3-Axis CNC Milling in Architectural Design
Robert Aitcheson, Jonathan Friedman and Thomas Seebohm
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Physical scale models still have a role in architectural design. 3-axis CNC milling provides one way of making scale models both for study purposes and for presentation in durable materials such as wood. We present some types of scale models, the methods for creating them and the place in the design process that scale models occupy. We provide an overview of CNC milling procedures and issues and we describe the process of how one can creatively develop appropriate methods for milling different types of scale models and materials. Two case studies are presented with which we hope to convey not only the range of possible models that can be machined but also the way one creatively explores to arrive at appropriate milling strategies. Where apposite, we compare 3-axis CNC milling to newer technologies used for rapid prototyping but rapid prototyping is not a primary focus.
1. Introduction

Computer-numerically-controlled (CNC) milling has recently joined newer technologies for rapid prototyping in architecture whereby one proceeds directly from three-dimensional computer model to manufactured object by way of a physical prototype. Our focus in what follows is not rapid prototyping, however, but rather the creation of physical scale models with 3-axis CNC milling technology. We are interested in the types of scale models that can be created, the methods for creating such models with the technology and the place of such models within the architectural design process. After an overview of the issues and the process we describe two case studies each of which involves the making of a different type of scale model. We are excited by the results not only because of the joy that can be achieved in mastering the process and the room for creativity within the process but also because of the joy derived from creating, touching and looking at physical models. Just as it has been recognized for some time that digital techniques can complement manual techniques so physical models can complement virtual, three-dimensional models. Indeed, virtual models are the prerequisite. It should also be added that physical scale models provide an overview of a design but cannot substitute for the experience of being immersed in real architecture. Other digital technologies such as stereoscopic, immersive walls, Cave Automatic Virtual Environments (CAVEs) and stereoscopic, head-mounted displays can simulate immersive experiences.

Unlike other technologies that are used for rapid prototyping, such as the 3D printer by ZCorp that is used to print physical scale models of design alternatives, 3-axis CNC milling does not produce physical models at the touch of a button. 3-axis CNC milling is much more related to craft in the sense that for different shapes and materials different milling strategies must be devised. That is in itself a creative process. Although the use of CNC milling in architectural applications has recently been the subject of a number of publications [1, 2, 3, 4, 5] details of the strategies used for milling different shapes and materials and the parameters associated with these milling operations are generally not discussed. One reason may be that CNC milling is seen as just another rapid prototyping technology that ought to be as simple to use as the other technologies. Another reason may be that the materials cut are often quite forgiving such as rigid foam or insulation requiring no special skills in CNC milling. We are interested in wooden models that do require special expertise. An overview of the basics of CNC milling operations is provided in [6]. Let it therefore suffice to list the capabilities of 3-axis CNC milling, in particular, those that can be carried out with a 3-axis CNC router (really a CNC milling machine with a very large bed, about 127 cm square (50 inches square) in the case of the machine to be discussed). The capabilities of this machine are as follows: 1) Cutting large sheets of material such as plywood sheets. In this sense the...
CNC router is like a powerful laser cutter but the CNC router has the added advantage of being able to cut special edge profiles rather than just vertical cuts. 2) Milling large terrain models. Such models generally have large widths and lengths but relatively small elevation changes compared to the length and width. 3) Half-rounded objects are easy to machine because the cutting tool in a 3-axis machine can only machine from one side. 4) Fully round objects. This is accomplished by rotating the piece to be cut so that cutting can be accomplished from more than one side (one of the case studies below involves two-sided cutting. It is, of course, possible to mill from more directions with a five-axis milling machine where the cutting tool can move in five degrees of freedom, usually accomplished with a tool that can move in three directions \((x,y,z)\) and a table that can rotate and tilt. The octahedral hexapod by Ingersoll Milling Machine Co. can move the tool in five degrees of freedom by attaching the tool head to six moveable arms. 3-axis milling machines and routers are lower cost machines more likely to be available, however.

2. Overview of CNC Milling procedures and issues

CNC machining to make wooden scale models is not an automatic process. Only some of the steps are semi-automated. How each step is executed determines what is possible, how long it will take to machine and what quality of finish will result. Although the procedures described here were developed for a particular CNC router (made by Techno-latif), they are of general applicability. Like all such machines, the router has a gantry that moves over the working surface or bed in the \(y\) direction. Attached to the gantry is the spindle assembly that moves in the \(x\)-direction along the gantry. The spindle and the spindle motor, to which the drill-like cutter is attached, move up and down in the \(z\) direction on the spindle assembly. Each of the \(x\), \(y\) and \(z\) directions of motion is provided by a dedicated servo motor. The spindle motor rotates the spindle at rotations up to 18000 rpm, in our case.

The overall procedure for milling an object is to create a three-dimensional computer model of the object in three-dimensional modeling software and then to export this model to software that allows the creation of tool paths. Tool paths are instructions that tell the tool how to move in order to carve out the desired object from piece of material referred to as the stock. The instructions thus produced are in a generic set of codes called G-codes stored in text file format. Before the milling machine can execute the G-codes they are converted to machine specific instructions by the machine interface software that resides on the on-board computer that drives the milling machine. The software makes use of a controller card which sends signals to the controllers that control the motion of the servo motors which, in turn, move the spindle assembly in the required \(x\), \(y\) and \(z\) directions.
We highly recommend cutting a test model first. Pink, rigid insulation is an excellent material for cutting test models (though we do not recommend Styrofoam because of its granular structure). It is inexpensive and forgiving of mistakes in tool path strategy and machine operation. We have found that, in an academic setting, where each scale model to be machined is sufficiently different, cutting a test model wholly or partly is essential. So each of the following steps should be executed first with test material and then repeated with the real material. Occasionally, we also recommend cutting a partial model in the final material in order to confirm feeds and speeds and cutting strategies. Here is an overview, in more detail, of the steps we go through to mill an architectural scale model in wood.

1) Exporting to stl: Export the three-dimensional computer model to stl (stereo lithography format). This format is the most common format used for rapid prototyping of all sorts. The stl format represents surfaces as tiny triangles (for curved surfaces good stl representations use more triangles in areas of high curvature and allow the user to specify the chordal tolerance or error, namely, the distance from the surface of a triangle to the curved surface it approximates). The computer model must be the same size as the actual physical model to be produced.

2) Cut the stock: Cut a piece of material, called the stock, from which a scale model is to be machined.

3) Model the stock: Create a three-dimensional model of the stock that is exactly the same as the physical test stock. This model can be created in a three-dimensional modelling package or directly in the tool path software if the shape is simple.

4) Generate the tool paths: Use tool path generation software (we use Visual Mill but there are several others) to create the tool paths that will guide the CNC milling machine to cut the scale model from the stock. This process does not require knowing how to do program tool paths with G-codes but it does require knowledge of the different tool path strategies and the appropriate tools to use for each strategy as well as associated parameters such as feeds and speeds to be used by the cutting tool. Feeds and speeds depend on the type of material being cut. For example, rigid insulation may be cut at high feed rates (the rate at which the cutting tool moves through the material to be cut) and high rotational speeds of the tool, whereas different kinds of wood each have a speed limit depending both on how fast the cutter can remove material as well as the heat produced (which can produce burning) and the type of finish produced. With basswood, for example, we often noticed fuzzy edges being formed which can be minimized by selecting appropriate cutting speeds. The values to use for feeds, speeds and associated parameters when cutting wood do not seem to be available in the literature or on the Web. The general feeling among CNC users cutting wood seems to be that the values are so case specific that they must be determined by experience. The closest we have
come to finding any recommendations was for cutting large sheets of thick plywood with fairly large diameter cutters. We found these speeds to be much too high for cutting curvilinear models in basswood, for example.

Tool path strategy refers to the fact that there are different ways that the cutter can be programmed to remove material to produce the desired shape. For example, in parallel machining, the cutter moves in parallel paths following the x or y coordinate directions with each path overlapping the previous by a specified amount. For parallel machining of curvilinear surfaces, the tool used is likely to be a ball nose cutter (a drill bit-like tool with a round end). Usually, a tool path strategy involves several different machining operations ranging from rough cut operations, with a large diameter, flat-bottom tool, to finish operations with a smaller diameter ball nose cutter.

When deciding on what tools to use for different tool path strategies and on the strategies themselves, consideration must be given to clearances. For example, will a given length of cutter allow cutting a valley of a certain depth without the tool spindle assembly or the collet (the part of the spindle which actually secures the tool) striking material that has not been cut or striking the clamps that secure the stock to the work surface? The final surface finish of a curved surface is determined by the size of the scallops (valleys with a semi-circular cross section and sharp ridges between valleys where the valleys intersect each other) resulting from parallel finishing. The height of the ridges can be calculated from the spacing between parallel cuts and the radius of the end of the cutting tool according to the formula: \( D = 2 \sqrt{2rh - h^2} \) where \( d \) is the stepover distance between cuts, \( r \) is the radius of the ballnose of the cutter and \( h \) is the scallop height. A light manual sanding operation will remove the scallops altogether if the scallops are sufficiently small.

5) Securing the stock: Securing the stock to the work surface does not at first seem to be a significant issue or to require much planning. In fact, how a stock is secured is very significant because it is possible for the cutting tool to run into the clamps when trimming the sides of the stock. For this reason it is good practice to place some wood blocks between the metal clamps and the stock in case the cutter does accidentally move into this location. Ideally, careful planning of tool paths and setting of limit planes avoids such problems. When cutting large surfaces from flexible materials it is not sufficient to only clamp the edges. For such situations, a vacuum working surface allowing the flexible middle of the stock to be sucked down against the surface is useful.

6) Setting the origin. Generally it is customary to set the coordinate system origin at the lower left of the top surface of a rectangular piece of stock. This position avoids accidentally cutting into the stock during a horizontal motion to the initial milling position (if other precautions have not been taken). Ideally, one should create the three-dimensional computer
model in such a way that it includes some stock that will not be cut away. That will allow the selection of an origin that will remain throughout the milling process. If the intention is to rotate the stock to the other side in order to mill the stock from two sides, we have found that it is easiest conceptually to locate the origin on the axis of symmetry on the top surface, that is, on the middle of the top left edge. To position the tool precisely at the origin we have been using a very straight nail (with head removed) secured in place of a cutting tool so that the x and y coordinates of the origin can be precisely located at the tip of the nail. We then replace the nail with the actual tool and locate the z value of the origin at the value where a piece of paper can just be moved between the surface of the stock and the tip of the tool.

7) Changing tools: After each milling operation, the tool must be changed. Each new tool is likely to be of a different length thus requiring a change in the z value of the origin to be set. Our technique is to move the tool-holding assembly away from the stock, insert the new tool and reposition at the x, y location of the origin over the stock. We then lower the tool slowly to the surface of the stock, so that a piece of paper can just barely be moved between the tip of the tool and the surface of the stock. Finally, we reset the z of the origin to zero in the machine interface software.

2.1. Overview of critical issues

Knowing what feeds and speeds and related parameters (such as the degree of overlap of parallel tooth paths and the depth of cut) to use for a particular type of wood is the most important issue. Once these parameters are known, other issues fall in place. The best way to determine these parameters is to take some samples of the wood to be machined and to try different kinds of milling operations on the samples such as rough cuts with large diameter tools and parallel finish cuts with different size of tools.

The next most critical issue is to find the minimum number of tool paths and the most appropriate ones that will achieve the desired shape and surface quality in minimum time. Less than optimum tool path strategies can run into extremely long milling times. For example, intuitively, one would think that parallel finishing with a very small diameter round ended tools (ball nose cutters) would lead to the most precise and smooth surface. While this may be true, the resulting milling times can be extremely long (literally days for a large model). Often, an equally smooth and precise surface can be achieved with a much larger diameter tool in much less time. The time that it will take to complete milling a scale model is, fortunately, easily obtained, because tool path generation software allows one to simulate a milling operation and to estimate the time it will take. Determining the most appropriate tool paths is one area where creativity is involved.
Perhaps the most challenging aspect of CNC milling is cutting fully round shapes with 3-axis technology. This involves deciding how to divide the three-dimensional computer model of the object to be cut into two or more models depending on the number of sides to be cut. If an appropriate origin for each milling operation is chosen, then when the stock is turned to expose another side to be cut, the milled surfaces will align precisely. More details on this operation follow in the case studies.

Further decisions regarding milling strategy are made after machining of the final model has already begun. We have, for example, occasionally decided to repeat all or part of a tool path with different parameters or after a slight readjustment of an improperly set origin. We have tried two different methods. We have actually learned to understand the basics of G-codes, allowing us to remove the parts of the code that did not need to be repeated and we have used a facility of the tool path software that allows us to repeat the tool path from a given percent of completion.

3. The case studies

We present two case studies of two completely different kinds of models whose machining has not been discussed in the literature to our knowledge.

The first is a large urban site model combining topography and buildings consisting of several city blocks and comprising mostly flat surfaces because the buildings are rectangular and the terrain is nearly flat. The second model is a curvilinear object that is fully round requiring using a 3-axis milling machine as a four-axis machine by turning the stock by 180 degrees to allow machining from two sides.

3.1. Urban site model

The urban site model represents the Liberty area in Toronto bounded by Dufferin Street in the west, Shaw Street in the east, the Gardiner Expressway to the south and King Street to the North (Figure 1). The corresponding digital model is shown in Figure 2. The scale model was machined at a scale of 1:1000 so that the length and width of the physical model was 109.5 x 67.6 cm (43.1 x 26.6 in.) with the tallest building being 7.6 cm (3 in.) high. This size fitted comfortably within the 127 x 127 cm (50 x 50 in.) of the work surface of the CNC router and within the 16.5 cm (6.5 inch) maximum clearance under the tool (limited by the height of the gantry which supports the spindle assembly). A base of 2.54 cm (1 in.) below the lowest elevation helps the visual appearance of the model and assists in clamping the model to the base during milling. The purpose of the urban site model was to allow insertion of alternate building proposals for a several blocks on the site. It was therefore planned to create a final version of the site model with the buildings on these blocks removed to allow insertion of new building proposals.
The three-dimensional computer model of the site was created by digitizing the contours on a detailed paper map of the Liberty area. An alternative, where accurate Geographic Information System (GIS) terrain data is available to 0.5 meter accuracy, is to export contour lines to AutoCAD format and then to import the contours into a 3D modelling package that is able to generate a surface model of the terrain from the contours. In the case of the Liberty model, the contours were used to generate a triangulated mesh in formZ. Street-side curbs were then modelled by Boolean subtraction from the terrain.

Figure 1. Aerial orthophoto of the Liberty area in Toronto (c. 1999)

Figure 2. Aerial perspective view of the digital site model as seen from the south
modelled by extrusion from a digital AutoCAD drawing of building footprints (such drawings can be exported from GIS data bases which most medium to large cities have). Building heights are generally not recorded in GIS data. For the Liberty model building heights were estimated from building photographs by photographing the buildings with an assistant holding a scale against the building. An alternate method is to use a range finder to calculate building heights by triangulation from the angle of laser beams directed to the top and bottom the building and a horizontal beam.

The origin was selected at the lower left corner of the top of the stock. In retrospect, as noted earlier, this meant that it was difficult to reset the Z value of the tool after a tool change because the lower left corner of the model was cut away. Fortunately the height of the tallest building could be used as a Z reference point.

The test model was cut from a rigid piece of pink insulation obtained by laminating together three layers of one-inch insulation with spray glue. Ideally, insulation should be used that is thick enough not to require lamination because laminations do show after milling and some delaminating tends to occur.

The first tool path strategy for cutting the test stock that was tried consisted of: 1) horizontal roughing with a 2.54 cm (1 in.) flat end mill stepping down 1.27 cm (1/2 in.); 2) two re-roughing tool paths with a 2.54 cm (1 in.) and a 1.27 cm (1/2 in.) flat end mill stepping down 0.953 cm (0.375 in.) and 0.318 cm (0.125 in.), respectively; 3) parallel finishing with a 0.953 cm (3/8 in.) ball mill; 4) pencil tracing with a 0.625 cm (1/4 in.) flat end mill. Horizontal roughing and re-roughing tool paths produce a stepped contour model of the object that is then smoothed with parallel finishing to produce the scalloped surfaces mentioned earlier. The final tool path, valley finishing, is generally carried out with a small diameter ball nose tool in order to carve out small radius corners. The urban model, however, has sharp rectangular corners. For that reason a flat end mill was used for pencil tracing as shown in Figure 3. The total machining time estimated for this tool path strategy was 979 minutes.
A second tool path strategy was then devised in which the horizontal re-roughing tool paths were removed because they largely repeat what the first roughing tool path has already done. Re-roughing only makes sense if a small diameter tool is used with smaller z increments in order to approximate more closely the final surface. A final pencil tracing tool path was added to get into small corners. With the second tool path strategy the total machining time was reduced to 835 minutes, in other words, not quite two working days. The revised tool path was tested on another piece of insulation but to save time, only a part of the model was cut by setting a boundary region in the tool path software.

For final machining in basswood the feeds and speeds had to be reduced to the values shown Table 1. Note that the cut speed was reduced further by up to 64% in certain critical areas by manual override. Images of both the test models and the final model are shown in Figures 4 and 5.

<table>
<thead>
<tr>
<th>Tool Cut Speed</th>
<th>Transfer Speed</th>
<th>RPM</th>
<th>Plunge Speed</th>
<th>Retract Speed</th>
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<tbody>
<tr>
<td>cm/min. (in./min.)</td>
<td>cm/min. (in./min.)</td>
<td>rpm</td>
<td>cm/min. (in./min.)</td>
<td>cm/min. (in./min.)</td>
</tr>
<tr>
<td>2.54 cm (1 in.) flat mill</td>
<td>190 (75)</td>
<td>305 (120)</td>
<td>12000</td>
<td>127 (50)</td>
</tr>
<tr>
<td>0.953 cm (3/8 in.) ball mill</td>
<td>178 (70)</td>
<td>305 (120)</td>
<td>12000</td>
<td>127 (50)</td>
</tr>
<tr>
<td>0.635 cm (1/4 in.) flat mill</td>
<td>101.6 (40)</td>
<td>305 (120)</td>
<td>12000</td>
<td>127 (50)</td>
</tr>
<tr>
<td>0.318 cm (1/8 in.) flat mill</td>
<td>25 (63.5)</td>
<td>305 (120)</td>
<td>12000</td>
<td>127 (50)</td>
</tr>
</tbody>
</table>

Table 1. Basswood: feeds and speeds

Figure 4. Completed test model of the Liberty site machined in rigid insulation.
3.2. Comparison with laser cut site models

A larger scale model at 1:500 for a portion of the urban site was required for a more detailed design investigation. This provided an opportunity to investigate another method of physical modelling; in this case, with a laser cutter. More manual work is required to create a three-dimensional model with a laser cutter than with a milling machine because the two-dimensional sheets that it cuts must then be manually assembled. Moreover, the three-dimensional site model cannot be used directly but must be sliced horizontally and the slices exported to individual two-dimensional CAD drawings for cutting in the laser cutter to create a stepped contour model. The buildings were “unfolded” in formZ and the unfolded outlines exported to AutoCAD where the cut lines and score lines were set to different colours so that the laser cutter could score and cut the appropriate lines. The building models were then folded and glued. A further complication is that a common bed size for laser cutters, 81.3 x 45.7 cm (32 x 18 in.) in our case, means that the site model has to be composed of tiles because the work surface of the CNC router is larger.

3.3. The Bridge Model

The purpose of this particular model was to test the capabilities of the 3-axis CNC router in a large, complex project with curvilinear surfaces requiring milling on more than one side. We wanted to push the limits of what was possible. The prospect of working with award-winning British architect Michael Stacey of Brookes Stacey Randall Architects, London (England) in producing a physical model of the firm’s stunning, curvilinear

Figure 5. Completed final model of the Liberty site machined in basswood
pre-cast, concrete bridge at Ballingdon in Suffolk proved to be an invaluable opportunity to test the machine, the interface software, and the tool path generation software and its operations. Figure 6 shows images of the real bridge soon after completion in 2003. The following account of this case study is written in a somewhat anecdotal form to convey the creative thinking that went on in parallel with the machining operations. What we were actually modelling in the following case study is the pre-cast concrete structure with its curving arches and elegant piers (The roadbed and sidewalks with railings were then poured on top or the structure on site).
We had hoped originally to make physical models of the individual pre-cast sections that make up the supporting structure. Due to contractual problems we were not able to obtain digital files for the pre-cast sections. Instead, we obtained the original 3D design model of the pre-cast structure in 3D Studio format (Figure 7). To this model we added blocks of solid material on each end representing stock material that would not be cut during the milling processes in order to provide a means to secure the model to the work surface and to simplify turning the model over. The 3D Studio file was scaled to the actual size (about 40 inches overall length at a scale of 1:33).

3.4 Test model 1
We decided to do a test cut in rigid insulation of the top, side A, before cutting the final model in wood. As in the case of the urban site model, the stock for test model 1 consisted of several 1.9 cm (3/4 in.) layers of rigid insulation laminated together with spray glue. For our initial tool path strategy we chose five passes: a horizontal rough cut with a 2.54 cm (1 in.) flat mill, a re-roughing cut with a 1.27 cm (1/2 in.) flat mill, horizontal finishing with a 1.27 cm (1/2 in.) ball mill (parallel, horizontal paths along the faces of near vertical surfaces), a parallel finishing cut with 0.635 cm (1/4 in.) ball mill and an edge tracing cut with a 0.318 cm (1/8 in.) ball mill to carve out the corners. The tool path software estimated this initial strategy to take 10 hours. A revised strategy where we increased the cutting speed (having found that rigid insulation can be cut very easily) and reduced the number of tool paths to three, and brought the total cutting time for side A down to five hours. For a large model such as the bridge we realized that we could eliminate the parallel finishing tool path with the 0.635 cm (1/4 in.) ball nose tool as well as the edge tracing tool path with the 0.318 cm (1/8 in.) diameter ball nose tool because there were no sharp corners in the model. We also experimented with different diameter tools and crossover ratios (crossover refers to the overlap of one tool path over the previous tool path).

We then turned the model over and began cutting side B. After milling side B we found that side A and side B were slightly out of alignment. Several variables, we reasoned, could affect alignment, among them the location and accuracy of the origin and resetting the origin after tool changes.

3.5 Test model 2
We were confident enough after milling in rigid insulation to proceed to a partial test cut in basswood, the material selected for the final model. To improve the accuracy of the alignment of sides A and B, we relocated the origin at one end of the stock as before but on the centreline. Thus the stock could be rotated about a plane of symmetry without shifting the
origin. For a more accurate method of aligning the tool with the origin we resorted, as mentioned earlier, to the use of the straightened nail with a sharp point to locate the x and y position of the origin. The vertical z position of the tool was then set using the method of just being able to slip a piece of paper between the stock and the bottom of the tool. We feel that it is imperative to take time and care in setting the origin and to become comfortable with starting and stopping the machine and changing tools.

We also went through the exercise of thinking through the clearances that would be needed by the tools and the spindle assembly. While side A did not present any interference problems because the maximum depth that had to be cut was only 2.54 cm (one in.), side B was more challenging. From the surface of the blocks of stock at the ends, the model plunged straight down for 9.53 cm (3.75 in.) as did the piers of the bridge. If we used a 7.62 cm (3 in.) cutter we would have had to lower the spindle assembly. That would have allowed us to cut the required depth but the spindle assembly would have struck the end pieces of the stock and the 2.54 cm (1 in.) diameter of the collet that holds the tool would have struck the stock at the ends. The solution was to order tools for each of the tool paths that were long enough for the 9.53 cm (3.75 in.) depth of the final cut and of constant diameter for that length.

As noted earlier we had no sources of information to draw on regarding appropriate speeds for various kinds of wood. Although we reduced all speeds by half from the values we used for machining rigid insulation, they still proved to be too fast, especially the plunge speeds. This assessment was based on machine vibration and roughness of cut. Before we started to machine the bridge model we had only machined small wooden objects where the impact of different tool path choices did not result in unmanageable total machining times. Moreover, the total machining time was excessive. We then decided to reduce the total machining time by using only the three tool paths used for the second test with rigid insulation but with the diameter of the finish tool path reduced to 0.953 cm (3/8 in.) from 1.27 cm (1/2 in.). Final feeds and speeds are listed in Table 2. Figures 8 and 9 show the wooden model being machined.

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Our final anecdotes do not relate directly to machining techniques but rather they underline the need, unlike other rapid prototyping technologies, for someone to be present at the machine for the entire duration of the machining operations and to be constantly alert with the stop button in...
hand in order to stop the machine in case there was a tool path error (e.g., cutting into the clamps that hold the stock or the spindle assembly striking the stock) or machine failures. One such error occurred when, after a tool change, we failed to raise the tool before allowing the tool to resume cutting by moving from the location beside the stock where we changed the tool, to the current cutting location. Before we could react, the tool had plunged through the stock, creating a deep gouge in the stock. Fortunately,
the material was soft, rigid insulation. After this event, we set a transfer plane in the tool path software that forces the tool to rise above this plane before moving horizontally to a new cutting position. We also moved the tool to the origin after a tool change. On another occasion disaster struck following the first tool change. Without warning the tool suddenly vibrated and then plunged into the wood stock. Each time we repeated the tool path the tool would plunge again into the wood at a location close to the previous hole. The problem only appeared when the spindle was rotating and the tool was in motion. Working with the vendor we went through a detailed process of narrowing down the possible cause of the mishap. Eventually the z-axis servo motor and associated controller were identified as the problem. The unit was then shipped to the vendor and promptly replaced.

4. Conclusions

We have given an overview of the process of creating wooden scale models with 3-axis CNC milling technology with the aid of two case study descriptions of two very different kinds of scale models. One of these is a model integrating terrain and buildings in a site model at 1:1000 covering many city blocks. The other was a scale model at 1:33 of award-winning Ballingdon Bridge in Suffolk County, England which required using the 3-axis milling machine as a 4-axis machine by milling from both the top and the bottom of the bridge.

We provided some insight into the process used for determining tool path strategy, feeds and speeds and related parameters. When exploring new procedures, we found it very important that the two machine operators talk to each other, to think out loud what each one was doing and thinking, so that we could check each other, to make sure that we were not forgetting something and that there was no flaw in reasoning. Errors or forgetfulness can be disastrous to the stock and the machine. We highly recommend testing tool path strategies with stock consisting of rigid insulation preferably of the required thickness rather than laminated together from thinner sheets. One can mill rigid insulation at the highest speed the milling machine permits thus minimizing testing time. Rigid insulation is also very forgiving of mistakes. The quality of surface achievable with rigid insulation is very good. Thus we recommend this material for study models where speed of milling and low cost of material are important.

Different procedures are required for different types of projects: There is no one single approach to milling; each scale model needs to be evaluated on an individual basis, based on material and the shape of the surfaces of the model. We discovered, for example, that the integrated site model, because it consists of relatively flat or vertical surfaces can be milled with only one roughing tool path followed immediately by a single parallel finish cut because little material remained for the parallel finish tool path. The
curvilinear bridge model by contrast required no further tool paths after the parallel finish tool path but the integrated site model required pencil tracing and valley finishing to clean out the 90-degree corners which do not exist in the bridge model. The degree of smoothness of the final surface finish depends on personal judgment but depends on the height of scallops left between adjacent tool paths that can be calculated from tool radius and tool path overlap.

Different materials also require different feeds, speeds and related parameters. This requires experimentation with different samples of materials and different types tool paths. Careful documentation of the results can save much time for future users. To this end we provide values of the tool sizes, feeds, speeds and major parameters for the case study examples.

Among the benefits of using CNC routers for creating scale models over other technologies used for rapid prototyping are the following: The relatively low cost of material such as wood and very cheap testing material such as rigid insulation. The robustness of the CNC milling machines (although we had the unfortunate experience of a servo motor failing this was an exception possibly caused by pushing the machine beyond recommended speed limits). Larger scale models can be produced with CNC routers than with comparably priced additive rapid prototyping machines or laser cutters. Among the disadvantages of CNC milling is the fact that CNC milling is more complex than other technologies used for rapid prototyping. Another disadvantage is that for large models with small details requiring small diameter tools one should be prepared for long cutting times. This would not be problematic except for the requirement that a machine operator be present at all times so that the machine can be stopped immediately if there is a problem.

With the regard to the place of CNC milling of scale models in the architectural design process, we have found that physical scale models with curved surfaces provide a critical understanding of the shape of the surfaces that cannot be attained with rendered three-dimensional virtual models. According to Michael Stacey, CNC models would be very useful as a refinement tool early in the design process [11]. In the case of the bridge model we did not really understand the nature of the undercut over the piers until the physical model had been machined. In the case of the integrated site model, other types of models such as stepped contour models with cardboard buildings are possible to achieve the same understanding of a design context. The integrated milled models can save time, however, over manually cutting individual buildings. In addition the milled model in wood is visually very appealing. Well finished, CNC models are therefore ideal as final presentation models, especially for use in exhibitions. Figure 10 shows the Ballingdon Bridge model in a Fabrication Exhibition in London.
While it was not our intention to write about rapid prototyping, it should be mentioned that machining scale models can be a step in the design of the fabrication process of the full-sized object. For example, in the case of the bridge, there is a stage during which the actual form work for the pre-cast section is designed. CNC milling could have been used to model the individual pre-cast sections and the nature of the joints. Moreover, while the curvilinear concrete forms for Ballington Bridge were built manually out of plywood by highly skilled but elderly craftsmen, in the future, CNC milling might be used to create the forms because there seem to be few apprentices around to take the place of the current craftsmen. Indeed this has already been done. Curvilinear concrete forms have been milled from rigid foam [10]. Milling full-scale formwork is just one possible application of CNC milling on the route from scale model to fabrication. Creating molds for casting in metal or for injection molding in plastic provides other possibilities that are now common and which extend the range of physical scale models to models of architectural components that architects can design with the aid of CNC milling technology. Moving from
the minds eye to physical scale models remains an important component of
design in which 3-axis CNC milling provides unique opportunities that we
are just beginning to explore.

Acknowledgements
The authors wish to thank Michael Stacey and Brookes Stacey Randall
Architects for images and geometry files of Ballingdon Bridge.

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