Digital Fabrication and Component Optimization Using DFM

Integrating Two-Dimensional Cutting and Three-Dimensional Milling in Wood Panel Fabrication

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Abstract: *This research explores new ways to integrate manufacturing knowledge in to design phases. Through the use of design for manufacturing (DfM) concept, and looking at relations between its potential application in component design 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; a knowledge systematization process; and the incremental development and refinement of design heuristics and metrics. Subsequently the attempt on this research 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.*

Keywords: *Design Computing; design for manufacturing; knowledge based design; digital manufacturing.*

Aims and significance

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. This knowledge constitutes a body of principles, rules, and regulations, which commands the building's design and its realization—therefore it constitutes a preliminary datum for its comprehension, and thereby it is of theoretical importance.

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 design process is also a negotiation process 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 remain ignored (Lyon, 2006).

In an ongoing process, this research 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.

Method

This research uses case study research methodology to inquiry about design and manufacturing knowledge integration. Coherently it concentrates on curved surfaces fabrication using one CNC technology and two manufacturing processes. A case study 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). The researcher collected data, obtained from design experiences, using structured questionnaires; semi-structured interviews; structured non-participant observations; and content analysis. As consequence, design and fabrication process were documented exhaustively. However, students, without any instructions or supervision from the researcher, manufactured each component. Then the author compiled and systematized design and manufacturing knowledge in the form of design heuristics and metrics. Later the author organized them according to issues in a previously obtained DfM model (Lyon, 2008).

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. 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. 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. 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.

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.

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 final 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. The component 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. Students were required to treat the fabrication process as a work of design in its own right.

Critical topics explored in this final case study were; increased complexity in the CAD CAM workflow; and multiple CNC manufacturing processes integration. Manufacturing processes combination 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.

Results

The researcher documented the process without intervening in it. Then the author compiled data in the form of design heuristics and metrics. 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 "by default" values. 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 to lack of support in the CAM system for linking alternative manufacturing operations. Since one manufacturing process objective is to produce the workpiece for the second, the research presents special attention to errors and inconsistencies from workflow. Accordingly workpiece fabrication, assembly process, and tolerances in each of the two fabrication techniques were extremely relevant.

Most important contribution in this research resides in its potential use as a framework for new educational approaches in the studio environment. The main purpose in the research is to represent how different stages in a design to production 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 framework as analogical thinking device in developing other design to production teaching approaches.

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:

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 de 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. $MchSz \geq Csz \leq WpSz$ or $MchSz \geq Csz \leq Mtsz$.

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.

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.

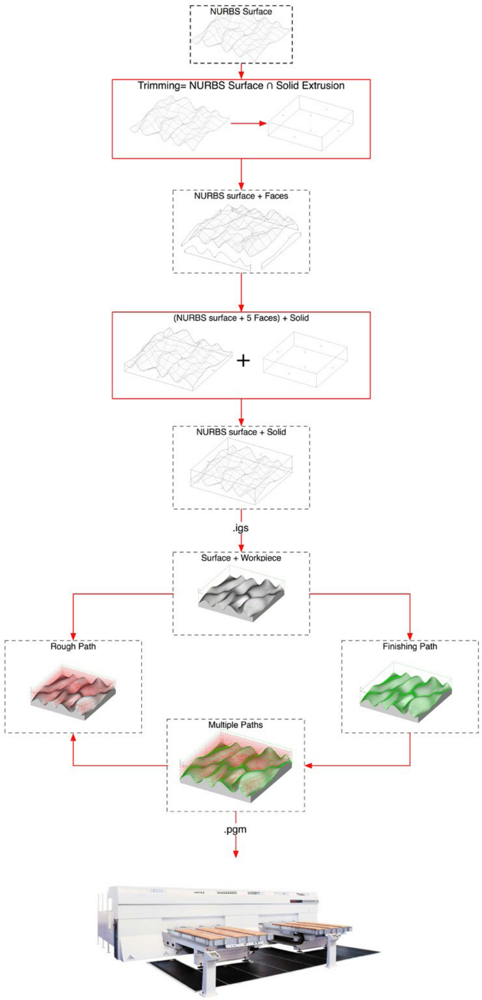
Cutting width: Normally, and according to the material being cut, cutting width is tool diameter for rough paths and at least 1 mm. for finishing path.

Summarizing this research showed multiple design issues and few 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 diagrams were developed to explore the CAD/CAM/CNC workflow in a more comprehensive way—seen in figure 1 and 2 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 3. 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.

Conclusions

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



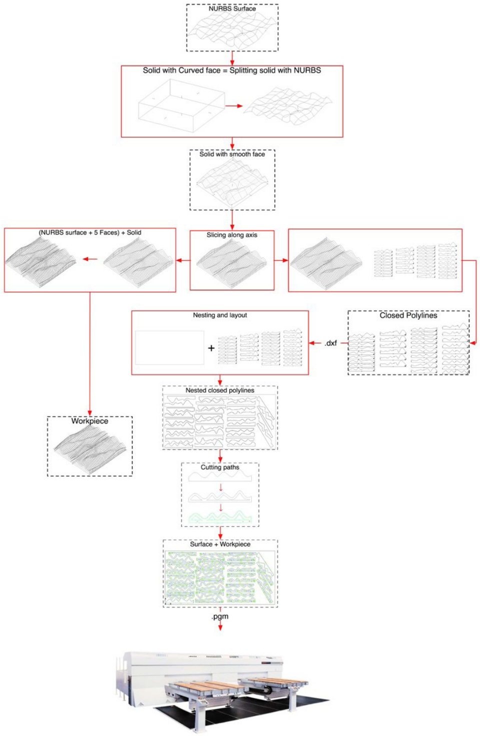


Figure 1 (left)
CAD working flow for two-dimensional cutting including all geometric transformations

Figure 2 (right)
CAD working flow for Three-dimensional milling including all geometric transformations

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.

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