BIM-enabled Production Paradigm Transformation in the Construction Industry: Experience from Other Industries and Development Model

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ABSTRACT

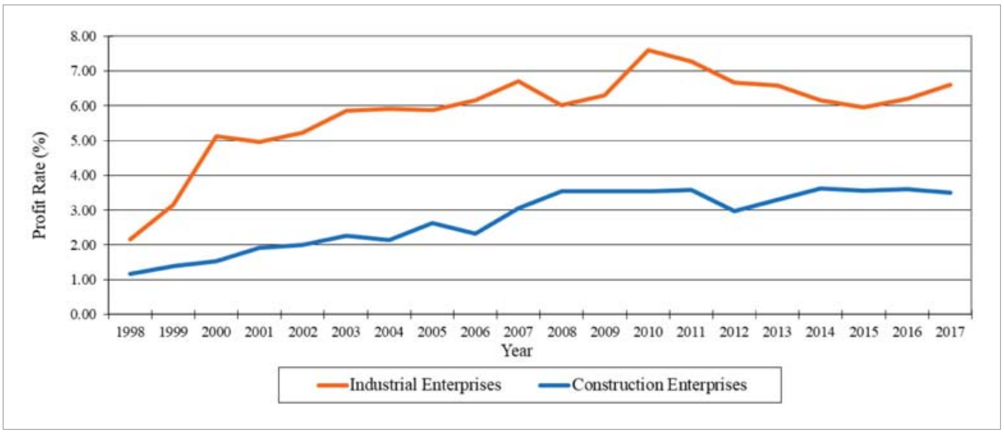
The construction industry has long been criticized for being reluctant to adopt innovative technologies and slow to improve its relatively poor production performances. This paper first analyses the problems rooted in traditional design, construction and product operation processes in the construction industry and then provides an overview of how the aircraft manufacturing industry uses the model-based technology to streamline its production process. Based on these analyses, the primary transformation directions for the production paradigm in construction as well as the role of building information modeling (BIM) as a model-based technology in enabling the transformation process are then discussed. This paper also proposes a technology-organization-business-environment (TOBE) framework to facilitate the BIM-enabled paradigm transformation process.

Keywords:
Construction industry; building information modeling (BIM); production paradigm; innovation adoption; development model

INTRODUCTION

As an important pillar of the economy worldwide, the construction industry plays a critical role in the sustainable development of the social and natural environments as a whole. It is estimated that the industry not only accounts for 6% of global gross domestic product (GDP), but also acts as the largest consumer of raw materials and produces 25-40% of the world's total carbon emissions (Barison and Santos, 2016). Despite its important role, the construction industry also faces several challenges and is considered to be lagging behind many other industries. During the past decade, building information modeling (BIM) as a fundamentally new way to create, share, and utilize project life-cycle data has been increasingly regarded by both practitioners and researchers as a milestone technology to reshape the construction industry (Eastman et al. 2011; NBS 2018; NRC, 2009; Cao et al., 2014). This paper aims to discuss how such the model-based technology enables the transformation of the production paradigm in the construction industry.

The remainder of this paper is organized as follows. The next section analyses the primary problems rooted in traditional design, construction and facility operation processes in the construction industry. Section 3 provides an overview of how the aircraft manufacturing industry uses the model-based technology to streamline its production process. Section 4 discusses the primary transformation directions for the production paradigm in the construction industry as well as the role of BIM in the transformation process. Section 5 proposes the Technology-Organization-Business-Environment model to facilitate the BIM-enabled production paradigm transformation



<Figure 1> Profit rates of enterprises in different industries in China during 1998–2017

in the construction industry. Section 6 summarises this paper.

Problems with the Production Paradigm in the Construction Industry

The traditional production paradigm in construction has been long reported to be inefficient. According to Lopez and Love's (2012) investigation of 139 construction projects in Australia, for example, the average direct and indirect costs caused by design errors could account for 6.85% and 7.36% of project contract value, respectively. With respect to cost overruns, US Department of Transportation's investigation of rail transit projects in the US shows that the actual costs of the studied projects were 61% higher than the initial project budgets on average (Pickrell, 1990). Similar project performance problems have also been widely reported in many other countries such as China (Zhang et al., 2008), Saudi Arabia (Assaf and Al-Hejji, 2006), the UK (Olawale and Sun, 2010) and Zambia (Kaliba et al., 2009). As illustrated in Fig. 1, further comparison of organizational performance also reveals that the profit rate of construction enterprises has been persistently lower than those of other industrial enterprises in China during the past twenty years (NBSC, 2018)〈Figure 1〉.

While inherently associated with some industry characteristics such as the one-of-a-kind nature of construction projects, the presence of these performance problems could also be attributed to the relatively conservative culture of the construction industry in implementing innovative technologies to streamline traditional design and construction processes (Reichstein et al., 2005; Smyth, 2010) as well as the widespread use of traditional 2D information management technologies in the industry (Eastman et al., 2011). This type of technologies not only generally fails to fully represent the product information of constructed facilities as well as the interdependence among the information (Froese, 2010). As a consequence, the traditional production paradigm based on the 2D information management technologies in the construction industry not only lowers the efficiency of daily design, construction and operation activities of individual participants, but also results in a typical "throw the wall" production process in which the procedures and information of different project participants are substantially segmented throughout the facility lifecycle (Eastman et al., 2011). In this "throw the wall" production paradigm, the requirements of project clients and facility end users are also largely under-fulfilled.

Model-based Production: Experience from the Aircraft Industry

IBM Global C-suite Study in 2015 interviewed 5,247 C-suite executives (CxOs) to find out what they think the future will bring and how they are positioning their organizations to prosper in the "age of disruption." It is revealed that, from the perspective of chief executive officers (CEOs), technology factor is the most important factor that would shape enterprise's future (IBMIBV, 2015). Technology is not only part of the fundamental element for ensuring implementation of business strategies but also the key factor for forming up new strategy. In this report, client orientation and collaboration are considered to be a future trend that will impact organizations' evolution. More than two-thirds of all CEOs anticipate adopting a more individualized approach to customers, which requires more collaborations with employees and partners to speed up the pace of innovation. As a result, three keywords can be concluded for the transformation and innovation in today's business environment: technology, customer and collaboration.

A successful example of transformation and innovation for the construction industry to learn is the aircraft manufacturing industry. In 1970s, each aircraft hull was constructed first in one big frame, and everything else was built into the hull as it went up. The lifecycle processes of development, design, manufacturing, assemble and inspection were organized in the serial type and generally separated with each other. Different contractors and suppliers communicated with each other generally through traditional 2D drafting documents. As a consequence, the whole production process used to be slow and inefficient. However, this production paradigm had changed dramatically. During the project of Boeing 777 twin-jet airliner, for example, Boeing began to adopt a concurrent engineering method to organize the lifecycle development and production process. Boeing now not only encourages the involvement of end users in early production development stages to identify user requirements as early as possible, but also tries to ensure the collaborative design and development of different participant organizations through efficient sharing of product information.

A key technology underpinning the production paradigm transformation is recognized as the Model Based Definition (MBD) technology. MBD is the practice of using 3D digital data (models) combined with other data (3D dimensions and tolerances, etc.), within 3D CAD software, to provide a technical definition for individual components and product assemblies (Quintana et al., 2010). Based on MBD, modern manufacturing process is to build digital model, analog simulation, and define product. It is a transitive and expanding procedure that transfers product data from design upstream to parts manufacturing, product assembly and inspection downstream.

The Boeing 777 project, which was one of the first in the aircraft industry to have a 100% digital design process, is a successful example of using the MBD technology (Dietrich et al., 2007). While the design of the 777 project involved more than 10,000 people in 238 teams scattered all over the world across 17 time zones, the design processes were collaboratively conducted through the Dassault's Computer Aided Three-dimensional Interactive Application (CATIA) CAD system. The model-based digital representation of product data enabled each designer to access the full product design and instantly retrieve information related to any specific product component. Digital data were also used to drive the manufacturing processes whenever possible, with the entire aircraft assembly process simulated using model-based digital techniques (Quintana et al., 2010). A Boeing 777 aircraft is made up of more than 130,000 parts and more than 3,000,000 individual pieces (including standardized duplicate components), these individual pieces can be efficiently designed and manufactured all around the world and then effectively assembled together in the Everett assembly plant in Seattle. The model-based production process not only enables the final product to effectively fulfil the needs of end users, but also enables hundreds of project participant teams work in a collaborative, concurrent and efficient manner.

BIM-enabled Production Paradigm Transformation in the Construction Industry

Based on the analyses of the problems rooted in traditional production processes in the construction industry as well as the experience of how the aircraft manufacturing industry uses the MBD technology to streamline its production process, it is suggested that the construction industry can transform its production paradigm towards the following directions:

1) Product innovation with clients' experience and participation. The involvement of clients and end users in projects is generally weak in traditional design and construction processes. They generally

"throw" their ultimate needs to designers but not heavily involve in daily decision-making and innovation activities. The way that clients communicate with designers and contractors is also relatively original, which is primarily based on words and 2D drawings. More involvement of clients in daily project activities as well as the use of model-based technology and supporting technologies such as virtual reality (VR) could help to better identify clients' needs and find out better design and construction solutions.

2) Organization innovation through integrating life-cycle supply chains. The traditional production paradigm in the construction industry has suffered from the fragmentation of product, organization and process information along life-cycle supply chains for a long time. The adoption of innovative products and technologies in construction projects often requires the joint effort of different project participants throughout project supply chains. Therefore, the integrated collaboration among clients, designers, general contractors, subcontractors and suppliers, both in time and space, is quite important for the efficiency and effectiveness of project activities.

3) Process innovation through integrating cyber and physical systems. In many countries, construction activities still rely heavily on manual methods of placement and assembly. Daily construction management activities are still largely based on the experience and intuition of project managers but lack the support of automatic process controlling technologies. Building high-valued physical products without using appropriate digital technology is considered to be a special characteristic of the traditional construction industry, which has substantially lowered the efficiency of daily production and management activities. More use of automatic data collection and processing technologies such as ultra-wideband (UWB), radio frequency identification (RFID), computer vision and cloud computing could help to better integrate the virtual model with actual physical construction process and thus realize the automatic and efficient control of project production processes (Akanmu and Anumba, 2015; Louis and Dunston, 2016; Luo et al., 2018).

A core technology underpinning the production paradigm transformation is BIM, which can be described as the MBD technology in the construction industry. The building models crated and managed by BIM technology have several specific characteristics (Eastman et al., 2011): facility components are represented with digital objects not only carrying computable graphic and data attributes that identify them to software applications, but also containing parametric rules that allow them to be manipulated intelligently; model data are consistent and non-redundant so that changes to component data are represented in all views of the component and the assemblies of which it is a part; model data are coordinated with each other. BIM can be used in a variety of areas such as clash detection, energy analysis, cost estimating, schedule simulation, offsite fabrication and asset management throughout the facility lifecycle (Cao et al., 2015; Eastman et al., 2011). If used appropriately, BIM could not only help to facilitate the concurrent collaboration among different project participant organizations and better identify the requirements of project clients, but also enable the intelligent analysis the project progress and the automatic control of project lifecycle process. These changes will result in a more integrated production paradigm which can generate substantial benefits in terms of, for instance, fewer design errors, reduced production cycle times, lower construction costs and better lifecycle energy performance (Bryde et al., 2013; Eastman et al., 2011; Giel and Issa, 2011).

Technology-Organization-Business-Environment Model to Facilitate the Production Paradigm Transformation in the Construction Industry

Despite its great potential, the advancement of BIM and its enabled integrated production paradigm in the construction industry is still in a relatively infant stage, with a large proportion of construction projects still sitting on the sidelines of BIM adoption (Bernstein, 2015). Even for those organizations that have already adopted BIM in their projects, a relatively high percentage of them are using BIM out of social or trial motivations and have not obtained expected benefits from their implementation practices (Cao et al., 2016, 2017). In these practices, BIM is primarily implemented as a visualization tool, whereas its potential in areas of integrating project lifecycle processes and organizations have been largely unfulfilled. Factors impeding the advancement of BIM and its integrated production paradigm include not only technical problems but also cultural and organizational issues (Cao et ail. 2015; Eastman et al., 2011).

In the innovation management research area, the technology-organization-environment (TOE) framework developed by Tornatzky and Fleischer (1990) is a widely accepted model comprehensive identifying the factors influencing innovation adoption and implementation (Baker, 2012). The TOE framework posits three aspects of an organization's context that can influence the process by which it adopts and implements a technological innovation: technological context, organizational context, and environmental context. As the construction industry is a typical project-based industry and the implementation of BIM in the industry is principally in temporary project networks which are composed of different project participant organizations, the business context in which different organizations collaborate with each other for specific project tasks also significantly influences the adoption and implementation of BIM in design and construction activities. As shown in Fig. 1, therefore, a technology-organization-business-environment framework is proposed to elaborate the factors influencing the advancement of BIM and its integrated production paradigm in the construction industry based on the TOE model〈Figure 2〉.

<Figure 2> Technology-Organization-Business-Environment framework

The technological context describes the characteristics of both new technologies available in the market (i.e., BIM and related technologies supporting the integrated production paradigm) and the technologies that are already in use in traditional production paradigms. Factors elaborated in this context include not only the cost, benefits, maturity and complexity (ease of use) of BIM, but also the compatibility between BIM and technology already in use. The organizational context alludes to the characteristics, resources and strategies of related organizations (e.g., designers, contractors, consultants, clients) in the industry. Factors elaborated in this context include organizational innovation culture, top management support for BIM implementation, organizational technology infrastructure and organizational technology development strategy. The business context depicts the project business context in which organizations collaborate with each other as temporary coalitions to accomplish specific tasks. Factors elaborated in this context include contractual issues, level of inter-organizational trust, maturity of project conflict resolution mechanisms and the development of project delivery methods. The environmental context describes the characteristics of the industry environment. Factors elaborated in this context include the regulatory environment, the structure of the industry, the industry standards solving data interoperability problems among different BIM tools, and the industry training system for new technologies.

Among the factors elaborated in the TOBE framework, the development of the industry standards, which aim to solve to data interoperability problems, will play a relatively important role in facilitating the advancement of BIM and its integrated production paradigm in the industry. It is not only related to integrating data from different project participant parties, but also integrating data from different tools which provide different ways to define objects and relations. Another relatively important factor is the development of project delivery methods, which is related to both organizational and process transformation in the production paradigm in construction. While BIM supports the concept of integrated project delivery (IPD) which is a novel project delivery method to integrate people, systems, business structures and practices into a collaborative process to reduce waste and optimize efficiency throughout the project lifecycle, the successful implementation of BIM also requires an integrated project delivery process (Eastman et al., 2011). However, as current project practices in the construction industry are still widely using the traditional and fragmented delivery method of design-bid-build (DBB), the development of integrated delivery methods such as IPD will constitute acritical parts in the transformation of BIM-enabled production paradigm transformation.

Conclusions

The traditional production paradigm in the construction industry is characterized with process fragmentation and inefficiency. It is time for the industry to learn from other sectors and transform the traditional production paradigm. BIM as the MBD technology in the construction industry could enable the transformation of the production paradigm towards the following directions: product innovation with clients' experience and participation; organization innovation through integrating life-cycle supply chains; and process innovation through integrating cyber and physical systems. Advancing the transformation needs taking into account the following aspects of factors: technology, organization, project businessand industry environment. The transformation will be a systemic and inter-disciplinary process, which needs the whole industry, including both practitioners and academics, to collaborate closely with each other.

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