Knowledge-based methodology for architectural robotics fabrication

REAL-TIME IMPACT ASSESSMENT THROUGH A PROCESS FLOW ANALYSIS SOFTWARE

VASCO PORTUGAL
MIT PP / IST - Sustainable Energy Systems, USA # vascopt@mit.edu

ABSTRACT:
The main goal of the project is to generate a framework for a knowledge-based-methodology (KBM) within a parametric software. This is accomplished through a combination of the design software and robot simulation with real-time assessment based on a process-flow-diagram (PFD) structure that compiles the main environmental parameters of the manufacture process. The intention is to create a methodology to directly report the impact of the manufacture of a specific design, from the materials embodied energy to the energy consumption of each step. This framework provides valuable information which may monitor the developer towards alterations to increase the CAD/CAM performance. In the context of this paper, this methodology was applied in the conceptual design and manufacture of a housing structural insulated panel prototype using parametric design software and robotic equipment. The purpose is to generate a quasi-automated design process linked with real-time analysis and assessment of the fabrication process, offering real time environmental and cost analysis of a panelized structure house manufacture logic. The suggested methodology outputs information to compare and optimize the manufacture outline, and supports the screening and assortment of appropriate tool paths or combination of fabrication tools based on environmental/cost data, user-specified requirements and context characteristics.

KEYWORDS:
CAD/CAM; Parametric design; Robotics in Architecture; Process flow diagrams;
1. Introduction

The built environment is increasingly dependent on computational principles at the root of its development process. A progressive proliferation of techniques for digital models composition came to encourage the establishment of similarly innovative manufacturing processes and protocols involving robotics and industrial manufacture equipment. Two fields converging into a new methodology for the conception of habitable spaces. A fresh approach centered on the underlying mathematical logic and consequent metrics that allow to generate and optimize objective information, not only on the creation of the physical spaces but also to respond to the needs of prospective users. A logic that allows the conception of housing solutions based on contextual information, establishment of pre-set rules and constraints or optimization search. These are important steps, which will launch a radical improvement in the performance and impact of the built environment. But it is not just computation that can contribute into a new way of making architecture. The introduction of robotics in architecture can likewise play a vital role to mitigate the environmental impacts of building production, as it provides means to drastically improve the manufacturing and construction processes, consequently allowing the implementation of a more sustainable and informed design method, empowering local and resilient manufacturing protocols. It offers good prospects towards a system of house construction able to respond positively against the negative effects of exceeding waste of energy and materials.

With the introduction of rapid prototype engineering techniques in the built environment context, many researchers are leaning towards advancing these types of methodologies to undertake full-size scale construction projects. In order to achieve this, new interfaces between design, manufacture and assembly have been explored in the recent years with recent advancement in the development of software solutions for robotic simulation (Braumann, 2010), optimization (Mardaljevic, et al., 2006) (Caldas & Norford, 2002), collaboration and manufacturing of various scales (Llach, 2007) (Botha, 2006). Although there are many process-specific technologies capable of adequately fabricate full-scale habitable spaces, and we still lack a cohesive interface able to integrate all the fabrication equipment, context data, design, simulation and materials. Especially because there is a number of new manufacture possibilities, and this number is growing daily. So, now is essential to distinguish what are the best combinations of machines and processes to complete specific tasks and measure the impact of external manufacture services against a local and closed fabrication circles. So it becomes easier to compare, evaluate and optimize the sustainability of a building construction scheme.

1.1 Fabrication Laboratory’s and the Industry

The manufacturing industry as we know today is built on sequences of fast processes enabling mass production at lower costs, two advantages that are difficult to overcome by a bottom-up fabrication approach. However, in recent years there have been several research groups exploring the developing of an analogous premise by introducing a CAD / CAM logic and local fabrication spaces that potentially may enable the execution of a customized high quality fabrication. If indeed fabrication laboratories have advantages by presenting a more flexible and bottom-up approach, the accomplishment of a new method for the fabrication of habitable spaces is still dependent on a certain degree of market competitiveness, either in cost, quality or environmental impact. And it is precisely here that it is crucial to develop a methodology able to simplify the evaluation of the impacts that processes and materials have. “It’s a lesson that has been repeatedly learned over the last decade in the development of new clean-energy technologies. Innovators may create smart designs for technologies such as solar panels, but ignoring the costs and practical details of manufacturing the new products is a sure path to failure.” (Rotman, 2013)

2. Method

To test the proposed KBM a mock-up of the methodology was developed within a Rhinoceros plugin called Grasshopper (GRS), a graphical algorithm plug-in for Rhino developed by David Rutten at Robert
McNeel & Associates (McNeel, 2010). This streamlines the implementation of the KBM in the same work environment used to design the digital model of the house to fabricate. GRS allows the design of a parametric model inside a fully programmable context. It provides an intuitive parametric framework enabling the necessary cohesive interface to test the proposed methodology. This is accomplished by a customization of its components using C# programming language and by linking outputs from components with inputs of subsequent components. Impacts associated with raw material extraction and productions were gathered from existing databases in the LCA software SimaPro (Matters, 1990) while data for the panel production was gathered from industry sources. The cost analysis of producing each unit was conducted using values from RS Means - Online Assembly and Construction Cost Data (RSMeans, 2010) and manufacturers.

2.1 Case-study manufacturing logic

For the purpose of this paper a case-study fabrication logic was needed to implement the KBM. It was selected a manufacturing protocol that is being investigated under the supervision of Professor Mark Goulthorpe at MIT Architectural Robotics Laboratory (ARL). The geometric form of the building to manufacture is irrelevant and therefore it was decided to assess a simple structural insulated panel. It was also preferred to ignore the creation of windows and doors as it would only be a repetition of the same manufacturing logic. The fabrication logic takes into consideration the existing equipment in the ARL:

1. A KR Kuka 100 HA with extended arm on a 50ft track, a high accuracy robotic arm extremely versatile easily integrated for any application, from cutting to material handling and processing of large work pieces.

2. Two vacuum tables 50ft length and 5ft wide, which allow fastening the material pieces while the milling cuts are carried out by the Kuka.

This is an initiative that uses a panelized sandwich structure, featuring Twintex skins and a foam core. The MIT Twintex panel system consists of composite panels with two layers of Twintex composite skin sandwiching an insulating core. To form the overall structure, panels are connected together using biscuit joints made of pultruded composite embedded in the insulating core immediately behind the Twintex skin. Panels joined by these pultruded biscuits form the interior and exterior walls, roof, and floors of the building. The panels are prefabricated off–site and arrive ready to assemble. Because of the panel weights and the design of the connectors, the panels are intended to be placed in their final location and manually snapped together using no tools and with a crew of two people. This study assumed that the construction is sufficient as stated above. In order to simplify the implementation of the proposed KBM this study will restrict itself to a single insulated panel that comprises 3 main components that must be manufactured:

1. A polystyrene core material that provides insulation and a substrate to the structural skins, digitally milled to accommodate edge pultrusions;

2. Thermoplastic or thermoset pultruded edge profiles to protect the core and provide structural rigidity to the panels and accurate jointing to permit easy screwed connection;

3. A skin layer made from Twintex commingled polypropylene (PP) and continuous glass fibers. laminated via ASC’s patented process onto the core/pultrusion assembly to give a highly durable, resilient, low-maintenance structural panels;
To obtain this structural panel a structure of operations has been set: 1) Fix the polystyrene plate in the vacuum table so it would not move during the following operations and identify the point xyz (0,0,0) so the robot can recognize the panel in space; 2) carry out the milling of the polystyrene panel by milling with the Kuka in accordance with pre-defined instructions of the software; 3 and 4) Place the edge thermoset pultruded profiles in the pockets milled with the Kuka, these profiles will permit not only to snap the panels together but also serve as structural elements for the house prototype once assembled; 5) Addition of the Twintex skins, consolidated by isothermal compression molding, by heating at 180 °C and applying pressure, before cooling step under pressure; 6) A new milling operation to remove surplus material and create the necessary angle to fit In the following panel.

The result is accurately finished panels that can be jointed only using hand tools and simple mechanical connections, effectively streamlining current building industry practice by huge reduction of labor on the building site via ease of assembly.

2.2 Knowledge-based-method

Once identified the equipment available and the subsequent manufacturing logic, it was necessary to develop the PFD (Figure 2) of the case-study protocol, this allowed the identification of the necessary components that need to be made in GRS to replicate that same PFD digitally and within the design software to extract the impact data from each fabrication operation. The PFD is a diagram scheme that indicates all the general flows regarding the machines and related fabrication operations. This scheme was used to tabulate the process design values for material, mass, waste, energy and cost of each operating mode, sustaining as the structural logic for the intended KBM. The KBM is then accomplished...
by the creation of GRS components that replicate the PFD procedures. CAD plays a significant role in the execution of the KBM, since it allows retrieving highly detailed information from the digital model. There are two options to introduce the digital model of the panel in GRS, it could be either modeled in Rhino and then imported as a BREP, or modeled with GRS which would allow the user to take advantage of the plug-in parametrical features and established interdependencies between the shape and features of the panel to subsequently define the impact of the resultant variations using the proposed KBM. In order to replicate the PFD it was necessary to create two main GRS components: the machine component and the operation component. Both of them are intended to be flexible enough to calculate different machines and operations, but for the purpose of this study it was essentially focused on the previously mentioned fabrication protocol and in the equipment available at the MIT ARL.

2.2.1 Machine

It was created a component to estimate the KUKA specific energy consumption, this value can be directly measured from the power plug with an energy meter, however it would not allow making an immediate assessment or benefiting from the parametric features of the software. There are several equations to calculate specific consumptions for milling fabrication in the manufacturing sciences literature (Draganescu, et al., 2003) (Diaz, et al., 2012). Models that establish dependencies between the parameters of the machine like spindle speed, torque at the spindle, material hardness, distance from the base to the mill, weight, for the proposed KBM a simpler equation was preferred ignoring all the dependencies that were nearly insignificant on the overall efficiency of the panel manufacture and its total costs.

The machine component has a list of values assigned to the model and operation speeds, the inputs on tool and material have a given percentage in which the based values must increase according to the resistance of the material and diameter of the mill. The outputs are the specific energy consumption for the explicit operation and time as an efficiency parameter and input to cost assessment. The toolpath was generated with the GRS component for industrial robotics programing HAL created by Thibault Schwartz.

2.2.2 Operations

For the operation component it was accounted the embodied energy of each material, data that for the purpose of this test was imported from the external software SimaPro database, assuming that in the future the proposed methodology will have a library of materials with these figures. The original volume of the polystyrene plate is modeled in Rhino and then imported into the GRS canvas as a BREP.
This object will provide the initial volume before any operation and allows the calculation of the waste from the initial plate to the final design. For each new material the volume is acquired from the model itself, directly linked to the component, this way it is possible to track the volume changes in the panel from between operations and determine the energy per volume of material. The operation component was created in the GRS canvas to gather all the set parameters, simulate the operation and get the results. Any component in GRP needs input data to process data back. These inputs are the parameters \( (m_1, m_2, m_3, E_A, E_1) \), and will provide the necessary data to resolve the equations (1), (2), (3), (4), and obtain the results for specific consumption per operation \( (SC_A) \) and for each material \( (SC_1) \) residue formation factor \( (RF_1) \) and mass proportion \( (MP_1) \). To perform the energy analysis of the KBM the following equations were integrated to attain outputs for specific consumption for each operation \( (CE_A) \) eq.1 and for each Material \( (CE_1) \) eq.2

\[
CE_A = \frac{\text{Energy Consumption of Operation}}{\text{Production of Operation}} = \frac{S_A}{m_3} \text{ kJ/kg} \quad \text{(eq.1)}
\]

\[
CE_1 = \frac{\text{Energy consumption in previous operations}}{\text{Mass of 1}} = \frac{E_A}{m_3} \text{ kJ/kg} \quad \text{(eq.2)}
\]

Residue formation Factor \( (S_A) \):

\[
S_A = \frac{\text{Materials input of operation A}}{\text{Production of A}} = \frac{m_1 + m_2}{m_3} \quad (S_A \geq 1) \quad \text{(eq.3)}
\]

Mass proportion \( (f_1) \):

\[
f_1 = \frac{\text{Materials input of operation A}}{\text{Total materials input of A}} = \frac{m_1}{m_1 + m_2} \quad (f_1 < 1 e \sum f_i - 1) \quad \text{(eq.4)}
\]

3. Conclusions

The development of a new protocol for the fabrication of houses through the use of robotics and digital principles is a complex exercise but it opens up a number of new possibilities. One such possibility is the ability to extract indirect information that allows us to estimate and optimize local CAD-CAM fabrications. This methodology was developed with the purpose of associating concrete values to the decisions made during the development phase of the project prior to construction and production. This methodology seeks to provide a significant contribution through aspects that are usually considered only after the creation of a finalized digital model or even during manufacturing. This study allowed the understanding that the consumptions and performance of certain machines depend also on the desired target and how they are used. In the explicit case of the robotic arm (KUKA 100 HA) studied in this paper, it has a wide range of possible applications from moving objects, cutting, bending or
milling materials. This flexibility of latent processes highlights the applicability of a more informed development methodology, able to respond with explicit information in a digital environment, during the planning process and before manufacture.

This allows the achievement of a desired approximation to the existing industry model, but with a customized approach and with greater flexibility, able to achieve the performance of a manufacturing unit and the values of an economy of scale. One aspect often neglected in the discussion of strategies for integration in the CAM architecture, but with a considerable weight on the market acceptance and consequent revitalization of the manufacturing process. These are fundamental characteristics to move from laboratory trials to a more sustainable and competitive approach than the existing. By integrating a Knowledge Based Methodology, established with a PFD logic within the design environment in which the project is engendered. This allowed the execution of a fairly reliable forecast of performance, indicating the various factors affecting the arrangement of different manufacturing processes for a particular purpose.

ENDNOTES

1. The study aims to help CAD/CAM to get closer to the existing industry model, while maintaining its best qualities; a local and customized approach with great flexibility.
2. This methodology allows the creation of a fairly reliable forecast of performance, indicating the various factors affecting the manufacturing outline.
3. Understanding the factors of waste is important not only for the optimization of each operation but also for future integration of recycling operations.
4. The integration of a cost analysis in the KBM, regardless of excessively depending on external sources, permits performing an interesting correlation between costs, processes and the energy consumed.
5. This experiment is one step of a more complex methodology; this was a necessary test that allowed piloting a number of principles to enable the creation of improved CAD/CAM software.

ACKNOWLEDGMENTS

The first person I have to thank is Professor Mark Goulthorpe for his advice, support and encouragement. I also benefited from the work of the Stanford Students that collaborated with the project for a life cycle analysis. Rob Best, Linda Brown, Claire Matthews, David Weiskopf, E.A. Jampole, I.C. Murillo, K.A. Oura, P.J. Sullivan,, M.C. Wachter, and S.L. Wert. The research relevant to this paper was supported by MIT PP and FCT-PhD grant SFRH / BD / 62481 / 2009.

REFERENCES