BIM technology, producing these customised components could be facilitated by what researchers and practitioners indicate to be an overlapping relationship between designers and fabrication professionals where there is a bi-directional dependency on information shared in the workflow between them (see Chapters 7 & 8 of [4], Chapter 5 of [5], Chapter 19 of [6]).

The discussions by these scholars revolve around a common concept: The potential use of digital objects between design and fabrication disciplines. For designers, unlike limited BIM objects which align to a MTS or MTO production strategy, these would be customisable ETO objects provided by fabricators to support them with fabrication concerns during design stages. In this sense, the process would avoid potential changes and rework once designs are received by the fabricator.

For fabricators, personnel have the opportunity to leverage incoming information from BIM objects for supporting fabrication operations, and could also support automated production methods in the form of CNC machines. These machines simply utilise digital information to control the fabrication task allotted to them [7].

Although these discussions outline a framework for investigating how BIM objects of ETO components could mediate this dialogue between designers and fabricators, this area of research has been seldom explored. To echo this gap, a recent study by Tillmann et al. [8] on production planning of ETO mechanical components highlights the need for further research to clarify the ambiguity surrounding the forms of information needed within BIM applications to support workflows from design to production.

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https://doi.org/10.1016/j.autcon.2018.02.031
Received 16 October 2016; Received in revised form 10 December 2017; Accepted 16 February 2018

In this regard, the work in this paper presents the findings of a research project undertaken in collaboration with an ETO component fabrication company that specialises in the wood-work industry in Cairo, Egypt. The basis for this research alliance was highlighted by a mutual interest between the authors and the company to investigate how BIM objects of their components could support the workflow between designers and fabricators. More specifically, two interdependent objectives initiate this research: 1) how BIM objects could support architectural or interior designers in customising their products before handover for fabrication; and 2) with respect to the available fabrication tools and machinery used by the company, the ways in which information within these BIM objects could be used downstream for fabrication, especially where CNC machines are used.

To avoid a generic investigation, the authors acknowledge that different types of components use different production methods that relate to a variety of factors. Some of which include but are not limited to: industry standards; local expertise; available materials and machinery. Through this lens, an in-depth study of a specific domain of components is argued to provide more informative insights than a general-level investigation. Later on, lessons learned could be useful during other studies for different domains.

In so doing, the research reported in this paper uses the domain of custom cabinetry as a backdrop to demonstrate the idea for how BIM objects could be developed and then used to support the workflow between designers and fabricators. The choice of custom cabinetry was influenced by three reasons: First, the range of knowledge available in the form of normative standards and best practices, from which rules and constraints could be embedded into parametric objects. Second, the domain of custom cabinetry relies on ETO components aimed at fulfilling the needs of the user or project. In this sense, fabricating custom cabinetry through the use of BIM objects would facilitate part of the link between BIM and Mass Customisation (MC) [9]. Third, contextual reasons regarding technological adoption in the Egyptian design and manufacturing sectors combined with one of the authors' experience in the cabinet industry provided an opportunity to conduct a practical investigation that could be applied to the Egyptian setting.

Initially, the paper briefly reviews research efforts related to how BIM objects could be semantically enriched for their use between design and fabrication professionals. This includes discussion on knowledge-based efforts for informing the object's parametric behaviour, as well as the recognition and extraction of features and process planning information for CNC machining. Later, the paper shows how a BIM object could be used to support the workflow between both disciplines by reporting work on a four-cycled action research project aimed at developing a prototype BIM object for a component whose development is guided by Lee, Sacks, and Eastman's parametric modelling process, which was originally presented during work for the precast concrete industry in the United States of America [10]. Work done during each cycle is discussed sequentially up till the actual fabrication of the component. Afterwards, further investigation for future research is outlined.

2. Related work

The following sub-sections will discuss research efforts that embed the domain knowledge of either design or fabrication disciplines into BIM applications. Afterwards, an overview on essential topics of CNC technology and the possible links it could have alongside BIM is provided.

2.1. Knowledge-Based Building Information Modelling (KB-BIM)

Langenhan, et al. [11] point out that generally, the use of the term 'knowledge' overlaps with information and data. Accordingly, to eliminate ambiguity between these terms, they provide their own clarification by stating that 'it is the preparation of information in data structures that makes it useful as knowledge'. To relate this to BIM, Sheward and Eastman [12] indicate that these data structures are 'in the form of design rules, parametric constraints, and/or parametric objects' which convey what is known as professional expertise. The expertise is usually acquired by a professional or company over the course of practice. It represents the knowledge capital for how the individual or company personnel deal with tasks in their profession. Explicitly encapsulating such expertise and embedding it within BIM applications is formally defined by them as Knowledge-Based BIM (KB-BIM).

2.1.1. Knowledge-based implementations for architects

Types of knowledge differ between each specialty and depend on the intended use of the model as well as the phase of the project. Some of the examples aimed for architects before handover phases to other disciplines include: maintaining proportions of building objects according to established rules dating to classical architecture [13]; adherence of building objects to certain technical requirements [14,15]; ensuring the constructability and stability of unorthodox wall forms before handover to structural engineers [16]. These efforts have demonstrated the variety of possible applications of KB-BIM. They embed knowledge that is commonly not within the province of designers, into objects using a variety of sources, to assist the designer in the decision-making or cognitive burden involved in a particular activity.

2.1.2. Knowledge-based implementations for fabricators

Although the aforementioned examples discuss the knowledge-based implementations from an architect/designer's perspective, research efforts related to the fabrication of BIM objects has been compartmentalised to the domain of fabricators. Specifically, these studies focused on either facilitating the generation of shop drawings, or automating it entirely. Most notable is the work of Charles Eastman, Rafael Sacks, and Ghang Lee for the North American precast concrete industry [10,17–19].

The above-mentioned scholars developed a library of parametric objects that represent various components used in the pre-cast concrete industry. The parametric behaviour in these objects is informed by the knowledge of experts who took part in an industry consortium. As a result, the developed library is reported to have facilitated design exploration for precast concrete structures as well as automating the production of documents necessary for fabrication to a certain extent.

Despite these benefits, the developed objects are solely used by fabricators. I.e. the formalised knowledge is embedded into a fabricator-specific application. In this sense, the objects are not available for use by designers during earlier phases.

Further, in a study by Manrique et al. [20], the researchers embedded knowledge from structural engineers and wood framing professionals into 3D objects of components used in residential wood framing construction. These objects are later used by a customised plug-in to automate the generation of shop drawings for fabrication. However, the developed system was aimed solely for the use of contracting companies with no explicit link to how it fits in a workflow with designers.

In another study by Nath et al. [21], the researchers aimed at proposing a new workflow for streamlining the generation of shop drawings for precast concrete components through the use of multiple BIM applications across the workflow between design and fabrication disciplines. To do so, they used a set of technical documents to develop a standardised library of BIM objects with some parametric behavioural capabilities. Through feedback sessions with experts, the researchers projected that these knowledge-rich objects would provide productivity improvements in terms of the time taken during activities required to generate shop drawings for the precast parts.

Nevertheless, in a similar manner to the abovementioned studies, what remains unclear was the usability of the pre-cast BIM objects in the workflow with the designers prior to handover to the fabricator. In