Design for manufacture and assembly in off-site construction: Advanced production of modular façade systems

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Abstract – Product development for commercial façade systems is a complex procedure. Since the Grenfell Tower disaster in London in June 2017, the import, use and sale of polyethylene core Aluminum Composite Panels (ACP) has been reduced. This encourages research on development of new façade systems using advanced production techniques such as additive manufacturing and CNC milling. The aim of this paper is to analyze the two techniques considering principles of design for manufacturability and assembly (DfMA). Results show that in advanced manufacturing of façade elements, a large percentage of project budget is related to acquisition costs for equipment such as CNC machins and 3D printers. Despite these high costs, non-traditional manufacturers are likely to see return of investments over future development projects for the modular façade systems.

Keywords –

3D printing; Additive Manufacturing; CATIA and DELMIA software; Design Optimization; Industrialized Buildings; Moulds; Prefabricated Structural Element; Primavera P6; Project planning and management; Rapid prototyping

1 Introduction

Complex façade systems are increasingly used in construction of iconic buildings. Such façade systems often utilize hyperbolic paraboloid surfaces to maximize aesthetic attraction. While traditional site-built construction is unable to deliver such levels of complexity, off-site prefabrication of façade modules provides an optimal alternative [1].

Modern manufacturing techniques such as 3D printing and CNC milling can further increase the efficiency of façade prefabrication [2]. Coupled with principles of design for manufacture and assembly (DfMA), such manufacturing-led initiatives have the potential to optimize product development in modern construction.

The focus of this research is on production of modular façade systems with hyperbolic paraboloid surfaces. Such façade production includes off-site prefabrication of modular corner façade surfaces, modular straight façade surfaces, and modular curved façade surfaces (see Figure 1). The elements are to be held together by interlocking mechanisms. The aim of modular prefabrication is to allow the production of robust combinations of various façade patterns for clients.

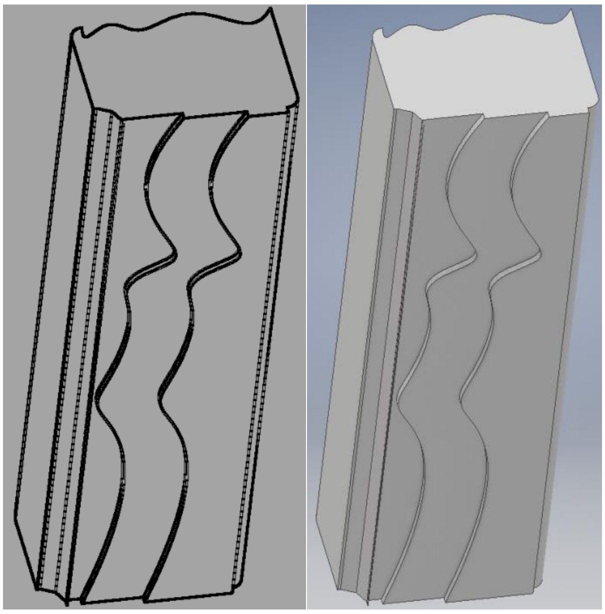

Figure 1. Sketch illustration and realistic view of

a complex façade system with hyperbolic paraboloid surfaces

The current paper explains principles of DfMA in modular prefabrication of complex façade systems. Then it reviews the advantages of using advanced production techniques of CNC milling and additive manufacturing. In the remaining part of the paper, a case study approach is used to analyze the cost and time requirements. At the end, concluding remarks are presented.

2 Modular prefabrication of complex façade systems- Design for manufacture and assembly

Modular prefabrication of Principles of complex façade systems is optimized by adopting principles of design for manufacture and assembly (DfMA). This is due to adoption of manufacturing-led and advanced processes in product development [3]. Furthermore, DfMA encourages multidisciplinary collaborations in product development where manufacturing and resourcing constraints are considered in designing parts and assemblies [4].

Successful implementation of DfMA requires parametric modelling software that supports collaborative work of designers, engineers and manufacturing teams [5]. Strong software such as CATIA and DELMIA have assisted off-site manufacturers of building elements to increase efficiencies and productivity [6]. CATIA is a software suite with multiple platforms for product lifecycle management (PLM), computer-aided design and computer-aided manufacturing [7]. DELMIA is also a software suite developed by Dassault Systems and focuses on manufacturing simulation [8].

The construction literature identifies most important principles of DfMA, including:

- Interdisciplinary collaborations in the early-stage design. Previous research shows that at least 80% of total project costs are committed during concept design stage [9, 10]. Project cost, time and quality of delivery will be optimised by involvement of design engineers, off-site manufacturers, assembly and on-site teams in early concept decisions [11]. This involvement also minimises the amount of rework or re-entrant flow, which is a key source of waste in construction projects [12, 13].

- Addressing past issues related to manufacturability and assembly. Design attributes in future projects are informed by challenges in previous projects. This way, issues that have caused difficulties for manufacturability and assembly will not be repeated [14, 15]. Past issues should be recorded in DfMA and CE knowledge repositories and properly addressed in future designs [16-18].

- Considering constraints in off-site and on-site construction. This DfMA principle optimises product design and process development so that both off-site and on-site limitations are satisfied [19]. Previous research has observed and analysed many cases in which desig of building components has been problematic in terms of transportation [20], crane operations [21], and safety of operations [22].

- Standardisation of design attributes. Excessive variation in design complicates manufacturing and assembly [12, 23, 24]. Some initiatives can minimise errors in assembly and installation such as designing paired parts instead of left/right hand parts [25]. Furthermore, paired-part designs support economy of scale in the supply chain by doubling purchasing volume when compared to mirror image parts [26, 27].

3 Prefabrication of complex façade systems- CNC milling

CNC milling can be used to produce required moulds for prefabrication of façade modules and panels, as well as the panel interlocking mechanisms [28]. The primary justification of using CNC milling at the prototyping stage is the ability to use CNC milling while transitioning from prototyping to final production [29]. Essentially, the ease to scale from prototype size to production size makes CNC milling an attractive approach. Furthermore, the basic skill sets required by CNC machining allows for cost-effective workers to be employed [30].

To enable the optimal production of façade systems using CNC milling, the workflow and product requirements must be understood and implemented. In order to determine the necessary activities for the project and the activity sequence, the following workflow needs to be analyzed and evaluated:

The workflow for CNC production includes design, program, setup, manufacture, assemble and evaluate.

- **Planning:** Throughout the planning process, product development teams identify the objective, specifications and requirements for the project. It is within this stage that risks, challenges and restrictions are identified, as well as establishment of scheduling and product plan outline.

- **Design:** The Design process for CNC requires the use of a 3-dimensional design definition that is constructed in CAD. Generated data can be complex and requires the time and labor of a CAM programmer. However, to initiate the design phase detailed engineering drawings must be provided to the CAM programmer and also CAD data must be reviewed considering DfMA requirements.
- **Program:** The program phase is the process of defining the machine operations. At this point, CAD data is imported into CAM programs, so the manufacturing process can be manually defined. The main components of the machine that must be defined are parts interlocking mechanisms, required number of machine passes, necessary cutters, and feed rates. As each façade design is unique, these decisions are made on a feature-by-feature basis.

- **Setup:** For CNC façade moulds, the set-up process is reasonably quick for machine operators. However, when there are multiple setups because of holes or pockets in moulds, processes need to be constantly repeated that will add time implications to the project. The setup process, however, requires machine operators to load required cutters onto machines and then fixture work pieces.

- **Manufacture:** Using 3-axis CNC, work pieces are repositioned to cut upon faces that are not in the original orientation for facilitating access by cutters. In order to reposition, the operator has to reorient and re-fixture the work piece. Due to the nature of CNC production, time is impacted by the volume of materials subtracted and the removal rate. Such rates are then impacted by specific tolerances and part thicknesses.

- **Assemble:** Depending on the required form of façade moulds, there are mandatory secondary operations after the CNC milling.

- **Evaluate:** Production process is reviewed by the evaluation process when comparisons to the initial design plan is conducted. Evaluation analyses the efficiency of time, cost and quality to determine if the CNC system will be substitute for the production of moulds in manufacturing façade modules.

The activity selection process in this research is based on the aforementioned stages to identify the sequence and flow of detailed project activities. The activity sequence has been identified below in the work breakdown structure illustrated in Figure 2.

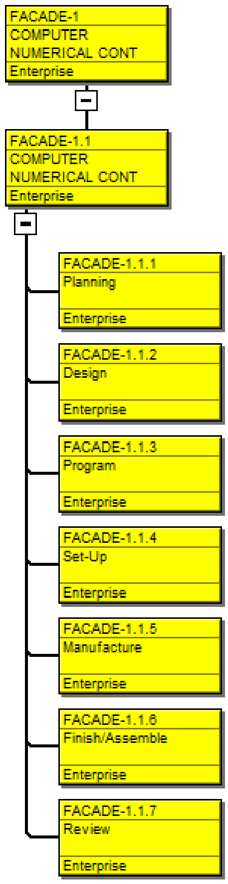

Figure 2. Workflow for manufacturing façade moulds using CNC- Developed in Primavera P6

4 Prefabrication of complex façade systems- Additive manufacturing

Additive manufacturing or 3D printing can be used to create prototypes of façade elements such as small interlocking mechanisms for modules. The applications of 3D printing generates benefits over standard processes during the production of curved elements façade modules where expertise and time are required to form materials into hyperbolic paraboloid surfaces [31].

To further mimic the characteristics of real material, different filaments can be utilized to create similar forming processes. Filament typically utilize a mixture of plastic (usually PLA) and other fibres. As such, they can undergo similar finishes to façade materials such as sanding and staining. The risk of utilizing commercial fibres in 3D printing is reduction of strength and flexibility compared to real-life scenarios. However, as the prototypes are primarily used for design validation and not for structural or endurance testing, this risk can be retained.

Key 3D printing considerations include but are not limited to printing speed, thickness of printed layers, extrusion process, retraction setting, variable speed setting, and printing temperature.

5 Case study- Time and cost analysis

Towards the aim of this study and in a similar approach to Liu, et al. [32], a case study method was adopted as it allows retaining a holistic approach towards the research problem at hand [33]. Selected façade production projects in Australia were deemed suitable to analyze time and cost within off-site project settings. A purposeful selection of case studies targeted maximum level of complexity in project production flows. Main factors contributing to project complexity included the hybrid production mode (on-site and off-site), the complex hyperbolic paraboloid surfaces in facade, and complicated design and construction processes across several project modules.

The average durations of the selected projects were calculated using Primavera Project Planner and is equal to 37 working days. The average total cost for a project is $108,240. The project cost has been calculated based on human resource costs and equipment hire. The resources have been distributed amongst activities to reduce costing. Resource costs have been identified in Figure 3.

Resource Name	Resource Type	Price / Unit
Machine Expertise	Labor	$60.00/h
Product Development Team Memeber	Labor	$35.00/h
Product Development Team Leader	Labor	$45.00/h
Designer	Labor	$45.00/h
Engineer	Labor	$65.00/h
Programme Technician	Labor	$60.00/h
Machine Operator	Labor	$42.00/h
Senior Management	Labor	$60.00/h
CNC Machine	Nonlabor	$110.00/h
CAD Software	Nonlabor	$50.00/h
Spindle	Nonlabor	$20.00/h
Cutters	Nonlabor	$5.00/h

Figure 3. Resource costs for manufacturing façade modules- Developed in Primavera P6

Cumulative cost for each WBS level can also be calculated. As can be seen in Figure 4, majority of project cost incurs during the program and set up stages. This is due to engagement of specialized resources in the two stages. These resources include but are not limited to engineers, designers, program technicians and machine operators. The labor intensive nature of aforementioned stages increases the total cost associated with human resources.

Layout: Resource Cost Profile — Filter: All Activities

Activity ID	Activity Name	Start	Finish	Budgeted Labor Cost
FACADE	COMPUTER NUMERICA	09-Oct-17	29-Nov-17	$108,240.00
A1010	Start Milestone	09-Oct-17		$0.00
A1000	Start	09-Oct-17	09-Oct-17	$0.00
FACADE.1	COMPUTER NUMERIC.	09-Oct-17	29-Nov-17	$108,240.00
FACADE.1.1	Planning	09-Oct-17	13-Oct-17	$12,000.00
FACADE.1.8	Design	12-Oct-17	31-Oct-17	$19,750.00
FACADE.1.3	Program	31-Oct-17	15-Nov-17	$21,950.00
FACADE.1.4	Set-Up	08-Nov-17	14-Nov-17	$21,000.00
FACADE.1.5	Manufacture	14-Nov-17	23-Nov-17	$12,120.00
FACADE.1.6	Finish/Assemble	23-Nov-17	27-Nov-17	$7,520.00
FACADE.1.7	Review	27-Nov-17	29-Nov-17	$13,900.00

Figure 4. Cost and duration analysis for different stages of façade prefabrication

6 Conclusions

Previous work has documented the effectiveness of using prefabricated façade elements in complex construction projects [34, 35]. Such studies, however, have not analyzed the use of modern production techniques such as additive manufacturing and CNC milling for prefabrication of complex façade modules.

Results of the current study show that multi-platform software such as CATIA and DELMIA are capable of increasing effective collaboration amongst product development teams and supporting design for manufacturability and assembly. Product development teams for prefabricated façade projects should be kept fairly small to reduce cost and increase efficiency. To save costs, a single Plant Operator (PltOp) should handle setups for both 3D printing and CNC milling.

In advanced manufacturing of façade elements, a large percentage of project budget is related to acquisition costs for equipment such as CNC machins and 3D printers. Despite these high costs, non-traditional manufacturers are likely to see return of investments over future development projects for the modular façade systems.

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