COMPONENT BASED DESIGN AND DIGITAL MANUFACTURING:

A DESIGN FOR MANUFACTURING MODEL FOR CURVED SURFACES FABRICATION USING THREE AXES COMPUTER NUMERICAL CONTROLLED ROUTER

A Thesis
Presented to
The Academic Faculty

by

Eduardo Lyon

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PhD in Architecture in the
College of architecture

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COMPONENT BASED DESIGN AND DIGITAL MANUFACTURING:
A DESIGN FOR MANUFACTURING MODEL FOR CURVED SURFACES FABRICATION USING THREE AXES COMPUTER NUMERICAL CONTROLLED ROUTER

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To my daughters Lorenza and Clara
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<td>DfM</td>
<td>Design for Manufacturing</td>
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<tr>
<td>CAD</td>
<td>Computer Aided Design</td>
<td></td>
</tr>
<tr>
<td>CAM</td>
<td>Computer Aided Manufacturing</td>
<td></td>
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<tr>
<td>CNC</td>
<td>Computer Numerical Control</td>
<td></td>
</tr>
<tr>
<td>CAPP</td>
<td>Computer Aided Process Planning</td>
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<tr>
<td>KBD</td>
<td>Knowledge-based design</td>
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<tr>
<td>BIM</td>
<td>Building Information Modeling</td>
<td></td>
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<tr>
<td>DFA</td>
<td>Design for Assembly</td>
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<tr>
<td>DfMA</td>
<td>Design for Manufacturing and Assembly</td>
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<tr>
<td>PAW</td>
<td>Producibility assessment worksheet</td>
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<tr>
<td>GT</td>
<td>Group Technology</td>
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<tr>
<td>CE</td>
<td>Concurrent Engineering</td>
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<tr>
<td>QFD</td>
<td>Quality Function Deployment</td>
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<tr>
<td>JIT</td>
<td>Just in Time</td>
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<tr>
<td>DNC</td>
<td>Direct Numerical Control</td>
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<tr>
<td>NC</td>
<td>Numerical Control</td>
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<tr>
<td>NURBS</td>
<td>Non Uniform Rational Bezier Splines</td>
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<tr>
<td>STEP</td>
<td>Standard for the Exchange of Product model data</td>
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<tr>
<td>STEP-NC</td>
<td>Standard for the Exchange of Product model data for numerical control</td>
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<tr>
<td>ISO</td>
<td>International Standard organization</td>
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<tr>
<td>COA</td>
<td>College of Architecture</td>
<td></td>
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<tr>
<td>GATECH</td>
<td>Georgia Institute of Technology</td>
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<tr>
<td>eCAADe</td>
<td>Education and research in Computer Aided Architectural Design in Europe</td>
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<tr>
<td>MDF</td>
<td>Medium-density fiberboard</td>
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<tr>
<td>Abbreviation</td>
<td>Description</td>
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<tr>
<td>DXF</td>
<td>Drawing Exchange Format</td>
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<tr>
<td>DWG</td>
<td>proprietary file format of AutoCAD</td>
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<tr>
<td>IGES</td>
<td>Initial Graphics Exchange Specification</td>
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<tr>
<td>STL</td>
<td>Standard Tessellation Language</td>
<td></td>
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<tr>
<td>pl</td>
<td>Laser Pulse</td>
<td></td>
</tr>
<tr>
<td>d</td>
<td>Distance</td>
<td></td>
</tr>
<tr>
<td>P</td>
<td>Power</td>
<td></td>
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<tr>
<td>v</td>
<td>Speed</td>
<td></td>
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<tr>
<td>T</td>
<td>Time</td>
<td></td>
</tr>
<tr>
<td>dl</td>
<td>Laser spot diameter</td>
<td></td>
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<tr>
<td>RP</td>
<td>Rapid Prototyping</td>
<td></td>
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<tr>
<td>RPM</td>
<td>Revolution per minute</td>
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<tr>
<td>Csz</td>
<td>Component Size</td>
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<tr>
<td>MchSz</td>
<td>Machining Size</td>
<td></td>
</tr>
<tr>
<td>Mtsz</td>
<td>Material Size</td>
<td></td>
</tr>
<tr>
<td>WpSz</td>
<td>Workpiece size</td>
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</tr>
<tr>
<td>AWPL</td>
<td>Advanced Wood Product Laboratory</td>
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SUMMARY

This thesis explores new ways to integrate manufacturing processes information in to design phases. Through the use of design for manufacturing (DfM) concept, and looking at relations between its potential application in architectural production and its implementation using digital manufacturing technologies, the author implemented a DfM model that varies from previous models by incorporated learning in the process. This process was based on the incremental development and refinement of design heuristics and metrics. The DfM model developed in this research is a process model to be implemented as a framework within educational settings. The proposed model is based in two basic strategies; first a process description in the form of alternative design strategies; and second, the implementation of design heuristics and design metrics. Subsequently, the author tested and refined the model using a sequence of case studies with students. In the final stage, the research evaluated and further developed the DfM model in a component design case study. The general purpose in performing this case studies sequence was to test the proposed DfM model. The second objective was to refine the DfM model by capturing knowledge from the case studies. As a summary, this research conceptualizes 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; DfM teaching approaches development, design processes improvement; and DfM methods development.

The final purpose is to provide better foundational constructs for architectural education and to improve teaching approaches that integrate design and manufacturing.
CHAPTER 1

INTRODUCTION

Advances in computation, both regarding its treatment and technology, have stimulated the design and implementation of an ever-growing number of Computer Aided Design (CAD) and Computer Aided Manufacturing (CAM) applications. Application elaboration both responds to and generates new conceptualizations of architectural knowledge (Lyon, 2006a). Until recently, the use of CAD systems in building production was limited to drafting systems. The introduction of solid modeling and recently the development of parametric three-dimensional modeling are providing a new platform for embedding design and fabrication knowledge.

1.1. The division between Design and Construction

From its origins, building production has been characterized by an intricate relation between construction techniques (tectonics) and a specific image of the building (aesthetics). Since the renaissance the production of drawings, or design activity, has been at the center of this process, and has delineated the architect’s role within the building production process (Perez-Gomez and Pelletier, 1997). Since then, drawings were the instruments by which architects have provided the information necessary to

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1 For the purpose of this research, a **CAD system** is a combination of hardware and software that allows three-dimensional modeling of physical artifacts, enabling engineers and architects to design artifacts from simple parts to airplanes. Consequently, a **CAM system** is a combination of hardware and software that enables engineers and architects to communicate work instructions directly to CNC manufacturing machinery.
construct buildings, and it is in drawings where building descriptions and construction
information happen together.

By the eighteenth-century architectural discipline had been profoundly affected
by the demands for the reorganization of knowledge (Pérez-Gómez, 1983). The questions
that confronting the discipline involved not only ontological queries regarding
disciplinary boundaries or the matter that constituted architecture’s body of knowledge
but also a growing demand for an epistemology of the architectural knowledge that
would allow architecture to be taught as a formal discipline. Changing social structures
reinforced such abstract questions by requiring the removal of the vestiges of past
practices. This new order provoked a deep and still open incision into the body of the
discipline and was clearly noticed not only in the division of the practice according to
design and construction activities but also in the division of the newborn formal
architectural education following the distinction of architecture as a science or as an art
(Groák, 1992). As a result, design activities has been based on a sequential process model
with a clear-cut division between the generation of information to describe artifacts
followed by the provision of information to construct them. Design for manufacturing
(DfM), on the other hand, tries to resolve within the design process how the artifact is to
be constructed. 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)²

² 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...
In addition to considering construction knowledge during design becomes especially important when exploring alternatives to traditional construction methods, where the space of construction alternatives is not well understood. The core problem is that architects ignore that up to seventy percent of production cost is determined at design stage. Moreover, designers are concerned on describing and placing artifacts in space. Meanwhile contractors are concerned on producing components and locating assembly processes over time. Better integration is needed (Groák, 1992, Fox, 2002, Groák, 2001, Hill, 2005). The benefits of integrating design with construction knowledge can be understood through study of the cost of resolving problems as they occur early or later in the design process. Problem resolution late is expensive, early is cheap (Ahmadi and Wurgraft, 1994, Anumba and Evbuomwan, 1997, Pasquire and Connolly, 2003)

1.2. Form generation capabilities and fabrication technologies:

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, their use was limited by the lack of adequate representations to manipulate 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 they require the development of specific realization process. A good example of this is found in the series of building produced by Frank O. Gehry and associates (FOGA) in the last ten years. These buildings required not only deployment of non-traditional constructive techniques but also use of advanced digital technologies, like parametric three-dimensional modeling and CNC manufacturing technologies (Schodek et al., 2004, Dal Co et al., 2003, Kolaveric, 2003). In addition, bridging from a CAD system to a CAM system is mostly performed at the shape description level based on neutral files or proprietary exchange formats. At the object level CAM systems rely 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 (Miao et al., 2002). The main issue is that integration between CAD and CAM systems remains mostly unsolved (Liu, 2000). Even architectural tools now being developed for Building Information Modeling (BIM) continue the traditional partitioning between design and construction. That is, they maintain the old stereotype that makes the new integrated conceptualization difficult.

1.3. Production of Space vs. Building Production

Architectural design ultimate aim is the production of space. However, since space is not a malleable matter, structures are needed not only to define the space but also to produce and control specific spatial conditions that are required.

Design can be thought as a process of composition and refinement of concepts and technologies, while construction is the decomposition of design units into its
producible components and its execution processes. Both, design and construction are encompassed within the building production process. If the units of design also support analysis and decomposition for construction, then the space of construction alternatives and potential errors is greatly reduced—as well as the risk of later changes. This is specially relevant if we realize that the proportion of construction productivity and quality problems attributable to inadequate design is still about fifty percent (Fox et al., 2001).\(^3\) The advent of CAD and CAM technologies and associated manufacturing technologies in architecture, has introduced not only a twist in traditional separation between “design intent” and “means of construction” but also has exposed inefficiencies coming from the division of design and construction. Furthermore these exceptional circumstances offer the opportunity to architects to be leading this new form of architectural production, recovering to some extent the role of master builder\(^4\) and reestablishing the connection between design and construction (Kieran and Timberlake, 2004, Kolaveric, 2003).


\(^4\) Kieran and Timberlake state "Hundreds of years ago, all of architecture could be held in the intelligence of a single maker, the master builder. Part architect, part builder, part product and building engineer, and part materials scientist, the master builder integrated all the elements of architecture in a single mind, heart, and hand. By recognizing commodity as an equal partner to art, architecture is made as accessible, affordable, and sustainable as the most technically sophisticated consumer products available today.” in KIERAN, S. & TIMBERLAKE, J. (2004) *Refabricating Architecture*, New York NY, McGraw-Hill Companies. pg.xi
1.4 A DfM model as a framework for Design Learning:

Viewed from the vantage point of architectural theory, the body of knowledge in architectural education has been constructed mostly around questions involving the origin and history of architectural form and the classification of it according to building types for instructional purposes. Meanwhile, knowledge about alternative ways to realize buildings remains separated, taught in separate required courses, but not necessarily ever applied in studio settings. Commonly this knowledge is just ignored in design experiences that constitute the most important learning environments in architectural education. Consequently, construction knowledge stays isolated and circumscribed to instructional courses and construction techniques texts. As a result, the separation between design and making runs like a fissure through the history of architectural education.

Design education is mostly based on teaching approaches based on the professor as a master or role to imitate and design objects as types to imitate or instantiate from. Therefore, teacher and building types became both models to emulate. What stays implicit and ignored within this learning approach is not only the process of making artifacts but also the “learning by doing” or “thinking in action” process that constitutes the core of design thinking. (Goldschmidt, 2003). The problem in here is that procedural knowledge, in specific realization or manufacturing knowledge stays ignored, and education is concentrated on declarative knowledge in the form of object knowledge.

Finally, the value in learning from our actions in the design environment and through the methods that we use to make those artifacts is almost ignored. Design learning is not only about transferring of knowledge from previous design experiences
but also about creating, manipulating and structuring design knowledge within the process.

Formal education in architecture has been reduced to emulation practiced through apprenticeship in design experiences with design masters without an organizing framework or a model of design processes. Unfortunately this paradigm remains the dominant scenario in architectural education (Goldschmidt, 2003). Looking at the place of design theories, models, methods and instruments, we would like to think of designers as engaged in a model of design process involving continuous form, process and materiality evolution. (Lyon, 2006b).

After this introduction chapter, this thesis is organized as follows: **Chapter 2** contains a close examination of the DfM method in product development. The author explores fundamental strategies and approaches in DfM. Next material and manufacturing process selection is analyzed, and alternative ways to evaluate a product’s manufacturability are presented. DfM metrics are laid out as mechanisms to determine and measure potential design improvements. Finally, DfM methods and DfM tools are presented, as ways to implement those improvements, making them available to designers.

**Chapter 3** is devoted to an expanded discussion about the DfM model in product development, its incipient application to building production, its relevance, and benefits. This chapter also includes a review of the relation between building production and constructive systems, and a discussion about related work in relation to constructability and buildability. Alternatives framework for DfM implementation in building production,
are discussed, and lean construction; concurrent engineering; teamwork organization approaches are introduced.

In chapter 4, a discussion about component-based design is utilized as a way to introduce different approaches to apply a DfM model in building production. Within this context i.e. component based design, the use of CAD and CAM systems in building production and some of its implications are discussed. Closing the chapter, a basic overview of curved surfaces representation in geometric modeling is presented and expanded in relation to CNC technologies used in building production.

Chapter 5 is introduced with a brief discussion about knowledge-based design (KBD) research and different types of knowledge are introduced. After that design and manufacturing knowledge are presented, as the main knowledge types explored within this research. After knowledge based design approach is introduced, and design knowledge and manufacturing knowledge has been exposed, next section describes how knowledge is obtained. Accordingly, knowledge-capturing techniques are discussed and use of them in building production highlighted. Subsequently a formal and consistent method of capturing knowledge, in the form of design heuristics and design metrics, is introduced and discussed in the final section.

Along chapter 6, research methodology used in the thesis is described. In the initial section, the author introduces a general research approach. Within that framework, the author presents the research philosophy, approaches, and techniques in the form of a research framework. Afterwards, case study research strategy is introduced including; case's design strategies; alternative data sources; and analysis of evidence. Finally, a DfM model is presented as theoretical proposition to provide and adequate framework for the
case study approach incorporating, and assessing design heuristics and evaluation metrics obtained from structured design experiences.

In **chapter 7**, the research organization is laid out. Initially, research phases are exposed and its development through cycles is outlined. Within that outline, three research stages are presented. An initial research stage was based on semi-structured and non-participant teaching experiences with students. As result of the initial research stage, an early DfM model is proposed. At the second stage, the initial DfM model was tested and refined—using a sequence of case studies with students. In the final stage of the research, a refined DfM model was evaluated and further developed—In a component design case study. Finally, in a closing section an introduction to each research stage including techniques used in its implementation and graphic descriptions of the case development is presented.

**Chapter 8** mainly deals with analysis of data obtained from structured design experiences; the organization of it according to its purpose and scope; and its application during the design process. Along this chapter, four case studies, that are essential part in this research, are introduced. After an introduction, and a brief section presenting structured design experiences, each case study is laid out and discussed including; process description; technologies involved; critical topics explored; data analysis and manufacturing knowledge in the form of design heuristics and metrics are depicted.

**Chapter 9** uses a component based design case study as way to test the proposed DfM model. The chapter covers the case study that is based on producing a component for an existing wall system. Along this chapter, the case study is described, data collected
organization and its analysis presented. Purpose in here is to evaluate how efficient and effective were the design heuristics and metrics.

Chapter 10 presents a summary with the research conclusions. Research results' relevance, precision, contribution, and a comparison with related research results are described. In addition, a statement about how results fit into the existing body of knowledge and if they are consistent with current theories is laid out. New insights and potential new methodologies or mechanisms are presented.
CHAPTER 2

DESIGN FOR MANUFACTURING (DFM)

Design for manufacturing, or DfM, is an important area in product development and application in all manufacturing areas (Boothroyd et al., 2002, Bralla, 1999). The objectives of DfM are to develop and organize information to produce knowledge that can be applied in designing products to improve their manufacturability. DfM has led to important improvements in manufacturing effectiveness, resulting in cheaper products, of higher quality, that are fast to produce, that are easier to service, maintain and replace (Poli, 2001). These improvements have been achieved while product quality has been raised. The benefits in applying the DfM approach are coming from shortening production cycles\(^5\), improving part quality, and reducing manufacturing cost (Fox et al., 2001, Susman, 1992, Dertouzos, 1989, Boothroyd et al., 2002)\(^6\). DfM benefits have often been quite remarkable and production cost reductions of up to 50% has been widely reported (Boothroyd et al., 2002, Ulrich and Eppinger, 1995b).

DfM is also a major aspect of productivity improvement in such global areas of manufacturing as automobiles, electronics and aircraft. Companies like Ford, General Motors, Xerox and Boeing has applied DfM and obtained benefits from reducing product cost, reduction in product production cycle and quality improvements (Boothroyd et al.,

\(^5\) For clarification purposes, a production cycle includes design, manufacturing and assembly stages.

\(^6\) Theses authors reported product cost reduction in using DfM methods ranging from 50% to 70%.
Improvements come from reducing assembly times, reducing the number of different parts, optimizing the number of total parts, reducing the number of manufacturing operations and manufacturing time.

DfM is a well structured research area in product development. In this area is possible to find not only abundant literature but also DfM systems that support design (Vliet et al., 1999, Susman, 1992). According to Shah most of these systems have a limited scope, because they either focus on material/process selection or they perform detailed analysis for a specific manufacturing process (Shah and Wright, 2000). Most importantly, people do not have an overview of manufacturability analysis and there is little work completed on specifying the generic steps to perform manufacturability analysis tasks irrespective of a particular technology (Shah and Wright, 2000).

DfM is an approach that emphasizes the inclusion of manufacturing knowledge during design phase. Consequently, DfM is a process centric approach and targets the design process. Subsequently in applying the DfM approach it is important to consider that designers are required; to design products that structure design information properly.

Boothroyd provides a comprehensive review of DfM and DfA from its origins in mid seventies till present days. They include several case studies and experiences from different manufacturing areas and companies including Ford, GM, NEC and Xerox. They also produce one of the leading DfMA software in the industry. For them DfM and DfA are part of the same process but they recognize that there is conflicts between manufacturability and assemblability objectives. Its method and its implementation has been also subject to inquiry by STONE, R., MCADAMS, D. & VARGHESE, K. (2004) A product architecture-based conceptual DFA technique. Design Studies 25, 301–325.

in order to integrate production knowledge in design; to select adequate materials, processes; and to evaluate alternative design solutions in relation to its manufacturability (Boothroyd et al., 2002). Normally, literature in DfM tends to address integration of this issues focusing on a single one in isolation, and ignores interactions between them. Additionally if is important to realize that many products are manufactured out of two or more processes and this increases process complexity.

The fundamental strategy in DfM is to first verify a potential product design or alternative ones, second to select material and a feasible manufacturing process or vice versa, then to analyze product’s manufacturability, determining potential design improvements. Improvements are implemented through DfM metrics, DfM methods and DfM tools (Vliet et al., 1999, Shah and Wright, 2000, Boothroyd et al., 2002).

2.1 Material and Process Selection

Material and manufacturing process selection must occur before DfM starts and affects all succeeding decisions. In addition material and process selection process is complex due to multiple attributes involved in the decision making process (Ashby and Johnson, 2002, Giachetti, 1998) 9.

The material and manufacturing process selection decisions are difficult due to several reasons. Selection process must be performed during preliminary design phase

9 Ashby sates that products in a given market sector have little to distinguish between them in either performance or cost. When many technically near-equivalent products compete, market share is won or lost by the industrial design of a product: its visual and tactile attributes, the associations it carries, the image it creates in the consumer’s mind and the quality of its interface with the use and the environment.
where design objects are characterized by qualitative requirements descriptions, lack of adequate geometric description or imprecise data, and lack of design object complexity assessment (Giachetti, 1998). In addition there is multiple criteria that is relevant in the decision making process with unequal and sometime unknown relevance. Of the multiple factors that influence material and manufacturing process selection, most of them can only be estimated, for example production volume, machining time or batch size. Additionally, most design requirements can be categorize as soft requirements or designer preferences and consequently, they are flexible. Finally material availability is quite extensive, there is over 100,000 alternatives of materials and new material appear frequently (Brownell, 2006, Ashby and Johnson, 2002), consequently to select an adequate manufacturing process and commonly you have more than one process candidate for a product. Finally many products are produced out of more than one process (Giachetti, 1998)

2.2 Manufacturability assessment

At the core of the DfM approach, is manufacturability evaluation. Manufacturability is generally defined as the extent to which a product can be, easily and effectively, manufactured at minimum cost and time, and according to design specifications. Manufacturability evaluation is divided in three stages: Product

10 Blaine Erickson Brownell, author of Transmaterial, known to thousands of web users for his "product of the week" email service alerting designers to new materials that are reshaping our world, wrote this reference book to record the most interesting and most useful new materials.
manufacturability verification; Product manufacturability quantification; and Product manufacturability optimization (Vliet et al., 1999, Tharakan et al., 2003).

In order to be able to evaluate product manufacturability we need to establish relations between attributes in the product and relevant aspects in the production process i.e.: decomposing the products in elements with a manufacturing significance, This is also known as feature mapping as opposite to feature recognition which relies mostly on feature recognition algorithms (Shah et al., 1994). Consequently difficulties in assessing product manufacturability are coming from the two dimensions found in the problem; one dimension is coming from different levels of abstraction found at products attributes, which are subject to manufacturability analysis. There are general part attributes like overall shape, size, features size range and complexity found in the part, material etc. In a different level, we have detailed part attributes like; dimensions; tolerances; and surface finishing. The second dimension, in assessing manufacturability, is found at different level in where it can be analyzed i.e.: at process level; at workshop level; and at machining level (Tharakan et al., 2003). At all of these levels, manufacturability assessment involves the use of metrics to determine what level of manufacturability a product has. Some of those metrics are presented and reviewed in the next section.

2.3 DfM metrics

DfM metrics are specific measures to establish optimum material and manufacturing process combination for a specific product design. These metrics are normally found in the form of rules, and guidelines, organized according to part geometry, manufacturing process and material, manufacturing time and cost estimation. The most common one in use refers to part count, manufacturing time, complexity index,
weight and lead-time. Shah proposed a organizational framework using the following
categories: qualitative score based on good practice rules; direct cost estimation; time
based manufacturability rating; producibility assessment worksheet (PAW); design
tolerances to process capability ratios; Boothroyd Dewhurst rating; value based DfM
metrics and DfM based on Taguchi method\textsuperscript{11}. (Shah and Wright, 2000) In the next
paragraph, we present them using the previously mentioned framework

**Evaluation metrics** based on qualitative scores using DfM rules and guidelines
are the most common found in design community. DfM rules are organized according to
geometry based, process based, and material based rules. Subsequently few of these rules
are independent from the chosen manufacturing process. Accordingly, specific rules are
found in the implementation of DfM tools for particular manufacturing processes. Some
examples of domain independent rules in DfM are: maximize use of standard
components, tools, and materials; minimize required resources; minimize part count and
geometric complexity, loosen tolerances, investigate possibilities of new processes and
materials. Examples of domain specific rules are: keep wall thickness as uniform as
possible in castings; avoid flat bottomed holes for machined parts; create tapered features
for easy assembly; use low melting point alloys for die casting (Shah and Wright, 2000,
Vliet et al., 1999).

\textsuperscript{11} Shah evaluates measures of manufacturability and classes of \textbf{DfM} methods and
frameworks independent of the specific manufacturing processes. Criteria used in
evaluation include theoretical foundation, accuracy, flexibility in choosing
utility/objective function, domain independence, ease of use, level and extent of
information required, computational cost, ability to incorporate uncertainty and market
factors.
**Direct cost estimation** is another approach to evaluate manufacturability and as it is implied consist in to evaluate manufacturing cost by comparing alternative processes, alternative parts or materials. The main problem in here is accuracy in the cost relies not only in the part but also in the process plan. Accordingly, a component design needs to be detailed enough to obtain some level of accuracy in the estimation.

**Time based manufacturability rating** is used when time-to-market or leading time is relevant and metrics are based on manufacturing time.

**Producibility assessment worksheet (PAW)** employed by the Navy is based on a set of standardized survey forms for various aspects, such as system modules (mechanical, electrical), procurement, and program management. The Navy defines producibility as the measure of the manufacturability a product. Each form contains eight individual ratings (0-1) for key factors relevant to that aspect (Shah and Wright, 2000, Aurand et al., 1998).

**Boothroyd Dewhurst rating** is one of the most widely recognized DFA methodologies and it is integrated in DFMA commercial application. DFMA software is a combination of two complementary tools: Design for Assembly (DFA) and Design for Manufacture (DFM). DFA software is used to reduce the complexity of a product by consolidating parts into elegant and multifunctional designs. DFM software then allows the design to estimate the cost of producing the new design and to compare it with the cost of producing the original design (Boothroyd et al., 2002).

**Value based DfM metrics**, the metrics already discuss only consider how to reduce manufacturing cost. Value engineering, however, considers the relationship between quality and cost. The value of a product can be increased by decreasing its cost.
while maintaining or improving its quality. Consequently, value may be defined as the ratio of product quality to cost, or benefit/cost ratio. Value may be determined by comparison of design alternatives. Many performance parameters and product attributes must be taken into account in determining product quality. Similarly, cost must include not only manufacturing cost but also the complete production cost including financing, sales, distribution, etc. (Shah and Wright, 2000)

**DfM based on Taguchi method** involves the use of statistical design of experiments for robust design of a product. Robust Design focuses on improving the fundamental function of the product or process, thus facilitating flexible designs and concurrent engineering. Taguchi defines quality as signal-to-noise ratio; a design with lower sensitivity to uncontrollable variations is preferred. Several different formulas have been proposed by Taguchi to measure the goodness of a design depending upon whether we are doing parameter or tolerance design (Taguchi et al., 1998). Parameter design is the determination of a combination of design parameters that affect a design product. Tolerance design comprises defining the limits for design parameters tolerances. Taguchi method uses a loss function to define design parameters tolerances. Parameter variation from the intended values results in a loss. Tolerances are defined in relation to cost calculations of losses (Dixon and Poli, 1995).

These metrics are fundamental in assessing manufacturability in a specific product. However, they do not constitute an organized and systematic way not only to analyze and evaluate manufacturability but also to improve designed products manufacturability without losing design quality. In the next section, some existing methodologies to improve design manufacturability are presented and explored.
2.4 DfM methods

A DfM method is a systematic approach, strategy or a combination of them to improve manufacturability in a specific product during design process. Some authors consider that there is no formalized DfM method but they recognized that multiple approaches in implementing DfM are available. The problems are the multiplicity of forms that this approaches present and the lack of differentiation in between a DfM method and its implementation i.e.: a DfM tool. The most common found DfM approaches are based on the availability of DfM rules and guidelines. Most of these rules and guidelines are available in charts and text form, or implemented as rule checking systems. One of the biggest challenges in DfM development is the provision of a systematic methodology to obtain, and organize manufacturing knowledge according to its availability during the design process. In addition, there is also process optimization approaches, like concurrent engineering (CE), group technology (GT) and quality function deployment (QFD) that provides an adequate framework to implement DfM methods. In addition, material and/or process selection, implementation and computer supported DfM tools for specific material or manufacturing process are available today.

Summarizing, most of the methodological approaches use one or more of the metrics that were reviewed in the previous section. They also include at least one of the following criteria in improving design: technological feasibility; economic feasibility; design trade-off or design optimization. Finally, in the next section we review some of the existing DfM tools and systems that consist in the implementation of these methods.
2.5 DfM tools

Benefits coming from quality improvement and cost reductions in wide variety of manufacturer using DfM approaches have stimulated the development of a bigger variety of DfM tools along the academic and industrial sectors. A DfM tool is the embodiment of a DfM method. (Shah and Wright, 2000, Vliet et al., 1999). Theses tools evaluate manufacturability from a range of approaches, focus on different levels of product realization, and concentrate in specific manufacturing process or issues within those processes. Nevertheless, some initial attempts to organize DfM tools according to its similarities have been presented. The broadest differentiation can be traced around its developers i.e.: DfM tools resulting from academic research and commercially available DfM oriented tools. A less general classification can be organized in relation first to material and process selection tools and cost estimators. A second category can be manufacturability verification, quantification, and optimization tools. A third category can be design and decision support systems and CAD systems with DfM functionality. Since these tools address different issues and are created to solve specific problems at different design stages and in different domains, Shah proposed that they can be categorized based on some similarities in their approach in relation to: Input to the system; output from the system; and the assessment mechanism (Shah and Wright, 2000).

Some examples of these tools are material or process selection systems. They are tools that explore alternative material and/or process for part manufacture. They are also known as material and process selectors. These tools utilize part attributes, and evaluate matching those attributes to with different process and material to provide output. Examples are the Cambridge Material Selector and the Cambridge Process Selector (CPS) (Tharakan et al., 2003, Ashby and Johnson, 2002).

Domain specific tools typically use attributes or geometric data at part and feature level to assess manufacturability by applying specific manufacturing process rules. Some examples of such tools are the Boothroyd and Dewhurst DFMA tool (Boothroyd et al., 2002) and DieCast which is a DFM tool that combines Pro/Engineer with a knowledge-based system, developed in Nexpert Object (Liou and Miller, 1991, Vliet et al., 1999). The tool analyzes and evaluates product design for die-casting based in relation to size, envelop weight and wall thickness.

Finally, we have tools that work within a specific manufacturing process, and in particular manufacturing circumstances. In these systems, material and manufacturing process restrictions are unambiguously declared and in-depth manufacturability analysis is performed. The input is part information at the feature level and the output is a quantitative ranking in relation to manufacturing cost or manufacturing time. Cybercut milling is an example of such a tool where the part is designed by a “design-by-feature” approach with severe restrictions on material and part geometry, and the manufacturability is evaluated with a heuristic process plan (Vliet et al., 1999, Ramaswamy, 2006, Tharakan et al., 2003).
CHAPTER 3

DFM IN BUILDING PRODUCTION

In the previous chapter, we performed a close examination of the DfMA approach in product development. In this chapter, we examine its incipient use in building production, looking for its similarities and differences in relation to product development. If we can assume that construction is an industry (Groak, 1994)\(^{13}\), the most relevant discrepancy between product development and building production arises from the differences between the manufacturing and construction industry. As we reviewed in the previous chapter, in many manufacturing areas DfM has became an important approach in improving product development productivity through design. 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\(^{14}\) (Anumba and Evbuomwan, 1997). Fragmentation is due to two major issues; one coming from the division between design and construction; and the second from the increasing number of disciplines, consultants and specialists concurring in the building construction process (Yates and Battersby, 2003).

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13 Steven Groák discusses intensively about conceiving construction as an industry and states that the parameters to look at the existing paradigm are; buildability; fragmentation; and feedback in: GROAK, S. (1994) Is Construction an Industry. Construction Management and Economics, 12, 287-293

14 Nevertheless, architectural graphics standards and other constructions standards in text form are provided to illustrate some forms of best practice for conventional constructive systems.
It has been recognized in both the manufacturing industry and the construction industry that productivity and quality can be enhanced by integrating production knowledge into design stages. Within the manufacturing industry, different forms of production knowledge integration have led to radical improvements in productivity and quality. However, in the construction industry, low productivity and poor quality continue to be extensively found and no comparable improvements have taken place in construction (Teicholz et al., 2001, Fox et al., 2001). A number of recent studies has indicated that construction productivity has stayed even or declined slightly, although there are also counter views (Goodrum et al., 2002). What is not in dispute is that construction has not achieved near the same productivity improvements of manufacturing.

Traditional design documentation produces detailed systems and sub-system descriptions i.e.; spatial; structural; mechanical; electrical; and acoustics. Interaction between these systems is assumed to be coordinated by the designer. Component production and assembly processes are implicit until bidding and sometimes until

execution. The core problem is, ignoring the fact that up to seventy percent of production cost is determined at design stage (Giachetti, 1998, Boothroyd et al., 2002), designers are concerned with describing building shape and space allocation. Consultants are focused in placing systems and subsystems in space, while contractors are concerned with producing components and locating assembly processes over time, better integration is needed. 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).16

As we can conclude, core issues are; architects’ lack of methodologies equivalent to DfMA; poor understanding of buildability; difficulties in production knowledge integration into design stages; and the disproportionate dependence on individuals experience within an increasingly fragmented work environment.

This chapter is organized as a review of alternative methods to integrate design and fabrication knowledge in building production, and some potential approaches to implement DfM in building production. Initially, a review of buildability concept is used as entrance point to discuss different types of construction knowledge and historical evolution in building production. Then lean construction, concurrent engineering, and teamwork organization are reviewed as alternative integration approaches. A closing section will provide some reflection in relation to the disproportionate fragmentation in

16 In this specific issue Fox references to: Harding, C. Down with designers in Building, 25 June, 1999.
building production and how Building Information Modeling (BIM) is supposed to
decrease it.

3.1 Manufacturability vs. Buildability

One of the most important purposes in applying DfM approach is to allow
manufacturability analysis in product design. Fundamentally, DfM considers
manufacturability as part of design constrains. Consequently, in applying DfM to
building production it is important to discriminate between manufacturability and
buildability. Buildability has evolved from being considered just a production objective
that usually tackles problems in the assembly process in building construction up to a
concept applied all along the design and construction process\textsuperscript{17}. This evolution reflects
how building production has evolved from an environment with clear-cut division
between design and construction to a more integrated work environment in recent years.

Traditionally buildability was achieved based on standardization and project
simplification strategies, expressed as design trade-off. By contrast, DfM can be
described as a design method that incorporates production objectives in generating and
evaluating alternative designs. Accordingly, design formulation needs to consider
manufacturability and to produce the necessary information to feed manufacturing
processes (Fox et al., 2001)

\textsuperscript{17} For an in depth revision of buildability concept evolution, including a review of key
research centers relevant to that see ENG, C. S. (2002) Buildability/constructability. IN
BEST, R. & DE VALENCE, G. (Eds.) Design and construction: building in value
Buildability is referred by Lam as: "to the extent to which a building design facilitates efficient use of construction resources and enhances ease and safety of construction on site whilst the client’s requirements are met" (Lam et al., 2006). Nevertheless, this has not always been the interpretation of the concept; somehow, the term has evolved as the construction industry evolves. Buildings, in the early half of the 20th century, were relative simple from a systems perspective. In the 1920s and 30s, for example, a major building could be constructed by stone masons and carpenters, with a plumber and electrician (Kostof, 2000). It was only in the early 20th century that structures were quantitatively analyzed and the rise of more complex buildings including mechanical systems, communication systems, vertical circulation, and fire safety.

Traditionally, buildability has focused on problems arising in the design and construction phases. Nowadays it is interpreted in a wider perspective that addresses the entire building production lifecycle. This approach emphasizes the applicability of buildability along from design to construction phases and to all project participants. Buildability cannot be effective as a stand-alone tool. It has to be implemented as part of an approach that clearly specifies the primary project objectives and the techniques that allows buildability to be assessed (Fox et al., 2001). Buildability has been connected to improvements in building quality, ease of construction, and to more efficient and economical construction (Lam et al., 2006, Fisher et al., 2000, Jergeas and Put, 2001).

Constructability is a concept similar to buildability and is defined as the optimum use of construction knowledge and experience in different project stages to achieve overall project objectives. (Lam et al., 2006, Fisher et al., 2000, Jergeas and Put, 2001, Arditi et al., 2002, Pocock et al., 2006, Pulaski and Horman, 2005)
In manufacturing industry, DFM has been used successfully to evaluate and improve manufacturability in different products ranging from computers and cars to airplanes. Detractors to initial efforts to apply DfM to building production argued that manufacturing industry is quite different from construction industry, even affirming that construction is not an industry\textsuperscript{18}. Others affirm that DfM is not suitable for building because of building's lack of complexity as manufacturing industry products have. This is true if we compare an aircraft like the Boeing 777, contains an average of 3,000,000 parts\textsuperscript{19} with a house that contains around 30,000 components\textsuperscript{20}.

However, it is different if we look at cars that are much smaller, and have far fewer components than a house. A car has 10,000 components (Michaels and Lunsford, 2005, Gann, 1996, Heisserman et al., 2000).

Unfortunately, process complexity is still seen as a barrier in defining buildability\textsuperscript{21}.

Subsequently production knowledge related to buildability remains largely tacit or

\begin{quote}
\textsuperscript{18} Groák affirms that construction is more a technological paradigm rather than an industry. He affirms that construction industry is to be defined as a temporary coalition of people and organizations that are essentially organized around a project rather than a firm GROAK, S. (1994) Is Construction an Industry. Construction Management and Economics, 12, 287-293.

\textsuperscript{19} Heisserman states that out of those 3,000,000,- parts 135,000,- are unique. Consequently he present a consistent design representation to organized and manipulated them in HEISSERMAN, J., CALLAHAN, S. & MATTIKALLI, R. (2000) A Design Representation to Support Automated Design Generation. IN GERO., J. S. (Ed.) Artificial intelligence in design '00. Dordrecht ; Boston, Kluwer.

\end{quote}
informal and reliant on intuitive use. Such informal approaches to integrating design and production may have been effective when traditional craft practices and a few versatile materials were used to construct buildings. Nevertheless, ubiquity of technological innovation means that building designers now have to select from a rapidly increasing number of building components and innovative manufacturing processes (Fox and Cockerham, 2000, Gann, 1996, Groak, 1994).

Summarizing, incipient efforts in applying DfM to construction has been deferred or disregarded by the widespread notion that construction industry dissimilarity to manufacturing industry. However, in the construction industry, low productivity and poor quality continue to be extensively found and reported (Fox et al., 2001). Other counterpoints to integrate DfM to building production, affirm that fragmentation in construction industry is a major obstacle. As we mentioned in a previous section, fragmentation in the industry is due to two mayor aspects, one is the division between design and construction activities and the second one is the large number of specialists, consultants and technicians that are involved in the building production process, and the resulting knowledge dispersion.

21 Stephen fox states, "that there is no simple answer to evaluating buildability because of the complexity of the construction process".
Next section will explore how, production systems from the manufacturing industry are being increasingly incorporated to the construction industry. This situation is definitely blurring the differences between manufacturability and buildability and making DfM implementation extremely feasible. Under this unprecedented conditions construction industry is getting closer to manufacturing industry providing an adequate substratum for DfM implementation in building production.

3.2 Building Production and Constructive Systems

For most of history, construction has been a craft passed through apprenticeship that relied on fairly static, “tried-and-true” construction methods. These practices were built into building codes from the 17th century on, led by the Dutch in New York and Amsterdam. As long as architectural design was based on these methods, the issues of buildability were embedded in the practices of the different crafts, and not analyzed by the designer (Moore, 1996). Today, constructions practices are well known, embedded in Ramsey and Sleeper’s series of Architectural Graphic Standards (Ramsey et al., 2000). These long lasting reference books, developed by teachers at the New York Mechanic’s Institute for architectural draftsmen, captured both the building practices of the days and their appropriate representation, for the last 80 years. Updates and new version have been undertaken regularly, showing the evolution of standard construction practices over the last four decades. They provide detail regulations that prescribe what is within accepted practices and implicitly, what is outside. Their spanning tables for wood joists, guides for wood framing of different heights and stories, also reflect standard construction practices, although in a less deterministic manner.
Building codes closely reflect standard construction practices in the US and most other countries. Within the shared domain of standard construction practice, architects could define what is to be built simply by providing high-level direction of the extraordinary aspects of a design, without resorting to a complete coverage of all aspects of what was considered ‘common knowledge’. Reference in the contract documents to ‘standard construction practices’ was sufficient to address the non-specialized aspects of the design. As a result, any new construction method or material that is promoted for widespread use has as an initial challenge to gain acceptance within the various regional building codes.

Another dimension of buildings in the early half of the 20th century is that they were relative simple from a systems perspective. In the 1920s and 30s, for example, a major building could be construction by stone masons and carpenters, with a plumber and electrician (Kostof, 2000). It was only in the early 20th century that structures were quantitatively analyzed. Rise of more complex buildings, mechanical systems, communication systems, vertical circulation, fire safety etc. originated new forms of construction knowledge organization i.e. system building. During 1950's and 1960's, traditional construction techniques were systematized around factory-manufactured components and concepts like standardization, pre fabrication, modularization, quality control and dimensional coordination. Under the pressure of industrialization, this systematization process not only gave place to improvements in to traditional constructive techniques but also gave birth to new constructive systems. The massive post-industrial housing demand in the sixties provided an adequate testing bed for those
systems that became conventional to building production (Gann, 1996, Moore, 1996, Groák, 1992).

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, Gibb, 1999). Component-Assembly model refers to on-site assembly of components manufactured off-site, and constitutes a basic construction knowledge organization. Component-Based design uses that construction knowledge organization, and facilitates DfM implementation in building production.

3.3 Alternatives framework for DfM implementation in building production

3.3.1 Lean Construction is a design and construction management approach based on Japanese “lean manufacturing principles” that promote efficiency and reduces waste. Lean construction intends is to expand two main objectives; one is minimizing waste; and second maximizing value (Howell, 1999). Lean production management is implemented through the development of specific tools and techniques for lean construction project delivery. Lean production has made important improvements within the manufacturing industry and there is general agreement that increasing the amount of factory based

23 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, London ; New York, E & FN Spon. Page 174
manufacturing of buildings components, is a fundamental and logical method in incorporating lean production into building production (Salem and Zimmer, 2005).

3.3.2. Concurrent Engineering (CE) is a systematic approach to the integrated, concurrent design of products and related processes, including manufacture and maintenance. This approach considers the whole product life cycle from conception through recycling or disposal, including quality, cost, schedule, and user requirements. CE is a management and operational approach which main objective is to improve product design, production, operation, and maintenance by developing an environment in where all discipline experts (design, marketing, production engineering, process planning, and support) work together and share data along product life cycle (Anumba and Evbuomwan, 1997, Hartley, 1998).

Concurrent engineering (CE) can be adopted in the construction industry to provide an effective framework for integrating the construction process has led to various efforts to develop appropriate tools for its implementation in the industry (Evbuomwan and Anumba, 1998).

3.3.3. Teamwork organization is a management approach that is considered as an essential, component of companies’ decentralization. Introducing teamwork is not only about to reduce hierarchy but also to change it. This implies switching from giving and carrying out orders to agreement. This form of coordination can be described as discursive coordination. The teams are obliged to regulate their tasks and this self-regulation is a type of discursive coordination because it requires processes of negotiation and agreement between teams and their superiors as well as within teams. (Woodhouse and Nieusma, 1997, Walker and Newcombe, 2000).
Since these are approaches coming from the manufacturing industry, the main discussion around their implementation is in relation to adapting them to traditional constructive systems. Others see these approaches as fitting within an industry that is evolving from traditional practices to a model that is closer to the manufacturing industry (Best and De Valence, 2002). Nonetheless, these approaches constitute general framework or general objectives to pursue. Even though much work around these approaches has been devoted, few implementations are ready to use today. Additionally concurrent engineering is organized around the integration as main objective, but it is evolving around quite dissimilar implementation techniques and tools including DfM(Evbuomwan and Anumba, 1998)\textsuperscript{24}. On the other hand, lean construction fundamental dogma of "creating value while minimizing waste" constitutes a production objective that needs to be implemented at multiple level along the design and construction process. But mainly needs to be based on off site manufacturing(Pasquire and Connolly, 2002)\textsuperscript{25}. As we can

\textsuperscript{24} According to Evbuomwan concurrent engineering offers the potential for a radical transformation of construction into a more competitive, more efficient and more collaborative industry. To take advantage of this potential, there is the need for effective communication at all levels within the industry. He proposed a framework to integrate multiple aspects and technologies using the concurrent engineering approach. EVBUOMWAN, N. F. O. & ANUMBA, C. J. (1998) An integrated framework for concurrent life-cycle design and construction. Advances in Engineering Software, 29, 5587-597.

easily perceived DfM approach can be integrated within concurrent engineering as well within lean manufacturing. Teamwork organization is difficult to adapt to traditional construction in where management is highly centralized while knowledge is extremely disperse.

In the next chapter, three alternative ways to implement DfM in construction are presented and discussed.
CHAPTER 4

IMPLEMENTATION OF DfM IN BUILDING PRODUCTION

DfM in building production has one clear objective that is to improve buildability on designs without affecting design quality, and fulfilling design requirements. Nevertheless, implementation of DfM in building production can have two different motivations. One motivation is to address the design and construction of buildings and building components clearly outside of standard construction practices and the second one is to improve existing construction practices or existing building components. Improvements are obtained mostly by evaluating buildability in specific processes and components or by comparing buildability in alternatives processes or components. Summarizing, the definition of a process model that rationalizes, optimizes and facilitates the fabrication and erection of a new or existing building components are the essential goals of DfM in building production.

In the context of craftsman-based construction, there have been continuous cases of buildings using innovative construction practices, usually ties to some other forms of design innovation like the use of non-Euclidean geometries. Examples include the Sydney Opera House, in figure 4.1 (Murray, 2004, Tombesi, 2004), the TWA Terminal at Kennedy Airport in New York, in figure 4.2 (Stoller, 1999), the series of buildings by Frank Gehry, starting with the Guggenheim Museum Bilbao in figure 4.3 (Dal Co et al., 2003, Gehry, 1986), and the series of buildings by Norman Foster in figure 4.4 (Jenkins, 2005).
Figure 4.1 Sydney Opera House by Jorn Utzon

Figure 4.2 TWA Terminal by Eero Sarineen
Figure 4.3 Walt Disney Concert Hall by Frank Gehry Architects

Figure 4.4 City Hall London, UK, by Norman Foster and Partners
In each of these cases, the design was not based on standard construction methods and specialized methods had to be developed. In the first two cases, the costs and construction time were very high. In latter cases, the architects worked out the construction method as part of the design. This is the first way to apply DfM in construction: to define a process for fabrication and assembly of custom-designed components of a building that ultimately leads to the entire building fabrication process design. Each of these projects was considered unbuildable in their days, without the special planning inputs of the architect. In each case, the designer had to also plan the construction and to evaluate alternative designs and its buildability. The focus of this type of DfM is the definition of a systematic and clear process plan to show that the design is buildable.

A second way to implement is to apply DfM analogically to construction in order to improve productivity. This use of DfM applies rules regarding materials and fabrication practices to an existing process, subassembly or component, to systematically evaluate it and improve upon it in terms of cost, constructability, reliability or maintenance. This means using DfM to evaluate and assess buildability in a specific design or to compare buildability in alternative designs. Because most of these buildings are one-of-a-kind or bespoke type of buildings and most of building components are not reused in future building, there are only limited opportunities to refine buildability and to apply improvements.

Third type of DfM implementation is developing; large standard components or subassemblies; new prefabricated houses; new prefabricated units i.e.: bathrooms, kitchens, etc.; precast concrete construction and large steel assemblies. Most probably, this is the closest to manufacturing industry that construction industry has go until today.
Since these are large components with many parts, they are excellent candidates for buildability evaluation and later optimization using DfM (Fox and Cockerham, 2000). An excellent example in this type of application is the Japanese industrialized housing industry. Manufacturing principles derived from the car industry have been successfully used to produce attractive, customized and affordable homes see Figure 4.5 and 4.6. Some of these housing industries benefit by using advanced manufacturing techniques developed in other manufacturing industries (Gann, 1996). Toyota and Sekisui Heim are two of the biggest industrialized house companies in Japan. Toyota's largest housing factory produces 2000 houses per year. Toyota factory manufactures around 4000 component types for each house type. In doing that, Toyota makes use of production methods developed in Toyota’s automobile production system, including just in time production (JIT) and CNC fabrication. Each house contains around 30,000 items, including 700 different component types (Barlow et al., 2003). Other example is found in Sekisui House. This company produces around 20% and 25% of its houses' value within its factory. About 30% is produced by external suppliers. Site work reports for 20% of the house's value, and sales, marketing and management operating cost account for 25%. Sekisui House’s factory is the largest in Japan, producing 750 houses per month, employing 500 people (Barlow et al., 2003, Gann, 1996).
These previously proposed implementation criteria do not apply easily to traditional construction practices. Traditionally architects and contractors have accommodated late changes after construction begins, because they could do so. The predominance of such fabrication techniques as in situ cast-in-place concrete results in production adjustments as fabrication takes place, adjusting pour extents, lockouts and reinforcing. However, new construction practices are quickly making these practices obsolete, with the true cost of late adaptation being recognized and identified. These new construction practices are resulting of important changes in the building production. The changes include:
The use of parametric three-dimensional modeling as the representation of the building, defined as Building Information Modeling (BIM) (Eastman, 1999). The parallel move to component-based construction and moving to increased off-site prefabrication (Groák, 1992).

Building Information model (BIM) incorporation to building production could also be seen as knowledge integration approach in solving construction industry fragmentation. BIM provides means to support a very accurate three-dimensional integrated model to support design and integrated analysis and engineering. It also supports fabrication level models that integrate with CAM software and through it to CNC machinery. Additionally production management is supported through material tracking and production management software. With this integration, one-of-a-kind products can be produced with similar efficiencies as mass product products. This new approach is also being adopted in manufacturing, under the moniker of “mass-customization”.

Next section is initiated with a brief introduction to component-based design as context to DfM implementation in building production. Within this context, curved cladding systems are presented. These systems constitute the main interface for the component type that is subject to this study. In the next two sections, CAD and CAM implementation in architecture and the incipient use of CNC technologies in architecture is introduced as fabrication technology for the chosen component type. Closing the chapter a basic overview of curved surface's representation in geometric modeling is presented.
4.1. Component Based Design

As it was previously reviewed, traditional constructive systems were based on processes mostly performed on site with high labor use. Since industrial revolution, this model relying on handcraft started to be replaced by customization of previous experiences. In situ activity reduction, standardization and prefabrication of parts, and process mechanization, became the main characteristics of a new model on construction industry known as system building\(^26\).

Component based design has been part of the reality of industrial design for quite some time; their use in the production of buildings is not new but rather underutilized and misinterpreted under more general approaches as; standardization; modularization; and prefabrication. It is important to distinguish component-based construction from pre-fabrication. Pre-fabrication relies on mass-production of identical units, in where repetition is the basis of economy. On the other side, component-based production relies on mass-customization that minimizes the differential cost between standard component and made to order ones. Mass-customization is based on cost reduction of variation and customization using Computer Aided Manufacturing. Component based production of unique or tailored building components no longer require an increase in costs due to specialize labor or exceptional manufacturing techniques. (Kieran and Timberlake, 2004).

The origins of component based design can be traced back easily to ancient Greece and has been developed during several years. Recent archaeological reconstruction has shown evidence of component-based design in the Parthenon see Figure 4.7 and 4.8.

Figure 4.7 Misplacing of columnate parts at the Parthenon, Athens, Greece.

Figure 4.8 NC milled new column parts at Parthenon Restoration, Athens, Greece.
Consequently it is connected with the first steel frame buildings during the eighteen century (Groák, 1992). Menier chocolate factory see figure 4.9, Eiffel’s steel structures, and Paxton’s crystal palace are well-known examples, figure 4.10 and figure 4.11.

Figure 4.9 Menier Chocolate factory in Noisiel, France by Jules Saulnier


28 In the Eiffel tower case, all the 18000 components were manufactured in a factory outside of Paris, where Eiffel's company was located. Each component was designed and calculated, with an accuracy of a tenth of a millimeter. Three hundred workers on the building site performed the assembly. SNTE (2004) The construction of Eiffel's tower. http://www.tour-eiffel.fr.
Figure 4.10 Eiffel tower Paris

Figure 4.11 crystal palace Sir John Paxton
Later and after the second world war prefabrication movement in United Kingdom and subsequently in United States gave birth to the assembly component model (Sebestyén, 1998). During the sixties, prefabrication’s concepts were systematized, and they gave rise to “High Tech Architecture”, architects like Norman Foster, Renzo Piano and Richard Rogers are the best exponents of this style highly connected with component based design, see Figure 4.12 (Stacey, 2001).

Figure 4.12 Pompidou Center Paris, France by Renzo Piano and Richard Rogers

Summarizing component based design is embedded in a model of building production based on off site production of parts and components in factories and shops, according to design specifications and later taken into the site to form specific assemblies (Groáč, 1992). Within the building, different assemblies organize those parts and components. Parts are the basic units and together form components, components are arrangements of parts, and assemblies are arrangements of sub assemblies, parts and or components. Assemblies, subassemblies, components, and parts must include connections or joining systems. Connections or joining systems tie together parts and components, and also fasten together and secure assemblies. Design of pre manufactured components does not distinguish between the use of standard components and the design
of one of a kind component. Because of that, the term component-based design operates in at least three different approaches; standard components from manufacturer catalog; components as variation of existing ones; and unique or tailored components. In the two last cases is the designer, not the builder, who becomes responsible for the creation of drawings (now digital) that guide the manufacture of components for the assembly of buildings (Stacey, 2001).

The main advantage in component design approach comes from using a common partonomic structure for design and construction, i.e. "part of", or knowledge taxonomy. This shared partonomic structure makes easy to organize knowledge simultaneously at the design stage and at the production level, in this way design units corresponds to construction units. Nevertheless having this correspondence does not guarantee an adequate flow of knowledge along the building production process. In using digital fabrication, this knowledge flows from design to production in digital format. Accordingly, knowledge is encapsulated within and the work flow between two major technologies CAD and CAM. Within next section CAD and CAM use in architecture is presented as a way to understand how knowledge is represented and transfer from design to production of components.

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29 Stacey provides a description of component design and states the need for DfM use in architecture, see pages 1-12.
4.2. CAD and CAM Systems:

The information technology has stimulated design and formulation of a big number of CAD and CAM systems. It elaboration suppose a new conceptualization of our discipline knowledge, in a body of principles and regulations which commands the artifact’s design and its realization. This conceptualization prefigures and later commands the artifact construction, therefore this conceptual framework structures design information in specific ways. CAD systems demand a description of information and the storage of it in databases. This data is written and stored in binary code, but in order to easily manipulate and to build new set of parameters to determine new relations between data, representations are needed.

Each CAD system contains it own limits, which foreshadow the objects capable to be produced according to possible or legal functions included in each modeling interface. Object and space modeling provides a powerful analysis media of those entities and allow to analyze a certain number of elements, selecting appropriate criteria. Solid modeling systems are grouped according to methods that they use in representing its geometric components. The most common methods are constructive solid geometry

30 For the purpose of this research, a CAD system is a combination of hardware and software that allows three-dimensional modeling of physical artifacts, enabling engineers and architects to design artifacts from simple parts to airplanes. Consequently, a CAM system is a combination of hardware and software that enables engineers and architects to communicate work instructions directly to CNC manufacturing machinery. Accordingly, three-dimensional models of components generated in CAD systems are used to generate CNC code to drive numerical controlled machine.
(CSG) and Boundary representation (Brep) (Mäntylä, 1988). In addition, for describing curved surfaces most surface modelers use polygonal meshes or NURBS technology.

In the other hand, CAM systems traduce design information from CAD systems into different manufacturing routines in order to produce NC code for CNC machinery. Every piece of CAM software must first solve the problem of CAD data exchange where in the CAD system that is producing the data often stores it in its own proprietary format. Usually it is necessary to force the CAD to export the data using a neutral file extension like dxf, iges or stl formats that are supported by a wide variety of software. The output from the CAM software is usually a simple text file of G and M code, usually containing thousand of lines of code. Later this code is transferred to a machine tool using a direct numerical control (DNC) program. This translation process becomes extremely important in developing a DfM approach.

Other less known techniques in building production for transferring data from CAD to CAM systems are; feature recognition; and feature mapping (Shah et al., 1994). Although feature extraction algorithms have been improved, they are still inaccurate and incomplete (Shah et al., 1994). Because this method is a post process approach, feature recognition ignores original design intentions and makes impossible to provide with feedback to design stages. Even though many building components contains known manufacturing features like holes, pockets etc few CAD systems in use in building production makes use of them. Moreover, specific feature definitions for building production are evidently underdeveloped.

Nevertheless, complexity found in exchanging between multiple data formats in each application's viewport along the process became an independent issue along this
thesis. Early stages in form generation process are widely supported by a variety of file formats, from DXF and IGES to STEP part 203, being the last one specially suited for solid models but rarely used in building production. Currently STEP technology is better suited for NURBS surfaces parametric data, nevertheless in using NURBS as curved surface representation IGES is still the most popular exchange data format (Pratt and Anderson, 2000).

Once we transfer geometric data from a CAD system to a CAM system and manufacturing data needs to be produce, a bottleneck is found. Programming for CNC machine tools is normally done by using ISO 6983(G, M code). This standard dates back to the time of punched cards and does not cover the demands of modern CNC technology. Within several research projects, European industries and university institutes have developed AP-238, a new STEP-compliant programming interface, which is based on object-oriented data model, known as STEP NC or STEP-C-NC. While a part program according to ISO 6983 describes movements (G1, G2, G3) and switching instructions (M3, M8), the new AP-238 covers manufacturing plans and tasks and uses manufacturing features and tool paths. Programming with ISO 6983 results in huge programs, which are difficult to handle; last-minute changes or correction of machining problems on the shopfloor are hardly possible and control of program execution at the machine level is severely limited. Even worse, due to many different languages and vendor-specific add-ons to the programming language, part programs are not interchangeable (Newman et al., 2002). Even though STEP NC was not available in any of the applications used in this thesis, implications in how manufacturing knowledge is
organized within STEP NC turn out to be a key issue in developing the design for manufacturing model in this research.

In a wider perspective this research envisions a CAD system that supports automated reasoning and design generation process, which permits to advance through the different elaboration stages and design alternatives, in a process with permanent feedback from manufacturing and assembly alternatives. Given that curved surfaces fabrication using CNC technology is the main subject in this research, a basic overview of curved surfaces representation and CNC technologies used in architecture is presented next and expanded later in relation to the following technologies: two-dimensional cutting using laser cutter, three-dimensional printing using Rapid Prototyping technology and three-dimensional milling using 3-axis router.

4.3. Curved Surfaces Representation:

From decades architectural form generation was limited to Euclidean geometry constrains. It was not until 1868 that Beltrami proved that non-Euclidean geometries were as logically consistent as Euclidean geometry (Mlodinow, 2002). In three-dimensional space, there are three classes of constant curvature geometries. All are based on the first four of Euclid's postulates, but each uses its own version of the parallel postulate. The "flat" geometry of everyday intuition is called Euclidean geometry (or parabolic geometry), and the non-Euclidean geometries are called hyperbolic geometry.

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This is already available in some manufacturing areas, such as molded plastic design. For a comprehensive coverage of DfM applications in manufacturing industry see BOOTHROYD, G., DEWHURST, P. & KNIGHT, W. A. (2002) Product design for manufacture and assembly, New York, Marcel Dekker.
(or Lobachevsky–Bolyai-Gauss geometry) and elliptic geometry (or Riemannian geometry). Spherical geometry is also a non-Euclidean two-dimensional geometry (Weisstein, 2004c).

Even though curved surfaces were part of the architectural vocabulary, it use was limited by the lack of adequate representations to manipulate its geometry. Some of the remarkable exemptions are found in the work of Antonio Gaudi, Le Corbusier, John Utzon, and specially Frank Gehry in the last two decades. Most of these architects used extensive physical modeling combined with geometric analysis of curved surfaces. As an example, see figures 4.13, showing the use of spherical geometry in Sydney Opera Hall design by John Utzon.

Figure 4.13 Spherical geometry in Sydney Opera Hall design by John Utzon
Lately and because of the widespread use of solid modeling, a notable increase in the use of curved surfaces in architecture has been noticed. Designers considering curved surfaces perform Gaussian analysis of its curvatures, trying to reduce expensive to built-double curvatures. One common way to avoid double curvatures is using ruled surfaces. Consequently, designers can easily obtain accurate geometric definition and allowing the development of the curved surface as a flat shape. Curvature analysis and surface optimization according to desired resolution significantly affects manufacturing cost (Kalpakjian and Schmid, 2002)

4.3.1. Non-Uniform Rational B-Splines (NURBS)

Before computers, architects would draw their designs for buildings and the like by using pencil, paper, and various drafting tools. These tools included rulers and T-squares for drawing straight lines, compasses for drawing circles, circular arcs, and triangles and protractors for making precise angles. Of course, many interesting-shaped objects couldn't be drawn with just these simple tools, because they had geometries that were more complex. Frequently, a curve was required that went smoothly through a number of predetermined points. This problem was particularly important in boatbuilding: although a skilled draftsman could consistently draw such curves on a drafting table, boat builders often needed to make full-size drawings, where the sheer size of the required curves made drafting tables impractical. Because of their great size, such drawings were often done in the loft area of a large building, by a specialist known as a loftsman (Chapelle, 1941). As computers were introduced into the design process, the physical properties of such curves were investigated so that they could be modeled mathematically on the
computer. Curved surfaces by means of computers are produced using polygonal meshes or NURBS surfaces—as seen in figure 4.14.

Figure 4.14 Curved surface produced by polygons mesh on the left and NURBS surface on the right

Meshed surface constitutes collection of points that form polygons and most commonly triangles. Even though meshes are quite accurate describing curved surfaces, they need long processing time and large data storage space, especially when large mesh size or high curvature resolution is found.

NURBS, Non-Uniform Rational B-Splines, are mathematical representations of 3-D geometry that can accurately describe any shape from a simple 2-D line, circle, arc, or curve to the most complex 3-D free-form surface or solid. Because of their flexibility and accuracy, NURBS models are intensively used in process from illustration and animation to manufacturing. A NURBS (Non Uniform Rational B-Spline) surface is a mathematical model used for generating and representing the surface of a model. This model is continuous, as opposed to the discrete polygon model composed of triangles and vertices.

NURBS surfaces are the standard method for importing and exporting data to CAD, CAM, and CAE applications; with ‘IGES’ and ‘STEP’ being two of the most common file interchanges formats. Most applications can also accept polygon models,
often using the ‘STL’ format. In most cases, the need for using NURBS or polygon models will be decided by the downstream requirements and applications. NURBS geometry has important qualities that make it an ideal choice for computer-aided modeling (Farin, 1999):

There are several industry standard ways to exchange NURBS geometry. This means that designers are able to move their geometric models between various modeling, rendering, animation, and engineering analysis programs.

NURBS have a precise and well-known definition. The mathematics and computer science of NURBS geometry is taught in most major universities. This means that specialty software vendors, engineering teams, industrial design firms, and animation houses that need to create custom software applications, can find trained programmers who are able to work with NURBS geometry.

NURBS can accurately represent both standard geometric objects like lines, circles, ellipses, spheres, and tori, and free-form geometry like car bodies, human bodies or building components.

The amount of information required for a NURBS representation of a piece of geometry is much smaller than the amount of information required by common faceted approximations like polygonal meshes.

There are several NURBS surfaces generation methods and we included the most commonly found in solid modeling software; NURBS Surfaces from edges or Boundaries, lofting, sweeping, from revolving and from points. NURBS Surfaces from edges or Boundaries:
4.3.2. **Gaussian Analysis**

Since not all curved surface are possible to fabricate, is becoming extremely relevant to understand surface curvature in order to determine its manufacturability. The curvature $k$ at a given point on a curve, is defined by the expression $k=1/r$, where $r$ is the radius of curvature. According to its curvature $k$, curved surface can be classified as single curvature surfaces, double curvature surfaces, or compound curvature as seen in figure 4.15, next page. Single curvature surfaces have one directional curvature, double curvature surfaces have curvature in two directions and then can be synclastic if the principal curvatures are both of the same sign or anticlastic if the principal curvatures are of opposite sign. Compound curvature is found in combinations of the previous classes.

In order to examine surface curvature there are several different techniques being Gaussian analysis the most used one. Gaussian curvature is performed analyzing curvature in every point of the surface. Subsequently the data is represented in a graphic form projected over the curved surface as seen in figure 4.15, in the right column, next page. In the same figure green color represent Gaussian curvature 0, blue is Gaussian curvature positive and red represent Gaussian curvature negative. The Gaussian curvature of a regular surface in $\mathbb{R}^3$ at a point $p$ is formally defined as $K(p)=\det(S(p))$ where $S$ is the shape operator and $\det$ denotes determinant(Weisstein, 2004b). For Euclidean space, the Gaussian curvature is $K = 0$. For Gauss-Bolyai-Lobachevsky space, the Gaussian curvature is $k=-1/a^2$ (Weisstein, 2004b). A developable surface is the one on which the Gaussian curvature $K$ is everywhere 0 (Weisstein, 2004a). A surface on which the Gaussian curvature $K$ is everywhere positive is called synclastic, while a surface on which $K$ is everywhere negative is called anticlastic (Weisstein, 2004b).
Figure 4.15 Types of curved surface in the left column and its Gaussian analysis on the right.
4.3.3. **Surface Curvature Assessment for Manufacturing:**

Once surface curvature is clearly understood, in general some level of curvature manufacturability assessment is needed. This type of assessment is mostly driven by aesthetics, manufacturing and assembly considerations. An aesthetical concern typically refers to a desired surface curvature or a specific surface subdivision or panelization module. Manufacturing considerations refer not only to specific material properties, like material bendability and material strength, but also to specific manufacturing technology specifications, like work-piece minimum or maximum size and manufacturing cost.

NURBS surfaces since are parametric surfaces can be optimize managing its own parameters but in few cases they are used as direct input to CNC or RP machinery. Consequently, to be visualized, analyzed and manufactured, NURBS are subject of some discretization process. Normally they are tessellated and then visualized, analyzed or transformed into specific geometric or manufacturing data. In manufacturing is quite common to find tessellation procedures in where a three dimensional model is approximated by triangles or facets, sliced and then fabricated by using those slices as manufacturing data. However, the geometric descriptions used to represent objects in CAD systems significantly affects the accuracy and quality of the final parts produced especially in the case of curved surfaces. Once tessellated the surface is displayed as a set of patches. Various attributes can be set to control the display of the patches that represent the surface, including a specific face tiling size, face angle, or a maximum face edge size. Even though it involves some more complex considerations, curved surface manufacturability assessment process is commonly performed by tessellation first and then surface subdivision and or surface slicing.
CHAPTER 5

KNOWLEDGE BASED DESIGN

In implementing the DfM to building production it is important to consider that designers are required to properly structure design knowledge, to integrate manufacturing knowledge in design, to select adequate materials and processes, and to evaluate alternative design solutions in relation to its manufacturability (Shah and Wright, 2000). As we can perceive, DfM implementation in building production is a knowledge intensive approach and this chapter is dedicated to explore Knowledge Based Design approach.

According to Tomiyama\textsuperscript{32}, knowledge can be classified as recognized or unrecognized, codified or not codified. Unrecognized knowledge is related to skills and experience. Not codified knowledge is typical experienced based knowledge that is recognized and used by humans, but is very difficult to describe. Systemization of knowledge is a process in where recognized but not codified knowledge is transformed into recognized and codified knowledge (Vliet et al., 1999). Experienced based Knowledge can be stored declaratively as facts or procedurally as courses of action. Used forms of representation are rules, predicates, frames, associative networks, model-based reasoning, case-based reasoning, qualitative reasoning, temporal reasoning and artificial neural networks (Vliet et al., 1999).

Concurrent engineering, teamwork organization and expert advice approaches rely on tacit knowledge coming from shared or individual expertise, which is difficult to transfer or reuse in future experiences. Since every building is context specific and frequently designers, contractors and sub contractor teams change on each building; the intent, knowledge and reasoning used to produce the building is lost (Evbuomwan and Anumba, 1998). Subsequently the attempt on this thesis is twofold. One is to realize a process to capture and organize manufacturing knowledge, and second to organize that knowledge and make it available as a DfM model for component design using specific CNC technology. In that context, the process of design generation was characterized as being reliant on knowledge transformation process based on specific design strategies or alternative combination of them (Eastman, 1968). This sort of reasoning is concerned with making judgments and decisions using incomplete or uncertain knowledge of the domain, knowledge that has been derived from experience of that domain. This type of experience-based, is often defined as heuristic knowledge (Inhelder, 1983).

5.1. Design Knowledge

Design is a cognitive process that consists of consensual production of meaningful artifacts through a knowledge capture, manipulation and communication process (Lyon, 2005). Designers investigate certain topics and through them artifacts are; composed; decomposed, analyzed; and built. Those topics establish the design knowledge. Furthermore, the architectural design process is also a negotiation process.

33 Evbuomwan refers to design intent, design knowledge and design rationale
between multiple actors and several related aspects flowing together into an artifact conception-elaboration process. Design process consists of the transformation of concepts and relations of high abstraction into artifacts with a high level of physical complexity. The parameters needed to guarantee design process coherence are many; while its conception mechanisms remains ignored (Lyon, 2006a).

Design knowledge can be classified in two major classes; declarative knowledge; and procedural knowledge. Declarative knowledge similar to description corresponds to knowledge of objects and events and how these are related to other objects and events. On the other hand, procedural knowledge is about tasks that must be performed to reach a particular objective or goal, and it is characterized as knowing how. Procedural knowledge is often difficult to verbalize and articulate than declarative knowledge. For the purpose of this research three categories of general design knowledge are presented:

- **Object knowledge**, knowledge on the characteristics and properties of components and their materials
- **Manufacturing knowledge**, knowledge on the various manufacturing processes, plans and steps to be used to realize designed components
- **Process knowledge**, knowledge about the characteristics and properties of design for manufacturing processes, which can be used to produce a DfM model.

The identified types of design knowledge concern entities, functions, attributes, topologies, relationships and manufacturing methods. Especially the relationships between entity, function, attributes and manufacturing method are important in building production (Pulaski and Horman, 2005). Even though design repertoires contain these three types of general design knowledge. Architect’s knowledge repertory consists predominantly of object knowledge (Goldschmidt, 2003). In addition, some realization knowledge, which will be used to realize their designs, is also found (Aken, 2005). This knowledge is commonly found as part of conventional constructive systems. This recognized and codified knowledge has low potential to be taken into account at component design, like in Design for Manufacturing. Additionally it may contain only a limited amount of explicit process knowledge. Most designers obtain their realization knowledge by their own experience and by reusing it from previous realization processes for that reason design knowledge is characterized of being dynamic, unstable, subjective, incomplete, and conflicting in nature.

Process knowledge from realization tends to remain largely tacit; often designers find it difficult to define their approach to realizing its designs. Consequently, next section is focused on manufacturing knowledge as fundamental knowledge to incorporate into design process to improve buildability of building components.
5.2. Manufacturing Knowledge

In traditional design process, after design has been made, the artifact in question has to be realized through a manufacturing process. Even though the selected manufacturing approach is considered to be a feature of design, often that process is completely ignored until manufacturing. In building production, fabrication process is already present as conventional constructive systems that can be applied to or adapted to new design. As we reviewed in previous chapter, constructive process may be the result of historic evolution of traditional practices and techniques, but nowadays can also be the result of an explicit and unique fabrication approach (Kolaveric, 2003, Schodek et al., 2004, Chaszar, 2006). Such fabrication plan is often made as a variant of an already existing manufacturing processes or a combination of them (Kulon et al., 2006, Schodek et al., 2004). The fabrication approach, mentioned above, is organized around two basic knowledge categories; knowledge about materials (declarative knowledge); and manufacturing processes knowledge (procedural knowledge). Material knowledge refers to material and its properties. The most relevant material properties are mechanical, physical, chemical and these ones define the manufacturing properties. Manufacturing process knowledge specifies the nature of the various manufacturing processes and the equipment used in each one, and predetermines the specific conditions in each of these processes. This manufacturing knowledge is organized around manufacturing plans, manufacturing steps, manufacturing features, tool paths and fixtures (Rosso et al., 2002).

5.3. Knowledge acquisition techniques:

At this point, once a knowledge based design approach and the types of knowledge needed have been described, it is necessary to explain how this research will
obtain that knowledge. Therefore, it is necessary to introduce some formal, consistent method of capturing that knowledge. Knowledge acquisition is a process of acquiring problem-solving knowledge from human experts, literature, computer files, and other knowledge sources. Knowledge acquisition has been recognized by researchers as the key bottleneck in the development of knowledge based approaches. Knowledge acquisition is an expensive and time-consuming process, and good knowledge engineers are hard to find. In addition, knowledge engineering expertise is not well structured (Potter et al., 2003).

Mainly building production knowledge is obtained from literature, and from design expertise, but is far from satisfactory. Literature in the field tends to be too technical either being just information referring to a conventional construction system or to a specific manufacturing process. Another drawback is how knowledge is represented in building production. Frequently construction knowledge is presented in the form of tables and manuals, or oriented towards construction management and not very useful for production (Groák, 1992). Finally and as mentioned previously capturing knowledge from experts, a task normally performed by a knowledge engineer, has important disadvantages. 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). Nevertheless when there are identifiable experts in an area, then the expert knowledge approach is

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35 Groák discusses extensively the issue of production knowledge in building production in chapter 11; 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.
valid and has been used with success (Woodhouse and Nieusma, 1997). When the area is ill defined, as DfM in building production is, then other approaches, such as learning by doing, are valid. Subsequently a different source of manufacturing knowledge would be of immense benefit to the development of DfM model. Accordingly, the alternative method used in this research is to inquire students directly using structured design ‘‘experiences’’ for capturing manufacturing knowledge (Potter et al., 2003)\(^\text{36}\). In the context of this research, design experiences with students include a design problem specification and the corresponding design solution (Potter et al., 2003)

As mentioned before, DfM is a design approach that incorporates manufacturing knowledge in design stages (Fox et al., 2001). Within DfM approach it is important to properly organize and represent manufacturing knowledge. Allowing designers not only to select adequate materials, processes and components but also to evaluate components manufacturability (Shah and Wright, 2000). Consequently, our next section presents design heuristics and design metrics as way to systemize manufacturing knowledge in where recognized but not codified manufacturing knowledge is transformed into recognized and codified manufacturing knowledge in the form of design heuristics and design metrics.

\[\text{36 Stephen Potter et al. proposed this alternative way to capture heuristic based on design experiences in the form of a design specification and the corresponding design solution contain the information necessary for deriving the appropriate heuristic knowledge. in YIN, R. K. (2003) Case study research: design and methods, Thousand Oaks, Calif., Sage Publications.}\]
5.4. Design Heuristics

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). Design heuristics provide a framework for solving the design problem in contrast with a fixed set of rules 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 in using component based design.

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.

5.5. 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.

Maybe these design heuristics and design metrics may sound atypical to our field, but we have several of them that are of similar in nature for example a design metric in staircase design is “twice the rise plus the going must equal between 550 and 700 millimeters” (Fox et al., 2001).

In the next chapter, research methodology used in the thesis is described. It mainly include a general research methodology description, based on a research philosophy, which guides alternative research approaches and uses different research techniques, all of them described along the chapter.
CHAPTER 6
RESEARCH METHODOLOGY

In the initial section, the research introduces a general research approach. Within that framework, the author then presents the research philosophy, approaches, and techniques in the form of a research framework. Afterwards, the author introduce case study research strategy including; case's design strategies; alternative data sources; and analysis of evidence. The initial intent in this research was to use a research approach that was supportive to issues under examination, in effect to adapt the research approach to the research problem, and not the research problem to the research approach. The availability of that flexibility was crucial in choosing the case study approach. A case study in research is a research strategy, equivalent to an experiment, historical record, a prototype, or an event simulation, although is neither related to a particular type of evidence nor to a specific data collection methodology (Yin, 2003). Furthermore, it was appreciated that different types of issues would be encountered during the development of the research, and that these often-dissimilar issues would be best tackled by different research techniques (Groat and Wang, 2001).

37 Case study is a valuable method of research, with distinctive characteristics that make it ideal for many types of investigations. It can be used in combination with other methods. Its use and reliability should make it a more widely used methodology, once potential researchers had better understand its features. For a more in depth revision see FLYVBJERG, B. (2006) Five Misunderstandings About Case-Study Research. Qualitative Inquiry, 12, 219-245. and YIN, R. K. (2003) Case study research: design and methods, Thousand Oaks, Calif., Sage Publications.
In the final section, I introduce the process model used in this thesis as theoretical proposition. The model is not to be pursued or presented as an algorithmic approach, but rather than that it shows how different stages in a DfM approach would have to be connected, how one design decisions would lead to another, and what kinds of aspects of the problem are relevant in improving component manufacturability. Accordingly the proposed model meant to be use not only to improve manufacturability in a specific building component design but also to allow alternatives component and or manufacturing process evaluation. Even tough the real potential in the model resides in its use as analogical thinking device in approaching other DfM teaching approaches.

6.1. General research approach

The author developed an overall research framework to provide the necessary contingency-based, but integrated, research methodology. The research framework purpose is to accommodate differing research objectives in a coherent and consistent way. This research model is based on a general research philosophy that guides alternative empirical research approaches, and uses different research techniques, see Figure 6.1.

![Figure 6.1: Research framework.](image)
Research approaches consist of the dominant theory generation and testing methods, and research techniques comprise data collection tools (Groat and Wang, 2001). This research uses an empirical research approach, in which a pre-understanding and understanding cycles of research issues are developed through experienced based learning, along the process theoretical proposition are tested and improved (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. In addition, the researcher has some initial level of understanding gained through their familiarity and experience with the phenomenon, which allows him to interpret meaning in context and in relation to the situation. (Odman, 1997, Leonard, 1994)

6.2. Case study research approach:

Not using large samples and avoiding rigid protocols to examine a limited number of variables, case study method consists in an in-depth examination of a single instance or event or a sequence of them that constitutes or appear like a phenomenon or process i.e.: a case. The method can provide a systematic way of looking at events, collecting data, analyzing information, and reporting the results. As a result, the researcher may obtain a better understanding of why the case evolved as it did, and which are the issues to look at more extensively in future research. Case studies may lead to both generating and sometimes to testing hypotheses (Flyvbjerg, 2006).

A case study can also be defined as an empirical inquiry that investigates a phenomenon within its real-life context (Yin, 2003). Case study research can comprise single and multiple case studies, can include quantitative evidence, relies on multiple sources of evidence, and benefits from the prior development of theoretical propositions
like a methodology, a model, or a theory. Yin states that case studies should not be
confused with qualitative research and points out that they can be based on any mix of
quantitative and qualitative evidence\(^3\) (Yin, 2003).

6.3. Designing the Case Studies

There are multiple suggestions for a general approach to designing case studies,
and recommendations for exploratory, explanatory, and descriptive case studies\(^3\) (Yin,
2003). In this research, the approach was to use both exploratory and explanatory case
studies. Along the research, the author developed multiple-case studies, most of them
were replicatory, and not sampled cases. In both cases either explanatory or exploratory,
the author defined research questions and hypotheses before fieldwork, and data
collection. Since these were complex and multivariate cases, evidence analysis that the
author performed was strictly in relation to the main research objectives i.e.: to test the
proposed DfM model and to refine it by extracting manufacturing knowledge from the

\(^3\) Some researchers suggest that if case studies were conducive to statistical analysis,
the process would be easier and more adequate. Nevertheless, not all case studies are well
suited for statistical analysis. Alternatives analytic techniques such as rearranging the
arrays, creating a matrix of evidence categories, creating process models, flowcharts
or data displays, tabulating events’ frequency, using means, variances and cross
\underline{tabulations} to examine variables’ relationships, and other techniques to facilitate case
studies data analysis in FLYVBJERG, B. (2006) Five Misunderstandings About Case-

\(^3\) In exploratory case studies, \underline{fieldwork}, and \underline{data collection} may be undertaken prior
to definition of the \underline{research questions} and \underline{hypotheses}. Exploratory cases are suitable
for doing \underline{causal studies}. In complex and \underline{multivariate} cases, analysis can make use of
design experiences. Subsequently case evidence analysis was fundamental in determining critical aspects in the DfM model; how different stages in a DfM model would have to be connected; how one design decision would lead to another; what kinds of aspects of the problem are relevant in improving component manufacturability; and last but not least how design decisions are linked to component manufacturability.

6.4. Analyzing Case Study Evidence

In this research, the author used alternatives analytic strategies. The most important one was to create a process model, second was paying special attention to manufacturing errors as well as to manufactured product deviation from design intent. Third analytic strategy was to map relations between design decisions and relevant manufacturing variables. The author also used other techniques to better represent the issues under scrutiny in order to map them during the process, in order to facilitate case studies data analysis.

40 Once the relevant knowledge has been obtained, it needs to be represented and encoded within the model. The model needs to represent knowledge in some formal manner, which is comprehensible to the designer and transferable to the specific case. Perhaps the most common way of encoding explicit design heuristic knowledge is in the form of design rules or guidelines, the drawback in this approach is design rules represent action to be taken but they neither represent or encode reasoning behind nor the information necessary to perform those actions.

41 Accordingly, in the explanatory case studies, and within the structured design experiences with students in particular, I defined a case-study protocol including the following aspects; project’s framework; project’s overview; process procedures; questions; and project report.

42 Case study research identified at least six sources of evidence in case studies; Documents; Archival records; Interviews; Direct non-participant observation; Participant-observation; and Physical artifacts in: POTTER, S., CULLEY, S. J., …
Unavoidably there must be an analytic strategy at the macroscopic level, that will lead not only to general conclusions but also to frame microscopic level analysis. In this research, that strategy was to rely on theoretical proposition i.e.: the DfM model in the study, and then to analyze the evidence under that theoretical framework. Still at the macroscopic level, but at the case level, the strategy was to use an accurate case description that provided a framework for organizing the case study. Within the case, the researcher used what it is known, in design research, as structured design experience. At the microscopic level pattern-matching is another major mode of data analysis used in this research used primarily for matching design intent against actual product. This type of logic compares an empirical pattern with a predicted one. Internal validity is enhanced when the patterns coincide. Within this research, special attention was given to improvements in manufacturability aspects out of specific design and manufacturing variables previously defined within the DfM model. An additional pattern matching approach also used in this thesis was to map manufacturing errors as undesired patterns, and to connect them to design decisions as dependent or independent variables.

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44 If the case study is an explanatory one, the patterns may be related to the dependent or independent variables. If it is a descriptive study, the predicted pattern must be defined prior to data collection in LEE, J. (1997) Design Rationale Systems: Understanding the Issues. IEEE Expert, 12, 78-85.
Next section describes the process model used in this research and explains how relevant knowledge is represented and encoded within the DfM model.

6.5. DfM model as theoretical proposition

The DfM model proposed in this research is a process model. And is based in two basic design strategies; first a process description that represent an advice for making design decisions in the form of a design strategy i.e. a sequence of procedures that can be repeated and transferred; and second, the implementation of design heuristics that integrate production knowledge and the availability of some design related to production evaluation metrics. The key idea is that design is a continual inquiry process, in which the designer performs actions in the form of design strategies based on design knowledge availability. Nevertheless, the rationale behind theses design strategies is commonly ignored. The types of rationale that I looked in this research were not only about what type of design strategies were used but also what aspects were relevant in design decisions, and resolutions of manufacturing issues (Burge and Brown, 2000).

Accordingly in capturing manufacturing knowledge in the form of design heuristics and metrics from teaching experiences allows me to enrich the model with knowledge not only about what is being designed but about also how it will be produced. As summary within the model procedures are not only the deployment of observable design strategies i.e. design history but also the inclusion of relevant aspects of those

45 Design Rationale is the collection of reasons that lead to the design of an artifact i.e. why an artifact was designed the way it was BAPTISTA, R. & SIMOES, J. F. A. (2000) Three and five axes milling of sculptured surfaces. Journal of Materials Processing Technology 103, 398-403.
actions for the designer i.e. design rationale. In addition the model’s objective is not only to provide designers or students with a framework to be use as a step by step DfM guide but also to use the model as a analogy to create other DfM models or other DfM teaching approaches. As a summary the model represents a process that it is there to understand or to find out about some other processes, with which it is not identical.

It is important to realize that design strategies, design heuristics and metrics are the main components within a DfM model but they do not constitute the model. It is the knowledge that is encapsulated in the model what really constitutes the model. Nevertheless, this knowledge of how to perform the task and indications about the relevant knowledge to perform it effectively is precisely that heuristic knowledge that is required for a DfM approach. Consequently design strategies; design heuristics and metrics within the model are guidelines representing design experiences and best practices.

Next chapter introduce research organization and each research stage including techniques used in its implementation, evidence analysis and graphic description from the process.
CHAPTER 7

RESEARCH ORGANIZATION

In this chapter the author initially exposes research phases and outlines its development through cycles in an organizational diagram. Within that diagram, the research presents three research stages. An initial research stage was based on semi-structured and non-participant teaching experiences with students. As result of the initial research stage, I proposed an early DfM model. At the second stage of the research, the initial DfM model was tested and refined through a sequence of case studies. In the final stage of the research, a refined DfM model was evaluate and further develop in a component design case study[^46]. Finally, in a closing section I present an introduction to each research stage including techniques used in its implementation and graphic descriptions of the whole process. Nevertheless in the next chapter I will present a more in deep coverage of cases studies that were 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, during the spring semester of 2006. After that chapter there is an additional one that covers the case study that is based on producing a component for an existing wall system

[^46]: This case study is based on producing a component for an existing wall system. The component was conceived as a wood curved module for a wall system, fabricated using three axes CNC router. 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.
The author organized this research chronologically according to stages, and operationally in relation to research context and research implementation. Consequently, this research was performed along three research stages each one developed in a specific research context and implemented through a series of case studies including the use of alternative research techniques. After the initial research stage a DfM model is produced and is updated after each of the next research stages as seen in the organizational diagram in figure 7.1.

Within that diagram vertical columns shows, from left to right; research stages; research context; research implementation; and research techniques. Research stages correspond to three major research steps and they are chronologically organized from top to bottom, as follows; an initial stage denominated pre-understanding, a second one denominated understanding and the final stage. Next column is research context and correspond to the context in where the research was developed, in this research this context refers to specific academic environments. The third column corresponds to research implementation and relates to the type of research strategies used in each stage. Finally, the last column refers to research techniques and is there to describe data collection and analysis used in this research. These techniques are especially relevant since the objective of data collection is not statistical analysis but knowledge capture. So were not collecting just data I am capturing process knowledge to produce and enhance a process model and knowledge that links design decisions with relevant manufacturing aspects.

47 The diagram is organized chronologically from top to bottom and operationally from left to right. Numbers in parenthesis indicates number of cases developed and the number of participants in each case.
Figure 7.1: Research Stages Organizational Diagram

INITIAL STAGE:
Pre-understanding
2004-2005

RESEARCH CONTEXT:
COA 8833:
The Design of Digital Manufacturing
Monica Ponc de Leon
Eduardo Lyon

RESEARCH IMPLEMENTATION:
One guided explanatory case study (12/1)
Three exploratory case studies (3/4)

RESEARCH TECHNIQUES:
Semi-structured interviews
Structured non-participant observations
Content analysis

SECOND STAGE:
Understanding
2006

COA 8803:
Design for Manufacturing: Curved Surfaces Fabrication using CNC Technology
Eduardo Lyon

Three guided explanatory case studies (3/1)
One guided exploratory case study (1/1)

SECOND DIM MODEL

STRUCTURED DESIGN EXPERIENCES
Structured questionnaires
Semi-structured interviews
Structured non-participant observations
Content analysis

FINAL STAGE:
CASE STUDY
2006-2007

RESEARCH CONTEXT:
CASE STUDY:
Graph System by Fry Reglet
Eduardo Lyon

RESEARCH IMPLEMENTATION:
One explanatory case study (1/1)
One exploratory case studies (1/1)

RESEARCH TECHNIQUES:
Structured participant observation
Content analysis

FINAL DfM MODEL

FINAL DfM MODEL
The initial stage in this research is defined as pre-understanding, and after it, I obtained a tentative DfM model from teaching experiences\(^{48}\). In the second stage that I denominate understanding, I test and refine the DfM model through a sequence of case studies using structured design experiences\(^{49}\). Accordingly, the author derived design heuristics and design metrics from students using structured questionnaires. 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. Knowledge acquisition to improve the DfM model was accomplished by capturing new design heuristics and metrics. Both were determined based on the design

\(^{48}\) That first DfM model was developed after teaching experiences in the course “The design of digital manufacturing”, directed by professor Monica Ponce de Leon and co-taught by the author in between Fall semester 2004 and Spring semester 2005. Within that course, one guided explanatory case study and three exploratory case studies were conducted. Structured non-participant observation was used to determine DfM model applicability and efficiency.

\(^{49}\) The general purpose in performing these case studies is to test the proposed DfM model. The second objective is to refine the DfM model by deriving knowledge from the design experiences to improve it. These design 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.
history and its rationale. In fact, this is the type of evidence analysis commonly found in DfM literature (Boothroyd et al., 2002, Fox et al., 2001, Pasquire and Connolly, 2003).

The final objective of the research is to produce a DfM model that allows designers not only to review and improve manufacturability of specific architectural components but also to provide a framework for teaching DfM approaches. In addition, the DfM model provides a framework not only to structure the case studies along the research development but also to organize design heuristics and design metrics obtained from case studies sequence. Finally, the proposed DfM model is not about how DfM must be done. Moreover this model is more a reflection about the nature of design processes and looking for alternatives to increase the integration between design and construction in building production. We are entering a new epoch in architecture, where we are explicitly concerned with not only the form and function of architecture, but also how it is produced and this requires new methods of design and also of education.

7.1. Initial stage (pre-understanding)

The initial DfM model, and the process of capturing heuristic knowledge and design metrics to improve it was initially performed by the author as part of his doctoral research and presented at eCAADe 2005 conference, in Lisbon, Portugal (Lyon, 2006b). This initial research stage, and in specific, the DfM model obtained from it, was develop after teaching experiences in the course “The design of digital manufacturing”, directed by professor Monica Ponce de Leon and co-taught by the author. Teaching approach was explicitly oriented towards a clean-cut division between design and fabrication. Even though much attention was given to fabrication issues in the class, those aspects were presented as independent from design decisions. Consequently, students were instructed to design first and then to fabricate those designs. At any point during design phase, the
teaching approach asked the students to realize a process to manufacture their designs. Accordingly making correlations between manufacturing errors and design decisions became difficult, even though there were plenty of them. In addition, design intent differs dramatically from manufactured artifacts in some of the teaching experiences. Within that course, twelve students developed one guided explanatory exercise and three exploratory exercises. The guided experience uses CNC milling, foam as material, and consisted in designing a modular drawer and it is presented in Figures 7.2 to 7.5. Each of the three exploratory cases consisted in an installation part of the building at the College of Architecture in GaTech. Each case was related to a specific material and was developed by a five-student team. The first one uses acrylic as material and CNC cutting and heat forming as manufacturing processes. The case study is presented in Figures 7.6 to 7.12. The second case study uses wood as material and CNC cutting as manufacturing process. The case study is shown in Figures 7.13 to 7.23. Last case study uses aluminum as material and CNC cutting and manual bending as manufacturing process. The case is shown in Figures 7.24 to 7.29. In these teaching experiences, it was not possible to structure a DfM approach. Because of a clear-cut division in between design and manufacturing that was presented within the teaching approach. Nevertheless the teaching experiences were very useful in realizing non traditional manufacturing processes implementation, uncovering manufacturing errors coming from poor design decisions and in determining knowledge types that became relevant for the DfM model development.
7.1.1. First case study: Foam CNC milling:

The first teaching experience used CNC milling involved twelve students, each one designed a modular drawer, using foam as material. Material and manufacturing processes was defined in advance, and students received training in CAM software and NC code writing.

Form generation process was implemented using NURBS surface generation through lofting as seen in figure 7.2.

Figure 7.2: Digital three-dimensional model by Huzefa Rangwala.
Alternative curves combination in generating the surface was useful to study alternative modules or variations as seen in figures 7.3 and 7.4

Figure 7.3: Digital three-dimensional model by Huzefa Rangwala.

Figure 7.4: Digital three-dimensional model by Huzefa Rangwala.
Each of twelve students manufactured a foam module using an SCM Ergon 3 axes CNC router under operator supervision. Additionally an independent programmer checked code, in order to avoid machine damage. Few manufacturing errors were produced, and most similar i.e.: surface curvatures that were not possible to machine because of surface angle being out of router tolerances. A workaround for this problem is to machine the module with an angular inclination, using a jig or angled support. The CNC operator defined surface finishing to reduce machining time. Adequate surface finishing demanded long machining time and large pieces of code. Occasionally the computer controlling the CNC router was not able to manage large amounts of NC code. Other than surface finishing issue\textsuperscript{50}, design intent was consistently achieved.

\textbf{Figure 7.5: Foam prototype using 3-axis CNC router by Huzefa Rangwala}

Even though in the previous teaching experience was successful in relation to little manufacturing errors and accomplishing design intent, this was not the situation in all the three exploratory case in where a clear cut division in between design and manufacturing was presented within the teaching approach. Next teaching experience consisted in an installation part of the College of Architecture building at GaTech. Each case was related to a specific material that was assigned to a five-student group.

**7.1.2. Second Case Study: Acrylic wall using CNC cutting and heat forming**

The first group one uses acrylic as material and CNC cutting and heat forming as manufacturing processes. The installation consists of a modular wall system. Each module was fabricated out of a variation from a forming die made out of thirty MDF interchangeable slices. The standard profiles were defined at the design stage in the form of a grammar consisting in 30 shapes to produce 80 panels—as seen in figure 7.6 and 7.7.

![Shape Grammar for heat forming die by Tristan al Haddad et al.](image)

**Figure 7.6: Shape Grammar for heat forming die by Tristan al Haddad et al.**
Figure 7.7: Digital three-dimensional model by Tristan al Haddad et al.

The evident connection between design units and fabrication units made this case one of the most successful ones. Each module was cut out of green acrylic panels using three axes CNC router, and then attached to the MDF forming die and vacuum-heat formed. The wings that finally form each module box were bent immediately after the heat forming process, along bending lines previously marked using the CNC router. The wall system also includes a connection system not only to attach one piece to other but also to attach the system to the building according to requirements\textsuperscript{51}. 

\textsuperscript{51} GaTech building department required the installation to be temporary. Accordingly, a connective system needed to be in place, without having major changes in the existing building structure.
Even tough the heat forming process—in figure 7.8—helped in the consecutive bending process the lack of bending allowances made the bended wings uneven after the bending causing the only manufacturing error in the process—as seen in figure 7.9. Unfortunately, this small error has some important implication in two directions one weakening the joint in each module box. Second misalignment between modules is found in all pieces. Exhaustive numbering and layout organization allowed a smooth assembly and disassembly process.

Figure 7.9: Bending error correction using bending allowance.
Figure 7.10: Acrylic module ready for assembly by Tristan al Haddad et al.

Adequate combination of manufacturing processes and a modular design based on variation of standardized profiles allowed a very successful solution—in figure 7.10 to 7.12. High price in module and connection systems materials were some of the few negative aspect in the installation. Overall design and manufacturing was clearly assumed as one process from the beginning and performed completely based on digital information. Authors’ pre-existing manufacturing knowledge contributes to smooth the realization process.
Figure 7.11: Acrylic modular wall by Tristan al Haddad et al.
Figure 7.12: Acrylic structure by Tristan al Haddad et al.
7.1.3. Third Case Study: Wood structure using CNC cutting:

The second case study uses wood panels as main material and CNC cutting as manufacturing process. The original design was obtained as a NURBS surface and sliced to obtain the 80 unique profiles—in figure 7.13. Each profile was offset and then divided in 10 parts. Students manufactured around 1000 wood parts. Each part received a part number and a location letter after that they were nested manually in sixty 4”x8” wood panels. After that, they were cut in a Morbidelli Pratix three axes router. The case presented multiple manufacturing errors most of them unable to be detected until assembly. The first error was that curve resolution was not set properly in transferring from NURBS in to DWG profiles, producing excessive number of segments and by result long machining time.

Figure 7.13 Digital three-dimensional model by Paul Heret et. al.

Figure 7.14 Elevation and section by Paul Heret et. al.
Second error was that part size was determined ignoring material size producing excessive material waste. Another error is coming from poor joint design. Two independent systems were in place; one vertical joining parts forming each rib; and a second horizontal to align the pieces and produce openings in the surface. Alignment between the two was poorly design, especially over curved sections see figure 7.15 and 7.16.

Figure 7.15: Joining systems; horizontal on the left; and vertical on the right.

Figure 7.16: Joining systems; horizontal on the left; and vertical on the right.
The previous situation, combined with drilling operations manually performed, caused slight but regular misalignments along the ribs. Additionally, the vertical connections between curved ribs portions, in the second level, was completely flawed, being necessary to remove it and replace it with aluminum connectors. Even though the problem was caused by ignoring the existence of a two-dimensional curvature and just propagating the connection solution, obtain from one of the curves, along all the other ribs. See figure 7.17 and 7.18 next page.

Figure 7.17: Assembly errors in project by Paul Heret et. al.
Figure 7.18: Connection error and proposed correction.

The real issue in here is again the lack of and adequate representation of the problem and overall absence of a process framework. Finally, there was a tight fitting between each rib and the textures in the building, errors in measuring building surfaces required reworking the entire production drawings set. All over the process is possible to find the important repercussion in using two-dimensional representation of highly complex three-dimensional problem. Besides the previous nesting was done manually making it far from optimum, in figure 7.19.

Figure 7.19: Component nesting layout by Paul Heret et. al.
Overall, most of the errors were coming from early abandon of the three-dimensional model as design representation and continuing working based just in two-dimensional profiles. First, those lines were extracted from the NURBS surface as profiles through sectioning. Then they were offset in a two-dimensional CAD system and then transfer as two-dimensional shapes in to a CAM system.

Regardless of the amount of errors, design intent was accomplished. But time committed to rework of drawings was disproportionate. Overall design and manufacturing were clearly assumed as two processes from the beginning and performed completely based on two-dimensional digital information. In defining profiles, from early design stages supposed to made easy the production process flow. However, not having a comprehensive process framework i.e.: a process model; a more complete representation of the issues being solved i.e.: three-dimensional model; and a basic definition of components i.e.: wood ribs and its connections, made the process time consuming. Especially in the way that problems were solved at the time that they appear. Some of them showed up at the manufacturing process but most of them were visible at the assembly process, when was too late to fix them. In addition continuous changes, miss measurement, errors along the process and problems with file transfers make the production process extremely difficult. Comprehensive numbering and layout organization allowed easy part identification for assembly. Use of scaled models and mock-ups helped students realize about design issues along the process. Unfortunately models were at small scale and unable to make problems evident and part prototype when they were big enough they ignored most of the relevant manufacturing aspects focusing just on design issues, as seen in figure 7.20.
The joining system between parts was poorly designed. However, very different was the case with the connection system with the building that was successfully achieved—as seen in figure 7.21.

Figure 7.21: Connection system by Paul Heret et. al
Figure 7.22: Wood structure by Paul Heret et. al.
Figure 7.23: Wood structure by Paul Heret et. al.
7.1.4. Fourth Case Study: Aluminum canopy using CNC cutting:

Last case uses aluminum as material, CNC cutting and manual bending as manufacturing processes. In this case, students defined design intent early in the process through a series of scaled models, first in heat-formed acrylic, then paper and finally plastic—as seen in figure 7.24. After that, they generated a three-dimensional model using NURBS. Later they regenerated the three-dimensional model in a CAM system, in order to accommodate material and manufacturing process constrains. From the design point of view the most important drawbacks were absolute lack of a structural and manufacturing issues at the conceptual design stage and the excessive preponderances given later in design development stage to part design i.e.: aluminum bent strip. This causes that design intent evidently differs from manufactured installation.

Figure 7.24 Acrylic scaled model by Kelly Henry et. al.
Nevertheless, at the part level there was a clear relation between design units and manufacturing units. Main drawbacks come from three design issues. One was the lack of a coherent structural system. The aluminum bent stripes were not self-supporting, as a result an additional structure to support them was needed in place and was conceived too late and its integration difficult. Consequently, this structure is not part of the original design intent. Second, there was a lack of a connection system no only to provide a coherent integration between parts at the assembly level but also to understand them as a whole. Finally, bending lines were inadequately designed, causing breakage of parts. Fortunately this error was detected before final manufacturing phase and fixed as shown in figure 7.25.

![Figure 7.25 Component bending in project by Kelly Henry et. al.](image)

An independent manufacturing firm outside GaTech cut the aluminum stripes using laser cutting, without students’ intervention. Students bend them manually later and once bent they were attached together using socket cap screws and hexagonal bolts—as seen in figure 7.26. The amount of screws and bolts, three at least in each shape significantly increased the structure weight.
Figure 7.26 Component bending by Kelly Henry et. al.

A supporting structure consisting of metal columns and beams was in place; additional steel cables were also necessary as seen in figure 7.27

Figure 7.27 Component assembly by Kelly Henry et. al.
Figure 7.28 Aluminum canopy by Kelly Henry et. al.

Figure 7.29 Aluminum canopy by Kelly Henry et. al.
7.1.5. **Summary:**

Different research techniques were used in collecting and analyzing data from student’s work, which included; (a) semi-structured interviews; (b) structured non-participant observations; and (c) content analysis. After collection, data was organized and analyzed to produce a process model. Overall, the most critical issue in implementing a DfM approach was the absence of an adequate framework i.e.: a DfM model, not only to organize the DfM approach but also to capture, classify and organize manufacturing knowledge. 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 as seen in figure 7.30. Within each module or shell, alternative requirement structures or information 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, 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.
Figure 7.30: DfM model obtained from teaching experiences
7.2. Second stage: Structuring a DfM model (understanding)

In the second stage, this research looks closely at compositional processes in design and parallel processes in manufacturing including material removal, addition and redistribution processes. Structured design experiences were 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 emphasis is given in curved surfaces fabrication using CNC technology, with a special focus on prototyping using the following technologies: two-dimensional cutting using laser cutter, three-dimensional printing using Rapid Prototyping technology and three-dimensional milling using 3-axis router.

I introduced students to the DfM approach and the previously developed DfM model was introduced and discussed thoroughly. The class was structured over three new guided explanatory case studies. Each case study was organize as structured design experiences, each one focused in using one manufacturing process see from Figure 7.31 to 7.33 and one guided exploratory case study consisting in a component based design using an alternative combination of two manufacturing process, two-dimensional cutting and three-dimensional surfacing using a 3 axis CNC router, see from Figure 7.34 to 7.36. These case studies are fundamental part of this research and for the first time in the research, the proposed DfM model is used as formal framework to develop the cases. In addition, a quasi-experimental approach is introduced in using structured design experiences in each case study; we devote a special chapter to introduce them in depth.
Figure 7.31: Laser cut corrugated board by Lei Gao

Figure 7.32: Laser cut acrylic frame and three-dimensional print modules by Joe Lamb
Figure 7.33: three-dimensional mill foam by Joe lamb

Figure 7.34: two-dimensional cut wood module by Joe Lamb
Figure 7.35: Wood slices assembly by Joe Lamb

Figure 7.36: Three-dimensional mill wood module by Joe Lamb
7.3. Final Stage: Component Design Case study:

In the final stage of the research a case study was developed. The case study consisted in to manufacture a curved surface wood panel for an existing wall system in Figure 7.37. This wall system is called Graph and produced by Fry Reglet, a local architectural component-manufacturing firm\textsuperscript{52}. The researcher, using the DfM model as framework, manufactured the component. An initial proposal for a bespoke design with two alternative veneer orientations was developed. A final optimized modular design was obtained after component analysis, evaluation and optimization. The final case study, its implementation and conclusions are presented in an incoming chapter.

![Wall system Graph produced by Fry Reglet](image)

Figure 7.37: Wall system Graph produced by Fry Reglet

\textsuperscript{52} **Graph** is a component-based design platform that incorporates an unlimited range of vertical surface finishes into a pre-engineered platform grid system. This flexible grid is anchored to new or existing drywall, block, plaster or concrete, and then factory-fabricated panels are easily attached to it. More details in [www.fryreglet.com](http://www.fryreglet.com)
Along this chapter, the author presents four case studies that were essential part in this research. After an introduction, and a brief section presenting structured design experiences, each case study is presented and discussed including; process description; technologies involved; critical topics explored; and manufacturing knowledge in the form of design heuristics and metrics.

These case studies were developed as part of the class: Design for Manufacturing: Curved Surfaces Fabrication using CNC technology. The author taught this class during the spring semester 2006 at Georgia Institute of Technology. Four graduate students completed three guided explanatory case studies and one guided exploratory case study. Within each case, the researcher used structured design experience to organize the manufacturing knowledge extraction. A structured design experience includes a design model as a methodological framework, a design problem specification, and the corresponding design solution.

The emphasis in the case studies is given to curved surfaces fabrication using CNC technology, with a special focus on prototyping using the following technologies: two-dimensional cutting using laser cutter, three-dimensional printing using Rapid Prototyping technology and three-dimensional milling using 3-axis router. Each of the three explanatory case studies make use of at least one of these technologies not only as a frame to organize manufacturing knowledge but also as a way to introduce the fourth guided exploratory case study where those manufacturing technologies are combined.
8.1. Structured Design Experiences:

All design experiences were focused on the same component i.e.: a curved surface panel. Each design experience was presented as a one-page assignment, which included task description and a set of instructions—both were in written as well as graphics form. See annex A, B and C. Additionally each exercise was introduced using a three-dimensional file, which included the complete sequence from design to manufacturing separated in layers. As part of each exercise, students were asked to answer a 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. The researcher collected all CAD and CAM files from students, and documented the process with images.

The purpose in using structured design experiences was to test and refine the DfM model—by capturing knowledge from them. The process of capturing knowledge was structured in two stages. First students were exposed with design heuristics and second they identify the attributes and features that present manufacturing restrictions for a specific component design—in using a specific manufacturing technology. Although manufacturing processes are different, the way in which knowledge was structured in the model pointed towards a more generic type of classification. This brings a sense of domain independence to the DfM model but its keep some specificity within its framework. Thus, the manufacturing knowledge needs to be understood as both process independent knowledge and process specific knowledge. Accordingly, the way to represent them is different. Subsequently the model should be non sequential in the way that will be representing alternatives of manufacturability aspects and interaction between them.
8.2. Case Study 1: Curved Surface Fabrication Using two-dimensional Cutting

8.2.1. Slicing, unfolding and assembling

The first design experience, in annex A, was introduced with a discussion about different methods to generate curved surfaces in CAD systems, as we found out, these are standard methods that do not differ much from one CAD system to other. In addition, we discussed some basic issues about curved surface representation in CAD systems.

In our first design experience, students were asked to design and fabricate a square panel with the top face being a curved surface as seen in figure 8.1. Two alternative paths were presented. In path one, the curved surface was generated by lofting B-splines producing a NURBS surface, and in path two the curved surface was generated by displacing a polygonal mesh surface using an image map. The exercise was presented with a sequence of images as example—seen in figure 8.1 and figure 8.2.

![Figure 8.1: Example given to students in structured design experience 01](image)

The panel has to be fabricated using layered manufacturing by laser cutting of flat shapes out of either 5 millimeters corrugated board or 4 millimeters acrylic. Form generation was performed according to the two alternative paths. Students, pursuing path number one, generated the curved face using a NURBS surface. This surface was
produced out of a lofting operation using splines. Students, using the second path, generated a polygonal mesh surface out of an image map displacement. These alternative paths were also used to introduce students to different curved surface, generation, representation and its implications for manufacturing. After surface generation in path number one, the NURBS surface was tessellated and then sliced. In path number two, the polygon mesh was just sliced in order to produce the sections—as seen in figure 8.1 at the right. Sections or shapes in the form of closed polylines were obtained from both paths and then projected on the X-Y plane. After that, the closed polylines were exported as dxf files—As seen in figure 8.2 at the bottom of this page. Later they were imported from the laser cutter controller machine and used as cutting patterns.

Figure 8.2: Example given to students in structured design experience 01
8.2.1.1. Two-dimensional laser cutting: Two-dimensional laser cutting is more commonly referred to as laser cutting. In laser cutting, a cut is created through relative motion between the laser beam and the workpiece surface. This process allows intricate two-dimensional shapes to be cut on a flat workpiece. The physical process of material removal and energy losses are quite similar to those for drilling, where the incoming laser beam energy is balanced by the conduction heat, energy for melting or vaporization of material, and heat losses to the environment.

8.2.1.2. Machine: Students used a Universal Laser ULS-X660 60 Watts. This is a free-standing unit equipped with; integrated cart; motorized Z-axis; auto focus; X-Y beam positioning system with RACER™ motion technology; self adjusting spring loaded sealed bearings; stationary processing table and 18" x 32" cutting area. File formats supported for cutting: dxf, dwg, ai and image map and equipment Dimensions: 29 x 32 x 43 inches, in figure 8.3.

Figure 8.3: Universal Laser ULS-X660 from Universal laser systems.
Critical topics explored in this first design experience were curved surface representation, surface generation methods, and layered manufacturing. Students were asked to treat the fabrication process as a work of design in its own right. Students were consequently asked to document the process. They answered structured interviews in the form of a questionnaire in appendix B. The author compiled questions and answers in the form of design heuristics and metrics and organized according to issues in the DfM model.

The most relevant issues were found at the form generation stage and later in producing manufacturing information. Working with meshed model and producing the curved surface using image displacement was more popular than working with NURBS and generating the curved surface by lofting using splines. In both cases obtaining adequate resolution was key issue. After surface was generated and sliced, both processes coincide on the same path. Nesting and layout was done manually. Once finished with it the nested sheets were exported to a CAD system or other vector base system to be passed on to the laser cutter as cutting paths. The laser cutter acts like an ink plotter in which, in this case closed polygons, are transformed in to cutting path each contains a specific power and cutting speed. In assigning the cutting style, that are recognized as different color lines, specific power and speed are selected. Nevertheless, this process is normally done by trial and error but there some default assignments and tables for specific material and thickness.

53 This CAD system was running in the laser cutter controller computer.
8.2.2. NURBS surface generated by lofting splines.

The first path adopted by students is shown in figure 8.4. In this case, NURBS surface was generated by lofting splines, and then it was projected on a solid to form the requested panel. The purpose in doing this is to obtain closed polylines after the slicing the panel. The final panel is produced by laser cutting slices of 5 mm corrugated board. Surface resolution was not equivalent in both axes (x and y). Along this process, a geometric transformation goes from a NURBS surface to a closed polylines. First NURBS surface is tessellated i.e.: transformed into a polygon mesh, and then sliced to produce the closed polylines. Successive transformations attempt against curved resolution consistency and curvature deviation are the most important parameters in achieving adequate curvature. Initially surface resolution refers to display resolution and that should be the target resolution that is carried along the process until its reflected in the polylines used as cutting paths.

![NURBS surface generated by lofting splines](image)

**Figure 8.4: Sequence from structured design experience 01 by Lei Gao**
Multiple parameters affect surface curvature in using NURBS. Most of them are possible to be controlled while parametric data is maintained. Number of iso-curves, face angle, and facet size significantly affects surface curvature deviation. As an example alternative face angles produce significant surface curvature deviation as seen in figure 8.5.

Figure 8.5: Identical NURBS surfaces shown with alternative face angle.

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54 Face angle is the angle formed by two elements meeting in a common point and lying in a plane that is one of the faces of the polyhedron.
Normally before slicing the NURBS surface is tessellated i.e.: transformed in to a polygon mesh. After the slicing process, a set of closed polylines is generated out of the polygon mesh. The research determined that the slicing process should be performed starting from one of the edges of the solid and having the first contour half of the material thickness away from the edge and the rest of the contours in increments of one material thickness each. Consequently, the number of points and segments length, that forms the polylines, controls the resolution in those polylines—and it is not parametric. However, that type of geometric data is produced at the point in where the NURBS is tessellated. This transformation refers to two dependent parameters, the facet or mesh module size and the face angle. Facet or mesh size is the size of the segment in each polygon that forms the mesh. Face angle corresponds to the angle between two adjacent facets. Normally these values are set by default in most CAD systems, even though they have specific ways to control them. Figure 8.6 shows alternatives polylines obtained from the same NURBS surface just altering the face maximum angle. There are similar options at the time that allows the user to set the parameters before the geometric data is exported from a CAD system in to a CAM system.

![Figure 8.6: Polyline extracted from NURBS surface with alternative face angles](image_url)
8.2.3. Surface generated from a polygon mesh and a image as displacement map

The second path was originated out of a panel whose top face was transformed into a polygon mesh and then that face displaced using an image as displacement map. In any case this type of image displacement requires NURBS surfaces to be transformed into facetted surfaces. In the case, shown in figure 8.7, the image used as displacement map was a scanned image of the student’s hand. Each student will use the resulting surface along the next exercises. Consequently, resolution is contained in those facets that form the mesh.

Figure 8.7: Sequence from structured design experience 01 by David Esterline
The resulting surface is controlled by the mesh resolution and by the parameters in the displacement map. Parameters in the displacement map are mesh size, displacement values expressed in lineal units and curvature smoothness as percentage. As a result using the same image and keeping the displacement values fixed, changes in the mesh size or curvature smoothness produces significant changes in the surface curvature—as seen in figure 8.8.

Figure 8.8: Alternative images displacements maps using same displacement values and alternative mesh size and curve resolution.
After the slicing process this values are reflected of the amount of points that are found in each of the polylines obtained, as seen in figure 8.9 that compares one slice from a curved surface using two different mesh densities. Consequently, resolution is not homogeneous. In one direction, the slicing direction, resolution is obtained from the slicing distance. In the opposite direction is coming from resolution in the polygon mesh.

Figure 8.9: Polylines extracted from polygon mesh surface with alternative mesh subdivision

Even though this initial exercise was simple, it was very useful in introducing students to both surface representation issues and some of its implications for manufacturing. No manufacturing errors were detected and deviation from design intent was always related to surface curvature deviation from original. The problem was studied, as previously discussed, and its origins refer to; lack of understanding of component geometrical properties; and incremental decrease of geometric resolution along the process. Successive transformations in component’s geometry, from a three-dimensional object in to a two-dimensional one, to be used as machining path, causes surface curvature deviation from original surface’s curvature.
8.2.4. **Design Heuristics and Metrics:** The researcher collected data, obtained from the experiences, using structured questionnaires; semi-structured interviews; structured non-participant observations; and content analysis. Then the author compiled it in the form of design heuristics and metrics. Later the author organized them according to issues in the DfM model as follows.

8.2.4.1. **Component geometry:**

**Polygon mesh vs. NURBS**

Computer generated curved surfaces are produced using polygonal meshes or NURBS surfaces. Meshed surface constitutes collection of points that form polygons and most commonly triangles. Even though meshes are quite accurate describing curved surfaces, they need long processing time and large data storage space, especially when large number of meshes or high curvature resolution is needed. A NURBS (Non Uniform Rational B-Spline) surface is a mathematical model used for generating and representing a surface. This model is continuous, as opposed to the discrete polygon mesh surface composed of triangles and vertices. Because of their flexibility, parametric control and accuracy, they need short processing time and small data storage space. Unfortunately can not be used to drive CNC machine directly.

**Component size** must be determined by comparing allowable machining size, in this case cutting bed size, and material or workpiece size, giving always preference to machining allowances. Also relevant is machining time and material component tolerances.

**Surface curvature maximum deviation** is strictly constrained by work piece size and material dimensions. It is desirable that curve control points are equivalent for curved surface generation using lofting, if not software interpolation can cause deviation from
original surface. In using polygon mesh, the recommendation is a mesh module at least equivalent to material thickness and a maximum close to 0.1 of material thickness as was determined by this research and presented in incoming sections.

**Optimum curve resolution** after slicing surfaces are transformed in closed polylines and its resolution is determined by the number of segments that form them. This resolution is transferred in the cut shapes. After assembly we have a three-dimensional object with two different resolutions, as seen in figure 8.10, one is coming from the polylines resolution and the second one is coming from the thickness from the material in each slice. In order to make them equivalent maximum segment size in the closed polylines must be equals to material thickness.

![Figure 8.10: Resolution along the slice and along the slicing direction](image)

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**Polygon mesh Resolution vs. machining time**

Increasing curve resolution decreases segment size in machining path and increases machining time. Each segment represents one tool movement.

**Slicing process** should be performed starting from one of the edges of the solid and having the first contour (d) half of the material thickness (c) away from the edge (o) and the rest of the contours in increments (b) of one material thickness. Slicing starting point (o) and slicing direction (a) must be determined in relation material properties like grain direction, as seen in figure 8.11.

![Slicing process parameters](image)

**Figure 8.11: Slicing process parameters**

8.2.4.2. **Assembly Process:**

*A numbering process* is needed for identification and they must include assembly guidelines. In component assembly, a building involves a large number of similar pieces. Which piece goes where when they are assembled? While each individual piece can be uniquely labeled, this is overly restrictive. Usually, there are a number of duplicate pieces, for fabrication efficiency or for ability to continue construction in a piece is broken or faulty. Any duplicate piece can be substituted for another, so a piece-design
(often called a piece mark) should be numbered and the assembly drawings identify the piece design number going into each final location.

**Nesting and layout**

Given that materials are presented in different forms and shapes, the flat shapes produced need to be laid out and nested to avoid waste of material. Blanks should be designed to reduce material scrap, so layout and nesting requires special consideration in the design process. Nested parts require the same material and the same sheet thickness. Nesting can be performed manually or using nesting software that automatically calculates the best nesting layout to optimize material utilization. A sheet or panel number and a piece number should be provided not only to help in piece identification but also to assist assembly process.

8.2.4.3. Manufacturing process:

**Speed and power**

In some applications, precise control of laser power is essential to give the desired laser cutting quality at all speeds. This can achieved using to pulse (pl) the laser directly proportional to distance covered (d), or to set laser power (P) directly proportional to speed (v). (pl \( \propto \) d or P \( \propto \) )

**Cutting depth**

The main cutting parameter is cutting depth (T) and can be expressed as a relation between the energy power (P) divided by the product between the cutting speed (v) and the laser spot diameter (d): \( T \propto \frac{P}{Vd} \)
Normally, and according to the material being cut, the laser spot diameter is fixed. So, the cutting depth can be expressed as the power divided by the speed, and it will change according to specific material properties and material thickness.

**Cutting width**

Normally, and according to the material being cut, the laser spot diameter is fixed. But increasing the power and/or reducing the speed increase the cutting width, since more material is melting. Accordingly to keep the width smaller is possible to perform the cut in more that one path. In order to control this problem a good balance in between the amount of power in the cutting tool and the speed of it reduces the melting effects

8.2.4.4. Material properties:

*Work piece surface’s reflectivity* could affect the cutting operation by reflecting the energy ray with hazardous effects in the work environment.

*Material’s melting point* is directly related to cut’s accuracy and desired tolerance, to control this problem a good balance in between the amount of power in the cutting tool and the speed of it reduces the melting effects.

*Material evaporation and fumes* from the cutting process produce two undesired effects. One is dirtiness on the work piece, and the second potential fire from flammable fumes.

8.2.5. **Summary:**

As a summary students were presented with a design experience that seems to be simple but encompasses more than one complex manufacturing issue that got increasing importance along the development of incoming design experiences. Manufacturing a three-dimensional artifact out of two-dimensional shapes became our first basic fabrication technique. Later in the following design experience, this basic technique is
incorporated as fabrication technology i.e.: Rapid prototyping. Within this design experience the basic objective was to make students familiar not only with curved surface generation processes but also with the geometric transformation process needed to produce the manufacturing information and the potential dependences between these processes. In doing this the purpose behind was to introduce the idea that in designing we produced not only information about the artifact but also about the process to manufacture that artifact, and to keep a consistent relation between this two types of information. The implications behind geometric transformation processes remained hidden until fabrication and some of them until assembly. These processes were curved surface generation, solid geometry slicing process and unfolding of slices. Each process introduced some level of complexity and some loss of geometric consistency. Accordingly, each of these basic processes is subject of higher level of inquiry not only in geometric modeling research but also in manufacturing research.
8.3. Case Study 2: Curved Surface System

8.3.1. Combining three-dimensional printing and two-dimensional cutting:

Our first design experience included one object fabricated using layered manufacturing. In our second design experience, in annex B, that object was used as initial module for a more complex component-based system. The system is based on a panel and a frame as seen in figure 8.12.

![Figure 8.12: Acrylic frame and RP panels from structured design experience 02](image)

This case also involves new dimensional requirements. In addition to the needed design adjustments in the module, the frame was required to organize and hold modules together. The frame was prototype using laser cutting and structured using an interlocking connection system. Additionally students were required to resolve
connections between the modules and the frame. The main purpose in doing this prototype is not only to study possible design alternatives through combination and or alternative configurations but also to explore fabrication issues like connections and tolerances. Some dimensional requirements were in place. The students worked based on 2’ x 2’ Modules and/or 2’ x 8’, and the complete system dimensions must be no bigger than 5 modules height and length between 5 modules and 8 modules. Each student decided the scale in the prototype. The researcher introduced design task sequence as shown in a step by step process as shown in images sequence in Figure 8.13 and 8.14. Form generation was based on generating a NURBS surface lofting B-splines as shown in figure 8.13. Students had familiarity with NURBS surface generation process from the previous design experience. Consequently, they were aware about curved surface resolution issues and other parameters in NURBS surface generation.

Figure 8.13: Curved surface generation from example in structured design experience 02

After generated, students transformed the surface in to a solid, as seen in figure 8.13 on the right, using two alternative paths. Two students produced a solid out of a parallel offset of the previously obtained surface and other two students produced a solid with one face curved and the back flat. Some other implications in those development paths are discussed in incoming sections.
Once students generated the solid, they split the solid in the required modules as seen in figure 8.14 on the left. After that a frame was obtained to fit the modules as seen in figure 8.14 on the right. This process was performed through a sequence of Boolean and trimming operations. There was a discussion about setting up early in the design the relation between the frame and the module. Modules were fabricated using rapid prototyping and frame was fabricated using 0.4 mm acrylic and laser cutting.

Figure 8.14: Solid splitting from example in structured design experience 02

8.3.1.1. Two-dimensional Laser Cutting and Rapid Prototyping:

*Two-dimensional laser cutting:* This process was introduced in structured design experience 01 in page 112 and the laser cutter presented in page 114, figure 8.3.

*Rapid Prototyping:* There are number of RP (Rapid Prototyping) technologies on the market, all work under the same fundamental principles. CAD data, in a specific file format (STL), is processed and oriented in an special position. The data is then sent to the RP machine where it is numerically sliced into thin layers. The RP machine then fabricates each 2-dimensional cross section and bonds it to the previous layer.
**Machine:** Students used a ZPrinter 310 System as seen in figure 8.15. Features of the ZPrinter 310 System are as follows; build volume: 8" x 10" x 8" (203 x 254 x 203 mm); layer thickness is user-selectable from 0.003"- 0.010" (0.076 - 0.254 mm); equipment dimensions are 29 x 32 x 43 inches (74 x 81x 109 cm); material used is a proprietary powder and supported file format for Printing is STL.

![Figure 8.15: ZPrinter 310 System by ZCorp.](image)

Critical topics explored in this second design experience were component and sub-assembly fabrication, design modularity and connection systems. Again, students were required to treat the fabrication process as a work of design in its own right. Consequently, students documented the process. They answered structured interviews in the form of a questionnaire in appendix 2. The researcher compiled questions and answers in the form of design heuristics and metrics. Later the author organized them according to issues in the DfM model as follows.
This research found most of relevant design issues, leading into manufacturing errors and/or misfit between design intent and manufactured artifacts, were at the form generation stage and later in the manufacturing information production stage. Most common manufacturing errors were; non printable parts out of unreadable or corrupt STL files\(^{55}\); misfit between modules and frame; lack of adequate tolerances and/or lack of coordination between tolerances in two different manufacturing processes. The most relevant issues altering design intent was surface curvature deviation. Consequently, we will review those issues to find out its cause and potential solutions in incoming sections. There were multiple design issues out of alignment problems, fitting problems, and allowance issues in the frame design. Nevertheless, the students fixed most of them at the proper time without having impact in manufacturing issues or design intent deviation. Students found specific design issues, which challenged them, in relation to frame connection system. The exercise proposed an interlocked system that was widely adopted, but needed some work in finding a solution for the interlocking of corner pieces. In inserting modules in to the frame, other design issues also emerged. Consequently, a frame-panel connection system was needed. Accordingly, students designed a specific

\(^{55}\) The main problems with STL file are that file sizes is dependent upon the number of vertexes so the higher resolution files take up large amounts of space, due to redundancies in overlapping vertices. The STL files have many redundant features which make the file larger unnecessarily. The higher resolution parts with smooth curves require extremely large file sizes, to match RP machine resolutions. STL file only depict the surface of the object, so STL is not sufficient for FDM models made up of various materials. Finally STL file can be corrupted easily due to a lack of connectivity in the model or rounding errors, which requires extensive coding and processing time to find and repair these errors in ZHOU, L. & LIN, Y.-J. (2001) An Effective Global Gouge Detection in Tool-Path Planning for Freeform Surface Machining. International Journal of Advance Manufacturing Technology, 461-473.
solution for panels fitting in the frame. Additionally frame relation with the panel, at least at the visibility level, needed a specific joint design. Students were aware of this design issues and about the requirement to solve them. But error stay unsolved until assembly. Students generated NURBS surfaces using lofting operation, in figure 8.16. Students’ familiarity with curved surface generation encourages them in exploring more in depth formal issues. Few issues arrived at the form generation stage; and the only relevant one was coming from surfaces wrongly generated. This problem was originated from using a curve set with different curve direction. Students solved the issue immediately in reversing directions to match them properly.

Figure 8.16: Sequence from structured design experience 02 by Joe Lamb

Consequently, students were aware of issues not only about matching the number of points in the curves generating the surface but also about setting up properly each curve direction. Once the surface was produced, students transformed it in a solid by making an offset of the surface, resulting solid in figure 8.17.
After the students obtained a solid, grooves were produced by Boolean operations between the surface and the frame. The purpose of this was to set up the space for fitting between the surface solid and the frame before splitting the surface solid to obtain the panels. Accordingly, each module sits perfectly in the frame producing an invisible seam. In the next stage students split the solid in the proper module producing all the panel including the grooves to fit in the frame, see Figure 8.18.
Since the research analyzed laser cutting in the previous section, this section focus is in rapid prototyping. After students produced geometric information of each panel, next stage is to layout the panels to fit within the build box. At this point, panels are ready to be transformed in RP machine-readable files. Standard Tessellation Language (STL) is the most popular three-dimensional printer file format in the market. Consequently, STL is becoming the industry standard file format for rapid prototyping (RP). Once imported, in the RP software controlling the three-dimensional printer, the STL files are sliced and converted directly to machine output for printing. This slicing process is conceptually identical to the one presented in our first design experience. Consequently students had some familiarity not only with the process but also with design and manufacturing issues and its implications within it. Figure 8.19 shows how three-dimensional printed panels fits together in the acrylic frame.

Figure 8.19: Sequence from structured design experience 02 by Joe Lamb
The most visible problem faced by students in this manufacturing process was important curvature deviation found in the printed panels. The origin of the problem remains hidden at the stage in the process in where STL file were produced and will be discussed later. The main problems with STL file are that file sizes is dependent upon the number of vertexes and facets so the higher resolution files take up large amounts of space, due to redundancies in overlapping vertices. The higher resolution parts with “smooth” curves require extremely large file sizes and long processing times. Normally a CAD system exports STL files using by default parameters that not always match the desired resolution. Most commonly, this “by default” resolution is low due to performance issues in the CAD system. Nevertheless, some systems provide complete STL exporting interface including parametric control like; different STL formats; alternative exporting methods; and scale and triangulation options. But most important, theses interfaces include object resolution control allowing to control STL file output resolution by controlling parameters like; the number of facets; length of segments that composed those facets; and face angle and surface deviation control.

In exporting files, students ignored the STL resolution issue and as a result printed panels resulted with visible curvature deviation on its surfaces as seen in figure 8.20, next page.
Figure 8.20: Errors in surface curvature from structured design experience 02 by Joe Lamb

What it is appreciated in the picture instead of a smooth surface curvature are the facets and segments that forms the surface. This issue was difficult to detect since most of the rendering engines on CAD systems smooth surface’s curvatures to improve visual results. In order to fix this problem and being able to detect it, best option is to render curved geometries ignoring the smooth surface option or just making edges visible. An example of it in figure 8.21, where the panel geometry is presented on the left and the render version on the right. In this case, the rendering was done removing smooth surface option and making the facets edges visible

Figure 8.21: Panels as designed on the left and “as exported” using “by default” options on the right from structured design experience 02 by Joe Lamb
Once detected the error is possible to solve at the STL file generation stage. Normally the solution should be to increase the resolution by increasing the number of facets in the STL file, according to object size. However, in doing that, significantly increases the size of the file. An optional path is to increase the resolution by determining a maximum facet angle as seen in figure 8.22. Highlighted, in the figure, it is the default resolution that causes the problem in student’s work shown in previous page.

![Figure 8.22: Table showing facet size according to alternative maximum facet angles](image)

Figure 8.22: Table showing facet size according to alternative maximum facet angles
8.3.2. Design Heuristics and Metrics: The researcher collected data, obtained from the experiences, using structured questionnaires; semi-structured interviews; structured non-participant observations; and content analysis. Then the author compiled it in the form of design heuristics and metrics. Later the author organized them according to issues in the DfM model as follows:

8.3.2.1. Component geometry:

**Optimum curve surface resolution** is obtained from comparing resolution between modules and frame. *Keep curvature resolution consistency through curvature analysis*

Since this manufacturing process includes two types of manufacturing technologies, there are two types of surface curvature resolution. One is coming from the frame, which is built using two-dimensional laser cutting, and the second is coming from the modules fabrication process using three-dimensional printing.

a) **Two-dimensional laser cutting**: Since the necessary cutting paths are derived from a three-dimensional solid through a slicing process, resolution is different in both axis (x, y) and depends on the slicing direction and the slicing distance, as already reviewed in page 124 and figure 8.11. Resolution in the machine is established by the amount of laser pulses per second. Resolutions of 300 - 600 dpi are recommended for most jobs, although laser-engraving machines allow for settings of up to 1200 dpi.

b) **Three-dimensional printing**: Curve surface resolution is determined both by **input format**, which is STL, and by **printing resolution** expressed as layer thickness.

Resolution is controlled by the size of each facet or triangle, mostly is determined, using different methods by the software, producing the STL file.
8.3.2.2. Manufacturing process:

Tolerances are obtained by comparing tolerances in each manufacturing technology and adding 0.1 mm for piece fitting.

Three-dimensional printing:

Orientation For Speed Parts oriented with their largest dimension along the y-axis, next longest along the x-axis and shortest dimension along the z-axis will print the fastest.

Orientation For Strength Part features that lie in the x-y plane will be stronger than those aligned along the z-axis.

Orientation To Prevent Warping Very thin planar part features printed may warp if they dry unevenly or they are excessively heated.

8.3.2.3. Assembly Process:

A numbering process is needed for identification and they must include assembly guidelines. In component assembly, a building involves a large number of similar pieces.

8.3.2.4. Material properties:

Three-dimensional printing:

Drying procedure after parts are printed a drying procedure needs to be performed. After that parts needs to be infiltrated i.e.: coated, and drying time will depend on the infiltration material. Drying time and part wall thickness are directly related.

Infiltrating The Parts: Infiltration is a coating process, applied to printed parts after drying time, to achieve application-specific functionality or to assess performance criteria. Infiltrants can be used to significantly improve the durability, humidity resistance and high temperature properties of parts. Parts can be infiltrated with a variety of materials, depending on the intended use for the parts.
8.3.3. **Summary:**

As a summary this design experience involved two manufacturing process that even though they were performed independently and using different manufacturing technologies they were integrated later in one assembly. As a result there was two types of issues; one coming from complexity found in each component production process in isolation; and the second coming from intricacy in the integration not only between geometric entities representing both elements but also between fabricated elements. Since laser cutting was already introduced in our previous design experience, there were no major issues around it. Different was the situation with Rapid Prototyping (RP) in where surface resolution was totally out of expected. Low surface resolution resulted from exporting solids in STL format with facet sizes too big. Now integrating processes was difficult. Fitting and tolerances between them became a more than relevant issue. Again, geometric transformation to produce these two objects was taken for granted and evolve in isolation. This problem resulted in that none of the students got correct fit between frame and panels. Curiously enough, both elements share the same geometric frame generator i.e.: a modular grid. Panels were obtained from splitting curved surface solid using the modular grid and the frame was produced extruding frame slabs form the same grid. Later Boolean subtractions produced the fitting between the two sub assemblies. Tolerance, allowances and the accumulation of them along successive transformations produced the lack of fitting between panels and frame. A complete description of each process CAD workflow including all geometric transformations is presented in figures 8.23 and figure 8.24 in the next pages.
Figure 8.23: Diagram showing CAD working flow for laser cutting including all geometric transformations.
Figure 8.24: Diagram showing CAD working flow for Rapid Prototyping including all geometric transformations.
8.4. Case Study 3: Curved Surfaces Using three-dimensional Milling CNC Technologies

8.4.1. Material removal using three-dimensional milling:

Along last two design experiences, we explored different curved surfaces generation and fabrication methods; as well as complexity within a modular system. In addition, we uncovered some basic issues about curved surface representation in CAD systems. Our first case study included one object fabricated using layered manufacturing. In the second case study that object or module became the basic unit for a more complex component based system. In addition to the needed design adjustments in the module, a frame was required to organize and hold modules together. The frame was fabricated using laser cutting and structured using an interlocking connection system. The module was fabricated using three-dimensional printing. Tolerances between these two fabrication techniques and connections in the system showed to be extremely relevant. In this third case study, in annex C, the research explores an individual panel or module in full scale. The prototype will be fabricated from a previously prepared 2’x2’ work piece out of a 4’x8’ polyethylene foam block (Foamular). The fabrication process involves; workpiece cutting in a saw table; and gluing of foam plies to form the workpiece. Later the panel was milled using CNC three-dimensional surfacing. The main purpose in doing this prototype was not only to study possible design alternative through combination and or alternative configurations but also to explore fabrication issues like surface finishing, surface curvature deviation and tolerances. Again, students were required to treat the fabrication process as a work of design in its own right. Consequently, they documented
the process. The researcher introduced design task sequence as shown in a systematic process as shown in images sequence in Figure 8.25 and 8.26.

Form generation process was similar to previous exercises. Students generated a NURBS surface by lofting splines. Students added a box to describe the workpiece and to control that the surfaces was within the boundaries of the required dimensions i.e.: the foam panel dimensions as seen in figure 8.26.

![Figure 8.25: Form generation from example in structured design experience 03.](image)

After surface generation, students added new geometries to complete the three-dimensional model. Consequently, as seen in Figure 8.26, the model consisted of three geometric entities; a NURBS surface; a box describing the panel; and five planes describing the four sides and the bottom of the panel. The purpose in doing this was to illustrate the need for alternative geometric representations to achieve alternative manufacturing issues.

![Figure 8.26: Geometries entities from example in structured design experience 03](image)
8.4.1.1. *Three-dimensional milling:* Three-dimensional milling refers to a material removal process that can be performed in three, four, and five axes CNC machines. Three axes CNC machine are computer controlled vertical mills with the ability to move the milling tool vertically along the Z-axis. This extra degree of freedom, over two-dimensional cutting such as laser cutting, permits their use in surfacing processes. In this type of milling processes are commonly known as 2.5 D or two and a half dimensional milling. In 2.5 D milling, surfaces are represented as a contour map, in where each contour is formed by points that shares the same Z value of the surfaces at each point. Later each contour represents a cutting tool movement and the displacement between them constitutes the cutting width.

*Machine:* Students used a Routech Ergon CNC Router in figure 8.27, which is a double table, double tool head router which allows simultaneous processing of different parts on opposite tables at the same time with high degree of manufacturing flexibility. The router comes standard with high quality aluminum grid tables that offer vacuum hold down. The Ergon’s tools spindle at variable speeds from 900 to 18,000 RPM and an on-board 12-position automatic tool changers.

![Routech Ergon CNC Router](image)

*Figure 8.27: Routech Ergon CNC Router used in structured design experience 03.*
8.4.2. Case Study Overview:

Critical topics explored in this third design experience were CAD CAM integration and CNC manufacturing since for the first time students were introduced not only to a full functionality CAM system but also to a full-size CNC manufacturing machine. As in previous exercises, students answered structured interviews in the form of a questionnaire in appendix 3. Then the author compiled it in the form of design heuristics and metrics. This case study presented no manufacturing errors but most of relevant design issues, leading into misfit between design intent and manufactured artifacts, were related to lower than expected surface finishing in manufactured panels. Consequently, the most relevant issues altering surface finishing in relation to design intent was surface curvature deviation. As in previous sections, we will review those issues to find out how and where along the process they are originated and potential solutions in incoming sections. There were multiple design issues out of geometric representation and mapping between design issues and manufacturing aspects.

An additional and not less important issue was file transferring. Students found some complexity in exchanging between multiple data formats along the process without loosing consistency with design intent. Using NURBS as curved surface representation supported early stages in our form generation process, and students used IGES as exchange data format, in transferring from CAD system to a CAM system. Students received training in CAM system, the instructor checked NC code, and an operator supervised machining. Nevertheless, inconsistency in the surface curvatures resided mostly in the transformation process within the CAM system. In here the machine operator assigned much of the values as default for everyone.
8.4.3. Surface generation in the CAD system:

Form generation was performed with no problems at all and students widely explore alternative surface curvatures. Having modeled the panel i.e.: material piece, made them aware of the workpiece size from early in the process. Students were also aware of surface normals and resolution issues. Even though, it is difficult to realize about facets and other surface curvature representation. As in previous case studies and in order to properly structure data analysis and focus on the most relevant issues, the research will concentrate in one of the examples from the students, in figure 8.28.

Figure 8.28: Panel from structured design experience 03 by Joe Lamb

As mentioned before most rendering engine in CAD systems use smooth surface option as default and it makes difficult to visualize surface curvature. In some CAD systems this “by default” option stays even for exporting NURBS surfaces. The main issues in here is that in some point NURBS parametric data needs to be interpreted and transformed in NC code that mainly describes points and segments that connects those points. Consequently,
curves are represented as polylines. Therefore, to obtain control over curved surface resolution it is necessary to be able to visualize and adjust its parameters before transforming it. Figure 8.29 illustrate how smooth surface option looked in the case being analyzed. Undoubtedly, surface resolution looks very adequate. However, if we turn off the smooth surface option we can visualize the display resolution as seen in figure 8.30. In this particular case this by default resolution was carried along the design and manufacturing process, resulting in poor surface finishing.

Figure 8.29: Panel render with smooth surface

Figure 8.30: Panel presented without smooth surface

Transferring from the CAD system into the CAM system was done using Initial Graphics Exchange Specification (IGES). IGES is a neutral format for exchanging CAD data
between software. In addition, IGES supports NURBS parametric data providing alternative version for different CAM software. As a result the students transfer and represented surfaces consistently in to the CAM software.

8.4.4. Manufacturing information at the CAM system:
Once in the CAM software, students choose the tools for the specific manufacturing process, in this case, surface milling. Surface milling consists in material removal operation using a spindle. CAM system slices the curved surface to produce tool paths each slice becomes a curve, consisting in points and segments that describes the tool path. The slicing distance or the distance between tool paths is denominated cut width. Accordingly, and as it was determined in exercise 1, curved surface resolution is different in two directions. One is along the slicing direction, the second one is along the tool path, and both have different ways to control them. The slicing distance determines the slicing direction resolution. This value, for the CAM system, is denominated cut width.
Resolution in opposite direction or along the cutting path is determined by the resolution of the curves obtained after the surface tessellation and slicing process. As a result, an interpretation or surface evaluation is needed. In incoming sections the research revises the resolution along the slicing direction or cutting width first. In this exercise the cutting width, it is just a parameter for the CAM system in performing surface milling operation. In this specific case, the cutting width was given by the machine operator and was too large; 4 mm. As a result, surface finishing was rough.
8.4.5. **NC code generation and surface milling:**

Students selected two types of tools according to two types of paths to perform the surface milling. One a rough pass was done using three-quarter rougher with flat end and 19.05 mm diameter as seen in figure 8.31.

![Figure 8.31: Rough path on the left and simulation on the right](image)

The first path left 4 mm. of stock to be remove with the finishing path. The finishing path was done using a half-inch ball end drill with 12.8 mm diameter and the cutting width was 4-mm. Rough path I shown in figure 8.32.

![Figure 8.32: Finishing path on the left and simulation on the right](image)
The fabricated piece was not successful since surface finishing was irregular, specially in visual aspect in where you can see not only tool path marks but also faceting from the surface geometry, as seen in figure 8.33.

![Manufactured panel by Joe Lamb](image-url)

**Figure 8.33: Manufactured panel by Joe Lamb**

Within next section, the research analyzes data from the case study to inquiry about surface finishing in relation to surface deviation. The purpose of this is to uncover where deviation it is originated and how it is possible to reduce it, for achieving design intent in a consistent manner. Nevertheless surface curvature was quite steep but it proved to be feasible to machine. Additional issues came from loose panel portions out of poor gluing of foam plies. Figure 8.34 shows a section of the machining simulation that was very useful in determining machining feasibility in narrow angles.

![Tool path simulation on the left and real process on the right](image-url)

**Figure 8.34: Tool path simulation on the left and real process on the right**
8.4.6. **Surface curvature deviation:**

The first stage in data analysis was to determine how deviated was the machined curvature from the original one. Figure 8.35 shows surface curvature deviation analysis using a 0,1mm tolerance value. It is clear that is far from optimum.

![Surface deviation analysis using 0.1 tolerance.](image)

**Figure 8.35: Surface deviation analysis using 0.1 tolerance.**

However, let's look at it closer. Green color denotes matching between intended and manufactured curvature. Gray color shows stock material under the surface being removed and red shows gauge. Gouging is an undercut phenomenon produced by lack of interaction between intended geometry and machining geometry or tool path. Gouge occurs in CNC machining, but it may also be caused in the design stage.

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This research explored ways to reduced gouge. Normally gouge it is reduced either by using a smaller cutter, reducing the cut width or by adjusting the original geometry. Better than using a smaller cutter and since the one used was the smallest in the router, the research explored two alternative solutions for the gouging problem. In the following section and using the same example, the research analyses these alternative ways to reduce surface curvature deviation. The first one refers to adjusting width of the tool path. In the case study the width used was 3.175 mm that resulted in bad surface finishing and 1 mm was used later in the research and demonstrated to be quite an improvement in the quality of the finishing. The drawback in this solution was that the amount of NC code line increased importantly and it was necessary to split the code in two programs. In any case, Figure 8.36 and figure 8.37, show a comparison between alternative cut width and visualization of its effect on surface finishing. Also significant is tool geometry, ball nose tools provide better finishing that end mill ones. However in five axes milling is possible to obtain better surface finishing and to reduce machining time by using a flat end tool inclined in the feed direction. (Baptista and Simoes, 2000) The second way to improve surface finishing is improving NURBS surface interpretation by the CAM software at the time that evaluated it. In this case, the CAM software provides an interface for that purpose. The main parameters within it were; cord tolerance along cut; and facet tolerance, these two parameters defines the polygonal mesh resolution before the software sliced it to produce the tool paths. Figure 8.39 shows alternative surface deviation analysis using different cord tolerances. The CAM software used in this research defines facet tolerance as a factor of cord tolerance.
Figure 8.36: Surface deviation analysis using alternative tool path widths.
Figure 8.37: Surface deviation analysis using alternative tool-path widths
Figure 8.38: Surface deviation analysis using alternative cord and facet tolerances
8.4.7. **Design Heuristics and Metrics:**

The researcher collected data, obtained from the experiences, using structured questionnaires; semi-structured interviews; structured non-participant observations; and content analysis. Then I compiled it in the form of design heuristics and metrics, and organized according to issues in the DfM model as follows:

8.4.7.1. **Component geometry:**

*NURBS resolution* must be determined before machining paying special attention to display resolution or/and to default resolution within CAD systems. In order to visualize facets properly, smooth surfaces option must be turned off.

*Component size* must be determined by comparing allowable machining size, in this case router bed size, and material or workpiece size, giving always preference to machining allowances. Also relevant is machining time and material component tolerances.

*Surface curvature maximum deviation* It is desirable that curve control points are equivalent for curved surface generation using lofting, if not software interpolation can cause deviation from original surface.

*Optimum curve resolution* for surface milling is different in both axis (x, y) and depends on the slicing direction. Slicing direction resolution is determined by cut width and 1 mm for wood milling is recommended. Resolution in opposite direction or along the cutting path is determined by the resolution of the curves obtained after the slicing process. The main parameters within it are; cord tolerance along cut (less than 0.1); and facet tolerance (0.25 of cord tolerance), these two parameters defines the polygonal mesh resolution before the software sliced it to produce the tool paths.
**Polygon mesh Resolution vs. machining time:** Optimum resolution is coming from matching resolution between model geometry and tool path geometry. Increasing curve resolution decreases segment size in machining path and increases machining time.

**Geometric and manufacturing data organization:** A file process to store and organized the sequence of files along the successive transformation processes is needed. Adequate selection of file extension is extremely important and must be determine in advance according to CAD and CAM system selection.

8.4.7.2. Manufacturing process:

**Surface milling method selection** initial rough passes must be done using z-contours method. Finishing paths must be use parallel method.

**Tool Selection:** Ball nose tools provide better finishing than end mill ones. However in five axes milling is possible to obtain better surface finishing and to reduce machining time by using a end ball tool inclined in the feed direction.

**Cutting depth** is determined by comparing tool geometry and work piece size and can be increased by dividing the milling operation in incremental paths.

**Tool geometry, dimensions allowances** must be considered in establishing feasible surface curvature in order to avoid collision.

**Surface Curvature angles** can be anywhere between 0 degree and 90 degree minus tool allowances tool in descending paths and between 180 degree and 90 degree plus tool allowances in ascending paths.

**Cutting width:** Normally, and according to the material being cut, cutting width is tool diameter for rough paths and at least 1 mm. for finishing paths.
8.4.8. Summary:

Summing up, students performed surface generation process successful with no errors and they were able to explore alternative surface curvature. Exporting curved surface was done using IGES with no major problems. However, revision of exported files and its comparison with original surface showed some deviation. Within the CAM, system in selecting the adequate machining options difficulties started to show. Even though much of the needed parameters were either given by default in the CAM system or recommended by the CAM instructor or by the machine operator. Most of them resulted in significant surface curvature deviation and all of them in visually poor surface finishing. These visual aspects were verified in two undesired results in the fabricated surface finishing. One was tool path visibility and second facet visibility. Consequently, the effort in this case study was to determine the causes. Tool path generation process was reviewed and tool path width, cord tolerance and facet tolerance resulted as the key factors in obtaining an adequate surface finish, adequate in relation of obtaining a smooth surface and removing tool path and facet visibility from the surface. Finally, in fixing this aspect, code length was increased and computer controlling the CNC router crashed repeatedly. A solution consisting in splitting the code in smaller portion was successfully implemented. Nevertheless, hardware configuration in the computer controlling the CNC router could also be affecting large code program management.
Figure 8.39: CAD working flow for Three-dimensional milling including all geometric transformations
8.5. Case Study 4: Component Design using two-dimensional cutting and three-dimensional milling CNC Technologies.

8.5.1. Integrating two-dimensional cutting and three-dimensional milling CNC Technologies.

This research gave an emphasis along case studies development to curved surfaces fabrication using CNC technology, with a special focus in using one the following technologies: two-dimensional cutting using laser cutter in the first case study, three-dimensional printing using RP technology in the second case study, and three-dimensional milling using 3-axis router in the third case study. Each of case studies make use of at least one these technologies not only as a frame to organize manufacturing knowledge but also as a way to introduced the fourth guided exploratory case study in where those manufacturing technologies are combined. This last case study consisted in designing a wood component for wall system. Students fabricated the component using a sequence of two manufacturing process, two-dimensional cutting, and three-dimensional surfacing both using a three-axes CNC router. Since one manufacturing process is to produce the workpiece for the second, the research presents special attention to errors and inconsistencies from this subject. Accordingly workpiece fabrication and assembly, and tolerances in each of the two fabrication techniques showed to be extremely relevant. In this final case study, the research explores an individual panel or module in full scale. The module is required to be fabricated out of one 4’ x 8’ plywood. Using two-dimensional cutting and assembling the pieces students produced a 2’x2’ work piece. Later the work piece was machined using CNC three-dimensional milling. Again, students were required to treat the fabrication process as a work of design in its own right. Consequently, they
documented the process. However, students manufactured the panel without any instructions or supervision from the researcher. Nevertheless, an independent programmer checked the NC code, in order to avoid machine damage. Students reported changes and errors to the researcher as fundamental part of the study.

8.5.1.1 Two-dimensional cutting: Two-dimensional cutting as process was introduced in case study one in section 8.2.1.1, in page 124. Nevertheless, the cut in this case is obtained through relative motion between the rotating spindle or tool and the plywood panel surface. This process allows intricate two-dimensional shapes to be cut on a wood panel.

8.5.1.2 Three-dimensional milling: Three-dimensional milling was previously presented in case study three in section 8.4.1.1, in page 156.

8.5.1.3 Machine: Students used a Routech Ergon CNC Router previously presented in section 8.4.1.1, page 146 and in figure 8.27.

8.5.2. Case Study Overview:

Critical topics explored in this final case study were increased complexity in the CAD CAM workflow realization and multiple CNC manufacturing processes integration. Since students are trained in not only managing CAM system but also they are familiar with the specific CNC manufacturing machine, the research expected few errors in those isolated aspects. Nevertheless, the combination of two CNC manufacturing processes required different geometric descriptions. In addition, these geometric descriptions needed to be integrated along the process. Students created a master file and out of it they produced alternative geometries for each process, consistency between them became an important challenge. For the first time the design of the production process became the
most relevant issues for the students. The researcher documented the process without intervening in it. Then the author compiled it in the form of design heuristics and metrics. This case study presented almost no manufacturing errors. However, most of relevant design issues were related to geometric information leading required for workpiece fabrication. As in previous sections, we will review those issues to find out its causes and potential solutions in incoming sections. There were multiple issues out of geometric representation and mapping between design issues and manufacturing aspects. Students found some complexity in exchanging between multiple data formats along production, and especially between the two processes. Using NURBS as curved surface representation supported early stages in our form generation process, and students used IGES as exchange data format, in transferring from CAD system to a CAM system. Students received training in CAM system, the instructor checked NC code, and an operator supervised machining. Nevertheless, inconsistency in the surface curvatures resided mostly in the transformation process within the CAM system. In here the machine operator assigned much of the values as default for everyone. An additional and not less important issue was file transferring. Finally and no less relevant consistency in the geometric data and continuity in the production process between manufacturing operations or steps became extremely difficult in relation of the lack of support in the CAM system for linking alternative manufacturing operations.
8.5.3. Surface generation in the CAD system:

Since students were familiar with surface generation, they accomplished form generation process without problems. Most of the students used lofting of splines for generating NURBS surfaces as seen in figure 8.40.

Figure 8.40: Surface generation using lofting

Afterwards, students generated a second surface out of a 4 mm offset, in the z-axis, from the first one, as seen in figure 8.41. This second surface was used to produce the workpiece and an additional 6 mm is to provide with material for the three-dimensional milling process. This procedure resulted in undetected errors that the research revises in incoming sections.

Figure 8.41: Surface offset for workpiece generation
After that, and using the dimensional requirements for the panel and the maximum machinable height for the Ergon router, students modeled a solid rectangular parallelepiped as seen in figure 8.42.

**Figure 8.42: NURBS surface and solid box with dimensional tolerances**

Later and using this solid box as guideline students trimmed both surfaces and produced the two main geometric entities for the manufacturing process. The first one is a solid with one curved face on top in figure 8.43 on the left, and the second one a set of five planar surfaces and one curved NURBS face on top in figure 8.43 on the right. Both the solid and the set of faces were position according to the CAM coordinate system in advance. The solid is used to produce the workpiece and the set of faces for the milling process.
Figure 8.43: Solid produced for workpiece generation before slicing on the left and the set of surfaces produced for the CNC milling process on the right.

Initially, and to produce the workpiece geometric information, the students sliced the solid produced for the workpiece fabrication, in figure 8.44 on the left. The purpose of this, is to generate a set of closed polylines as seen in figure 8.44 on the right. Students determined slicing direction and distance after previous experiences. Each slice was positioned at a distance equivalent to material thickness starting from one edge of the panel. Afterwards they unfolded, or projected in the horizontal plane, the set of polylines. Later they laid out and numbered the polylines and exported them to the CAM system using a neutral file extension, in this case DXF.

Figure 8.44: Set of closed polylines obtained after slicing the solid
8.5.4. **Manufacturing information at the CAM system:**

Once the polylines are imported in the CAM system, an inside offset of each polylines is generated to describe an inside tool path that hollow them as seen in figure 8.45.

![Figure 8.45: Polylines transformation for interior tool path.](image)

The purpose of this operation is to reduce the panel weight. Afterwards, a material panel is defined and the shapes are nested in the panel as seen in figure 8.46. As a result, the CAM software search for the best fit of the shapes within the panel and according to the parameters defined by the user.

![Figure 8.46: Layout and nesting of closed polylines in a 4’ x 8’ panel](image)
Afterwards, as seen in figure 8.47, tool paths including lead in and lead out; drilling and engraving operations; and support tags are incorporated. The material panel is a 4” x 8” Baltic birch plywood panel. There was two cutting paths; one outside each exterior polylines, that goes counterclockwise and a second one inside the interior polylines using the offset produced for this purpose that goes clockwise. Each slice receives two holes to insert in each one a cylindrical piece of wood to ensure the correct alignment between pieces during the gluing process. Finally, each piece received a number, engraved on it by the same CNC router. These numbers are very important since each panel was produce out of 42 slices cut from one a 4’ x 8’ Baltic birch plywood panel. The Baltic birch plywood panel was chosen because of its superior quality, uniform layering in two colors and overall for its almost invariable thickness.

Figure 8.47: Panel including tool paths, lead in and lead out, drilling and engraving operations.
In the CAM system the material panel is incorporated as an independent geometric entity. All geometries describing the objects are located in the geometry layer. Machining operations rest in the operations layer, and they are; tool paths; drilling; engraving etc. Tool path describes tool trajectories, including lead-in and lead-out lines. Lead-in is an angular trajectory to start the cut and lead out is the angular trajectory to exit the tool path without damaging the workpiece. Support tags are thin layer of material (1 mm) that are left in some portion of the tool path. The purpose of them is to hold piece in the panel during the machining process. Later students removed the supporting tags to finish the pieces. Drilling operations are also machining operations, and an engraving operation is a material removal operation that does not go all through material thickness.

8.5.5. NC code generation, workpiece fabrication, and surface milling:

At this point, the CAM system uses a specific post processor to output the NC code for the machining process. Nevertheless, the NC file or program is transferred to CNC controller computer. The machine operator opens the program and adjusts the material top level. This adjustment is required because on top of the machining bed there is a spoiling board protecting machine bed. The spoiling board slightly reduces the vacuum power in the bed. Consequently, plastic sheets are deployed in the bed’s non-used area to increase vacuum. Finally, The program is loaded in the CNC router using software that controls the machine and the operator starts the machining as seen in figure 8.48 on the left. Once the machining process is finished, the pieces are removed from the panel, finished and the remaining of tags support are sanded as seen on figure 8.48 on the right.
Later students assembled and glued slices together to produce the work piece as seen in figure 8.49 on the left. Students inserted small cylindrical wood pieces in previously drilled holes to ensure alignment between pieces as seen in figure 8.49 on the right.

To finish the work piece, students glued together the hollow slices. Then they closed both ends with a front and back cover piece. The final workpiece is ready for the milling process, as seen in figure 8.50. Students carried out the milling process in the same CNC router and the process consisted in just one finishing path using a ball end drill with 12.7 mm diameter and a 3.175 mm cut width. Cord tolerance along cut was
recommended by the machine operator to be 0.2 as well facet tolerance was set 0.5 of Cord tolerance. The final piece is presented in figure 8.51. There was multiple issues and error most of them related to problems found in the CAD/CAM/CNC workflow.

Figure 8.50: Workpiece finished

Figure 8.51: Panel finished
Along the incoming sections, the research analyzes data from the case study to inquiry about workpiece production, surface deviation, and CAD/CAM workflow. The purpose of this is to uncover issues related to errors in the workpiece production and in the manufactured panel. Even though surface curvature was quite steep and it probed to be feasible to machine, final panel’s surface deviation from original shape was significant but localized.

8.5.6. **Workpiece production process:**

The first issue was work piece production process. As presented in section 8.5.3 in pages 165-167, this process consists in the transformation of a three-dimensional object into two-dimensional shapes that after manufactured they are assembled to form the workpiece. Unfortunately and since this was not a curved surface, none of the curvature analysis packages were useful to detect surface curvature deviation and gauging from the original curvature to be milled. Afterwards in modeling the work piece out of the slices obtained and comparing them with the surface to be mill, was easy to discover the problem and its location as seen in figure 8.52 on the left. The image shows on the left; portions of the curved surface to be machine that were not included in the work piece.

![Figure 8.52: Workpiece deviation from intended surface](image-url)
Even comparing the original workpiece surface before slicing is possible to detect the most problematic zones on the surface, as seen in figure 8.52. Without this type of analysis, these errors passed undetected until fabrication, as seen in figure 8.53. Originally, the workpiece surface was determined by adding 6 mm on the z axis. This shortcut provided by machine operators it has proven to be somehow efficient, but it did not worked with some of the cases. Surface curvature presented some steep angles that needed more than 6 mm of extra material for the milling process. Unfortunately, this problem stayed undetected until fabrication because the workpiece was never modeled in CAD system before machining. Therefore modeling workpiece demonstrated to be very important process improvement not only to detected surface curvature deviation in the workpiece but also to detect other inconsistencies along the process.

Figure 8.53: Milling undercut in areas with no material
In addition the research found out that the 6 mm added were not enough to provide material for the milling process in all the surface. Some times in switching the slicing direction some improvements are found. In this case, draft angle analysis showed that the problem was just transferred to all curvatures having steep angles but now facing the other direction. Consequently changing slicing direction is not a solution for this case. However, slicing direction, and the process of unfolding the two-dimensional shapes is important in keeping surfaces normal consistent. The research determined that the slicing process should be performed starting from one of the edges of the solid and having the first contour half of the material thickness away from the edge and the rest of the contours in increments of one material thickness each. This helps in reducing the work piece deviation but there still areas, in where draft angle is too abrupt that remains without material to be milled, a comparison of slicing methods in presented in figure 8.54. Consequently, we looked closely in this issue in the following sections in order to improve it.

Figure 8.54: Diagram showing comparison of slicing methods
The first option is to use Gaussian analysis to get an curvature overview, in figure 8.55. But a better option for a more close inquiry is to use draft angle analysis. The draft angle is the angle that forms the surface facet with the base plane and depends on the base plane orientation. When the surface is vertical/perpendicular to the base plane, the draft angle is zero. When the surface is parallel to the construction plane, the draft angle is 90 degrees. Therefore, the author analyzed the curvature in the surface and the results are showed in figure 8.56 next page. The draft angle analysis was organized according to angle ranges in three segments; the first one from zero degree to ten degree; the second one from ten degree to thirty degree; the third one from thirty degree to forty five degree; and the last one from forty five degree to sixty degree. Using simple trigonometry a formula was created to determine the amount of material to be added in each range, as seen in figure 8.56 next page.

![Gaussian analysis of the surface.](image)

**Figure 8.55:** Gaussian analysis of the surface.
Figure 8.56: Draft angle analysis and amount of material to be added in each case.

- From 0 to 10 degree draft angle
  Using 18 mm Baltic birch
  Add 55 mm.

- From 10 to 30 degree draft angle
  Using 18 mm Baltic birch
  Add 32 mm.

- From 30 to 45 degree draft angle
  Using 18 mm Baltic birch
  Add 18 mm.

- From 45 to 60 degree draft angle
  Using 18 mm Baltic birch
  Add 10 mm.
This analysis resulted very useful and it is an effective way to analyze and fix the problem. Accordingly, next to each range a material z value increase is suggested for each range. The researcher obtained these values by simple trigonometry according to specific material thickness, using the following formula: Material to be added (a) equals to panel thickness (b) divided by the tangent of the surface facet angle (Tan β) as explained in the following section. Anyhow, adding material in everywhere increases material waste. Mostly because deviation in the workpiece happens just in one direction i.e.: the slicing direction. So let's look more closely to the manufacturing error to see how it was produced and how we can improve the solution. In order to analyze the issue in detail the research uses a sectioned three-dimensional model. The section line is passing through the area where the error is found as seen in figure 8.57.

![Figure 8.57: Section of the model along the affected areas.](image)
If we look closely to the area we find out that multiple angles are found. But we are looking in specific slices. If we look closely we can find the one in where the angle is steeper and determining the angle we can use the formula as shown in Figure 8.58:

![Figure 8.58: Draft angles in the affected area an material addition calculation.](image)

As a summary using draft angle analysis, we can found out about a general approach to determine the amount of extra material needed for the milling process. Then in using three-dimensional models of the work piece and comparing it with the target surface we can easily find the more problematic areas and treat them locally. Consequently, we can detect each specific slice in where additional material and determine how much material is needed. Even though this proposed method is time consuming proved to be efficient for most of the cases. Even though Curvature resolution is still and issue in this case study the research already reported it in the previous case study.
8.5.7. *Surface deviation:*

The second issue was surface deviation coming from draft angles that combine formed curvature radius that were not possible to machine. This error passed all the way to manufactured panel completely undetected. Unfortunately CAM system machining simulation was not useful at all in determining machining feasibility in narrow angles. Machining feasibility on those cases is just able to detect tool collision related to surface draft angles and tool geometry. In performing surface curvature deviation from the original surface was possible to detect the error as shown in figure 8.59. We analyze this issue in more detail in the following paragraphs and we look for early detection as well for solutions for it. One of the additional problems was that this error and the previously reported were locate in the exact same area, making them more visible, as seen in Figure 8.59 on the right.

![Surface deviation analysis using alternative tool-path widths](image-url)

**Figure 8.59: Surface deviation analysis using alternative tool-path widths**

The best solution in analyzing the problem is to use minimum curvature analysis if we set the minimum radius equals to tool radius. We immediately visualize the areas being over cut. Figure 8.60 next page show alternative analysis with different tool width ranges.

Tools available in the CNC router used in this research range from 5 mm to 20 mm of radius. The milling tool used in the case study was 6.35 mm. radius.
Figure 8.60: Minimum curvature range according to tool radius.
8.5.7. **CAD/CAM/CNC workflow**

Some of the issues that the research analyses in the following sections refers to the following; workpiece fabrication; continuity between manufacturing work steps, surface deviation, surface resolution and tool geometry. Other relevant aspects of CAD/CAM/NC workflow was related to different file extension used in the workflow and its implication in keeping consistency in the data along the process. shows not only the different file extensions used along the workflow but also software application used. This is important because different application write same file extension with significant differences.

The last issue was related to CAD/CAM workflow. Integration between the two processes was limited to geometric information exchange. Meaning geometric information was generated in the CAD system for both processes but was never possible to integrate them in the CAM system. The final product of the two-dimensional cutting process, in figure 8.61, was the initial material i.e.: workpiece, for the second process the three-dimensional milling process, in figure 8.62.

![Figure 8.61: CAD/CAM/CNC workflow diagram](image-url)
This research developed a geometric entity that represented the work piece for the second process. But within the CAM system was not possible to use this geometric information for feeding the second process. Even though the CAM system supported multiple and integrated manufacturing steps within one file, the system presented no support for alternative material or workpiece geometries. This resulted in errors that in one process were totally ignored until the second was finished.

Consequently machining simulation misrepresented the process showing extensive tool collision with the work piece as seen in red color in figure 8.63.
Along the same issue this misrepresentation hide real tool collisions coming from the combination deep and with steep angles valleys. One solution was to include an extra rough pass to simulated material removal and the do the finishing path. In running the NC program the machine runs both codes and the first one is just machining “air”. The important issue in here is being able to detect collision between the workpiece and the tool. First we need to detect which angles are candidate for collision with the tool. Angle value $\beta$ to look for is found in the relation between the tool geometry and curve geometry as seen in figure 8.64. And must be within the range in the expression $\partial \leq \beta \leq 180^\circ$, also in figure 8.64. After and using draft angle analysis, as seen in previous sections, we can to localize those angles. Next, we run the second condition, which is a comparison between depth of curvature and the depth of the tool that must be within the range in the expression $b \leq d$ in figure 8.64.

Figure 8.64: Tool geometry and curve geometry relationship.
8.5.8. **Design Heuristics and Metrics:** The researcher collected data, obtained from the experiences, using structured questionnaires; semi-structured interviews; structured non-participant observations; and content analysis. Then the author compiled it in the form of design heuristics and metrics. Later the author organized them according to issues in the DfM model as follows.

8.5.8.1. **Workpiece and Component Geometry:**

**Surface curvature analysis** must be performed to inquiry about potential manufacturing problems. Surface curvature analysis includes a series of visual surface analysis routines. These routines use NURBS surface evaluation and visualization to visually analyze surface smoothness, curvature, and other important properties.

**Gaussian curvature analysis,** Gaussian curvature is a product of the principal curvatures and gives the designer an overview about the surface curvature.

**Mean curvature analysis** refers to absolute value of the mean curvature. This type of analysis is specially suited for finding areas of abrupt change in the surface curvature.

**Draft angle analysis** depends on the base or reference plane orientation. If the surface is vertical/perpendicular to the base plane, the draft angle is zero. If the surface is parallel to the base plane, the draft angle is 90 degrees. This type of analysis is very important in uncovering surface areas in where steep angles are found. Comparing draft angle with tool geometry provide verification of machining-unreachable areas or potential tool-workpiece collision points.

**Minimum radius analysis** provides accurate information about feasibility to mill a surface with a specific radius tool. This type of analysis detects minimum radius location
on the surface. Therefore, any location on the surface that "curves" with a radius smaller than tool radius will cause over cut and surface curvature deviation.

**Surface curvature resolution** must be determined in advance and monitored to check its consistency along the CAD/CAM workflow, and paying special attention to geometric transformation involving NURBS evaluation or tessellation. In order to visualize facets properly, smooth surfaces option must be turned off. Consistency, in relation to equivalent resolution, must be accomplished between sequences of manufacturing processes.

**Workpiece geometry** needs to be produced to keep consistency along the CAD/CAM workflow and to avoid gauging during machining.

**Component size** (Csz) must be determined by comparing allowable machining size (MchSz), in this case router bed size, and material (Mtsz) or workpiece size (WpSz), giving always preference to machining allowances. $\text{MchSz} \geq \text{Csz} \leq \text{WpSz}$ or $\text{MchSz} \geq \text{Csz} \leq \text{Mtsz}$.

**Surface curvature maximum deviation** is affected by changes in resolution in geometric transformations in both CAD and CAM systems i.e.: Tessellation and slicing processes in STL export routines, Slicing geometries routines, Tool path generation routines, etc.

**Geometric and manufacturing data organization** A file process to store and organized the sequence of files along the successive transformation processes is needed. Adequate selection of file extension is extremely important and must be determine in advance according to CAD and CAM system selection.
8.5.8.2. Manufacturing process:

Surface finishing for surface milling depends on three factors; cut width o tool path width; cord tolerance; and facet tolerance. All these factors reside in the CAM system inside the tool path generation routine. The main parameters within it are; cord tolerance along cut (less than 0.1); and facet tolerance (0.25 of cord tolerance), these two parameters defines the polygonal mesh resolution before the software sliced it to produce the tool paths

Surface milling method selection initial rough passes must be done using z-contours method. Finishing paths must be use parallel method.

Tool Selection: Tool suitability can be checked by performing minimum radius analysis and applying a range equivalent with the range of available tool’s radius. Ball nose tools provide better finishing that end mill ones.

Cutting depth is determined by comparing surface curvature with tool geometry and work piece size and can be increased by dividing the milling operation in incremental paths.

Tool geometry, dimensions allowances must be considered in establishing feasible surface curvature in order to avoid collision.

Surface Curvature angles can be anywhere between 0 degree and 90 degree minus tool allowances tool in descending paths and between 180 degree and 90 degree plus tool allowances in ascending paths.

Cutting width

Normally, and according to the material being cut, cutting width is tool diameter for rough paths and at least 1 mm. for finishing path.
8.5.9. **Summary:**

Summarizing this last case study showed multiple design issues and manufacturing errors most of them related to manufacturing processes integration and CAD/CAM/CNC workflow. The research studied the most relevant ones and they were related to; workpiece fabrication; continuity between manufacturing work steps; surface deviation; surface resolution; tool path generation; and tool geometry. In addition, the research found out about its origins and laid out some potential solutions. In using surface curvature analysis this research demonstrated how powerful is three-dimensional modeling combined with analysis tools in assessing component manufacturability. Other relevant aspects of CAD/CAM/NC workflow were also reviewed. Most of them were related to the different file extensions used in the workflow. Consequently, special attention was given to keep consistency in the geometric data along the process.

Accordingly, the research detected some of the problems affecting geometric consistency but was not able to present a comprehensive solution. Frequently the origin of the problem resides in the lack of adequate neutral file extension that supports a DfM approach workflow. Two process diagram were developed to explore the CAD/CAM/CNC workflow in a more comprehensive way—seen in figure 8.65 and 8.66 in next two pages. These two diagrams were very useful in the improvements presented in the updated DfM model also presented in incoming page—see figure 8.67 page 191. The updated DfM model reflects minor changes. Those changes refer to incorporate a generic manufacturing process selection module. The module is located before the analysis and optimization shell. These generic categories refer to; adding material; removing material; and redistributing material.
Figure 8.65: CAD working flow for two-dimensional cutting including all geometric transformations.
Figure 8.66: CAD working flow for Three-dimensional milling including all geometric transformations.
Figure 8.67: Updated DfM model
CHAPTER 9

IMPLEMENTATION OF CASE STUDY USING FRY-REGLET FRAME AND INTERPRETATION OF RESULTS

9.1. Case Study definition and presentation

In the final stage of the research uses a component based design case study as way to test the proposed DfM model. The case study was developed at the advanced wood product laboratory (AWPL) at GaTech, in between August 2006 and January 2007. The case study consisted in to manufacture a curved surface wood panel for an existing wall system in Figure 9.1.

![Figure 9.1 Graph interior wall system by fry reglet.](image)

This wall system is called Graph and produced by Fry Reglet, a local architectural component-manufacturing firm. Even though the Graph system presents a good variety of finishes into a pre-engineered platform grid system. This flexible grid is anchored ...
panel and materials along with the aluminum frame, but they do not have a curved panel solution. Consequently, this component-based system presented a good opportunity to test the DfM model. The researcher, using the DfM model as framework, manufactured two alternative curved wood panel solutions. In the next section, the research introduces the Graph system by Fry reglet. After that, the research presents an initial proposal for a bespoke design with two alternative veneer orientations. Finally, the research introduces an optimized modular panel design obtained after component analysis, evaluation and optimization using the DfM model.

9.2. Graph System by Fry Reglet

The Graph Interior Surface System, developed by Fry Reglet, serves as a platform for mounting modular wall panels in a range of surfaces and styles. The system uses a pre-engineered aluminum grid that can be anchored to new or existing concrete, drywall, block, or plaster, and faced with a variety of factory-fabricated surface panels. The aluminum grid presents three alternative reveals for the panel-frame solution, as seen in figure 9.2

Figure 9.2 Graph interior wall system alternative reveals by fry reglet.

to new or existing drywall, block, plaster or concrete, and then factory-fabricated panels are attached to it. More details in www.fryreglet.com
Standard Graph panels are offered in wood, metal, glass, and translucent resin, as well as 3D metal panels. The system’s panel connection design allows for each panel to be individually accessible, making it simple to replace panels should they become worn, damaged, or outmoded. Point accessible panels also make it easy for the future addition or maintenance of electrical, data, or communication components located behind the wall covering. Compared to custom millwork, the Graph system costs less and provides more freedom to choose a variety of materials in a range of textures and treatments. The platform grid and finished panels arrive at the job site ready to install, with minimal field fabrication. Fry reglet provided the researcher with a two module aluminum frame to develop the curved panel, including two sample panels in figure 9.3.

Figure 9.3 Frame and sample panels provided by fry reglet.
9.3. Wood curved panel alternative 01

The initial approach was to develop a 15-module curved wall using the Fry Reglet wall system. In alternative 01 the idea was to produce a bespoke design being each of the fifteen panel unique. Surface generation process used lofting of splines for generating NURBS surfaces as seen in figure 9.4.

Figure 9.4: Surface generation using lofting

Afterwards, a solid was generated and then it was split in fifteen panels using a three-dimensional grid, as seen in figure 9.5.

Figure 9.5: Surface offset for workpiece generation
The complete wall was three-panel height and five panels along. Initially a full mock up was fabricated in foam as seen in figure 9.6 and figure 9.7. Afterwards the highlighted module in figure 9.7 was developed in plywood.

Figure 9.6: Foam prototype milling.

Figure 9.7: Wall system prototype in foam.
This foam prototype was extremely useful in visualizing tessellation in improving surface finishing as seen in figure 9.8.

Figure 9.8: Surface system with facets on top and smooth faces on the bottom.

After finishing the foam a prototype one panel was fully fabricated in plywood, the panel is highlighted in red in figure 9.8. Next section the research revises the complete wood panel production process.
The wood panel was fabricated using the same approach to those produced in the last case study with students. Consequently, we will focus on improvements over those previous experiences. In this case, through modeling the workpiece surface deviation was corrected before fabrication as seen in figure 9.9. Accordingly, 10 mm were added on the workpiece surface for the milling process.

**Figure 9.9: Workpiece improvement for reducing the surface deviation**

Once surface finishing and surface deviation was corrected information for the two manufacturing process was produced. Nested shapes, tool paths, numbering, support tags and alignments aids were included in the two dimensional cutting CAM file as seen in figure 9.10. The workpiece was produce in an Ergon router similar to the one used in previous exercises and presented in page 150 and figure 8.26. The workpiece was fabricated out of 42 slices cut from one a 4’ x 8’ Baltic birch plywood panel.

**Figure 9.10: Panel including tool paths, drilling and numbering.**
Afterwards slices were glued together and assembled to finish the workpiece as seen in figure 9.11. This process is done manually. Even though was done very carefully to ensure dimensional consistency, some misalignments were found out of excess of pressure during gluing and some inconsistency in the panel dimensions.

**Figure 9.11: Workpiece slices assembly process.**

Again, there was no way to input workpiece geometry in to the CAM system. Consequently, special care was given to workpiece assembly to obtain adequate tolerances and alignment for the milling process. After that the piece was milled using not only the same CNC router than in previous exercises, presented in page 150 and in figure 8.26 but also same production process. The machining routine consisted in one rough path using a 20 mm flat end drill with 19.05 mm diameter and a 15 mm cut width. Then one finishing path using a ball end drill with 12.7 mm diameter and a 0.75 mm cut width. Cord tolerance was set at 0.2 as well facet tolerance was set 0.5 of Cord tolerance.

**Figure 9.12: CAM files with rough path on the left and finishing path on the right.**
Figure 9.13: Final panel mounted on the Fry-reglet frame

Figure 9.14: Final panel mounted on the Fry-reglet frame
Even though CAD/CAM/CNC workflow, surface deviation, and surface finishing were significantly improved, the case study showed multiple design and manufacturing issues. Most of the issues were related to potential design and manufacturing process improvements. The research studied the most relevant ones and they were related to; workpiece fabrication, assembly and tolerances; panel weight; machining times; and veneer direction. These issues were developed and improved, under the DfM framework, in a second and final case study. The purpose was to develop and achieve these improvements and demonstrate the effectiveness of the proposed DfM model.

9.4. Wood curved panel alternative 02

Alternative 02 consisted in to develop a 15-module curved wall base in two types of panels. In this case the idea was to produce a modular design being each all the fifteen panel either a panel type a or a panel type b. Alternative panels curvature and combination of them were explored as seen in figure 9.15

Figure 9.15: Panel module variations studies.
In addition new constrains were added. First a dimensional constrain coming from a new type of router with different dimensional tolerances, a Morbidelli author 427S in figure 9.16,

![Router Morbidelli Author 427S.](image)

**Figure 9.16: Router Morbidelli Author 427S.**

The machinable height was reduced to less than 100 mm. Second constrain was to produce the panel out of one milling process, removing one machining process and workpiece assembly. In addition, workpiece tolerances were significantly improved. Consequently, the workpiece is made of horizontal plywood pieces. This produces two desired effects on the panel. One horizontal veneer that enhances curvature visualization and second material use was reduced fifty percent. Now two panels were produced out of one 4’ x 8’ Baltic birch panel.
Selected option for the wall system complies with all the requirements and combines two types of modules. Workpiece are obtained after assembling together four plies of Baltic Birch plywood. In this way and as mentioned before, two panels are obtained out of one plywood panel. Dimensionality is obtained at surface generation process by setting the b-splines within the panel dimensional tolerances represented as bounding box in figure 9.17 at the center. Each ply is also included as reference for checking surface curvature from each plywood slice, in figure 9.17 at the left. Modularity is produced at the time that the curved surface is generated by lofting b-splines in figure 9.17 at the right. The criteria is just to use the starting B-spline that generates the panel type a as the ending B-spline in the lofting that generates the curved surface for panel type b. Consequently, the ending b-spline in the lofting operation that generates the curved surface in panel a it is the initial b-spline in the lofting process that generates panel b.—as seen in figure 9.18 next page.

Figure 9.17: Final modular system showing module a, and module b.

Once generated these geometries are exported in to the CAM system using IGES file extension. In the CAM system material panel is imported as an independent geometric entity and transformed in to workpiece data. Afterwards Tool path describing tool trajectories are incorporated.
At this point, the CAM system uses a specific post processor to output the NC code for the machining process. Nevertheless, the NC file or program is transferred to CNC controller computer. The machine operator opens the program and adjusts the material top level, according to spoiling board dimensions. Then each piece is milled in the CNC router. The milling program is divided in two paths and the complete machining process takes 1 hour of machining time that is a 50% reduction over the previous process. Even though the panel is not hollow as the previous one, final panel weight was reduced around 80% compared to that.
The machining routine consisted in one rough path using a 20 mm flat end drill with 19.05 mm diameter, a 15 mm cut width and a maximum cut depth of 9.525 mm, leaving 4 mm of material for the finishing path, as seen in figure 9.19.

Afterwards a second machining routine was performed. And consisted of one finishing path using a ball end drill with 12.7 mm diameter and a 1 mm cut width. Cord tolerance was set at 0.1 as well facet tolerance was set 0.25 of Cord tolerance, in figure 9.20.

The rough path took 11 minutes and the finishing path took 54 minutes making a total of 1 hour and 5 minutes of machining time. This saved time is a considerable, if we compare it with alternative 01 that took 2 hours and 15 minutes of machining time.
The finished panels, in figure 9.21, did not require additional finishing, but they were sanded and coated for protection. Some minor errors were presented during machining coming from loose pieces in relation to poor gluing and mostly from not enough gluing drying time. For best results, each panel needs at least 8 hours of drying time with homogeneous pressure application, after gluing and before machining.

![Figure 9.21: Module-a and module-b after machining without sanding and coating.](image)

This final case study resulted in a variety of manufacturability improvements in the component design. The DfM model proved to be efficient in relation not only in reducing manufacturing cost by reducing machining operations, machining time, and material waste but also improving the Design for Manufacturing workflow by removing bottleneck in data exchanges and making errors detectable. All of the previous improvements were accomplish without reducing design quality in relation to accomplishment of design intent.
9.5. Summary:

The final DfM model implementation framework includes significant improvements in relation to the previous models—presented in page 103, figure 7.30 and in page 191, figure 8.68. This final model is presented in page 209, figure 9.22. This model defines component generation as the initial stage. After that, component’s geometric analysis provides an initial understanding of component’s geometrical properties. These properties are feed in to the material and process selection that now is treated as an independent shell. This material and process selection is now located before component evaluation shell. In addition, this shell includes most relevant material and process issues to consider—In selecting material and manufacturing process. After that, a component evaluation and prototyping shell is proposed, and it includes issues to consider in performing those steps. The component evaluation and prototyping shell and the manufacturing module together, structure the DfM knowledge base. This knowledge base includes not only the necessary knowledge to perform component evaluation but also constitutes the main knowledge base for providing feedback to the initial stages.

As summary, the final model was structured as follows:

A **component generation** shell in where components and its producible parts are designed.

A **geometrical analysis** module that allows designers to perform both surface curvature and other geometric data analysis for a given component.

A **material and process selection** shell to select and evaluate material and processes in a given component—now is located before the optimization shell.
A **component evaluation and optimization** shell, in where optimization is performed by choosing between alternatives aspects to optimize. The optimization and prototyping shell allows designer to evaluate manufacturability of a given component, checking if the influential factors are within the limits.

A **manufacturing** module containing relevant issues related to manufacturing data. This module describes relevant aspects to consider for manufacturing information generation.

Afterwards all the rules used in the final case study were compiled and organized, as seen in figure 9.23 through figure 9.26. Each rule is presented and organized according to different topics; first according to the stage in the DfM model that it is connected to i.e.: **component generation, geometric analysis, material and process selection**, and **component analysis and evaluation**; second in relation to the generic topic that it relates to i.e.: **Design, manufacturing, geometry, material, and data exchange**; third according to the class of rule that belongs to i.e.: **Process, material and geometry** distinguishing between **generic** and **specific** rules. Finally yet importantly the rules are organized according to the type of issue that the rule refers to.
Figure 9.22: Final DfM model
<table>
<thead>
<tr>
<th>DfM Ref.</th>
<th>Topic</th>
<th>Class</th>
<th>Type</th>
<th>Rule</th>
</tr>
</thead>
<tbody>
<tr>
<td>Along the whole</td>
<td>Design and Manufacturing</td>
<td>Process generic</td>
<td>Units</td>
<td>Use metric system</td>
</tr>
<tr>
<td>process model</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Along the whole</td>
<td>Manufacturing</td>
<td>Process generic</td>
<td>Tolerances</td>
<td>Match tolerances between processes</td>
</tr>
<tr>
<td>process model</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Along the whole</td>
<td>Manufacturing</td>
<td>Process generic</td>
<td>Manufacturing</td>
<td>Reduce the number of manufacturing processes</td>
</tr>
<tr>
<td>process model</td>
<td></td>
<td></td>
<td>Process</td>
<td></td>
</tr>
<tr>
<td>Along the whole</td>
<td>Material</td>
<td>Material generic</td>
<td>Material format</td>
<td>Reduce material waste</td>
</tr>
<tr>
<td>process</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Along the whole</td>
<td>Data exchange</td>
<td>Process generic</td>
<td>Geometric and</td>
<td>Set a file organization protocol to store and organized</td>
</tr>
<tr>
<td>process</td>
<td></td>
<td></td>
<td>manufacturing</td>
<td>data organization</td>
</tr>
<tr>
<td>Data exchange</td>
<td></td>
<td></td>
<td>data organization</td>
<td></td>
</tr>
<tr>
<td>Along the whole</td>
<td>Data exchange</td>
<td>Process generic</td>
<td>Manufacturing</td>
<td>Select the appropriated file extension for geometric</td>
</tr>
<tr>
<td>process</td>
<td></td>
<td></td>
<td>data organization</td>
<td>data exchange</td>
</tr>
<tr>
<td>Along the whole</td>
<td>Geometry</td>
<td>Process generic</td>
<td>Surface curvature</td>
<td>Surface curvature resolution must be determined in</td>
</tr>
<tr>
<td>process</td>
<td></td>
<td></td>
<td>resolution</td>
<td>advance</td>
</tr>
<tr>
<td>Along the whole</td>
<td>Geometry</td>
<td>Process generic</td>
<td>Surface curvature</td>
<td>Keep Surface curvature resolution consistent</td>
</tr>
<tr>
<td>process</td>
<td></td>
<td></td>
<td>resolution</td>
<td>along CAD/CAM workflow</td>
</tr>
<tr>
<td>Component generation</td>
<td>Geometry</td>
<td>Process generic</td>
<td>Part</td>
<td>Reduce the total number of parts.</td>
</tr>
<tr>
<td>Component generation</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Component generation</td>
<td>Geometry</td>
<td>Process generic</td>
<td>Part</td>
<td>Develop a modular design.</td>
</tr>
<tr>
<td>Component generation</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Component generation</td>
<td>Geometry</td>
<td>Process generic</td>
<td>Part</td>
<td>Avoid separate fasteners.</td>
</tr>
<tr>
<td>Component generation</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Component generation</td>
<td>Geometry</td>
<td>Process generic</td>
<td>Assembly</td>
<td>Minimize assembly directions.</td>
</tr>
<tr>
<td>Component generation</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Component generation</td>
<td>Geometry</td>
<td>Geometry generic</td>
<td>Surface Curvature</td>
<td>Avoid double curvatures</td>
</tr>
<tr>
<td>Component generation</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Component Generation</td>
<td>Geometry</td>
<td>Geometry generic</td>
<td>Surface Curvature</td>
<td>Avoid complex geometries</td>
</tr>
</tbody>
</table>

*Figure 9.23: Final compilation of captured DfM rules used in the final case study*
<table>
<thead>
<tr>
<th>DfM Ref.</th>
<th>Topic</th>
<th>Class</th>
<th>Type</th>
<th>Rule</th>
</tr>
</thead>
<tbody>
<tr>
<td>Component Generation</td>
<td>Geometry</td>
<td>Geometry specific</td>
<td>NURBS</td>
<td>NURBS can not be used to drive CNC machine directly</td>
</tr>
<tr>
<td>Component Generation</td>
<td>Geometry</td>
<td>Geometry specific</td>
<td>Surface deviation</td>
<td>Make curve control points equivalent for surface generation using lofting.</td>
</tr>
<tr>
<td>Geometrical analysis</td>
<td>Geometry</td>
<td>Geometry specific</td>
<td>Polygon mesh</td>
<td>Facet size determine curvature resolution</td>
</tr>
<tr>
<td>Geometrical analysis</td>
<td>Geometry</td>
<td>Geometry specific</td>
<td>NURBS resolution</td>
<td>Resolution must be determined before machining</td>
</tr>
<tr>
<td>Geometrical analysis</td>
<td>Geometry</td>
<td>Geometry specific</td>
<td>NURBS resolution visualization</td>
<td>In order to visualize facets properly, smooth surfaces option must be turned off.</td>
</tr>
<tr>
<td>Material and process selection</td>
<td>Material and Manufacturing</td>
<td>Material and process generic</td>
<td>Manufacturing Process</td>
<td>Select the optimum combination between the material and manufacturing process</td>
</tr>
<tr>
<td>Material and process selection</td>
<td>Geometry</td>
<td>Process generic</td>
<td>Component size</td>
<td>Compare allowable machining size (MchSz) and material (Mtsz) or workpiece size (WpSz), giving always preference to machining allowances. MchSz ≥ Csz ≤ WpSz or MchSz ≥ Csz ≤ Mtsz.</td>
</tr>
<tr>
<td>Component prototyping and evaluation</td>
<td>Manufacturing</td>
<td>Process generic</td>
<td>Tool paths</td>
<td>Reduce number of tool paths</td>
</tr>
<tr>
<td>Component prototyping and evaluation</td>
<td>Manufacturing</td>
<td>Process generic</td>
<td>Surface finishing</td>
<td>Reduce number of surface finishing operations</td>
</tr>
<tr>
<td>Component prototyping and evaluation</td>
<td>Geometry</td>
<td>Process generic</td>
<td>Machining time:</td>
<td>Increasing curve resolution increases machining time.</td>
</tr>
<tr>
<td>Component prototyping and evaluation</td>
<td>Manufacturing</td>
<td>Process generic</td>
<td>Optimum curve resolution</td>
<td>Cutting path resolution is determined by the number of segments in the polylines that form it.</td>
</tr>
</tbody>
</table>

*Figure 9.24: Final Compilation of captured DfM rules used in the final case study.*
<table>
<thead>
<tr>
<th>DfM Ref.</th>
<th>Topic</th>
<th>Class</th>
<th>Type</th>
<th>Rule</th>
</tr>
</thead>
<tbody>
<tr>
<td>Component prototyping and</td>
<td>Manufacturing</td>
<td>Process generic</td>
<td>Cutting depth</td>
<td>Cutting depth is determined by comparing tool geometry and work piece geometry. An example with formula is provided in figure 8.65 in page 184.</td>
</tr>
<tr>
<td>evaluation</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Component prototyping and</td>
<td>Geometry</td>
<td>Process generic</td>
<td>Surface curvature</td>
<td>Obtain equivalent resolution, between sequences of manufacturing processes.</td>
</tr>
<tr>
<td>evaluation</td>
<td></td>
<td></td>
<td>resolution</td>
<td></td>
</tr>
<tr>
<td>Component prototyping and</td>
<td>Geometry</td>
<td>Process generic</td>
<td>Surface curvature</td>
<td>Reduce Surface curvature deviation</td>
</tr>
<tr>
<td>evaluation</td>
<td></td>
<td></td>
<td>deviation</td>
<td></td>
</tr>
<tr>
<td>Component prototyping and</td>
<td>Geometry</td>
<td>Process specific</td>
<td>Optimum curve</td>
<td>Slicing direction resolution is determined by cut width. An example with formula is provided in figure 8.12 in page 124.</td>
</tr>
<tr>
<td>evaluation</td>
<td></td>
<td>(Surface milling)</td>
<td>resolution</td>
<td></td>
</tr>
<tr>
<td>Component prototyping and</td>
<td>Geometry</td>
<td>Process specific</td>
<td>Optimum curve</td>
<td>Resolution along the cutting path is determined by cord tolerance (Ct) and facet tolerance (Ft).</td>
</tr>
<tr>
<td>evaluation</td>
<td></td>
<td>(Surface milling)</td>
<td>resolution</td>
<td>Ct ≤ 0.1 mm.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Ft = 0.25*Ct</td>
</tr>
<tr>
<td>Component prototyping and</td>
<td>Manufacturing</td>
<td>Process specific</td>
<td>Tool path</td>
<td>Rough passes must be done using z-contours method.</td>
</tr>
<tr>
<td>evaluation</td>
<td></td>
<td>(Surface milling)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Component prototyping and</td>
<td>Manufacturing</td>
<td>Process specific</td>
<td>Tool path</td>
<td>Finishing paths must be use parallel method.</td>
</tr>
<tr>
<td>evaluation</td>
<td></td>
<td>(Surface milling)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Component prototyping and</td>
<td>Manufacturing</td>
<td>Process specific</td>
<td>Tool Selection</td>
<td>Ball nose tools provide better finishing that end mill ones.</td>
</tr>
<tr>
<td>evaluation</td>
<td></td>
<td>(Surface milling)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Component prototyping and</td>
<td>Manufacturing</td>
<td>Process specific</td>
<td>Cutting depth</td>
<td>Cutting depth can be increased by dividing the milling operation in incremental paths.</td>
</tr>
<tr>
<td>evaluation</td>
<td></td>
<td>(Surface milling)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Figure 9.25: Final Compilation of captured DfM rules used in the final case study.*
<table>
<thead>
<tr>
<th>DfM Model reference</th>
<th>Topic</th>
<th>Class of DfM rule</th>
<th>Type of DfM rule</th>
<th>DfM rule</th>
</tr>
</thead>
<tbody>
<tr>
<td>Component prototyping and evaluation</td>
<td>Manufacturing</td>
<td>Process specific (Surface milling)</td>
<td>Tool path</td>
<td>Dimensions allowances must be considered to avoid tool collision.</td>
</tr>
<tr>
<td>Component prototyping and evaluation</td>
<td>Manufacturing</td>
<td>Process specific (Surface milling)</td>
<td>Surface Curvature angles</td>
<td>Surface Curvature angles in descending paths. ($S_{\text{des}}$) can be anywhere between 180 degree and 90 degree minus tool allowances ($T_{\text{alw}}$) $(90^\circ \leq S_{\text{des}} \geq 0^\circ) - T_{\text{alw}}$</td>
</tr>
<tr>
<td>Component prototyping and evaluation</td>
<td>Manufacturing</td>
<td>Process specific (Surface milling)</td>
<td>Surface Curvature angles</td>
<td>Surface Curvature angles in ascending paths. ($S_{\text{asc}}$) can be anywhere between 180 degree and 90 degree minus tool allowances ($T_{\text{alw}}$) $(180^\circ \geq S_{\text{asc}} \geq 90^\circ) - T_{\text{alw}}$</td>
</tr>
<tr>
<td>Component prototyping and evaluation</td>
<td>Manufacturing</td>
<td>Process specific (Surface milling)</td>
<td>Cutting width</td>
<td>Cutting width for rough paths ($C_{wr}$) is tool diameter ($T_d$) $C_{wr} = T_d$</td>
</tr>
<tr>
<td>Component prototyping and evaluation</td>
<td>Manufacturing</td>
<td>Process specific (Surface milling)</td>
<td>Cutting width</td>
<td>Cutting width for finishing paths ($C_{wf}$) is at least 1 mm. $C_{wf} \geq 1 \text{mm.}$</td>
</tr>
<tr>
<td>Component prototyping and evaluation</td>
<td>Manufacturing</td>
<td>Process specific (Surface milling)</td>
<td>Surface finishing for surface milling</td>
<td>Cord tolerance along cut ($C_{t}^{al}$) is less than 0.1 $C_{t}^{al} \leq 0.1 \text{mm.}$</td>
</tr>
<tr>
<td>Component prototyping and evaluation</td>
<td>Manufacturing</td>
<td>Process specific (Surface milling)</td>
<td>Surface finishing for surface milling</td>
<td>Facet tolerance along cut ($F_t^{al}$) is 0.25 of cord tolerance along cut ($C_{t}^{al}$) $F_t = 0.25 \ast C_{t}^{al}$</td>
</tr>
<tr>
<td>Component prototyping and evaluation</td>
<td>Manufacturing</td>
<td>Process specific (Surface milling)</td>
<td>Tool Selection</td>
<td>Determine Tool suitability by performing minimum radius analysis and compare with the range of available tool’s radius.</td>
</tr>
</tbody>
</table>

Figure 9.26: Final Compilation of captured DfM rules used in the final case study.
CHAPTER 10

SUMMARY CONCLUSIONS

This thesis explores new ways to integrate manufacturing processes information in to design phases. The final purpose is to provide better theoretical constructs and teaching approaches for integrating design with manufacturing in building production.

Within that scope the DfM model implementation, evolution and refinement through the sequence of case studies demonstrated not only the model feasibility but also its relevance and effectiveness in the teaching approach and in the final case study.

Even though there is an increasing consensus about the significance of reestablishing the connection between design and construction within the architectural discipline, it is still unclear how this change will be implemented. Authors like Kieran and Timberlake envision a complete integration of design with the craft of assembly supported by the materials scientist, the product engineer, and the process engineer, all using the tools of present information science as the central enabler. This approach does not move away from the existing practices that keep the knowledge segregated in different specialists and does not tackle the main problem that is manufacturing knowledge integration. Kolaveric as others predict what will happen in the future in building production. Unfortunately, there is no indication about how this will happen.

What it is proposed is to look at aircraft and car industry, but there is no in depth analysis

about what we should look at. It is important to realize that those industries has been changing over the last twenty year and those changes are part of new models of production that looks not only at integration of digital technologies in product development but also at different ways to integrate design and manufacturing.

Finally Schodek et al presents an overview of computer-aided design and manufacturing processes. Even though they present a number of “application studies”, they do not provide a structured approach to collect, organize, and analyze the information presented. Consequently the cases presented are just examples with no further elaboration. In addition, they provide a description of different design environments to support computer-design and manufacturing but they ignore integration issues. They also provide an overview of Computer-Numerically Controlled (CNC) technologies. However, there is no definition about how these technologies will be incorporated in building production. In the final part of the book the authors laid out some general strategies organized as a set of issues, that mostly refers to "new architectural forms, elements and components, building systems and design processes", presenting them as areas of interest without further elaboration. For this research, those issues are part of the problem context. Consequently, the knowledge based approach and the proposed DfM model constitutes the framework for implementing solutions, and the starting point for this implementation is in architectural education

60 In Ibid.58
Research in DfM approach in architecture is very limited. On the contrary, examples of its implementation are highly published. However, the knowledge gained from those examples is not made visible and the technical expertise resulting is not made available. Consequently, the proposed DfM model in this research needs to be compared to existing DfM models in the product development area. One of the most referenced DfM models in this area is the one produced by Boothroyd et al. (Boothroyd et al., 2002) The model is presented in figure 10.1.

Figure 10.1: DfM model from Boothroyd et al.

The Boothroyd et al. model is organized along a sequence of modules or shells that systematize the design-to-production flow. There is three major components providing feedback to design; an initial Design for Assembly (DFA) shell; a material/process selection shell; and a Design for Manufacture (DFM) shell. DFA shell reduces the product complexity by consolidating parts. DFM shell then estimates the cost of producing the reorganized design to compare it with the cost of the original design. There are two major issues; there is no information about the type of issues considered within each shell or about the origin and type of knowledge used to evaluate designs. In addition, the evident conflict between assembly and manufacturing considerations is ignored. In addition, there is no feedback to design from the prototype realization.
Other well known DfM model in this area is the one produced by Ulrich and Eppinger (Ulrich and Eppinger, 1995a). The model is presented in figure 10.1.

Figure 10.2: DfM model from Ulrich and Eppinger

The model is based in reducing manufacturing cost through dropping cost of; components; assembly and supporting production. After that, the impact of those reductions on other aspects is considered. Finally, just the manufacturing cost is recomputed. After that goodness satisfaction criteria is used to decide if the design is satisfactory or not. If it is not the cost reduction loop is performed again until the design is accepted. Even though different costs are considered, interaction between them is not incorporated—because it is most of times conflicting. The model is just focused in one aspect i.e.: manufacturing cost. Consequently, the model neglects other aspects like product quality and production time. Moreover, tasks are just mentioned without giving any information how this task is performed or at least what type of aspects or knowledge are considered in performing them.
Even though this is a less known one, the model by Liu et al. (LIU et al., 1999), incorporates a multiple level model but without interaction between the two levels. One level is related to schematic design and a second to detailed design. The initial stage categorized the master design cycle is a very simple process description. In the second level identified as the detailed design circle an evaluation cycle is proposed based on DfM and computer aided process planning (CAPP). Even though three levels of DfM evaluation are proposed i.e.: Estimation, rough and detailed evaluation, there is no mention about its considerations or about the relation between DfM evaluation and the CAPP module proposed. In addition, it does not present much information about the task sequence proposed. Finally there is no mention about what type of improvement suggestion the model supports.

Figure 10.3: DfM model from Liu et al.
Other DfM model in this area is the one produce by Lee and Hahn. (Lee and Hahn, 1996). The model, in figure 10.4, is organized around two interactive shells, but without that interaction being defined at all. One shell is dedicated to product design and the second one about product manufacture. Both contain sub-shells each one organized as a continuous iteration of stages. The product design shell is organized around the development and analysis of how the product will be assembled from individual components. Within the product manufacturing shell and beyond the overall focus of manufacturing, two shells within this life cycle stage are highlighted; these are process and tooling development and final product assembly and integration. The final product assembly and integration segment serves as the stage of where the components are assembled together to form the product. Essential in this model is the process & tooling development sub-shell. There, the operations, processes and tools needed to perform the tasks of assembly are created and refined.

Figure 10.4: DfM model from David E. Lee and H. Thomas Hahn
Notwithstanding the popularity and success of these DFM models, there is much space for improvement. These DFM models are somewhat holistic in their attempt to integrate design and manufacturing. Holistic in the way that they are excessively concerned with the DfM process as a whole without dealing with the analysis and dissection of it into parts. Moreover, all these approaches lack any serious effort in considering DfM model as a model of design processes. They are more concerned with being considered a product manufacturability evaluation models or just manufacture cost estimation models. This is a critical point, considering 70% of the product’s cost is determined at the design stage. Another shortcoming of these models is their inability to organize knowledge obtained after analysis and evaluation of product manufacturability. They also fail in to provide redesign suggestions to modify components in the case of inadequate design. In addition, these models ignore mapping between design issues and manufacturing aspects. So they are able to determine component’s manufacturability but they are not able to consistently identify where redesign or adjustments should occur. One big methodological limitation within these DfM models is coming from inefficacy of their evaluation framework that is based on either manufacturing cost or production time. The problem with this framework is that those aspects does not always represent improvement in the quality of the actual design product.

Even though the DfM model presented in this research tackles most of these issues, it is still far from reaching an adequate level. Some of its limitations are exposed in the following paragraphs. Even though design heuristics and issues to consider allow design decisions based on a clear rationale. They do not guarantee the quality of the design solution. Design heuristics need to be tested in order to assure their effectiveness,
so they need a continuous process of improvement. However, it is possible to use design metrics to compare the effects of different heuristics 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 research was that knowledge captured in the case studies 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 model corresponds to important aspects of meaningful, real-world design tasks.

The results of this research are hopefully valuable for a better understanding of design thinking and design actions, and for further development of design theory through a theory of making or learning by doing. However, there is a lack of studies in the architectural domain comprehending both design and production. Consequently, literature to support specific aspects of the DfM approach and its application is rare. Also new to architectural production is the use of CNC machinery. Nevertheless, last five years ACADIA, eCAADe and SIGRADI conferences have provided some initial studies in the area.

A dramatic paradigm shift has occurred in the building production process regarding the design of new components. The new paradigm is to take out the 'walls' between the designers, manufacturers and testers so they can work together to generate the best product the first time. This new paradigm turns the process into an iterative system in which the design is analyzed and changed to improve manufacturability and function as it progresses. This manufacturability and function evaluation is performed via
computer simulation or rapid prototyping (RP). Computer simulation builds the component in a virtual factory with design tradeoffs evaluated on the computer screen as they are proposed. RP provides an actual component to test for form, fit and function.

More manufacturing technologies are becoming available for building fabrication. 3D printing has become popular for the production of small models; exploration is being undertaken to scale up this process and use it for the construction of building, using special fast setting concrete. (Khoshnevis, 2003) New methods of assembly, based on new connection methods are also worthy of exploration.

The fundamental strategy in the DfM approach in this research was first, to verify a component, second identify a feasible material and an adequate manufacturing process to produce it, then to analyzed and evaluate it, and finally to improve it. Subsequently in applying the DfM 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 according to its manufacturability. Normally, literature in DfM tends to address manufacturability evaluation focusing on a single issue in isolation. Most of these models are focused on manufacturing cost, ignoring production time and product quality. Moreover, they ignore integration between design and manufacturing.

DfM approach teaches to us is that in order to integrate manufacturing knowledge in to design stages, we need to clearly identify not only a suitable manufacturing process or a combination of them but also to recognize relevant knowledge from manufacturing processes affecting design decisions. Afterwards we need to capture that knowledge from the manufacturing process classified and then codify it according to the issues being
tackled and to the design process stage where this knowledge is relevant. Since each manufacturing process is unique, this knowledge is not transferable along them. However, organization of manufacturing process in more high level categories like adding, removing and redistributing material, allow designers to transfer some portion of learned knowledge from one process to other (Giachetti, 1998). On the other hand we need to recognize different knowledge levels; first a domain knowledge from manufacturing field and also domain specific knowledge from the manufacturing technology being used, second procedural knowledge from the manufacturing process itself and inference knowledge from the user interaction with the previous types.

In the case of two-dimensional cutting and three-dimensional milling, this knowledge is extremely useful along these techniques. More over the most relevant conclusion is coming from the CAD/CAM/CNC workflow that exhibits a very steady design process pattern. Curved surfaces and solids with curved faces needs to be transformed from three-dimensional to two-dimensional information to be manufactured. This geometric transformation process can be done by tessellating a solid and then either slicing it, or unfolding its facets. Those processes produce either two-dimensional shapes that are used as tool paths for cutting or one-dimensional curves for three-dimensional milling.

Along the research development, I have stated that the architectural discipline needs to reorganize its body of knowledge according to new scenarios within the building production process. This change must start from the core of the discipline that is the architectural education. Accordingly this thesis extremely encourages studio instructors to use more structured approaches to deal with the increasing complexity found not only
in the ubiquity of complex geometries but also in changes presented in the building production process itself. Digital design and digital fabrication technologies determine a unique opportunity for new educational approaches and where design is presented as a continuous research process in where designing and making are integrated as one thinking process. Accordingly, the most important contribution in this thesis resides in the potential use of the presented DfM model as a framework for new educational approaches in the studio environment. The main purpose in the model is to represent how different stages in a DfM approach are connected, how one design decision would lead to another, and what kinds of aspects of the design problem are relevant in pursuing its solution. Subsequently the real potential resides in the use of the proposed DfM model as analogical thinking device in developing other design for manufacturing teaching approaches. Therefore, the contribution in this thesis in proposing a DfM model is not only to provide an alternative approach as an extension to existing design models but also to make available a framework to produce alternative DfM models in an effective manner.

Potential usages of this research are many but most of them are related to three possible applications fields; DfM teaching approaches, design processes improvement; and DfM methods development. Finally, the proposed use of DfM in building production is not about how DfM must be done. More over it is more a reflection about the nature of design processes and the need for integration between design and construction. We are entering a new epoch in architecture, where we are explicitly concerned with not only the form and function of architecture, but also how it is produced and this requires new models for design and also new approaches in education.
APPENDIX A

DEFINITION OF TERMS:

**Design** is a cognitive process that consists of consensual production of meaningful artifacts through a knowledge capture, manipulation and communication process. Furthermore, design process consists of the transformation of concepts and relations of high abstraction into artifacts with a high level of physical complexity.

**Design Cognition** refers to the study of human information processing in design, using different theoretical and empirical paradigms.

**Manufacturing**: The most general definition refer to manufacturing as the entire set of activities within a product realization process, from design to production and sale. A more specific use of the word is used as synonym of production and refers to physical transformation of material, using different manufacturing processes, in to usable parts and components.

**Building Production**: Refer to the complete building realization process including ranging from design to production.

**Partonomic Structure**: A classification structure that is organize knowledge according to a part-of relationships.

**Buildability**: Buildability can be defined as 'the extent to which the design of the building facilitates ease of construction, subject to the overall requirements for the completed building'.

**Design Knowledge**: Design process brings up certain topics and through them artifacts are composed, decomposed, analyzed and built; those topics establish the design knowledge.
**Parts:** are the basic manufactured units and together form components.

**Components** are arrangements of parts.

**Assemblies** are arrangements of sub assemblies, parts and or components.

**Assembly Component Model:** Building organization model based on a partonomic structure which basic unit are parts, components, assemblies and sub-assemblies

Components based Design: Design of component based on the assembly component model.

**Design Heuristic:** A set of steps, empirical in nature and yet no proven to be always valid, to advance in solving a design task and to successfully find alternative design solutions.

**Design Heuristic Extraction:** Method of examination in which the researcher identifies modules in a design problem, structuring them according to design strategies, design tasks and design actions.

**Connections or joining systems** tie together parts and components, and also fasten together and secure assemblies.

**Design Theory:** A general statement which make no reference to and do not depend upon particular types of design(Smithers, 1996).

**Design Model:** A particularization and specialization of a design theory arrived at by assigning referents in such a way as to make the theory true(Smithers, 1996).

**Design Method:** A normative statement about ways of designing though particular to certain type of design(Smithers, 1996).
3D printing process: A layer manufacturing technology in which the layers are formed by using a printhead-like device to distribute an adhesive to bond the surface of a powder in the desired shape.

Computer Aided Design (CAD): The use of computer software to allow a user to design, modify, and simulate a three-dimensional part or assembly.

Computer Aided Manufacture (CAM): The use of computers to automatically control the machinery performing various manufacturing processes.

Computer Numerical Control (CNC): A CAM technology using computers to control cutting machines such as milling machines and lathes to cut specified three-dimensional shapes. CNC has been used since the early 1970s. Prior to this, machines were controlled by prepared tapes and the process was called simply Numerical Control (NC).

Prototype: A sample part with performance or properties representative of the final product.

Jig: A guide or holding fixture designed for the manufacture of a specific part.

Laminated Object Manufacturing (LOM): A layer manufacturing technology in which a part is fabricated by assembling and bonding layers of material cut to the desired shape.

Layer manufacturing: The fabrication of a part by depositing or bonding successive layers of material.

Rapid Manufacturing (RM): A broad term including the use of rapid prototyping, rapid tooling, and the direct use of layer manufacturing technologies to produce final products quickly.

Rapid Prototyping (RP): The speedy fabrication of sample parts for demonstration, evaluation, or testing. It typically utilizes advanced layer manufacturing technologies that
can quickly generate complex three-dimensional objects directly from computer-based models devised by Computer Aided Design (CAD). This computer representation is sliced into two-dimensional layers, whose descriptions are sent to the fabrication equipment to build the part layer by layer. Rapid prototyping includes many different fabrication technologies. Stereolithography (SL), selective laser sintering (SLS), laminated object manufacturing (LOM), and fused deposition modeling (FDM) are a few examples.

**Rapid Tooling (RT):** The application of rapid prototyping methods to the fabrication of customized molds, dies, and tools used to produce parts.

rubber pad forming: A sheet metal forming operation for shallow parts in which a confined, pliable rubber pad attached to the press slide (ram) is forced by hydraulic pressure to become a mating die for a punch or group of punches placed on the press bed or baseplate.

**Selective Laser Sintering (SLS):** A layer manufacturing technology in which the layers are formed by using a laser to bond the surface of a bed of powder material in the desired shape.

**Shape Deposition Manufacturing (SDM):** A layer manufacturing technology in which the layers are deposited and shaped by CNC, with temporary material also deposited to support layers with overhanging, undercut, and separated features.

sintering: The process of bonding adjacent surfaces of particles in a powder by heating. Sintering strengthens a powder mass and usually increases density.

**Solid Freeform Fabrication (SFF):** Processes that produce three-dimensional shapes from additive formation steps.
Stereolithography (SL): A layer manufacturing technology in which the layers are formed by using a laser to cure the surface of a bath of photo-sensitive polymer resin in the desired shape
APPENDIX B

ARCH-8803-EL Design for Manufacturing
College of Architecture
Georgia Institute of Technology
Eduardo Lyon (eduardo.lyon@coa.gatech.edu)
Senior Seminar, 2006. Th. 6:05-7:55 pm

CURVED SURFACE FABRICATION USING 2D CUTTING
First assignment: slicing, unfolding and assembling.

In the first two classes, we will be discussing about different methods to generate curved surfaces in CAD systems, as we will find out these are standard methods that do not differ much from one system to another. In addition, we will discuss some basic issues about curved surface representation in CAD systems. Our first assignment includes one object to be fabricated using layered manufacturing. This first object will be fabricated by depositing or bonding successive layers of material. Layers or shapes are obtained from slicing the object as shown in sequence 1-4. The intent is to explore how each of the steps in the process are affected by the different geometry of the object. You are asked to treat the fabrication process as a work of design in its own right. You are consequently asked to document the process. Some important questions to investigate are:

1) How do you determine optimum curve surface resolution?
2) How do you determine the slicing distance?
3) How do you identify pieces for assembly after slicing?
4) What holds the pieces together?

You will submit:
1. A .pdf file describing the process.
2. A fabricated object.

You are encouraged to consider your work as potential for the class final assignment. Consequently, you are also encouraged to consider ways in which the initial module can interact using repetition and configuration as elements of a larger construction or system. Finally, you are allowed to propose your own imagination of each of the modules, within the dimensional requirements.

ANTICIPATING THE FINAL ASSIGNMENT

For the final review, you will be asked to present your work as if it was a sequence of stages in producing a system. This means two things:

1. You have to consider how your work link one stage to next.
2. You have to ensure that your module is consistent with your overall system.

The final output will be discussed later on, but you should tackle your immediate work with the understanding that it should become a module of the complete surface system.

DIMENSIONAL REQUIREMENTS:
Modules 2" x 2" and/or 3" x 3"
Complete system: height, 5 modules, length min: 5 modules and max: 8 modules.
ARCH-8803-EL Design for Manufacturing
College of Architecture
Georgia Institute of Technology
Eduardo Lyon (eduardo.lyon@coe.gatech.edu)
Spring Semester, 2006. Th. 8:05-7:55 pm
CURVED SURFACE SYSTEM USING 3D CUTTING AND 3D PRINTING TECHNOLOGIES
Second assignment: slicing, unfolding and assembling

Along last three classes, we discussed about different methods to generate curved surfaces in CAD systems, as we will find out these are standard methods that do not differ much from one system to other. In addition, we discussed some basic issues about curved surface representation in CAD systems. Our first assignment included one object fabricated using layered manufacturing. This first object now becomes the initial module for a more complex component based system. The system is based on the previous component and its layout includes dimensional requirements at the bottom of this document. In addition to the needed design augmentations in the module, a frame is required to organize and hold modules together. The frame will be prototype using laser cutting and structure using an interlocking connection system. Additionally, students are required to resolve connections between the modules and the frame. Please keep in mind that the main purpose in doing this prototype is not only to study possible design alternatives through combination and alternative configurations but also to explore fabrication issues like dimensional tolerance. The critical topics to be explored in this second exercise are component fabrication, design modularity, and connections. You are asked to test the fabrication process as a work of design in its own right. You are consequently asked to document the process. Some important questions to investigate are:

1) How you determine optimum curve surface resolution?
2) How you determine adequate tolerances?
3) How you keep track of original pieces after successive transformations?
4) How you keep consistency in the system with original surface curvature?
5) Is the surface curvature resolution the same in both directions?

You will submit:
1. A part file describing the process.
2. Fabricated object (frame and modules)

You are encouraged to consider your own work as potential for the class final assignment. Consequently, you are also encouraged to consider ways in which this initial module can interact using repetition and configuration as elements of a larger configuration or system. Finally, you are allowed to propose your own interpretation of each of the modules, within the dimensional requirements.

ANTICIPATING THE FINAL ASSIGNMENT
For the final review, you will be asked to present your work as if it was a sequence of stages in producing a system. This means two things:
1. You have to consider how your work link one stage to next,
2. You have to ensure that your module is consistent with your overall system.

DIMENSIONAL REQUIREMENTS:
Modules 2' x 2' and/or 2' x 8'.
Complete system dimensions: Height: 5 modules, length min.: 6 modules and max.: 8 modules.

APPENDIX C
APPENDIX D

ARCH-8803-EL Design for Manufacturing
College of Architecture
Georgia Institute of Technology
Eduardo Lyon (eduardo.lyon@Gatech.edu)
Spring Semester, 2006, Th, 8.05-7.55 pm
CURVED SURFACES USING 3D MILLING CNC TECHNOLOGIES

Third assignment: material removal using 3D milling. Along the last two exercises, we explored different curved surfaces generation and fabrication methods, as well as explored complexity within a modular system. In addition, we discussed some basic issues about curved surface representation in CAD systems. Our first assignment included one object fabricated using layered manufacturing. In the second assignment the object or module from the first assignment became the basic unit for a more complex component based system. In addition to the needed design adjustments in the module, a frame was required to organize and hold modules together. The frame was fabricated using laser cutting and structured using an interlocking connection system. The module was fabricated using 3D printing. Tolerances in between these two fabrication techniques and connections in the system showed to be extremely relevant. In this third assignment we will explore the basic unit or module in full scale. The prototype will be fabricated from a polystyrene foam block (Foamular). This process now includes the fabrication of the work piece out of standard foamular panel. Involving cutting in a saw table and gluing foam pieces. Later once the workpiece is ready the module will be fabricated using 3D milling. For this purpose we will use a Modela 3.5 Axis CNC router.

Please keep in mind that the main purpose in doing this prototype is not only to study possible design alternative through combination and or alternative configurations but also to explore fabrication issues like finishing and tolerances. The critical topics to be explored in this third exercise are component fabrication, surface finishing and curvature complexity. You are asked to treat the fabrication process as a process of design in its own right. You are consequently asked to document the process. Some important questions to investigate are:

1) How you control optimum curve surface resolution?
2) How you determine adequate tolerances?
3) How you keep track of original pieces after successive transformations?
4) How you keep dimensional consistency in the cutting process?
5) What is relation between surface curvature and, tool geometry and dimensions?
6) What type of curvatures are allowed?
7) Why is tool path; width relevant?
8) How you determine maximum curvature deviation?

You will submit:
1. A file describing the process.
2. A fabricated object (foam prototype).

You are encouraged to consider your work as potential for the class final assignment. Consequently, you are also encouraged to consider ways in which this initial module can interact using repetition and configuration as elements of a larger construction or system. Finally, you are allowed to propose your own interpretation of each of the modules, within the dimensional requirements.

ANTICIPATING THE FINAL ASSIGNMENT

For the final review, you will be asked to present your work as it was a sequence of stages in producing a system. This means two things:
1. You have to consider how your work link one stage to next.
2. You have to ensure that your module is consistent with your overall system.

DIMENSIONAL REQUIREMENTS:
Modules 2' x 2' or 2' x 8'.
Complete system dimensions: Height: 5 modules, length min.: 5 modules and max: 8 modules.
REFERENCES


VITA
Eduardo Lyon received his architect diploma at Universidad de Chile in 1990 and his master’s of Architecture degree from University of Maryland in 1997. Prior to his acceptance into the PhD program at GaTech, he held a faculty position at Universidad de Chile. While a faculty member, he taught several studio courses, computer applications electives and directed "The influence of digital media in architecture" research seminar from 1998 to 2001. During that period, he was awarded as "best professor" in 2002. He is registered architect with a professional practice in Chile since 1990.

Mr. Lyon's research focus is on Digital fabrication and Design Cognition, and is grounded in the Design Computing program at GaTech. His interests include; Design for Manufacturing, Digital Manufacturing and research on CAD systems as cognitive instruments in design processes. Previous research interest includes studies related to the construction of the idea of space in literature, film and other narrative forms. Professor Lyon also has been exploring possible connections between emergence and Autopoiesis theories in artificial intelligence, and design processes. Within the area of digital manufacturing professor Lyon's research is looking at the development of design process models using new digital manufacturing technologies including CNC machinery and Rapid Prototyping Machines.

Externally, Mr. Lyon continues as a contributing evaluator for the Chilean Research Council (CONICYT), and as a member of SIGRADI International Scientific Committee. SIGRADI is the Iberoamerican Society of Digital Graphics. It joins architects, designers and artists related to new media, like the counterpart similar organizations in Europe (Ecaade), North-America (Acadia) and Asia/Oceania (Caadria).