UNIVERSITY COLLEGE LONDON
MSc Adaptive Architecture and Computation

Digital fabrication inspired design:
Influence of fabrication parameters on a design process.

Agata Guzik
2009-09-11

This dissertation is submitted in partial fulfilment of the requirements for the degree of Master of Science in Adaptive Architecture and Computation from University College London

Bartlett School of Graduate Studies University College of London September 2009

Declaration

I, Agata Guzik , confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis

Agata Guzik

Abstract:

The relation between architecture and building technologies has played a vital role in the development of both disciplines throughout the history. The link between the two is also valid in the present times, as the design and production processes are influenced by computational advances. Considering the use of a particular digital fabrication method, this research intends to look into the design-production relation and attempts to answer the question of how the manufacturing parameters can be integrated into the design process to facilitate the design-to-production communication. It is argued that the above is achievable through the application of a simulation-based algorithmic procedures derived from the inherent logic of a fabrication machine's functionality. The above stated was studied through creation of two custom tools facilitating the design process – namely a library for the Processing programming language and a bespoke design procedure - both based on a functionality of the CNC milling machines. Finally, the conclusion is made that broader implementation of custom design procedures with underlying digital fabrication logic has a potential of altering the design process and facilitate the design-to-factory communication.

Keywords: digital fabrication, design process, optimisation, genetic algorithm, CNC milling, 5 axis milling machine, G-code, path planning, depth buffer, Processing library, PGCode3D

Word count: 10 100

Table of Contents

Table of figures:

Acknowledgements

I would like to express my deep appreciation to my supervisors, Alasdair Turner and Sean Hanna, for their support and guidance with my thesis project and throughout the entire studies at University College London.

I thank Richard Grimes for his help, knowledge and time spent with me in the CAM Workshop.

I thank my parents for their love and support throughout my entire, never-ending education. It would not be possible without you.

In addition, a thank you to all the friends from MSc AAC, especially Michał Piasecki, Marilena Skavara, and Sahar Fikouhi. I've learned a lot from you and could always count on your help.

Finally, I would like to thank my boyfriend Aleksy for his patience and love.

Introduction

In contemporary architectural practice, flat sections and plans drawings are no longer a primary means of representation and communication with clients. Nowadays the widely used media in architecture include visualisations, animations and three-dimensional models. Now available digital fabrication techniques enable direct materialisation of virtually conceived designs either in small scale models or in building structural elements. This transition, executed after the design process is finished, is possible with the aid of CAD/CAM software tools, which enable conversion from computer-aided drafting (CAD) models to computer-aided manufacturing (CAM) code provided a CNC technique is used. Digital models require conversion into particular file types if a 3d printing or any other fabrication method is used. Digital fabrication tools are all the more essential in architecture due to attainable mitigation of building costs in the case of a design's increased complexity. Free form shaped designs comprising in the design stage of countless unique components require some sort of rationalisation of structure constituents before being materialised into real buildings.

Hugh Whitehead from Foster and Partners Special Modelling Group distinguishes three main rationalisation types, namely: pre-, co- and post-rationalisation approaches (Whitehead, 2003). They differ in generic attitude to designing and take into account the time and role of structural optimisation in the design process. Pre-rationalisation imposes a compositional system before the form creation phase begins. An example of this design method is the Beijing National Aquatics Centre by PTW Architects, China State Construction Engineering Corporation, China Construction Design International and Arup. The building structure was based on the Weaire–Phelan three-dimensional computational foam model, which uses two primary cells of equal volume and minimal surface to volume ratio. Although this model was used as a base for the Water Cube structure, during the design development the structure evolved into more structurally efficient configuration, which in turn resulted in a greater amount of different building elements increasing the complexity and cost of production.

Figure 1: (a) The Weaire-Phelan structure (Drenckhan & Weaire, 2004) and (b) (c) Water Cube Beijing (Ingenia, 2007).

In post-rationalisation the structural system is being assigned to an already completed design, which at times requires compromising the final designed form. The Greater London Authority by Foster and Partners is an example of such an approach. The initial design of a spherically shaped building had to be altered in order to enable physical realisation of the building. The egg shaped form was reshaped using planar quadrilateral (PQ) strips to meet fabrication criteria (Attar et al., 2009). Co-rationalisation, in turn, refers to a process of parallel finding of compositional system and form which are affecting one another. As in pre- and post-rationalisation ,where applying structural parameters is separated from the design process, the co-rational method implies multidisciplinary coordination on every design stage and suggests the use of generative procedures, which incorporate fabrication parameters among other formal and functional design rules (Fischer, 2007).

Figure 2: Greater London Authority by Foster and Partners (a) (Constructing Excellence, 2003) (b) (Oberholzer, 2006).

While the relation between fabrication parameters and designed objects has been previously explored, their interdependence was typically limited to integrating manufacturing constraints into the development of a form, as is the case in the pre- and co-rationalised design approaches described above. Considering the use of a particular digital fabrication method, this research intends to look into the design-fabrication relation from a different angle and to attempt to answer the question of how the manufacturing parameters can be integrated in the design process to facilitate the design-to-production communication. The design rationalisation parameters are meant to become a driving force of a design within a generative procedure with embedded fabrication logic. A generative design approach can potentially tie together the two often distinct processes of form exploration and final form machining. This thesis argues that the above is achievable through the application of a simulation-based algorithm procedure derived from the inherent logic of a fabrication machine's functionality.

For the purpose of this research, from the currently available digital fabrication techniques, CNC milling was chosen for setting the framework for the constraint-based simulation design procedure. Computer Numerically

Controlled milling machines are the most accessible and widely used in architectural and construction industries since they are capable to produce complex highly differentiated building elements in a relatively simple and cost effective process. Their basic principle is based on a numerically controlled drilling process and, depending on the number of axis in a machine, also turning of either the machine's head or/and the milled material. CNC machines are automatically controlled by programmed commands of Numerical Control programming language, also called G-Code thanks to the functions syntax. The NC program, apart from the general purpose machine's operation control functions, consists of additional commands related to the overall machine's actions - the so-called M-codes, which may differ in structure for particular machine model and producer. Although the majority of NC programs are created by CAM software, they can be also developed by the programmers directly. Because the tool path planning difficulty increases exponentially with the increased number of supported axis, the manual programming is limited to three axis machines, which are the most commonly used. They operate in three dimensions using X, Y, Z axis only, enabling sculpting landscaped surfaces with depth variation in Z axis, but only the higher dimensional machines are capable of cutting more complex geometry.

The research here described is divided into two separate, but equally important phases, both of which are created with the use of and for programming language Processing 1.0.1. At first, a vast exploration was made on finding a way of converting any given geometry from the Application Programming Interface into milling machine preparatory code, which would then be exported from the programming environment directly to the machine controllers. At this stage a custom-made library for Processing was developed in order to enable immediate transition from digital to physical models using a 2,5 or 3 axis milling machines. Certain aspects of path planning and optimisation were taken into account and were applied by the means of genetic algorithm. Subsequently, a generative simulation-based design procedure was created with the procedural logic incorporated from five axes CNC milling machine and, in particular, the one with three transitional axis and two rotary ones attached to a tilting rotary table. The principles implemented in the first stage of the research were further developed in the second one and thereafter applied to a particular design problem.

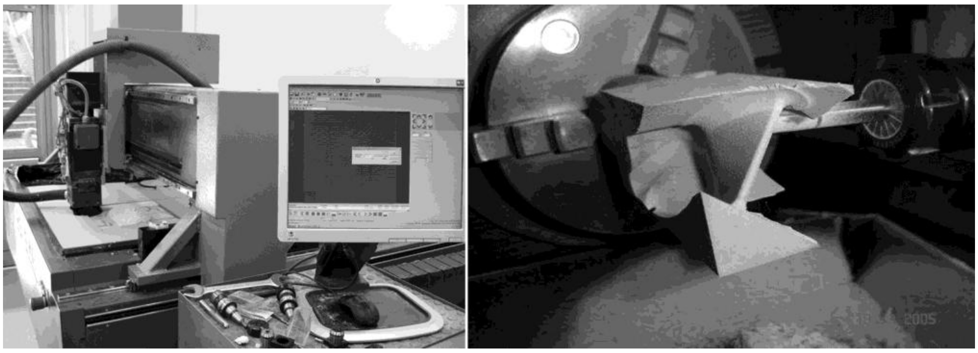


Figure 3: (a) 3-axis CNC milling machine (b) 5-axis vertical milling machine (Mahanoy, 2008).

Background

3.1 Design vs. fabrication technologies

The research presented in this dissertation concentrates on the interdependence of computer generated designs and the fabrication processes that succeed . They have already been a subject of substantial research both separately and in relation to one another. Widely discussed by Klinger (2001) the tendency throughout architectural history of inevitable close connectedness between mainstream building forms and at that time available construction technologies and materials underlie the formulation of these thesis objectives. Architecture's dependence on many other fields of knowledge and industry, especially construction industry and material development, results in its parallel and conditional evolution. Achievements in building technology are subsequently adopted to architectural solutions withal. Klinger refers in his paper to Le Corbusier's statement that "almost every period of architecture has been linked to research in construction" (1931) and describes how building industry achievements influenced the creation of architectural forms from the medieval to present times. Similar relations occur between stonemason craft and the form of medieval cathedrals as in contemporary skin-and-bones buildings and digital fabrication technologies. Although modern manufacturing methods allow construction of nearly every form which can be generated by computer visualisation software, there is a fundamental drawback of using this approach into designing. Visualisation software is capable of developing and immediately adjusting complex skin forms of buildings which can be created with the aid of interactive algorithmic or scripting tools - often incorporated in the software environment - thus enhancing the direct communication between the designer and the generated form. However, the majority of the above mentioned design tools incorporate neither physical properties of materials and environment nor the fabrication restrictions while providing easy to use file-to-factory communication functions. In order to fully take advantage of the currently available design and manufacturing techniques, the use of comprehensive design environment is suggested as a way of overcoming laid down design issues. Alongside the aforementioned discourse, Klinger also discusses the changing role and work spectrum of the designer - to whom he refers as to the craftsperson - in the past and nowadays. As in the industry age, when the designer had to combine design skills and building technology, these requirements are also nowadays expanding to the areas of computer modelling, visualisation skills and digital fabrication processes knowledge. Nevertheless, the designer is expected to be specialised in more and more disciplines, his work is nowadays largely dependent on software developers and programmers. It can be concluded that a skilled craftsperson in the digital era should also acquire programming knowledge concurrently with the primary design skills in order to bind the entire building's or object's development process by creating custom comprehensive environments for specific design scenario.

Not only can digital fabrication techniques be used for producing individual custom building elements or small scale models but also, as Bonwetsch et al. mentions to conduct the whole building process of – in this particular case – a parametric brick wall (2006). The computer-controlled manufacturing technologies originally developed for and used in other industries, e.g. in the automotive bile and aviation industries, open a window of opportunity to adopt them in modern architectural contexts in wide range of applications. The capability of such machines to perform highly complex precise assignments is usually still limited to executing repetitive tasks in the fully automated production lines. Digitally controlled machines' customisability could be utilised for creating unique mass-customised architectural forms. However, this kind of co-action requires developing specialised software and hardware for a particular design instance, as there is no general purpose CAD/CAM software for industrial all-purpose robots available.

The DFab research laboratory DFab, opened by Gramazio and Kohler in ETH, the Swiss Federal Institute of Technology in Zurich, aims to investigate the possibilities of informing designs with digital data by building big scale architectural prototypes with the use of a six axis industrial robot (2008). Within four years they have developed a series of commercial and academic experimental design procedures for building unique architectural elements.

One example of such experimental design approach developed in DFab is the "Programmed Wall" project, which examines digital additive fabrication technique in the design context (Bonwetsch et al., 2006).

Figure 4: The programmed wall project by DFab Laboratory (Gramazio & Kohler, 2006).

In this project parametric tools were utilised for generating two by three meters sized parametrically controlled wall designs composed of standard brick units. On account of using common construction material, the design process was intended to concentrate mainly on the construction technique rather than on material properties. A number of prototypes were constructed by the robot that is capable of reaching every point in a 3x3x8 meters space. The design information was used to create the so-called *informed architecture,* which is a result of directly linking design information with real architectural artefacts. Creating such unique architectural elements has become possible via creation of custom software and hardware tools for each particular exercise. Firstly a design method in MAYA software scripting environment was developed and secondly a post-processing script was created for translation of the output CAD models into robot specific procedural language. Also, a custom-made brick gripper robot's extension was built, which at further stages of the project was enhanced with a precise adhesive automated adhesive depositing onto each brick. This method was successfully adopted in a commercial architectural application for constructing a Winery facade in Fläsch with total surface area of 400 sq meters.

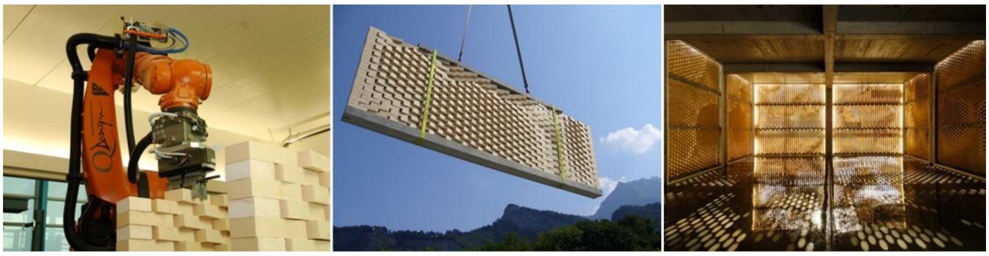


Figure 5: Facade Gantenbein Winery, Fläsch, (Switzerland (Gramazio & Kohler, 2006).

3.2 Digital manufacturing processes

Except the already mentioned additive digital fabrication principles, two other main types exist: subtractive and formative classified in respect of material formation rules. The machines used typically for each of the distinct processes include: stereolithography (additive), CNC milling or laser cutting (subtractive) and press brake (formative). Each of the listed types has its specific implications and limitations. As for the subtractive process the problem is the waste material that is generated during the production, which is not the case if of the other techniques, is employed. Furthermore the additive type processes prove to be much more expensive and time consuming for building even small scaled objects, when compared with for example CNC milling method, which is much more economically efficient for building trial objects and prototypes. Stereolithography should, therefore, be reserved for creating mostly final objects. Industrial multi-purpose robots as contrasted with small digital fabrication machines are capable of executing a whole range of tasks, and thus have a great potential for multi-requirement architectural applications.

The selfsame robot used for constructing “The programmed wall” project’s prototypes was also used in another study design instance conducted in DFab Laboratory in ETH Zurich. Here in “The perforated wall”, in turn, the subtractive method was implemented for creating full–scale perforated wall components also developed with the aid of parametric software (Gramazio & Kohler, 2008). Individual holes were defined by X and Y coordinates, radius and two angles – one related to the wall’s mass material and another with pivot point in the centre of each perforation. This approach, although limiting the design expressions to manipulation of a single element, provided with a wide variety of output forms. Yet the designs were purely based on visual qualities and - at this stage of the project - no higher purpose of wall panels such as shading or visual connectedness, was considered. The following research led to load bearing properties testing of a fabricated concrete perforated wall. Still, this property was not taken into account during the process of generating perforation patterns and was only tested thereafter. The two described projects from DFab Laboratory present an advanced approach to architectural design by incorporating bespoke developed hardware and software tools, implementation of which informed the architectural form and led to construction of unique objects unobtainable by standard design and construction procedures. There is no imperative requirement for single multi-purpose software development. However a comprehensive tool could tie together dispersed design-to-fabrication elements. This research intends to investigate the possibilities of implementing of such an approach in design process and study the consequential enhancement potential.

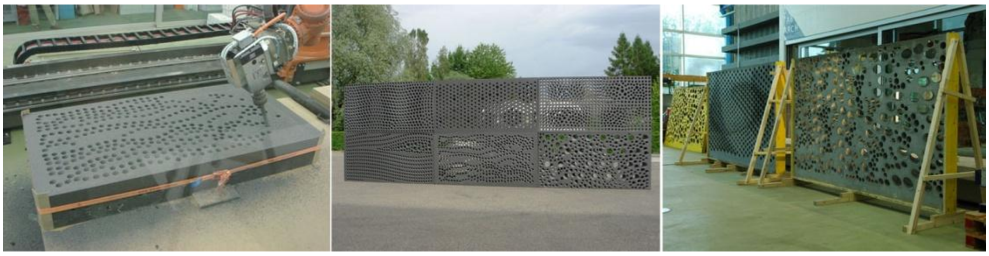


Figure 6: The perforated wall 1 & 2 by DFab Laboratory (Gramazio & Kohler, 2006).

3.3 Economic factor

The subtractive manufacture method, especially CNC milling, has recently gained new applications in architecture, which is caused by its low cost and time fabrication efficiency properties. Three- or more axis milling machines for instance can be used for forming concrete moulds of non-standard building elements (Kolarevic, 2006), as it was conducted in the construction of Zollhof Towers in Düsseldorf, Germany by Frank Gehry (2000). Materialisation of the design necessitated the creation of over 350 individual facade elements, which were designed in the CATIA software. The non-standard forms were milled in styrofoam by a numerically controlled machine and then served as moulds for the reinforced concrete panels.

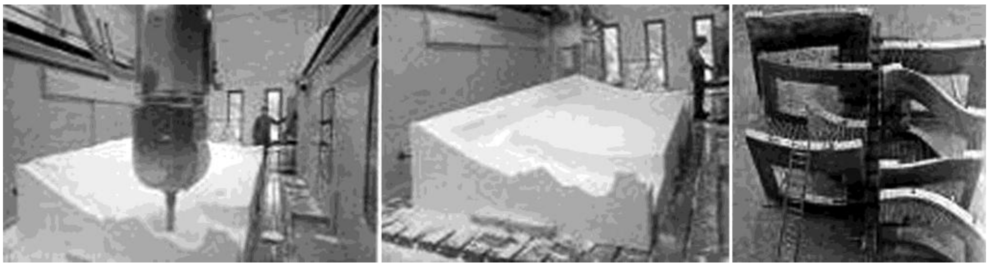


Figure 7: Styrofoam moulds milled by multi-axis milling machine for construction of Zollhof Towers (Afify & Elghaffar, 2007).

The implementation of digital fabrication technology does not necessarily entail costly solutions. For example the "Instant House" project examines the possibilities of designing low cost customised houses with the use of digital fabrication methods (Botha & Sass, 2006). Based on the fabrication criteria of two-dimensional plywood joints and with the parameters such as building's location, climate characteristic and stylistic variations an automated parametric system generates forms, which can then be modified, not only in building's appearances but also in spatial and functional properties also.

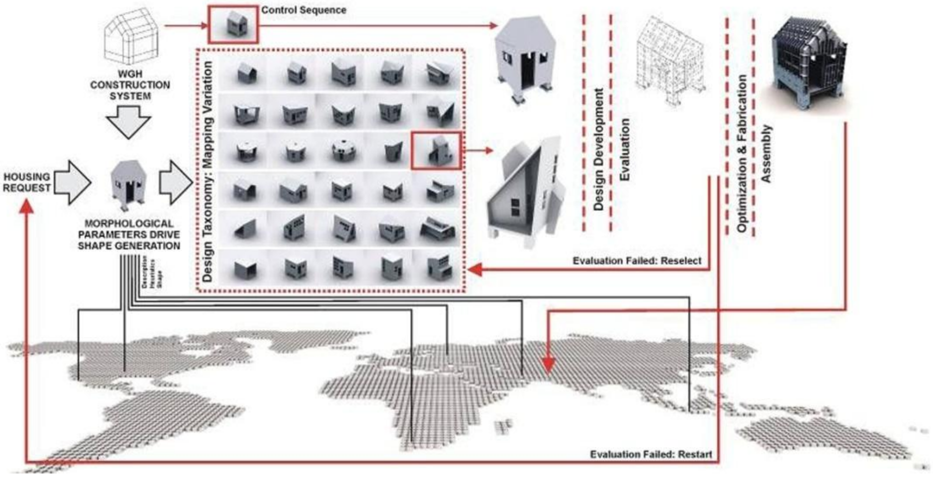


Figure 8: The implication on Instant House generative procedure (Botha & Sass, 2006).

The projects of Instant House and Zollhof Towers present two ideological extremes of the applications of digital fabrication in architecture – by either taking advantage of it in order to facilitate customisation of low cost buildings or by using it for materialisation of complex irrational forms – they both require tailored program's development. The bespoke programming tools assist in facilitating the essential communication between computed aided designs and materialisation facilities.

3.4 Hardware – software correspondence

Typically, the transformation of digital information from visualisation environment to procedural machine language is accomplished by the CAD/CAM converting software, which tends to be highly processor and memory-intensive even if working on high speed computers. Moreover, the CAD/CAM software turns out to produce erratic programmes, therefore the code verification by either simulation software or time-consuming and unsafe trials becomes crucial. Additionally, relaying on CAD models geometry can render to be troublesome due to an unavoidable inaccuracy and frequent anomalies occurring in complex CAD geometries (McKenney, 1998). Many efforts have been taken to find the appropriate algorithm for correcting and thereafter converting CAD geometries into the fabrication machine language, and thus overcoming the stated problems. The majority of solutions were based on applying parametric surfaces to given geometry, which was a correct approach for CAD geometries before the development graphics acceleration hardware which enforced the use of non parametric geometries. This shift in modelling tendencies becomes a prerequisite for more general geometry analysis. Depth buffer solution provided with adequate results to this problem, because by analysing every pixels' position in the display makes it possible to analyse and export data based on any given geometry (Carter et al., 2008). This feature available in more advanced graphic cards as a two dimensional array can be easily accessed from graphics Application programming interface (API). Therefore the depth buffer function was selected to be further exploited for the development of the programming environment described in following chapter of this thesis.

3.5 Aspects of optimisation in design and fabrication

For the fabrication process to be efficient the generated tool trajectory often requires subsequent optimisation to reduce redundant movements and the thereby the cutting time. Shorter production process influences concurrently the overall cost of the object and allow fabrication of greater number of elements in the same time.

The optimisation of milling machines' tool paths presents another complex computational task, which is similar in principle to the *travelling salesman problem* (TSP). The objective of this task is to find the shortest path for visiting every city on the list only once and returning to the starting point with the given numerical distances between every one city and all the other as a given database. TSP belongs to the group of the NP-complete (which stands for nondeterministic polynomial time) problems in the computational complexity theory, which have two main properties: one is that every solution to this problem can be quickly evaluated and the other is that if this problem can be solved quickly then so can any other problem. TSP is an important combinational optimisation problem which has not yet been entirely solved, since the solution search time increases exponentially with the number of nodes in the system. A great deal of publications and researches were dedicated to the TS problem dealing with heuristic algorithms suitability and the comparative performance of each search technique (Johnson & McGeoch, 1990). A particular study by Dorigo et al. in which the local search algorithms such as: genetic algorithms, genetic programming, neural networks, simulated annealing and ant colony search were compared showed the best performance of the ant colony search (1997). Also a few successful algorithms were created to specifically solve the TS problem, for instance the Keld Helsgaun's algorithm or the state-of-the-art Concorde TSP Solver by David Applegate, Robert E. Bixby, Vašek Chvátal, and William J. Cook (Montemanni et al., 2007).

The approximation algorithms tend to present close to optimal solutions for the TSP in a relatively short time. Among others like an ant colony or neural networks the evolutionary algorithms are the most commonly used for the specific example of travelling salesman problem, which is the CNC milling machine's tool path planning and optimisation. Hasan et al. presented an improved instance genetic algorithm for optimal collision-free path planning in two dimensional spaces (2007). In his research he presents a highly effective algorithm which renders better results than Voronoi diagram based Bhattacharya and Gavrilova algorithm that has been already proven to produce highly optimised paths (2007). Above described scientific studies show that no specific accurate procedure exists that best suits tool trajectory optimisation problem. Close to optimal and widely used for this task genetic algorithm occurs to be suitable for implementation for the purpose of this thesis.

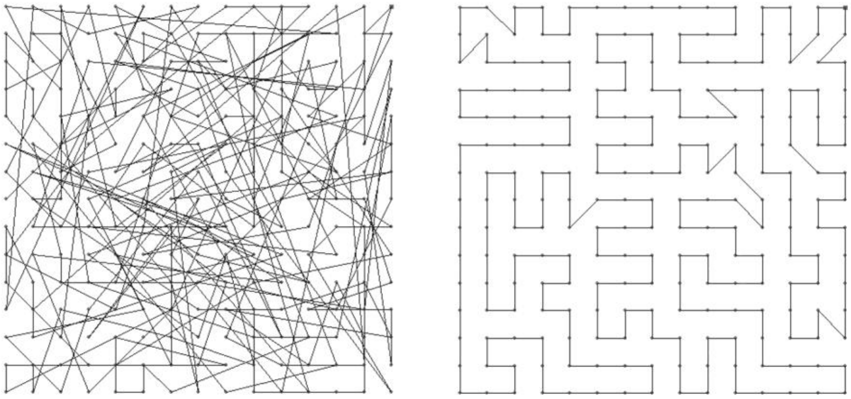


Figure 9: Genetic algorithm TSP optimisation (Saiko, 2005).

3.6 Aims and objectives

Although recently the evolutionary algorithms are being introduced in architectural practice as method for structural optimisation, the most dominantly EA in design are used as an experimental tool for form generation. The evolutionary algorithms' application as optimisation technique is therefore limited to post-rationalisation of a building structure and its potential for comprehensive implementation in design-related disciplines is still to be explored. Undoubtedly, genetic algorithmic strategies present the capability for joining together all of the aforementioned implementations in relation to architectural processes of design, optimisation and fabrication into one multi-objective design environment. This study, however, focuses predominantly on the exploration of the new design possibilities that arise from the digital fabrication technologies rather than on the manufacturing process optimisation or automation itself. The aspects of path planning are incorporated in greater extent in the first stage of this research, whilst the following design implementation stage concentrates largely on link between design and digital manufacturing

Phase1 - Methodology

4.1 G-Code export function and language syntax

The initial phase of this study constitutes the study of the correlation between a virtual model and a fabrication procedure of physical objects - from two dimensional images to three dimensional object analysis. This research phase has led to the development of a bespoke tool for exporting procedural code from Processing programming environment in order to directly execute the fabrication process of the designed objects on a CNC milling machine. At the outset the G-Code language syntax and principles will be introduced.

The G-Code is a low-level universal procedural language for CNC machines, the commands of which constitute the main body of Numerical Control programs. The G-Code functions refer immediately to the milling or cutting operations of the machine. The most commonly used functions include among others: G00 – rapid positioning of the tool without milling, G01 – linear interpolation to given point coordinates, G02 – circular clockwise interpolation, G10 – setting the coordinate origin system, G41 – cutter radius compensation left of path (Appendix 1). The remaining functions of NC programs include the M-functions responsible for machine comprehensive behaviour, T-functions refer to tool handling, S – to spindle speed setting, F- to feed rate, X, Y, Z – to absolute coordinates, finally A and B refer to two rotary angles for up to 5-axis milling machine handling (a simple G-Code program example for cutting a letter M is presented in Appendix 2). Although, the number of available G-Code commands has grown in number to support complex shaped tool paths programmed solely in NC language, the library described below employ only few basic functions. This is the result of a generalised approach to the problem and the aim of creating an effective algorithm for good approximation of the input geometry.

4.1.1 Two dimensional image analysis

As the ascendant exercise of G-Code export handling in higher dimensions, a flat image processing procedure was created based on colour analysis. For vector drawing conversion it required specification of exact colours corresponding with the engraving and full depth cuts. Concurrently the referring depths were specified. Similar conversion procedure is executed by a typical converter for a laser cutter. For the raster image G-Code export, the depth of the engraving is correlated with each pixel's colour brightness. Flat images are in this way converted into spatial relief, which depth is based on pixels' colours. The brightness values are stored in an array along with the corresponding pixels' positions in the display, thus creating a list of path coordinates.

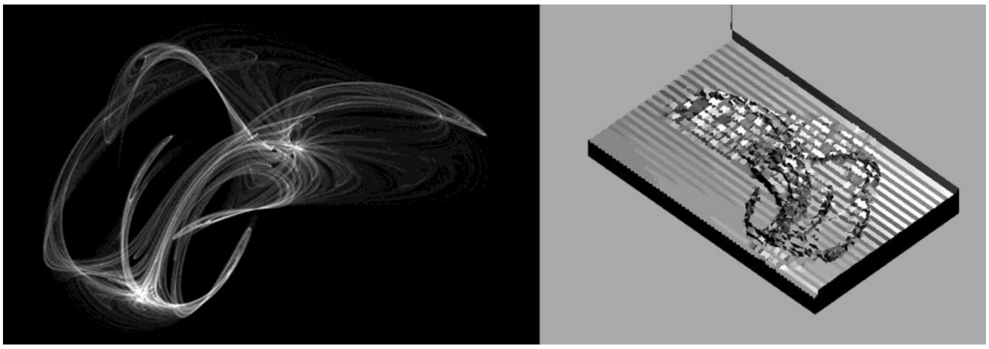


Figure 10: Raster image and its 3d representation created by colour brightness analysis.

The cut depth depends on material dimensions, as the brightness values are brought into a range of material thickness value:

```
PVector pos = new PVector(j,i, (mat_height-
(brightness(get(j,i))/255*mat_height)));
positions.add(pos);
```

The NC program starting and ending commands depend on the machine's type. Usually the starting functions include the tool selection, spindle speed and feed rate settings:

lines = append(lines,"T1M6"); - select tool

lines = append(lines,"M03 S2345 F100"); - spindle speed:2345, feed rate: 100

The array of positions is thereafter converted into a string of G-Code functions with vector coordinates as guiding points:

```
PVector vec = positions.get(i);
lines = append(lines,"G01 X " + vec.x + " G01 Y "
          + vec.y + " Z-" + vec.z);
```

Once the array of vector positions is created, the G-Code file can we written. The exported code proved to successfully convert two dimensional images into spatial representations, which was tested in the CNC simulation software.

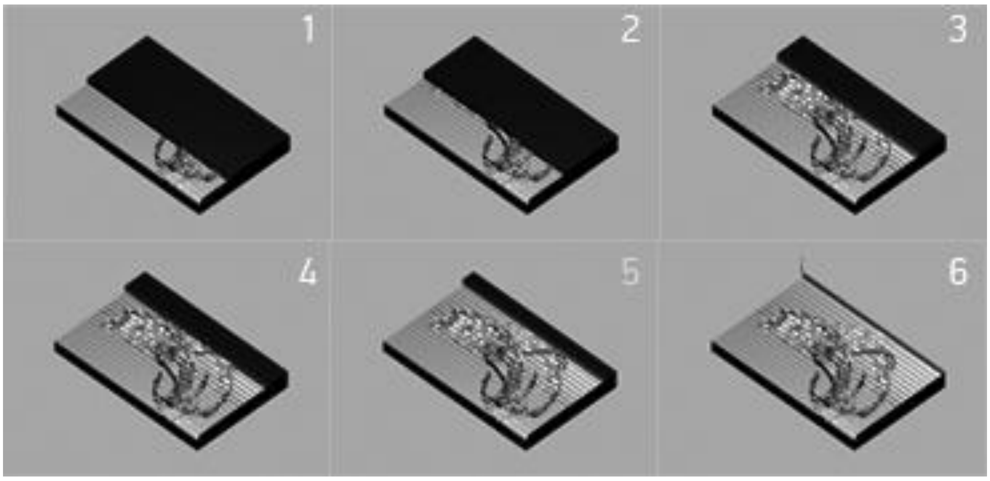


Figure 11: 3d raster image representation –Progress of a CNC milling fabrication process.

4.1.2 Three dimensional geometry

Building on recent research in the CAD/CAM algorithmic procedures and computer hardware advances in graphics handling a depth buffer method appeared to be applicable for the case of three dimensional geometry export. The depth buffer is considered as one of the simplest algorithms for visible surface computing (Joy, 2008). The z-buffer keeps the depth values for each pixel in the display, every new object that appears in the model space is checked as to whether the z-values for each pixel in its possible position are greater or smaller than the ones of the objects already visible in the scene. If the depth value is greater, then the z-buffer content is adjusted accordingly and a new view is displayed. In the algorithm described here the depth values of each pixel in the display are first translated into real values based on the perspective view transition matrix. Secondly the z-values are stored in separate arrays for the actual geometry and for the remaining space. The z-values included in each layer interval are stored in separate arrays and their values are sorted so that the machine processes the closest neighbouring vertex in the first place. This simple algorithm already produces a fairly optimised path. The more panoptical approach to path optimisation will be discussed in the following chapter with the implementation of genetic algorithm.

A simple pseudocode can be given for this particular implementation of z-buffer:

```
Given
3d geometry
Orthographic projection
An array z-buffer[x,y]

begin
for each pixel (x,y) do {
    calculate real values of z-buffer at (x,y)
    calculate maximum value of z-buffer
        if z-buffer[x,y] > max_buff then {
            Object[x,y,z] = Vector (x,y,z_buffer[x,y])
        }
}

Sort Object[x,y,z] and Background[x,y,z] by z Value
Create Layer_values (z)[x,y,z]
Calculate distance (me.Layer_values (z)[x,y,z],    other.Layer_values (z)[x,y,z])
Create Compare_values [x,y,z,dist]
Sort by distance
Create Tool_path (z)[x,y,z]
Create String with G-Code functions ["G01 X" + x + "Y" + y]
end
```

4.1.3 2,5 vs. 3 axis machine procedures

The differences between 2,5- and 3-axis milling machines lead to a distinct treatment of tool path planning in both cases. The 2,5-axis machine is capable of processing paths with simultaneous changes in only two from three available axes, whereas 3-axis machines are able to coordinate all the three axis at the same time. This characteristics results in different smoothness levels achievable by both types of machines. In the first case only the paths programmed in layers can be fabricated, the more complex trajectories are applicable to 3- and above milling machines only. This constraint is partially overcome by dividing the milling process into two phases: rough material subtraction and final finishing. The initial cut is executed with fixed Z axis, the detailed cut with fixed either X or Y axis. However, complex circular and curved movements in three dimensions are still inoperable, the manufactured models present adequate level of accuracy.

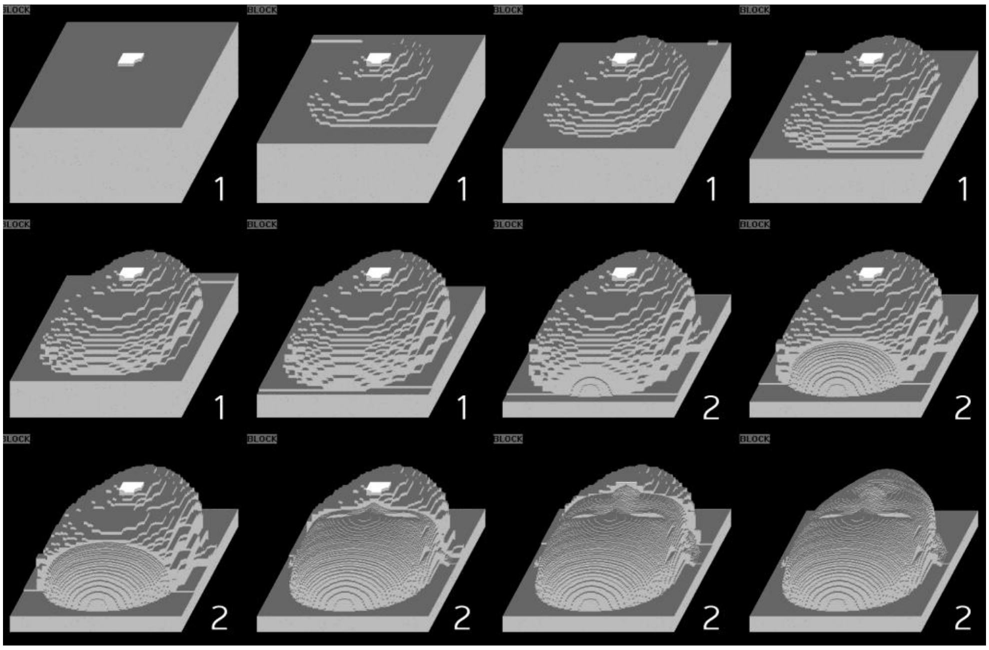


Figure 12: Two phases of 2,5-axis milling machine: (1) roughing, (2) finishing

4.2 The Library (PGCode3D)

The proceeding study on G-Code export function resulted in the development of a library – an external set of commands originally not available for use in a particular software - created for Processing 1.0.1. The library enables a user to easily export preparatory code for 2,5- and 3-axis milling machine in .nc and g00 files. The library definition requires specification of few basic parameters – up to two tool diameters, thickness of material and output file name.

`import PGCode3D.*;` - import library
`G_code_export gc;`
`gc  = new  G_code_export (this, 12.7, 6, "output", 50);` - class definition [T1 – 12.7 mm, T2 – 6mm, material thickness – 50mm]
`gc.print_data();` - model information printout [at the end of void draw]
`gc.export();` - export function [at the end of void draw]

4.2.1 Levels of approximation

From the two specified tools the first one – usually of a bigger diameter - is used for the first phase of milling, when the material is extracted from the workpiece leaving two tool diameters of offset from the actual model surface. The second tool is used for the smoothing cycle, which usually requires a smaller diameter for higher quality surface finish. If the second tool is not specified, both milling phases are executed with the same tool. The selected tool diameters also determine the approximation level of exported path, thus affecting the file computing performance and the time of fabrication cycle.

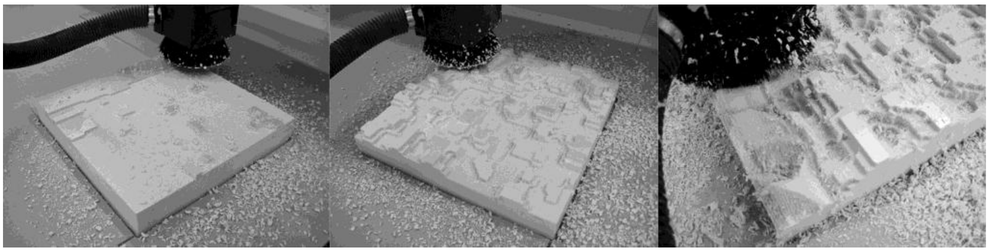


Figure 13: Fabrication study model #2, (a-b) roughing cycle, (c) finishing cycle

4.2.2 Stock and model dimensions

The discrepancy between the model size and maximum machine working height is very likely to occur. The library will produce part files for virtual models which are exceeding the specified material height in order to fabricate the object in separate pieces. Nonetheless, whenever the material dimensions are not specified the whole geometry is exported as a single file.

4.2.3 Machine settings control

Material characteristics are not taken into account automatically in the tool path generation algorithm, since the spindle speed, maximum allowed cut depth and feed rate parameters are closely related to specific material features and machine capabilities. The specification of these parameters and the offset height above material in z axis are left for manual adjustment before the file is exported.

```
gc.change_settings(5, 3000, 150, 3);
```

-offset above material – 5mm, spindle speed – 3000, feed rate – 150, max. layer thickness – 3mm.

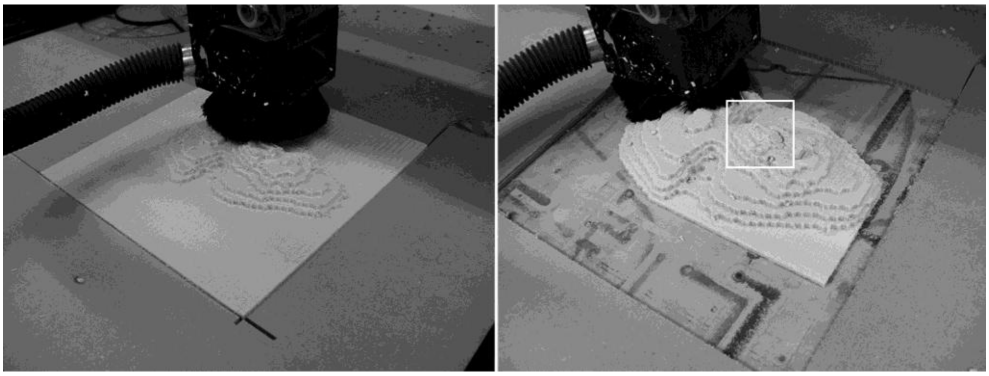


Figure 14: Fabrication study model #1, (b) collision between machine's head and material .

4.2.4 Application coding requirements

Both P3D and OpenGL renderers available in Processing are supported by the library. Relevant code sections demonstrating depth buffer handling in both cases are presented in Appendix 3. It is worth mentioning that the depth buffer readings forbid use of colour transparency and text fields in the scene, as it may cause faulty readings of z-buffer. It is also required to use orthographic projection to prevent processing of perspective distorted geometry – otherwise the ortho function will be applied automatically by the library without the possibility of control over projection shifting, as it occurs in P3D renderer for example.

4.2.5 Path optimisation (Genetic Algorithm)

The tool path produced by the above described procedure exhibits some level of optimisation, solely by the implemented vector positions' sorting procedure. Nevertheless, it appeared that the overall performance of the algorithm could be improved by adding the option of proper path optimisation. The genetic algorithm was selected on account of the discussed possibility of utilising single algorithmic procedure for accomplishing stated goals of form generation and object optimisation linked with the fabrication parameters in one comprehensive design environment.

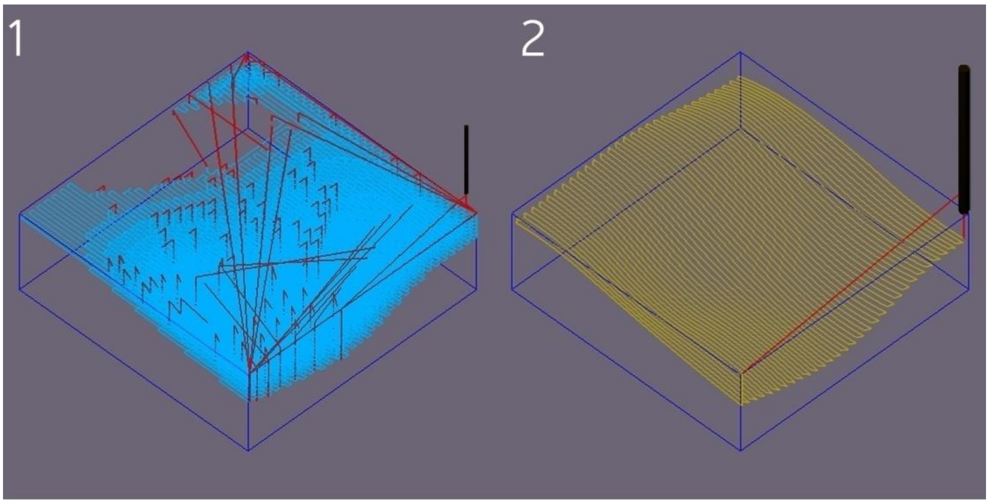


Figure 15: (1) layer by layer material subtraction and (2) smoothing trajectory aligned to model surface created by a basic sorting algorithm.

First, a simplified optimisation procedure was tested. In this case the genotype was governing the starting point of tool path on every layer by turns. The selected initial coordinates influence the whole generated path by the sorting procedure. This optimisation exhibits a good degree of improvement. However, some problem arises when the milled surface is very craggy then the layer based path planning is unreasonable due to the amount of redundant jumps between separate wells.

gc.optimise_path(4000); - 4000 of generations to be optimised

Another optimisation procedure, although potentially more efficient, did not prove to produce more optimised paths. The algorithm was searching the entire array of tool path positions and was each time searching for the closest vertex. Still the important requirement was to cut the higher Z values in the first place. At first sight the output path exhibited a potential of a shorter path being computed, as the machine was not extracting material layer by layer - as it was happening in the previous optimisation procedure - but this time was milling in some kind of clusters. Yet, the time measurements did not confirm that first impression. A more advanced algorithmic approach would therefore be imperative in order to generate highly optimised accurate NC programmes.

Phase1 - Results

4.3 Implementation and optimisation results

A number of study models were built to test the default library parameters, the approximation interval and path outcome performance in a real life scenario. The interim development stages were tested in simulation software only to prevent machine and material damages before the appropriate code was computed. The code was tested exclusively on one machine and a further development of the library requires testing on various machine types, which presumably will lead to necessary altering of the code initial and closing M-code functions.

The fabricated models served also as case study for the path optimisation testing. Two NURBS surfaces were milled with different levels of path optimisation. The first model was created with the basic algorithm only, the second one with the addition of path optimisation cycle, calculated over 4000 generations on a population of 20 individuals. The fitness function improved by a factor of 12,5%, which resulted in only 1,5% of time gain, for the first milling phase taken solely. Counting both cycles together the profit in time is meagre for the genetic algorithm implementation with layer by layer path planning.

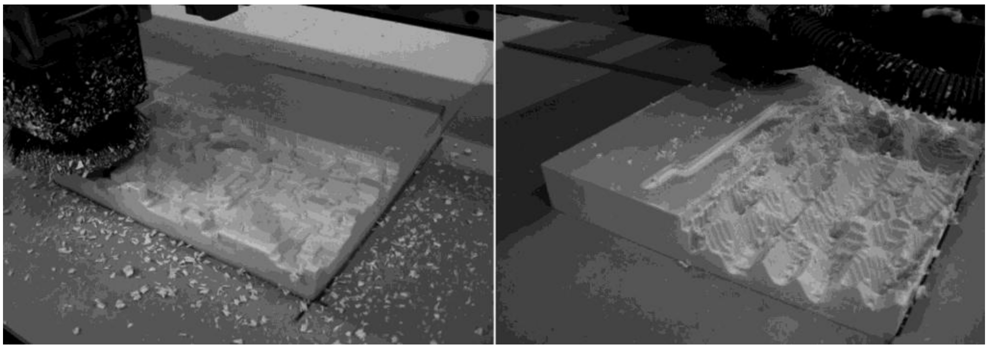


Figure 16: Fabrication study model #3, optimisation efficiency testing.

Optimisation performance was thereafter tested on different model sizes and surface shapes. The performance of initial optimisation algorithm strategy presented good fitness value improvement. Maximum achieved enhancement ratio equals 28% for machining of a NURBS surface of 30x30x5 cm size, calculated with 12.7 mm tool diameter for the optimised material disposal cycle. The genetic algorithm was evaluating a population of 20 individuals over 3000 generation. The optimisation process was terminated once there was no more fitness value improvement over 500 generation. Achieved fitness improvement equals to 3% of machine working time yield. These results prove that there is a strong correspondence between the actual model form and optimisation efficiency.

4.4 Computation performance

The adopted geometry analysis principle has proven to output good-approximation of any virtual models, which, for the given purpose of digital fabrication experimentations and models production appears to be sufficient at this stage of the research.

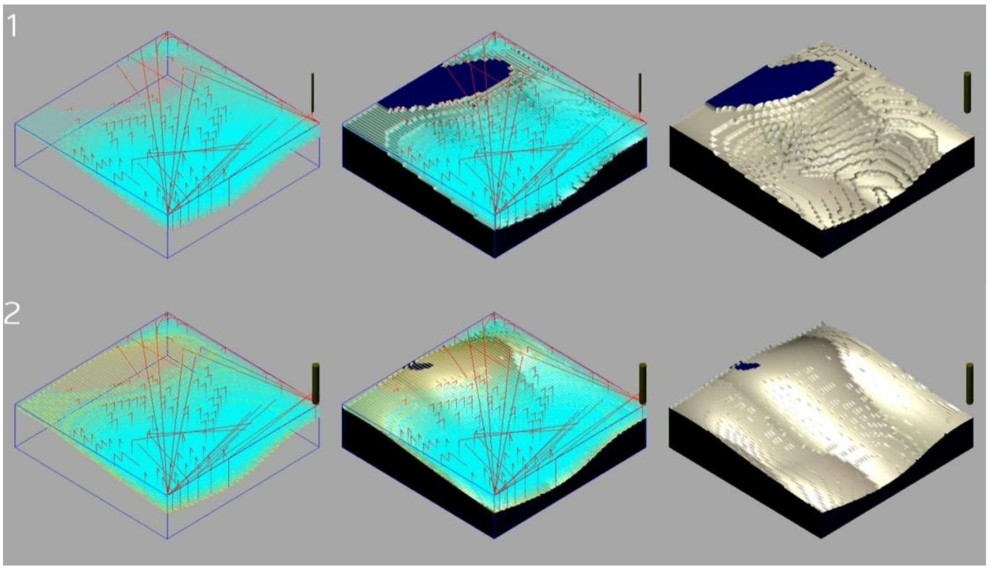


Figure 17: Tool paths and model surface in (1) roughing cycle and (2) smoothing cycle

The models up to 50x50x50 cm are easily processed in a satisfactory time (up to few minutes). The time required for file computation is inevitably dependent on the model size and diameters of specified tools, which define the vertex step (precisely half of the diameter size). Diameter of the first tool used for initial milling stage of material subtraction influences concurrently the optimisation parameters, as this is the algorithmically optimised phase of the process. The second cycle proceeds in the so-called *slices* along Y or X axis and follows all the vertices one after the other without any tool jumps. In the smoothing phase it is advised to apply smaller diameter tools and slower feed rate for more satisfactory results of surface finishing.

Phase 2 – Methodology

5.1 Multi axial machines

The quintessential part of this project constitutes the exploration of an unconventional design tool with fabrication processes embedded as dominant framework for form creation. The design environment was created on the basis of a five-axis milling machine's properties and, in particular, on a vertical type machine with additional two rotary axis attached to a tilting table. Three primary linear axis: X, Y, Z are attached to the movable milling spindle. The two rotational axis: 4th – the tilting angle (A) with range between 0 and 90 degrees against X axis and 5th –the rotary angle (B) with range between 0 and 360 degrees and direction perpendicular to the 4th axis. By manipulating the 5th axis only the machine can be utilised as a lathe-type tool.

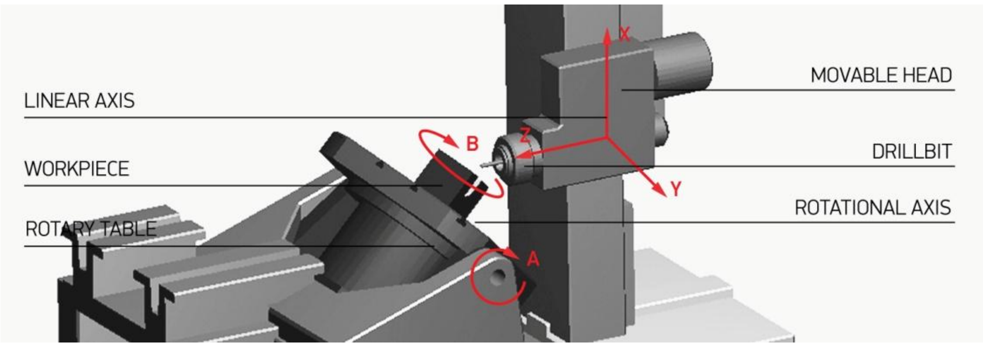


Figure 18: 5-axis vertical CNC milling machine parameters and elements

Evolving the three dimensional model handling precept, the algorithm was further developed to incorporate two more rotary axes in the geometry analysis procedure. At this stage of the research the analysis of any given form became unnecessary. Here the importance was transferred to form exploration mainly, thus sustaining the identical principles for dealing with geometry. Herein the depth buffer values are no longer stored only as physical model vertexes, of which the negative form is to be milled, but the actual readings determine which parts of a virtual black of material are available for milling subtraction. However, these values are still used for further physical model creation, but at the first stage of described procedure, which is the form finding process, these readings are used primarily for *subtractive* digital object generation. The design environment is set as a virtual fabrication machine driven by a genetic algorithm based procedure. The genetic algorithm is responsible for controlling the stage of form designing, in which the fabrication optimisation parameters are taken into account concurrently.

First of all it is crucial to specify exactly which type of digital fabrication method is going to be used for the particular design scenario, once it is settled. Thereafter, let us take a potential block of material that fits in the determined machine working space. The virtual counterpart of material block comprises of a voxel cloud made of small units the size of which corresponds to the model approximation step, which then refers back to the specified tool diameter. Similar dependence was present in the 3d G-Code export algorithm for the 3-axis milling machine. By rotating the virtual workpiece by machine two rotary angles within available ranges of each of them, the model view is analysed accordingly to the displayed current transition. The depth buffer values are stored together with angles related to each particular projection. The angular configuration of the model is here controlled by a genotype, which is composed of two strings of values - referring to angle A and B. The initial arrangement of angles comprises a set of random figures. These values are to be further adjusted in order to fulfil the design's form and manufacturing objectives. Appropriate angles' configuration and gradual voxel deletion - accordingly to programmed spatial relations of the form - leads trough generations of breeding virtual objects' representations to creation of a final model. The model is saved as a procedural machine code ready and optimised for digital fabrication.

5.2 Design procedure

5.2.1 The object

The established procedure case study is based on a design of a desk lamp, selection of which was motivated by its virtues of relatively small size, thanks to which the lamp object would easily fit in a machine working space is one piece. The object dimensions were an important design constraint for the initial procedure testing stage. Other features of the design taken into account were the object's light weight requirement, the level of equal light diffusion level in every direction, stability of the form and potential for the given function utilisation. Here the lamp is illuminated by small led lights which are placed in the form perforations. The lights are purposed to be wired together in the inside of the lamp volume. Therefore it is required to achieve a hollow shape, so that the output model would not require any additional work after being fabricated.

5.2.2 Design parameters

Form finding process is divided into three separate stages. The first one constitutes the virtual material initial subtraction. This process leads to the overall object's form determination. Secondly the smoothing cycle is executed, to be then followed by the final model perforation phase. First two stages are of general-purpose applicable to other design processes. The perforation phase is employed exceptionally for this particular design problem, due to the object function and light's diffusion fitness objective.

Lamp's shape is based on a bezier curve which runs throughout the entire height of the initial material block from and to middle points of the workpiece side planes. Two control points' positions are encoded in the genotype and are the main subject of adjustment in the form finding process. Output volume is created as a result of potential designs' testing whether the given curved shape, with specified offset in X and Y direction from the central cord, created by the chosen control points' locations, fits within the workpiece size. This criterion constitutes the first form's optimisation fitness function. Another fitness objective mentioned above is the object's stability. A centre of mass is calculated and used as a second form's evaluation criterion. Shapes which centre of mass projects outside the base outline are discarded being instable. Because of some machine's constraints the internal well in the object can only be created within a constrained outreach - limited to the maximum tool length. This parameter is also crucial for the fabrication of all the other parts of the model. Only the vertices reachable by tip of the drill and not lying deeper than the tool's length are processed in order to ensure prevention of collisions during the fabrication process. In every analysed view the maximum and minimum z buffer values are calculated:

```
Object [] sort_z_val = view_vertexes[rot_num].toArray();
Arrays.sort(sort_z_val);

float z_min = ((myPathData) sort_z_val[0]).z_coord;
float z_max = ((myPathData)
sort_z_val[sort_z_val.length-1]).z_coord;
```

Only vertexes which Z value is included in tool length range are added to tool path array:

```
if((vec.z ) >= (z_max - tool_length)){
path[rot_num].add(vec);
}
```

The genetic algorithm in parallel to handling main form parameters is responsible for adjusting the fabrication performance by adjusting the order of milled model's elements, so that the closest angles and vertices are grouped together.

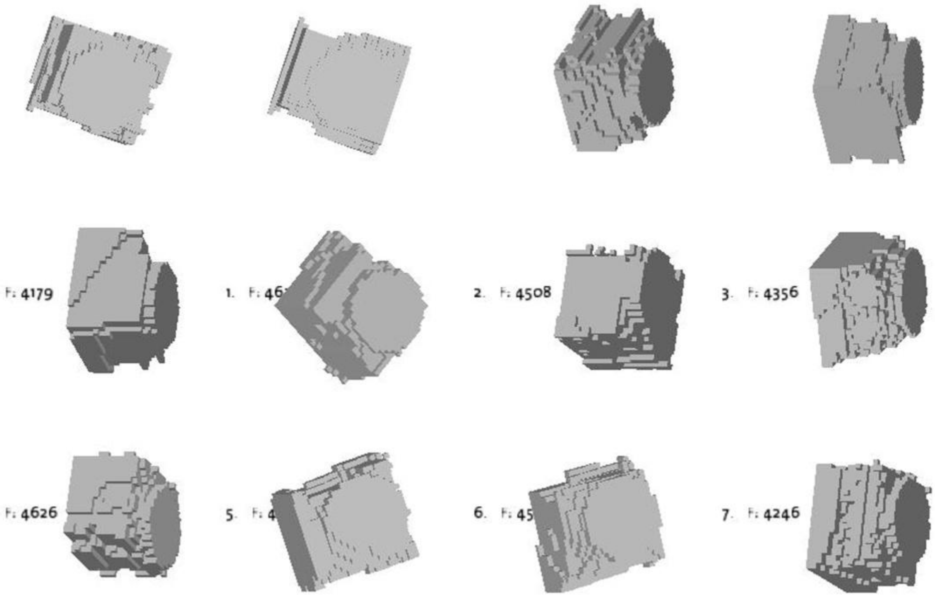


Figure 19: Form generation process using genetic algorithm. #1

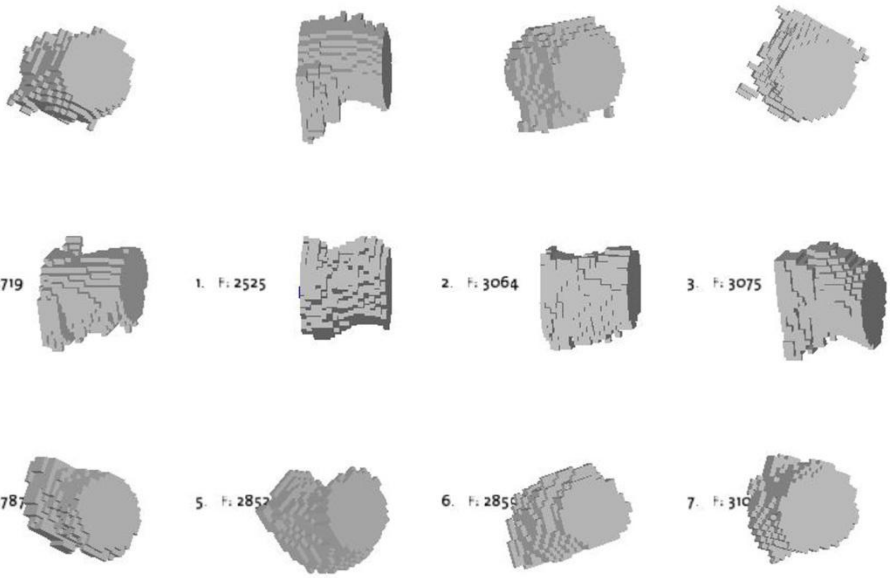


Figure 20: Form generation process using genetic algorithm. #2

This stage of design results in a creation of form that fulfils the stated initial requirements. The generated model is stored as a set of sorted tool path vertices and workpiece rotational angles as the material removal fabrication cycle is completed. Following procedure's stage is based on the output form from the first phase and its purpose is to treats and smooth out the given rough model's surface. Smoothing cycle is required for the form to become even, so that the tool scratches can be minimised. So far in this design procedure the 5-axis machine's advantages were not put in use to the maximum, because - although both angles were being adjusted in the same time - the X, Y and Z axis played the most important role in model creation and fabrication process. Smoothing cycle procedure is programmed with the aim of linear axis movement minimisation in favour of the rotational axis broader employment. Now only vertices positioned on the X axis can be milled and by implementing gradual change of angle B at fixed interval, which as a result leads to lathe-type machine's behaviour.

The last stage of the design process is the deployment of perforations on the object's surface. The fitness function calculates the number of drills in different angles compared to the model's surface normal vectors. The need of such a design element was included in the initial requirement of providing high level of light diffusion. This parameter is measured by the aggregated value of difference between drilled perforations' axis and model's normal vectors measured in the drill access point on the surface. Another factor which influences the light diffusion is the perforations' distribution. It is aimed to achieve maximum even distribution of holes on all sides of the model. Random angles' configuration from the first generation evolves gradually into more evenly sequenced angles, which results in both better primary model processing and fabrication and in the same time in more uniform distribution of perforations. All the perforations are of the same diameter, as only one tool is used for fabrication of this design phase, which was purely a design decision.

5.2.3 Potentials and Limitations

The creation and implementation of this type of a bespoke design tool in real life applications requires precise knowledge of preferred fabrication method with its detailed specifications in advance. Due to the constrained adjustability of the program the design possibilities are limited to the ones included in the predefined manufacturing method's scope. Similar issues are a subject of pre-rationalised approach to design to which this particular implementation belongs. In design pre-rationalisation if the main focal point is the structural system only, the production process of it might still need adjustments and fabrication post-rationalisation. The described procedure overcomes this problem, because only fully fabricatable objects can be created, on the other hand it restricts the potential design possibilities. Expanding Whitehead's classification of design approaches, another subcategory of so-called *fab-rationalisation* is introduced based on presented approach to design process.

Phase2 - Results

5.3 The prototype

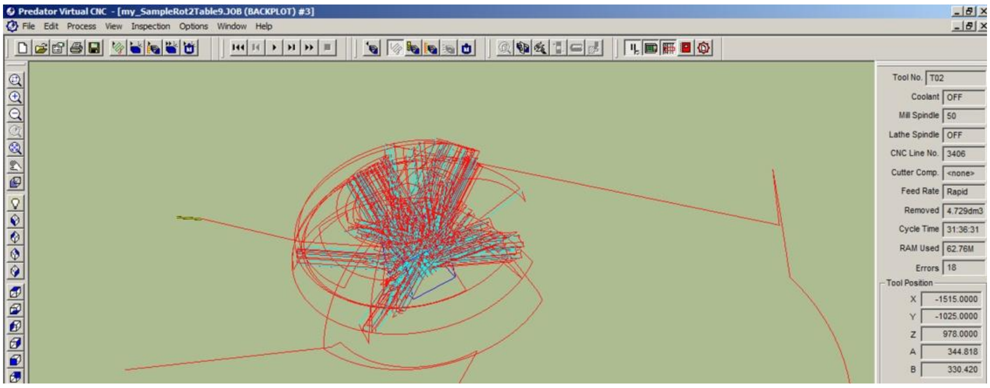
5.3.1 Output

On the current stage of the research the final procedure's output was tested in CNC Simulation software - particularly Predator Virtual CNC 2008 software was used. This decision was caused by limited access to the 5-axis machine. The software proved to be crucial for the output file testing. However, it is intended to build trial model on the purposed machine at an early date. Broad machining options and parameters adjustability available in Predator Virtual CNC software were corresponding with the predefined machine's options, and thus enabled the feasibility study model to be tested only virtually at this stage. The physical prototypes of the previous research phase fabricated on a 3-axis milling machine were also beforehand tested in the CNC simulation software. It was required to test the default parameters of layer thicknesses, tool diameters and generated tool path. Tool – model collisions and surface smoothness outcome was also a test parameter. It was proved that corresponding output was produced by both physical and virtual models. Therefore it is assumed that the research second stage design procedure's end-product tested in simulation software will exhibit similar correspondence with physically manufactured prototypes.

Testing designed objects in simulation software and fabricating physical models is all the more imperative, as the model comprised of point cloud appears to be very heavy in terms of computational demand and memory use, therefore employing a standard visualisation tool for the presentation of designs is highly inefficient in this particular case.

5.3.2 Form generation

The form generation procedure however in this case based on a simple geometric principle proved to have some underlying defects. The depth buffer values are being measured in rigid grid intervals superimposed onto a flat display window. Although, the units of equal size to depth buffer's interval are used for the point cloud's deposition in space, the relative location of both compared values do not correlate with each other, because the view becomes distorted in angular projection. Even though an orthogonal view is being evaluated the comparison between the depth buffer readings and the model voxels coordinates is not accurate, which can in result lead to incorrect geometry generation. Two plausible alternative solutions could be applied in order to improve the accuracy of geometry analysis. The first one requires implementation of an additional fitness function for the output geometry evaluation. Nonetheless, as the output form is not predefined – which is a primary discriminant of the designed procedure – the geometry evaluation would require employment of an intelligent learning algorithm to determine the correct and accidental shapes. Another more applicable possible solution, which is yet to be tested, is a deployment of increased resolution of depth buffer measurements with image sampling procedure, which compared to the point cloud units would discharge from the shifting between the two readings issue.



Tool No. T02
Coolant OFF
Mill Spindle 50
Lathe Spindle OFF
CNC Line No. 3406
Cutter Comp. <none>
Feed Rate Rapid
Removed 4.729dm3
Cycle Time 31:36:31
RAM Used 62.76M
Errors 18

Tool Position
X -1515.0000
Y -1025.0000
Z 978.0000
A 344.818
B 330.420

Figure 21: Tool path trajectory of an output code for 5-axis milling machine.

5.3.3 Fabrication efficiency

Generated tool paths tested in simulation software present a good level of accuracy for the material deposition phase. Subsequent material smoothing stage still lucks precision and requires further development in order to achieve results comparable with already available CAD/CAM conversion software. It has been achieved to produce collision-free tool paths, nevertheless the path-planning component of the procedure requires further improvements. Although a similar path planning rule has been implemented for both machines' types, the algorithm proves to be less efficient and do not meet the demand for the final models' fabrication using a 5-axis milling machine. While for the 3-axis machine the image in a zigzag manner, the output path proves to be effective and free from redundant movements, this is however not true for the 5-axis machine's output code. Calculations of the closest vertex results in complex often scattered paths that do not follow axial directions.

Discussion

6.1 Relevance to architectural profession

Digital revolution has influenced the architectural profession in various ways - the introduction of digital fabrication processes enhanced the production of custom made building elements so easily created by means of generative procedures. Application of computational techniques in the design process implies a tendency of adding increased complexity to forms, thus leading to a shift in what we perceive as good architecture. Nowadays the relation between designs and the way they were fabricated – also important throughout history of architecture - is even more prominent. The construction aspects of design are not only influencing the structural properties of buildings or materials used, but also alter the design process as a whole. Programming skills are becoming more and more in architectural profession, as they give the designer a possibility of setting the relationships between parameters of the design beforehand, which - if digital fabrication methods are considered - permit these parameters to become an important factor or a design core. Such a bottom-up approach impose on the designer a responsibility of establishing how much the designer himself can intervene in the process, parameters of which he can choose manually, which will be predefined or customised by an algorithmic procedure. Using custom developed program for form finding process also frees the designer from the imposed in standard computer software aesthetic tendencies. Bottom-up programming refers to the underlying relationship between building elements, parameters or spatial configurations of a building, so important for the forthcoming materialisation and attainability.

The main focus of this thesis was to investigate the dependences and possible influences of the two closely related elements of design process – the form creation and fabrication stages – analysed in the light of digital advances in both fields, namely the computer-aided design tools and digital manufacturing. The assumption that the two still disconnected processes could be linked together in a comprehensive design bespoke environment was researched on the basis of two complementary studies. The first one was designed to create a link between a designer-friendly parametric language such as Processing and rapid prototyping techniques by creating a user-oriented application for connecting the two. The interdependence of both processes was the main subject of this study, therefore an enhancement of a general purpose programming environment partially fulfils the main objectives already and enables multiple users to take advantage of it. The library however supports only 2,5 – axis machines, therefore the attainable incorporation in architectural forms manufacturing is restrained to panel-type elements or convex moulds. It can be also successfully utilised for various non-architectural purposes and mere form exploration. On the other side the G-Code export function, even though being very useful presumably, does not influence the design process at any degree. The assumption set out in the beginning of this research was the study of how the digital fabrication characteristics can alter and enhance the design process from the outset. Now then the library development stage did not provide any valid answer to that problem, although its outcome provided an indispensible starting point for creating the suitable scenario.

Diving into the subject it became clear that the mentioned programming skills of architects should play the most important role in tying the entire design-to-production process in such a way that the fabrication qualities inform the designed form by themselves. Design framework was devised from

5-axis CNC milling machine’s features. The generative procedure was established with the aim of incorporating a wide variety of parameters, such as for example: overall for of the object, its weight, light diffusion level and most importantly suitability for the particular fabrication method. Usually even if a bottom-up approach is taken while designing, the predefined form tends to affect the programmable design dependencies, so that the output will most likely fit within the designers’ established aesthetics, and therefore the emergent forms are less probable to occur. Similar issue was encountered during the lamp design process. Because the geometric was very basic and formal delimitations quite restrictive, the generated form was easily predictable. It seems to be more adequate to apply more general formal rules for the procedure to demonstrate its full potential. Counter arguing the above stated the predictable form was created in all probability not due to procedure’s internal errors, but because it was enforced. The constant back and forth parameters’ adjustment was in the first place caused by the need of exploration of possible design solutions. Procedures, which output did not fit the requisites, were discarded till the one that fulfilled the creation of desired shape was found. Therefore taken bottom-up approach was at some point stranded. Middle stage output forms are the most correct effect of the selected path. This argumentation is referring to the first stage of design development only, and can be a subject of further discussion. The perforation creation stage does not fall in this concern. In both stages the random factor was the one controlled by the genotype, but what they differ in is the range of changes that can be executed by the algorithm.

6.2 Potential improvement strategy

Incorporated in the application the genetic algorithm was responsible for handling many objectives in the same time. Although the most processor absorbing procedure is the constant depth buffer values acquisition and storing in resizable arrays. Collecting and storing countless vector coordinates and continuous multi-objective fitness evaluation caused the overall generation process to be inefficient and time-consuming.

The development of Graphics Processing Unit (GPU) also called the Visual Processing Unit - which is a specialised graphics processor detached from standard Computer Processing Unit - introduced major advances in computer technology over the past decade (Boggan & Pressel, 2007). GPU became responsible for performing complex three dimensional graphics rendering and image rasterisation operations and thus discharged CPU from liability of executing some highly demanding tasks. Lately programmable hardware became widely exploited in manufacturing related disciplines, for instance Roth et al. deployed an adaptive depth buffer method for multi-axial milling machines as a solution to the CAD/CAM conversion problem and gained substantial computation speed on calculating cutting forces (2003). In evolutionary algorithms the most processor effort is dedicated to calculating individual’s fitness function. Harding and Banzhaf present a solution for significant increase in computational efficiency for calculating genetic algorithm fitness function using Graphics Processing Unit (2007). By passing on the major calculations from CPU to GPU it is possible to reduce the time required for executing a single operation by hundreds of times.

Compute Unified Device Architecture (CUDA) developed by NVIDIA is a parallel computing architecture that is capable of utilizing Graphics Processing Units’ engine scope. Complex highly processor demanding calculations performed by applications developed with CUDA language require significantly less time than those using Central Processing Unit based languages only. The best performance can be achieved by using basic programming languages like C, but wrappers are available for other languages for example Java, C++ and MatLab. Therefore it is possible to implement CUDA functions within Processing programming language, as it is based on Java. It is though evident that high-level programming languages could perform complex calculations with conjunction to GPU much quicker, but advantages of using a simplified language dedicated for visual artists and designers has a significant predomination of direct visual response and user-friendly interface (NVIDIA Corporation, 2007).

6.3 Possible development and form generation procedures

Referring back to the issues with generative procedure principles, here some plausible correct approaches are presented. Fabrication parameters incorporation suggest that the form finding procedure should not be based on geometric relationships of the desired object, but the machining embedded principles should play a prominent role. The final shape should be created by manipulating the machine's activity by selecting different combinations of angles and positions of the drill bit in relation to the material block. This type of form finding would require more complex path planning for the output forms fabrication. The virtual sculpted-model can be freely created, but the physical model's milling constraints are imperative. Therefore it is not possible to simply set the form generation rules a priori, but the implementation of evolutionary algorithms for evaluating the correctness of each procedure. All that leads consequently to the conclusion that genetic programming implementation for stated objectives would most aptly fulfil the stated goals of this thesis, as it would evaluate the form generation procedures rather than the output of them.

Conclusion

Research progress described in this thesis presents a custom solution to a problem of linking two still disjoint processes of architectural design and building fabrication stage. The aim was to create a multirole environment for the designer to approach the form generation process from a different than usual perspective. In was suggested that the digital fabrication objectives could become a source of inspiration and a driving force of the design. In order to explore the feasibility of such approach two design facilitating tools were created. The first one was library for the Processing programming language that enables direct G-Code file export of any three-dimensional geometry from the design environment to 3-axis milling machine controllers. At this stage factors such as path planning and optimisation of the output code, computational efficiency and 3d geometry analysis were considered and the results incorporated in final library, which is available for an open source download. A more advanced step towards finding the relevant solution was derived from accomplishment of the first step.

From the analytical study a more design oriented attitude was adopted in the second phase of the research. Created design tool accomplished the primary research objective of joining all the design stages in one comprehensive application. Stages from form generation through optimisation to fabrication output file preparation were executed within single bespoke program. The aim was not only to join the processes together but redefine their interdependence on the design stage. Owing to implementation of real-time simulation of fabrication state at any stage which is a counterpart of visual object generation the interdependence was enhanced. Only forms that meet manufacturing constraints full are manageable, therefore no post-rationalisation procedures are required for the object to be materialised.

Broadening the Whitehead's classification of rationalisation approaches to design into pre-, co- and post-rationalisation a new sub-category of fab-rationalisation is introduced (2003). Similarily to pre-rationalisation the parameters for physical fabrication are imposed on the design from the early stages, however fab-rationalisation implies utilisation of these prerequisites for enhancement of computer program's creativity in forms' generation and is a crucial factor in design creation.

Both research stages proved to accomplish initial requirements in high degree. Main research objective was successfully tested in a custom made application and the link between design and production stages was re-established. Some misfits emerged during the advancement of the research, such as high processor load, maladjusted tool paths for the 5-axiss milling machine fabrication and a need for generative procedure principles re-evaluation as being the most important ones. The tool paths generation algorithm, although requiring further corrections, produces codes ready for use on CNC machines without need for alterations on this stage. It is the efficiency and time-consumption of the fabrication process that needs to be improved in the future. Also a few improvement methods were described for possible implementation on successive stages of the research. As a result of this thesis are being evaluated it becomes apparent that the developed solutions for stated research question are only a tip of the iceberg and broad further development following different paths is required in order to explore potentials of this approach in depth.

Further work

Further development strategies exist for this research and include first of all improvements of the generative procedure for form finding in the application.

It is necessary to create and analyse a number of case study examples in order to experiment with the design technique in different scenarios. In the next stage, which is also imperative for developing the design tool is the fabrication of series of prototype models, which will make it possible to test the tool trajectory in real life application as well as fabrication efficiency and objects' fitness for purpose.

Subsequently the improvements should be also made in the genetic algorithm performance and a study over various ways of evaluating the fitness function for multi-objective optimisation would be crucial for the procedure further development. The more the genetic algorithm is efficient the quicker and broader search of optimum solution can be performed. This goal could be achieved by both restructuring of the procedure itself and passing on the computationally heavy calculations to the Graphics Processing Unit via incorporation of CUDA programming language functions into the Processing language. GPU could also be tested for conducting the depth buffer calculations, which all the more are originally being retrieved from the graphic card hardware. As already mentioned in the discussion chapter the role of genetic algorithm in the procedure could be taken over by genetic programming procedure. Use of Genetic Programming indicate the possibility of overcoming some inherit drawbacks of the present procedure.

Studied design approach, based on a particular digital fabrication technique, could also be tested for eligibility for other digital manufacturing methods, in particular big scale additive fabrication processes using industrial robots.

Reference:

Afify, H.M.N. & Elghaffar, Z.A.A., 2007. *Advanced digital manufacturing techniques (CAM) in architecture*. [Online] Menoufia University, Egypt Available at: *http://www.ascaad.org/conference/2007/006.PDF* [Accessed 3 September 2009].

Attar, R. et al., 2009. *Physics-based generative design*. [Online] Available at: *http://www.autodeskresearch.com/papers/gendesign/CF09PhysicsGenDesign.pdf* [Accessed 29 August 2009].

Bhattacharya, P. & Gavrilova, M.L., 2007. Voronoi Diagram in Optimal Path Planning. In *4th International Symposium on Voronoi Diagrams in Science and Engineering*. IEEE Computer Society Press, 2007. Los Alamitos.

Binnard, M., 1999. *Design by Composition for Rapid Prototyping*. Massachusetts: Kluwer Academic Publishers.

Boggan, S. & Pressel, D.M., 2007. *GPUs: An Emerging Platform for General-Purpose Computation*. [Online] Available at: *http://www.arl.army.mil/arlreports/2007/ARL-SR-154.pdf* [Accessed 27 August 2009].

Bonwetsch, T., Gramazio, F. & Kohler, M., 2006. The informed Wall: applying additive digital fabrication techniques on architecture. In *Synthetic Landscapes, Proceedings of the 25th Annual Conference of the Association for Computer-Aided Design in Architecture*. Louisville, 2006.

Botha, M. & Sass, L.D., 2006. The instant House, Design and digital fabrication of housing for developing environments. [Online] Available at: *http://ddf.mit.edu/papers/09_botha_sass_caadria_2006.pdf* [Accessed 27 August 2009].

Callicott, N., 2001. Computer-Aided Manufacture in Architecture, The Pursuit of Novelty. Oxford: Architectural Press.

Carter, J.A., Tucker, T.M. & Kurfess, T.R., 2008. *3-Axis CNC Path Planning Using Depth Buffer and Fragment Shader*. [Online] CAD Solutions Available at: *http://www.cadanda.com/CAD_5_5__612-621.pdf* [Accessed 27 August 2009].

Constructing Excellence, 2003. *3-D model makes complex steelwork simple*. [Online] Available at: *http://www.constructingexcellence.org.uk/pdf/case_studies/M4I222%20GLA%20Case%20Study%20(DP%20219).pdf* [Accessed 3 September 2009].

Corbusier, L., 1986; first edition, 1931. *Towards a New Architecture*. thirteenth edition ed. New York: Dover Publications, Inc..

Dorigo, M. & Gambardella, L.M., 1997. Ant colonies for the traveling salesman problem. *Bio Systems*, (43), pp.73-81.

Drenckhan, W. & Weaire, D., 2004. *Some confluences of art and science in the physics of foams*. [Online] Symmetry: Art and Science, Tihany Congress Available at: *http://www.maths.tcd.ie/~wiebke/PHYSICS/MY_PAPERS/ConfluencesOfArtAndScience.pdf* [Accessed 3 September 2009].

Fischer, T., 2007. *Rationalising bubble trusses for batch production*. [Online] Available at: *http://www.sciencedirect.com/science?_ob=ArticleURL&_udi=B6V20-4HR75KR-1&_user=10&_rdoc=1&_fmt=&_orig=search&_sort=d&_docanchor=&view=c&_searchStrId=995334430&_rerunOrigin=google&_acct=C000050221&_v*

ersion=1&_urlVersion=0&_userid=10&md5=80aefa41caccd3cfb92 [Accessed 29 August 1009].

Gramazio, F. & Kohler, M., 2006. *Facade Gantenbein Winery, Fläsch (Switzerland), 2006, Non-Standardised Brick Façade*. [Online] ETH Zurich Departement Architecture Available at: *http://www.dfab.arch.ethz.ch/web/e/forschung/52.html* [Accessed 3 September 2009].

Gramazio, F. & Kohler, M., 2006. *The Perforated Wall, ETH Zurich, 2006*. [Online] ETH Zurich Departement Architecture Available at: *http://www.dfab.arch.ethz.ch/web/e/lehre/83.html* [Accessed 3 September 2009].

Gramazio, F. & Kohler, M., 2006. *The Programmed Wall, ETH Zurich, 2006*. [Online] ETH Zurich Departement Architecture Available at: *http://www.dfab.arch.ethz.ch/web/e/lehre/81.html* [Accessed 2 September 2009].

Gramazio, F. & Kohler, M., 2008. Manufactoring Material Effects Rethinking Design and Making Architecture. In Kolarevic, B. & Klinger, K. *Towards a Digital Materiality*. New York: Routledge. pp.103-18.

Harding, S. & Banzhaf, W., 2007. Fast genetic programming on GPUs. In Ebner, M. et al., eds. *Proceedings of the 10th European Conference on Genetic Programming*. Valencia, 2007. Springer.

Hasan, M., Gavrilova, M.L. & Ro, J.G., 2007. A Geometric Approach to Clearance Based Path Optimisation. In *ICCSA 2007, LNCS 4705*. Berlin Heidelberg, 2007. Springer-Verlag.

Ingenia, 2007. *Box of bubbles*. [Online] Available at: *http://www.ingenia.org.uk/ingenia/issues/issue33/Carfrae.pdf* [Accessed 3 September 2009].

Johnson, D.S. & McGeoch, L.A., 1990. The Traveling Salesman Problem: A Case Study in Local Optimization. In Goos G, H.J., ed. *ICALP '90: proceedings of the 17th international colloquium on automata, languages and programming*. London, 1990. Springer-Verlag.

Joy, K.I., 2008. *On-Line Computer Graphics Notes: The depth-buffer visible surface algorithm*. [Online] Visualization and Graphics Research Group, Department of Computer Science University of California, Davis Available at: *http://www.idav.ucdavis.edu/education/GraphicsNotes/Z-Buffer-Algorithm.pdf* [Accessed 1 September 2009].

Klinger, K.R., 2001. Making Digital Architecture: Historical, Formal, and Structural Implications of Computer Controlled Fabrication and Expressive Form. In *Education in ComputerAided Architectural Design in Europe (eCAADe) Conference 2001:Architectural Information Management*. Helsinki, 2001.

Kolarevic, B., 2006. *Digital Fabrication: From digital to material*. [Online] Available at: *http://www.iit.edu/~mcleish/arch497_DDF/branko_kolarevic.pdf* [Accessed 27 August 2009].

Makhanov, S., 2008. *Mathematical Methods for Optimization of Cutting Operations of 5-Axis Milling Machines*. [Online] School of Information and Computer Technology, Rangsit, Thailand Available at: *http://atcm.mathandtech.org/EP2008/papers_full/2412008_14580.pdf* [Accessed 3 September 2009].

McKenney, D., 1998. Model Quality: The Key to CAD/CAM/CAE Interoperability. In *MSC Americas Users' Conference*. Universal City, CA, 1998. MSC Software.

Montemanni, R., Barta, J., Mastrolilli, M. & Gambard, L.M., 2007. Heuristic algorithms for the robust traveling salesman problem with interval data. *Transportation Science*, (41(3)), pp.366-81.

NVIDIA Corporation, 2007. *NVIDIA CUDA Compute Unified Device Architecture*. [Online] NVIDIA Corporation Available at: *http://developer.download.nvidia.com/compute/cuda/1_0/NVIDIA_CUDA_Programming_Guide_1.0.pdf* [Accessed 1 September 1009].

Oberholzer, M., 2006. *Greater London Authority*. [Online] Available at: *http://www.owlnet.rice.edu/~arch214/gla_foster.pdf* [Accessed 3 Seotember 2009].

Roth, D., Ismail, F. & Bedi, S., 2003. *Mechanistic modelling of the milling process using an adaptive depth buffer*. [Online] (http://www.sciencedirect.com/science?_ob=ArticleURL&_udi=B6TYR-488VSB9-1&_user=10&_rdoc=1&_fmt=&_orig=search&_sort=d&_docanchor=&view=c&_searchStrId=997857252&_rerunOrigin=google&_acct=C000050221&_version=1&_urlVersion=0&_userid=10&md5=be2a6bee602c9740a29) [Accessed 29 August 2009].

Saiko, D., 2005. *Traveling Salesman Problem, Java Genetic Algorithm Solution*. [Online] Available at: *http://www.google.pl/url?sa=t&source=web&ct=res&cd=8&url=http%3A%2F%2Fjava-traveling-salesman.googlecode.com%2Ffiles%2Ftsp-documentation.pdf&ei=kX6oSpfBONefjAeGsejYBw&rct=j&q=travelling+sales*

man+problem+filetype%3Apdf&usg=AFQjCNGSBSSV6HxB336WetHvydeytJlbB [Accessed 3 September 2009].

Seely, J.C., 2004. *Digital fabrication in the architectural design process*. [Online] Massachusetts: Massachusetts Institute of Technology Available at: *http://dspace.mit.edu/bitstream/handle/1721.1/27030/56780968.pdf?sequence=1* [Accessed 27 August 2009].

Whitehead, H., 2003. Laws of Form. In Kolarevic, B. *Architecture in the Digital Age Design and Manufacturing*. New York and London: Spon Press. pp.82-100.

Appendix 1

G-Code and M-code basic functions according to

http://linuxcnc.org/handbook/gcode/g-code.html:

G0 rapid positioning

G1 linear interpolation

G2 circular/helical interpolation (clockwise)

G3 circular/helical interpolation (c-clockwise)

G4 dwell

G10 coordinate system origin setting

G17 xy plane selection

G18 xz plane selection

G19 yz plane selection

G20 inch system selection

G21 millimetre system selection

G40 cancel cutter diameter compensation

G41 start cutter diameter compensation left

G42 start cutter diameter compensation right

G43 tool length offset (plus)

G49 cancel tool length offset

G53 motion in machine coordinate system

G54 use preset work coordinate system 1

G55 use preset work coordinate system 2

G56 use preset work coordinate system 3

G57 use preset work coordinate system 4

G58 use preset work coordinate system 5

G59 use preset work coordinate system 6

G59.1 use preset work coordinate system 7

G59.2 use preset work coordinate system 8

G59.3 use preset work coordinate system 9

G80 cancel motion mode (includes canned)

G81 drilling canned cycle

G82 drilling with dwell canned cycle

G83 chip-breaking drilling canned cycle

G84 right hand tapping canned cycle

G85 boring, no dwell, feed out canned cycle

G86 boring, spindle stop, rapid out canned

G87 back boring canned cycle

G89 boring, dwell, feed out canned cycle

G90 absolute distance mode

G91 incremental distance mode

G92 offset coordinate systems

G92.2 cancel offset coordinate systems

G93 inverse time feed mode

G94 feed per minute mode

G98 initial level return in canned cycles

M0 program stop

M1 optional program stop

M2 program end

M3 turn spindle clockwise

M4 turn spindle counter clockwise

M5 stop spindle turning

M6 tool change

M7 mist coolant on

M8 flood coolant on

M9 mist and flood coolant off

M26 enable automatic b-axis clamping

M27 disable automatic b-axis clamping

M30 program end, pallet shuttle, and reset

M48 enable speed and feed overrides

M49 disable speed and feed overrides

M60 pallet shuttle and program stop

Appendix 2

G-Code sample program for cutting letter M:

```
N10 T2 M6  -
N20 G54 G90 S1500 M3
N30 G00 X10 Y10 Z10
N40 G01 Z-4
N50 X90
N60 X40 Y40
N70 X90 Y70
N80 X10
N90 G00 Z10
N80 G00 X10 Y0
N90 M30
```

Appendix 3

Depth buffer extract and convert function:

P3D renderer:

```
depth_buffer = ((PGraphics3D)g).zbuffer;
depth_buffer1 = new float [depth_buffer.length];
float cameraZ = ((height/2.0) /tan(PI*60.0/360.0));
float near=-10
float far=10

for (int i=0; i< depth_buffer.length; i++){
  float worldZ = (-near - (far-near)*depth_buffer[i]);
  depth_buffer1[i] = (worldZ + cameraZ);
}
float max_buff = (-near - (far-near)*3.4028235E38) + cameraZ;
```

OpenGL renderer:

```
  PGraphicsOpenGL pogl = (PGraphicsOpenGL) g;
  depth_buffer = new float [width*height];
  for (int i=0; i<height; i++){
    for (int j=0; j<width; j++){
      FloatBuffer z = FloatBuffer.allocate(1);
      pogl.gl.glReadPixels( j, i, 1, 1,
GL.GL_DEPTH_COMPONENT,GL.GL_FLOAT, z);
      depth_buffer[j+width*i] = z.get();
    }
  }
```

```
depth_buffer1 = new float [depth_buffer.length];
float cameraZ = ((height/2.0) /tan(PI*60.0/360.0));
float near = cameraZ/10;
float far = cameraZ*10;

for (int i=0; i< depth_buffer.length; i++){
  float worldZ = (-near - (far-near)*depth_buffer[i]);
  depth_buffer1[i] = (worldZ + cameraZ);
}

float max_buff = (-near - far-near) + cameraZ;
```

Appendix 4

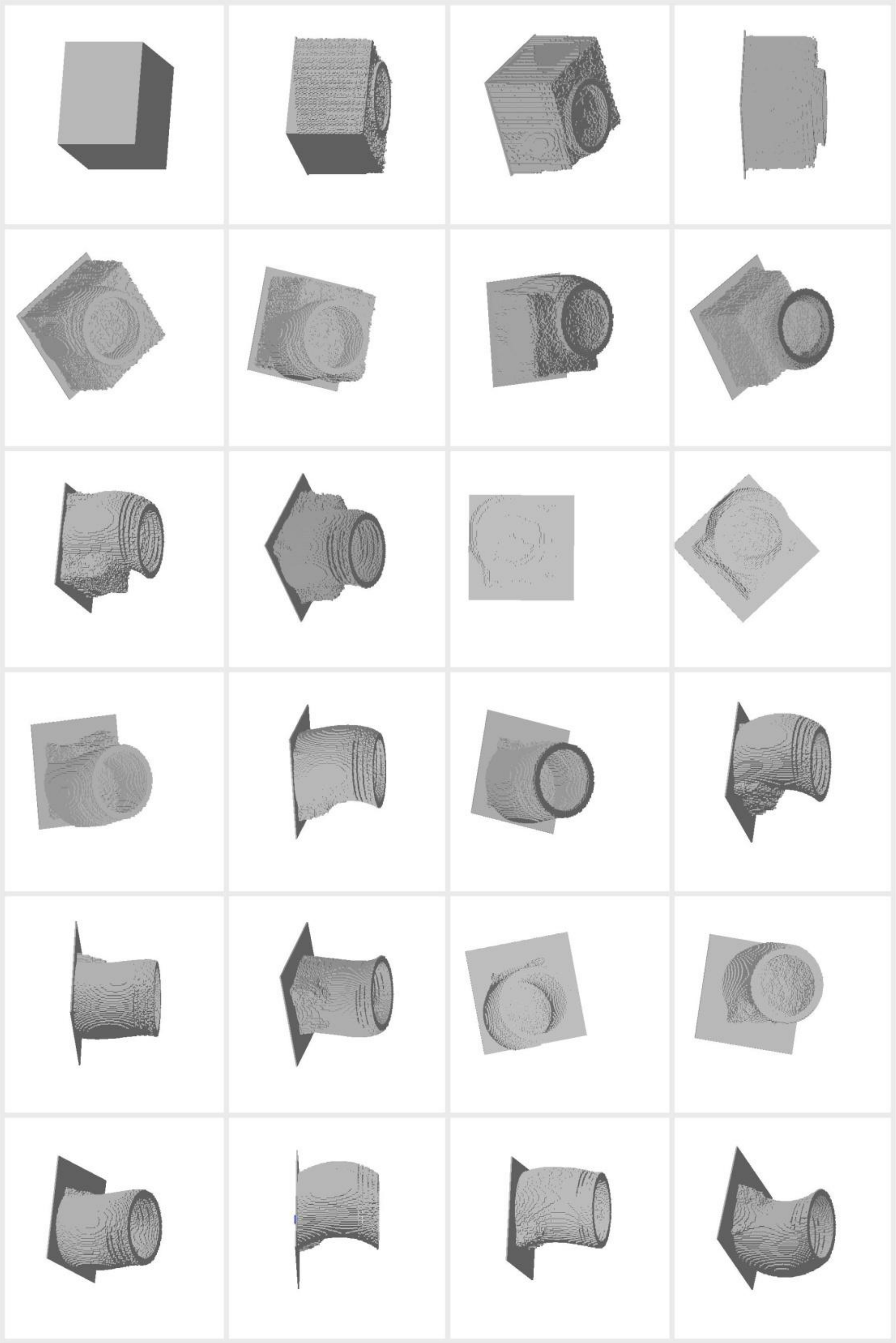
Sample code of a Processing sketch using PGCode3D library for exporting a simple box primitive for digital fabrication.

```
import PGCode3D.*;
G_code_export gc;

void setup()
{
  size(100, 100, P3D); // both P3D and OpenGL are supported
  gc = new G_code_export (this,6,3,”cnc_code_nowe”,200);
  //T01 – 6mm, T02 – 3mm, material thickness – 20 cm
  background(255);
  stroke(255);
  fill(0);
}

void draw()
{
  ortho();
  pushMatrix();
  rotateY(PI/6);
  rotateX(PI/6);
  translate(width/2, height/2,-height/2);
  box(30);
  popMatrix();

  gc.print_data(); //println the model data
```

```
 if(keyPressed){
   gc.change_settings(5,3000,150,3);
   // 5-offset above material, 3000 – spindle speed, 150 – feed rate, 3 – layer thickness
   gc.optimise_path(1000); //optimise throughout 1000 generation
   gc.export(); //will println “generated” when the view analysis is completed and “file written” for the complete export
   exit();
 }
}
```

Appendix 5

Form generation procedure – development of form.



Appendix 6

Form generation procedure – development of form in first generation:

respective rotation numbers: 2, 8, 16,