Component Based Design and Digital Manufacturing

A DfM Model for Curved Surfaces Fabrication using Three Axis CNC Router

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Through the use of design for manufacturing (DfM) method and looking at the relations between its potential application in architectural production and its implementation using digital manufacturing technologies, we analyze building construction processes and explore, in more detail curved surface fabrication using two dimensional cutting and three dimensional milling processes. Afterwards a DfM model for curved surfaces fabrication using three-axis computer numerical control (CNC) router is proposed. The proposed DfM model relies fundamentally in two supporting factors; the implementation of design heuristics that integrates production knowledge and the availability of some design related to production evaluation metrics. Subsequently, we test and refine the model using structured design experiences. This was accomplished by capturing new design heuristics and detecting useful evaluation metrics for production. In the final part of the research, a refined DfM model was tested in a component design case study. The case study is based on producing a curved surface module on wood for an existing proprietary component based wall system. As a summary, we conceptualize from this top-down development approach to create a design for manufacturing model that integrates design and construction in architecture, based on three possible applications fields: Design processes improvement, building production process improvement, CAD-CAM tools development.
Our purpose is to provide better foundational constructs and approaches for integrating design with manufacturing in architecture.

Keywords: *Design for Manufacturing; Design Cognition; Digital Fabrication;*

Introduction

Advances in computation, both regarding it treatment and technology, have stimulated the design and implementation of an ever-growing base of Computer Aided Design (CAD) and Computer Aided Manufacturing (CAM) software. Software elaboration both responds to and generates new conceptualizations of architectural knowledge.

CAD systems' expanded form generation repertories and enhanced object manipulation capabilities are providing designers with easier access to more complex geometries. Many forms and shapes produced out of those complex geometries are not related to traditional construction methods. Curved surfaces are indeed a specific case within this problem and the subject of this research. Even though curved surfaces were part of the architectural vocabulary, it use was limited by the lack of adequate representations to manipulate its geometry. Lately and because of the widespread use of CAD systems, a notable increase in the use of curved surfaces in architecture has been noticed. Constructive techniques to build them are neither stable nor determined and usually involve the use of advanced CNC manufacturing technologies.

In addition, bridging from a CAD system to a CAM system is mostly performed at the shape description level based on neutral file or on a proprietary exchange format. At the object level CAM systems relies mostly on feature recognition algorithms to obtain manufacturing knowledge from design stages, although feature extraction algorithms have been improved they are still inaccurate and incomplete.

Furthermore, the use of Computer Numerical Control (CNC) manufacturing technologies in architecture is already giving us a sense of how architectural production may change in the future. In some way, digital manufacturing technology is a definite shift away from Site based contractor-led models, and as such the organization of building production will no longer be limited to traditional forms of construction (Groák, 1992)[1]. Consequently, digital manufacturing represents a substantial change from conventional methods of mass production where repetition was the basis of economy. In using CAM systems, variation and customization no longer require an increase in costs due to specialize labor or exceptional manufacturing techniques (Schodek et al., 2004; Kolaveric, 2003)[2].

Design for Manufacturing (DfM)

DfM is a well structured area of research in product development. The objective of DfM is to develop information that can be applied to product designs to improve their manufacturability. DfM has led to important improvements in manufacturing effectiveness, resulting in products that are cheaper to produce, of higher quality, that are easier to service, maintain and replace (Boothroyd et al., 2002).

Subsequently in applying the DfM method it is important to consider that designers are required to structure appropriately design information, to integrate production knowledge in design, to select adequate materials, processes and components, and to evaluate alternative design solutions (Boothroyd et al., 2002). Normally, literature in DfM tends to address integration focusing on a single issue in isolation and ignores interactions between them.

The DfM model was originally applied in product development and its application relies fundamentally in two supporting factors; the implementation of design heuristics that integrates production knowledge and the availability of some design related to production evaluation metrics (Boothroyd et al., 2002; Fox et al., 2001). In this way, design changes can be made before they become time consuming and extremely costly.

The benefits in applying the DfM method are coming from shortening design and production cycle, improving component quality, and reducing manufacturing cost (Fox et al., 2001; Susman, 1992, Dertouzos, 1989; Boothroyd et al., 2002)[3].

DfM in Construction

By contrast, in the construction industry, building designers have not been provided with equivalent methodologies, and the integration of production knowledge into design stages continues to rely on the experience of individuals in an increasingly fragmented work environment[4]. Accordingly, Stephen Fox states “Architects are held responsible for the deficiency of this unsystematic approach. Architects’ ‘typical lapses’ include: specifying inappropriate materials, lack of knowledge of basic construction techniques, and not understanding buildability” (Fox et al., 2001)[5].

In order to examine DfM applicability in architectural production, we perform a close examination of the method looking for its similarities and differences in relation to building production. Out of this review, we strongly support a change from a construction model that has been traditionally based in on-site raw material shaping, assembly, and sub-assembly processes to a one structured by the component-assembly model (Groák, 1992; Fox, 2002)[6]. This model is based in on-site assembly of components manufactured off-site (Gibb, 1999). The assembly component model constitutes a basic knowledge organization structure to facilitate the development of a DfM model in architectural production incorporating CNC manufacturing technologies to traditional constructive systems repertoires.

The DfM model proposed in this research is based in two basic design strategies; the implementation of design heuristics that integrate production knowledge and the availability of some design related to production evaluation metrics.

Extracting Design Heuristics and Metrics from Structured Design Experiences

In this research, the adjective "heuristic" (or the designation "design heuristics") is used to represent a process that it is there to understand or to find out about some other process, with which it is not identical (Groner et al., 1983b; Groner et al., 1983a). Therefore, it is a model, which as it is never identical with whatever it models, is a heuristic device to understand the latter. Subsequently the model is not to be pursued or to present as an algorithmic approach, but rather, that it shows how different stages in a DfM method would have to be connected, how one design decision would lead to another, and what kinds of aspects of the problem are relevant in pursuing its solution.

Design Heuristics

Design heuristics provide a framework for solving the design problem in contrast with a fixed set of rules (algorithmic) that cannot vary. In this way designer uses a set of steps, empirical in nature, yet not proven to be always valid, to advance in solving a design task and to successfully find alternative solutions.

A typical design heuristics in DfM is "to develop a modular design" this is especially relevant since if a design module is equivalent to a manufacturing module, it means that it can be produced as one manufacturing unit, which is exactly the kind of integration that this research is proposing.

Another more trivial but no less relevant heuristics is "reduce the part count and part types" and can be translated into architectural production as "reduce component number and component types", others like "keep wall thickness as uniform as possible in castings" can be adapted in similar way to building production.

Design metrics

In order to assist the designer to develop components which can be manufactured, a design heuristics must be complemented with design metrics. These metrics would objectively, and quantifiably, contribute to measure component manufacturability, providing designers with immediate feedback as design progresses. A good example of efficient and effective metrics in a different domain, which proved successful, are those postulated and validated by Boothroyd and Dewhurst regarding the assembly of products (Boothroyd et al., 2002). Their success lies in the simplicity of the usage of the metrics (e.g., everybody can count the number of parts in an assembly) connected to the fact that their metrics are valid and indeed provide a good measure for the assemblability of a product.

Knowledge Based Design

At this point, once a knowledge based design approach and the constituent parts of the model i.e. design heuristics and design metrics has been exposed, it is necessary to describe how this research will obtain that knowledge. Therefore it is necessary to introduce some formal, consistent method of capturing design heuristics and design metrics that constitute the fundaments of the DfM model. Therefore, if building production knowledge is mainly coming from literature and from design expertise, is far from satisfactory. Literature in the field tends to be too technical either being information referring to a conventional construction system or to a specific manufacturing process. Another drawback is that construction knowledge is presented in the form of tables and manuals, or oriented towards construction management and not very useful for production. (Groák, 1992)[7].

Finally capturing knowledge from experts, a task normally performed by a knowledge engineer, has important disadvantages. Mainly because the knowledge engineering expertise it is not well structured and because the whole process is highly time consuming (Potter et al., 2003). In addition, experts tends to structure knowledge based on conceptual schemas that refers to how the task ought to be performed i.e. prescription rather than how it is performed i.e. description. (Potter et al., 2003; Ho, 2001; Ball et al., 1996). Subsequently a different source of design heuristics would be of immense benefit to the development of DfM model.

As characterized above, heuristics are derived from experience; so, rather than interviewing experts for their heuristics, an alternative method used in this research is to inquire directly using structured design "experiences" for capturing manufacturing knowledge (Potter et al., 2003)[8]. In the context of this research, design experiences including a design problem specification and the corresponding design solution contain the information necessary for deriving heuristic knowledge (Potter et al., 2003)

Research methodology

As initial stage this study uses a general research approach, in which a pre-understanding and understanding of research issues are developed through cycles (Odman, 1997). The approach assumes that the researcher, as result of research and professional experience is able to see or understand the phenomenon and its problematics (Odman, 1997; Leonard, 1994) This pre-existing knowledge is defined as pre-understanding and was obtained from knowledge and experience in the field gained through literature reviews, teaching and work experience. Based on that pre understanding this research attempt was to propose an initial stage including a tentative DfM model and to test its applicability and efficiency through teaching experiences[9].

Second stage in denominated as understanding and consists in re-structuring the DfM model according to conclusions obtained from teaching experiences in the first stage. In the third stage, once restructured, the DfM model was tested and refined using structured design experiences[10]. In the context of this research, a structured design experience includes a design model as a methodological framework, a design problem specification and the corresponding design solution. The first purpose in performing this structured design experiences is to test effectiveness and efficiency in the proposed DfM model. Effectiveness not only in obtaining the desired results i.e. a design that is easy to manufacture but also in relation to how comprehensive is the model with respect to the actual design experience. Efficiency in relation to how relevant are issues and metrics in the proposed DfM model. The second objective is to refine the DfM model by deriving knowledge from the design experiences to improve it. This was accomplished by capturing new design heuristics and detecting useful evaluation design metrics. Both were determined based on the design history and its rationale. In fact, this is the type of analysis commonly found in DfM literature (Boothroyd et al., 2002; Pasquire and Connolly, 2003; Fox et al., 2001)

In the final part of the research, a refined DfM model was test in a component design case study[11]. The component was conceived as a wood curved module for a wall system, fabricated using three axis CNC router.

Initial stage (pre-understanding)

The process of capturing heuristic knowledge and design metrics was initially performed by the author as part of his doctoral research and presented at eCAADe 2005, Lisbon, Portugal. That first study and in specific the DfM model obtained from it, was tested as part of the teaching experience in the course “The design of digital manufacturing”, directed by professor Monica Ponce de Leon and co-taught by the author. Within that course, one guided case study in Figure 1 and three exploratory experiences were conducted. Even though in the guided case study was possible to structure a DfM approach, this was not the situation in the three exploratory experiences in where a clear cut division in between design and manufacturing was presented within the teaching approach. Nevertheless those exploratory studies were very useful in uncovering manufacturing errors coming from poor design decisions and that information became also relevant for gather information on DfM model development and implementation, see Figure 2, Figure 3 and Figure 4. Different research techniques were used in collecting data from both case studies, which included:

a. semi-structured interviews;
b. direct observations; and
c. content analysis.

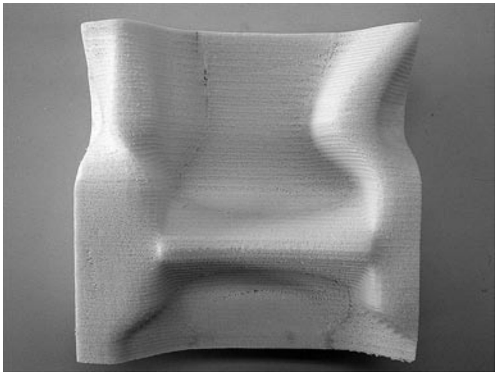

Figure 1
Foam prototype using 3-axis cnc router by Huzefa Rangwala.

Figure 2
Acrylic structure by Tristan al Haddad et al.

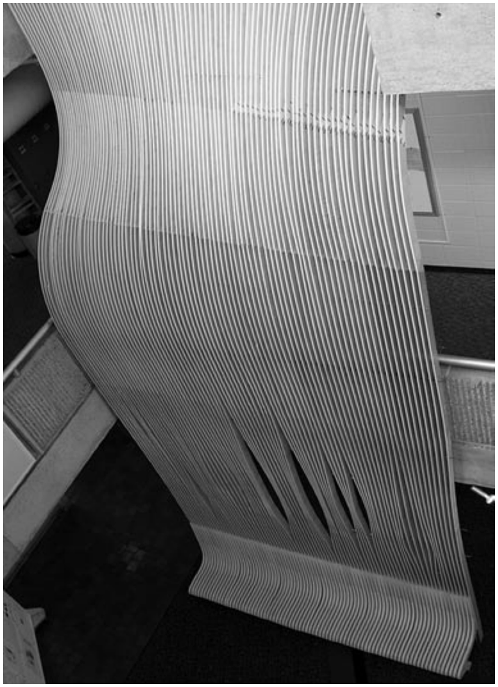

Figure 3
Wood structure by Paul Heret et. al.

Figure 4
Aluminum canopy by Kelly Henry et. al.

Second stage structuring a DfM model (understanding)

To address some of the initial research questions, a refined DfM model for 2D cutting and bending processes was proposed and developed to some extension. The DfM model development and implementation framework was based on general design task definition, divided in four modules or shells; form generation, analysis, optimization and manufacturing. Within each module or shell, alternative requirement structures were provided. Basically the model was structured as follows:

1. A form generation shell containing alternative paths to generate curved surfaces using NURBS technologies
2. An analysis shell allowing designer to perform both surface curvature and parametric data analysis for a given curved surface.
3. An optimization shell is provided after material selection is performed, optimization is performed by choosing between alternatives aspects to optimize according to the selected material and the process that the model relates to. The optimization shell allows designer to evaluate manufacturability of a given component, just checking if the influential factors are within the limits.
4. A manufacturing shell containing relevant actions to transform design information into manufacturing data, including relevant aspects to consider during this transformation process.

Third stage re-structuring and testing the DfM model (pre-understanding)

Based on the previous stage results, and the application of them in structured design experiences, as integral part of the class Design for Manufacturing: Curved Surfaces Fabrication using CNC technology, taught by the author at College of Architecture, Georgia Institute of Technology, the research looks closely at compositional processes in design and parallel processes in manufacturing including material removal, addition and redistribution processes.

The emphasis is given in curved surfaces fabrication using CNC technology, with a special focus on the following technologies: 2D cutting using laser cutter, 3D printing using Rapid Prototyping technology and 3D milling using 3-axis router.

The class was structured over three structured design experiences, each one focused in using one manufacturing process see Figure 5, Figure 6 and Figure 7 and one case study consisting in a component based design using an alternative combination of two manufacturing process, 2D cutting and 3D surfacing using a 3 axis CNC router.

Structured design experiences

Each design experience was presented as a one page assignment including task description, and a set of instructions, both as written as well as graphics, describing the task sequence and some design related

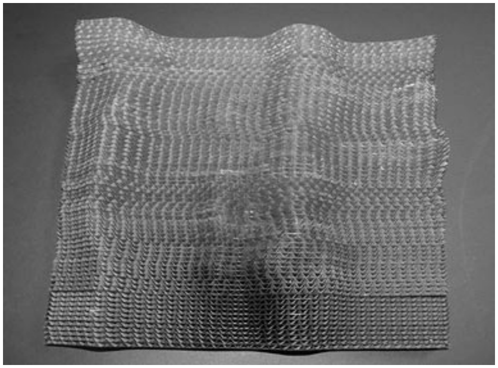

Figure 5
Laser cut corrugated board by Lei Gao

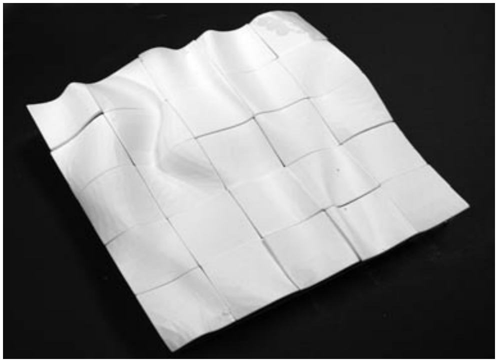

Figure 6
Laser cut acrylic frame and 3D print modules by Joe Lamb

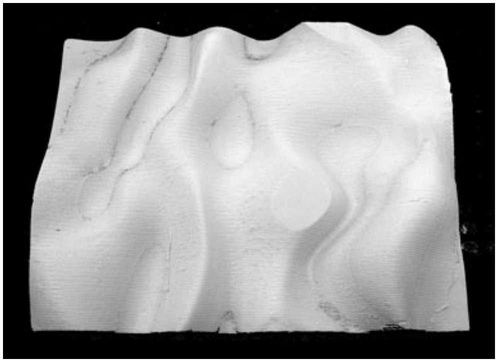

Figure 7
3D mill foam by Joe lamb

to production metrics. As part of the exercise students were asked to answer and set of questions and to keep track of the design process stages, in order to present it with the manufactured component in the final review. Additionally each exercise was introduced using a 3D file containing the complete sequence from design to manufacturing separated in layers within the file.

The main purpose in the design experiences was first to expose students with design heuristics and second to make them identify the attributes and features that present manufacturing restrictions for a specific component design using a specific manufacturing technology.

Case study

In the final part of the research students were asked to manufacture a curved surface module made out wood panel for an existing wall system, see Figure 8, Figure 9 and Figure 10. This wall system is called Graph and produced by Fry Reglet, a local architectural component manufacturing firm. The component was manufactured without any instructions or supervision from the researcher. Nevertheless the NC code was checked by an independent programmer, in order to avoid machining damage. All changes and errors were reported as fundamental part of the study.

Conclusions

Even though design heuristics and issues to consider allow design decisions based on a clear rationale. They not guarantee the quality of the design solution. Design heuristics need to be tested in order to assure its effectiveness, so they need a continuous process of improvement. However, it is possible to use metrics to

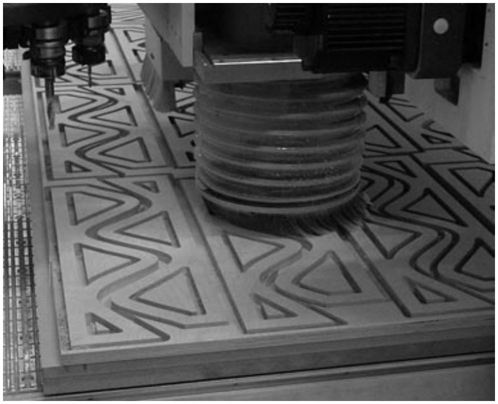

figure 8
2D cut wood module by Joe Lamb

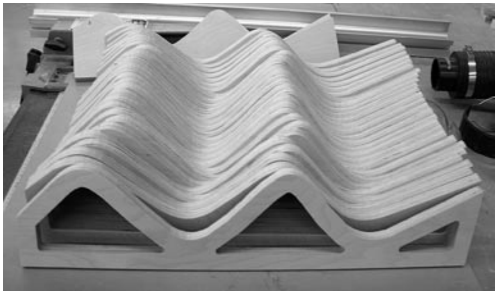

Figure 9
Wood slices assembly by Joe Lamb

Figure 10
3D mill wood module by Joe Lamb

compare the effects of different heuristics and transformation rules on the DfM model. The measured values can be used to recognize improvements resulting from changes on the DfM model.

A methodological limitation of the study was that the design task captured and later represented in the DfM model are only a part of a long-standing design process; transition from the first design idea to the production may take several weeks, whereas this study is focused only short term design tasks. However, the design task definition used in the study corresponds to important aspects of meaningful, real -world design tasks.

The results of this research are highly valuable for a better understanding of design thinking and design actions, and for further development of design theory through a theory of making. However, there is a lack of studies in the architectural domain comprehending both design and production.

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Notes

1 Groák discusses extensively the issue of production knowledge in building production in chapter eleven; technology transfer and in specific about literature in page 167. In addition, he expands about of different forms of building knowledge in pages 169-170.

2 In Schodek et al., 2004, page 16 and expanded in Chapter 18. Also in Kolaveric, 2003, chapter 3, pages 43-54

3 Theses authors reported product cost reduction in using DfM methods ranging from 50% to 70%. There is no equivalent data in building production, but the potential benefits of applying DfM to building has been recognized for some time, see Anumba, C. J. and Evbuomwan, N. F. O. (1997) Construction Management and Economics, 15, 271-281.

4 Evbuomwan analyzes the disadvantages of current construction practices and states that mainly they are: fragmentation of the different participants in the construction project; the fragmentation of design and construction data; the occurrence of costly design changes and unnecessary liability claims; the lack of true life-cycle analysis of the project; the lack of communication of design rationale and design intent.

5 In this specific issue Fox references to: Harding, C. Down with designers in Building, 25 June, 1999.

6 The assembly component model is termed by Fox as the "producer led model". Similarly, other authors like Groák who uses the term "manufacturer led model". All of them refer to off site production of parts and components in factories and shops, according to design specifications, and on-site based assembly processes. Fox analyzes in depth what Steven Groák defines in Groák, S. (1992) The idea of building: thought and action in the design and production of buildings, E & FN Spon, London; New York. Page 174

7 Groák discusses extensively the issue of production knowledge in building production in chapter eleven; technology transfer and in specific about literature in page 167. In addition, he expands about of different forms of building knowledge in pages 169-170.

8 Stephen Potter et al. proposed this alternative way to capture heuristic based on design experiences in the form of a design specification and the corresponding design solution.

9 That first study and in specific the DfM model obtained from it, was tested as part of the teaching experience in the course "The design of digital manufacturing", directed by professor Monica Ponce de Leon and co-taught by the author. Within that course, one guided explanatory case study and three exploratory case studies were conducted

10 These teaching experiences were structure as part of the course ARCH 8803 Design for Manufacturing: Curved Surfaces Fabrication using CNC technology. The author taught this class during the spring semester 2006 at Georgia Institute of Technology.

11 This case study is based on producing a curved surface module for an existing wall system. This wall system is called Graph and produced by Fry Reglet, a local architectural component manufacturing firm, for more details the product catalog is provided.