Fabrication-Aware Design of Concrete Façade Panels

A Computational Method For Evaluating the Fabrication of Large-Scale Molds in Complex Geometries

ABSTRACT
This paper presents a design methodology for concrete façade panels that takes into consideration constraints related to digital fabrication machinery. A computational method for the real-time evaluation of industrial mold-making techniques, such as milling and hot wire cutting, was developed. The method rapidly evaluates the feasibility, material use, and machining time of complex geometry molds for architectural façade elements. Calculation speed is achieved by mathematically approximating CAM-machining operations. As results are obtained in nearly real time, the method can be easily incorporated into the architectural design process during its initial stages, when changes to the design are more effective.

In the paper, we describe the algorithms of the computational evaluation method. We also show how it can be used to introduce fabrication considerations into the design process by using it to rationalize several types of panels. Additionally, we demonstrate how the method can be used in complex, large-scale architectural projects to save machining time and materials by evaluating and altering the paneling subdivision.
INTRODUCTION

The practice of adapting architectural design to practical, construction-related constraints is referred to as design rationalization. Reviews of contemporary rationalization practices (Fischer 2012; Pottmann et al. 2015) highlight the increasing use of these methods in architectural practice and illustrate the different methods typically used. A recent review (Austern, Capeluto, and Grobman 2018) demonstrates that the capabilities of Computer Aided Manufacturing (CAM) are an important rationalization goal and highlights the importance of developing parametric methods that address these capabilities early in the design process.

Typically, input from a fabricator is necessary in order to evaluate the fabrication implications of a design. However, this input is usually not available to the designer in the crucial early stages of the design process. This research aims to develop a method for extracting fabrication information directly from a 3D model so that it can be adapted to different fabrication goals. The method described evaluates the feasibility of creating a mold for a specific geometry as well as the resources needed to fabricate it. It was developed into a real-time analysis plug-in for the Rhino/Grasshopper (RH/GH) modeling environment. Due to the high level of abstraction used, it obtains fabrication-related information significantly quicker than traditional CAM methods that rely on machining simulations.

The background section of this paper highlights the need for such a method by discussing contemporary rationalization processes, as well as industrial mold-making techniques. The methods section details the developed computational method. The results section describes several case studies where the method was used for the rationalization of different types of geometry.

BACKGROUND

Fabrication Information in the Design Process

In a typical design process, the complex three-dimensional form designed by the architect is shaped at the concept stage, while the fabrication information is usually provided later by a specialist (Rabagliati, Huber, and Linke 2014). However, failure to acknowledge fabrication constraints within the early stages of the process can result in a need to adapt the design to the fabrication technique at a later stage. These changes lead to delays, incompatibility errors, and heightened tensions between the design and fabrication agencies (Pigram and McGee 2011).

A possible solution is to involve the fabricator at an early stage in the design process (Caneparo, Winkless, and Cerrato 2013). However, as tender processes usually introduce fabricators at a late stage, fabrication information is rarely embedded into the initial design (Scheurer 2010). Figure 2 shows how traditional design processes can be augmented by allowing the architect to introduce fabrication constraints before a fabricator is consulted. In the suggested process, the designer can use our method to evaluate the feasibility of the geometry as soon as it is designed and to optimize it towards a specific fabrication goal before the tender. Fabricators can also use the developed method for rapidly evaluating the design and to improve their fabrication strategy.

Rationalization in Contemporary Architectural Practice

At the turn of the millennium, Glymph described rationalization as the practice of introducing “rules of constructibility” into Gehry’s free-form designs (Lindsey 2001). Whitehead further developed the term, describing projects he developed at Foster + Partners as either pre- or postrationalized, depending on the timing at which geometries were translated into constructible forms (Whitehead 2005). Prerationalized approaches are
The presented research focuses on developing processes for accommodating constraints related to digital fabrication techniques. Recently, research in the field described methods for accommodating constraints related to digital fabrication techniques. Manahl et al. (2012) describe a method for translating free-form geometry into plates producible by 3-axis milling. Dritsas et al. (2013) describe a method of optimizing free-form shells so that components are optimally packed on sheets of material for 2.5D milling. Brander et al. (2016) describe methods related to designing with flexible hot blades. Louth et al. (2017) describe how complex structural geometries can be rationalized so that they can be assembled from lasercut kerf-bent sheet material. However, all of these methods are focused on a single fabrication process, and none of them enable the comparison of different digital fabrication techniques on the same geometry. An exception to this is the work of Eigensatz et al. (2010), who propose a façade-paneling algorithm capable of discerning the geometry (whether flat, single curved, or double curved) of the panels. However, this method does not differentiate between specific fabrication techniques, and instead classifies all complex double-curved panels into a single category.

Mold-Making Techniques in the Construction Industry

The presented research focuses on developing processes for rationalizing geometry towards the constraints of mold fabrication, focusing on molds for concrete. Concrete, the most common building material of our era, is exceptionally suited for producing free-form geometry due to its liquid behavior. In order to realize the full range of geometries that can be produced from concrete, complex 3D molds are required. In the construction industry, these molds are manufactured mainly from CNC-cut, bent-plywood sheets or from expanded polystyrene (EPS) milled or cut by hot-wire (Andersen et al. 2016).

Due to the large waste of materials and machining time incurred by the use of these molds, many have attempted to devise alternative fabrication techniques. Reusable, flexible molds are a promising technology reviewed extensively in Hawkins et al. (2016). Despite the many benefits of this technology, the review shows how geometric constraints, modeling issues, and uncertainty regarding its cost effectiveness still prevent the industry from adopting this technique. A different solution to the problem is the use of 3D printing in concrete to do away with the formwork completely (Khoshnevis 2004). Recent reviews of this technique (Duballet, Baverel, and Dirrenberger 2017; Wu, Wang, and Wang 2016) have indicated many factors that limit its use in the practice: material properties, lack of modeling frameworks, and a shortage of full-scale implementations. Nevertheless, the reviews indicate that the building industry is starting to adopt concrete-printing techniques, primarily for simple 2D extrusions. Large-scale additive techniques that can result in the complex geometries relevant to this study, such as those described in Hack and Lauer (2014), Lloret et al. (2015), and Laarman et al. (2014), are not yet ready for incorporation by the industry.

**METHODS**

In this section, we present a computational method for evaluating the fabrication feasibility of a geometry with different fabrication techniques. The method was developed for two common techniques in the contemporary building industry: milling and hot-wire cutting. By using mathematical abstractions, the method arrives at approximations much faster than traditional CAM simulations. This enables its use as a “fabrication viewer” in a corationalized parametric design process that rapidly assesses different fabrication scenarios.

The structure of the proposed method is illustrated in Figure 1. In the first stage of the process we accept a NURBS-geometry input (via Rhino/Grasshopper software) and optimally position it in space. The second stage consists of a dual analysis of the input geometry, once as a NURBS surface and once as a half-edge mesh. In the third stage the geometry is translated into molds according to the material and fabrication parameters, an action usually performed by a CAM operator. In stage four we introduce an innovative approach to estimating machining time by using mathematical approximations to predict the tool path length. This saves significant computational resources in comparison...
The surface is also translated into a half-edge mesh representation to provide information regarding the local conditions around the sampling points. Directed half-edge meshes were introduced by Campagna et al. (1998) to improve computation speed at the cost of memory, and were implemented for RH/GH by Piker (2017). The result is a dataset that includes the neighboring indexes, positions, influence areas, and normals for each of the sampling points.

Stage 3 - Mold Design
In a traditional design flow, the translation of the architectural form into molds is manually performed by a CAD operator at the Construction Documents stage. To be able to estimate the required fabrication resources, the suggested method includes an automated real-time mold-design module. Figure 4 shows the results of automatic mold-design operations for different fabrication techniques. For 2.5-axis sheet material cutting and assembly, we design a ‘waffle’ structure to support the mold face. For milling, the geometry is situated within blocks of EPS material, and its borders are extruded diagonally to ensure milling access. For hot-wire operations, we approximate the NURBS geometry using piecewise developable ruled surfaces, as extending the surfaces towards the material boundaries results in a model representing the hot-wire material removal operation.
Stage 4 - Approximating Feasibility and Machining Time

Stage 4 employs computationally efficient mathematical formulas to estimate the fabrication resources needed for each fabrication technique. The algorithms presented below were either developed for this research or adapted from existing research and practice. A more detailed explanation of the mathematics behind the algorithms can be found in Austern et al. (2018).

For feasibility calculations, we employ the combined data from the geometry-analysis stage as a base for our calculations. In 2.5-axis cutting, we use NURBS-curvature information to calculate whether the sheet material can bend according to the principle curvature radius and the Gaussian curvature at the analysis point. For 3-axis milling, we use the mesh representation to check z access and ensure spindle access by intersecting it with a simplified spindle model. Tool tip access is ensured by comparing the curvature radius with the available tool radius. For 5- to 7-axis milling we expand the search directions to a radial 3D array. In hot-wire cutting we first disqualify concave double-curved points and then rotate a line around the remaining sampling point until access is discovered.

After calculating the feasibility of all the sampling points, we use a different set of algorithms to estimate the machining time. In 2.5-axis cutting and assembly we unroll the ribs of the mold and nest them onto material sheets using packrat (Chatzikonstantinou 2017), a rectangle packing algorithm inspired by the extreme points concept introduced in Crainic, Perboli, and Tadei (2008), as illustrated in Figure 5. Then we approximate the path length by multiplying the total length of the geometry’s edge by the number of machining passes necessary.

In milling, we divide the path-length calculation into two parts: roughing and smoothing. In the roughing stage the tool path length is calculated by dividing the roughing areas by the tool diameter. For approximating the finishing path length, we calculate the optimal offset step at the sampling points and divide it by the vertex area. Summing the locally calculated results provides us with the shortest theoretically possible tool path without resorting to computationally expensive machining simulations. Flat, horizontal areas in 3-axis setups or parabolic areas in 5-axis setups are optimally finished using flat-end tools and are calculated using the maximal diameter as a step. Tilted or curved surfaces in 3-axis setups are finished using a ball-end tool, and the step can be calculated using a formula suggested by Han and Yang (1999). Double-curved surfaces in 5-plus-axis setups can be finished using tilted flat-end milling, which is more effective at surface finishing than ball-end milling (Jensen 1993). The formulas for approximating the offset step in these cases were developed by the authors and are presented in Austern et al. (2018), and are graphically illustrated in Figure 6.
After calculating the path length, we multiply it by a feed rate derived from a commercial "feeds and speeds" calculator developed by www.CNCcookbook.com. This calculator provides a reliable, industry-accepted standard based on material type, cut depth and width, and tool diameter. Ultimately, we arrive at an approximation of the milling time in a fraction of the time it takes CAM software to simulate the entire milling process.

For approximating the hot-wire path length, we use a rapid piecewise developable approximation of the original geometry, which is based on Elber and Fish (1997) and implemented in IRIT. The resulting surfaces are translated back into the RH/GH environment and extended towards the material boundaries, and their length multiplied by the hot-wire speed.

**RESULT CALIBRATION AND CASE STUDIES**

To calibrate our predictions, we tested them against a series of physical prototypes. So far, we have seen a good correlation, with almost no errors in the feasibility approximation and the material use, and a maximum of 10% deviation in the machining time prediction. However, we have observed that our results are very sensitive to the design tolerance and the feed-rate settings, which are highly individual and can cause significant changes in the machining time. Considering the extremely short evaluation time needed, our method functions as a good indicator of machining time. In the future, we plan to calibrate our method by comparing its predictions to commercial mold-fabrication companies, which use different hardware and software.

To test its functionality in a design process, we used our method to manually rationalize complex façade tiles designed to improve the thermal properties of the façade surface (Grobman and Elimelech 2016; Hershcovich et al. 2017). As shown in Figure 8, we used our method to analyze the original design, indicating areas that could not be fabricated using a 3-axis CNC mill with a round finishing tool. We then manually smoothed the areas where our method indicated that the minimal available tool could not penetrate.

The result was a geometry that could be directly transferred to the CNC operator and milled in one pass with a round 8 mm tool. By allowing a large tool to access all of the
geometry, the machining time was decreased by more than 50%. The resulting scallops shown on the right of Figure 8 were well within our design tolerance, demonstrating our increased control of the final design. The “fabrication viewer” we created operates as an expert system, continuously providing information traditionally obtained from fabricators.

In another case study, we tested the capabilities of our method on an architecturally scaled geometry: a 3D representation of ZHA’s Heydar Aliyev center, roughly modeled by us according to elevations available on the Internet. Figure 9 shows how the geometry was paneled into a grid analyzed using our method. The analysis, obtained in under a minute, clearly identified hot-wire cutting as the most effective fabrication technique for this geometry. All the molds were feasible using this technique, and the fabrication time was smaller by a significant factor for the same design tolerance. This result is supported by recent practical experience in hot-wire cutting (Sondergaard and Fenniga 2017).

Molds from plywood sheet material cut using a 2.5-axis setup were also indicated as an efficient fabrication method in terms of machining time, as demonstrated by large scale projects such as the ROLEX EPFL center (Scheurer 2010). However, our method indicated that in this case many of these types of molds were not feasible due to excessive double curvature or small bending radii (shown in red).

Another possible use for our method is to improve the fabrication efficiency of a paneling subdivision. To estimate the potential for improvement, we compared forty different paneling layouts for the same geometry while changing the amount of subdivisions. The lowest and highest analysis results varied by 26% in machining time and 63% in material use when averaged over all the techniques. The large variation indicates that using our method has a potential for producing significant savings in fabrication resources, solely based on changing the paneling grid size.

Later we chose a subdivision that performed well in the previous test and used attractors to introduce random variations to the paneling grid, then measured their influence on the fabrication parameters. Now the machining time varied by 21% and the material use varied by 13%. We attribute this to the fact that the panel size has a greater effect on the overall depth of the mold and hence on its material use.

The case study highlighted the usefulness of our method as a comparative tool between design options. In the future, it can be coupled with optimization algorithms that automatically adapt form to fabrication technique.

CONCLUSIONS
In this paper, we described a computational method that introduces fabrication evaluation to the architectural
design process. Contrary to the lengthy process of mold design and CAM simulation currently practiced in the industry, our method evaluates geometries in near real time within a typical architectural modeling environment. It provides both numerical and graphic results, assessing the required resources and indicating problematic areas in the design. Thus architects can interactively alter their design to better adapt it to its mode of fabrication.

We explored the design process made possible by this method using case studies at different scales. In single façade elements, we saw how a design can be easily adjusted to fit a specific setup, avoiding fabrication errors and minimizing machining time. In the case of façade paneling, we showed how the method can be used to determine the best-suited fabrication technique and to determine the most efficient paneling in terms of machining time and material use.

The introduction of CAM techniques into the building industry has required architects to obtain knowledge and intuition, which are often not available outside of the factory floor. In this paper we have described a design process that can help architects introduce fabrication logic into their designs by using computational means. It can serve to improve the overall quality of the architectural design and save expensive and unnecessary design iterations at a late stage.

REFERENCES


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**IMAGE CREDITS**

All drawings and images by the authors.

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