Rapid Prototyping and Rapid Manufacturing at Foster + Partners

OVER THE LAST 15 YEARS, RAPID PROTOTYPING HAS BEEN AN INTEGRAL PART OF THE DESIGN PROCESS IN THE CAR AND AEROSPACE INDUSTRY (BRAD FOX 2006). RECENTLY THE ARCHITECTURE PROFESSION HAS STARTED TO USE THESE TECHNIQUES IN ITS DESIGN PROCESS (GREG CORKE 2006), AND SOME ARCHITECTURE SCHOOLS HAVE BEGUN EXPERIMENTING WITH THESE TECHNOLOGIES.

FOSTER + PARTNERS HAVE BEEN ONE OF THE FIRST ARCHITECTURE PRACTICES TO FULLY INTEGRATE RAPID PROTOTYPING WITHIN ITS DESIGN PROCESS. THE TECHNOLOGY WAS INITIALLY SEEN AS A SKETCH MODEL MAKING TOOL IN THE EARLY STAGES OF THE DESIGN, IN PARTICULAR FOR PROJECTS WITH COMPLICATED GEOMETRIES. IT SURPASSED THIS PURPOSE WITHIN A YEAR AND IT IS NOW SEEN AN ESSENTIAL DESIGN TOOL FOR MANY PROJECTS AND IN MANY PROJECT STAGES. THE OFFICE'S RAPID PROTOTYPING DEPARTMENT NOW PRODUCES ABOUT 3500 MODELS A YEAR.

BESIDES, OR PERHAPS BECAUSE OF, RAPID PROTOTYPING, FOSTER + PARTNERS HAVE STARTED TO EXPERIMENT WITH RAPID MANUFACTURING. THIS FIRST WAS DONE THROUGH THE DESIGN AND MANUFACTURE OF A CHRISTMAS TREE FOR THE CHARITY ORGANISATION SAVE THE CHILDREN.
1 Introduction

Rapid prototyping is an important part of Foster + Partners design process. The making of physical study models has always played an important role in the development of an architectural design in the office. Architects explore conceptual form, layout and detailing concepts through the use of sketch design models. Rapid prototyping has been used as a technique in the office for many years; however, these rapid prototyped models were done only for presentation models, done under the supervision of the Modelshop and the Specialist Modelling Group (SMG), and done for projects involving forms or structures so complex that the model could not have been realized in any other way. The SMG is an internal research and development consultancy with the Foster + Partners architectural practice. The SMG’s expertise encompasses architecture, art, math and geometry, environmental analysis, computer programming and computation, urban planning, and rapid prototyping and rapid manufacturing (Peters and De Kestelier 2006).

With the introduction of in-house rapid prototyping machines, the architectural design process within the office has changed. This paper will outline the introduction and development of rapid prototyping technology at Foster + Partners in four stages: the trial of rapid prototyping technologies, retroactive modelling and trial projects, first projects to use 3D printing, and the adoption of 3D printing as a standard design tool. The paper will then outline some early explorations with rapid manufacturing using rapid prototyping technologies and discuss some research into new rapid manufacturing processes.

2 Trial of Rapid Prototyping Technologies

Rapid prototyping as an in-house process was brought to Foster + Partners through the Yacht Plus Boat Fleet project in May of 2005. It was felt that in order to model the hull geometry of the boat, one would require accuracy not achievable by an architectural assistant simply carving foam by hand in the sketch model shop. Before committing to any one technology, Foster + Partners brought in two different, relatively inexpensive, rapid prototyping machines to test in an architectural design environment: The ZCorporation Spectrum 510 3D Printer, which produces parts using glue and plaster-like powder, and a Stratasys Dimension Fused Deposition Modelling (FDM) machine, which produces parts in nylon plastic.

The 3D printer quickly became the favourite and was soon used on other projects. The 3D printer could produce models fast enough for the architectural design cycle, with a maximum build time of about 16 hours and an average build time of about 4 or 5 hours. It could also manage any complexity because it is a self-supporting process. The resolution was quite good at about 0.5mm, the print bed size was quite large at 250mm x 350mm x 200 mm, and multiple parts could be printed at one time. The FDM machine had much longer build times, up to 120 hours, and regularly took more than 24 hours for a print. Rapid prototype parts were not self-supporting and required the addition of support structure. This support structure required removal afterwards. This was supposed to be easy procedure; however, it proved to be anything but. The resolution of the machine was similar to the 3D printer, but the build size was smaller and only one part could be printed at a time. An advantage the FDM machine had over the 3D printer was in the strength of the parts produced.

The Boat Fleet project was the only live project using the 3D printer as part of its design process during this stage, though digital files from previous projects were used to test both printing technologies. The rapid prototyping machines were not getting much use at this point, with only one or two prints a week on average. With the Boat Fleet project it became clear that through rapid prototyping different physical models could be produced out of one digital file. The Boat Fleet project was, as shown in figure 1, printed in several different ways: “above waterline” models, sectional models, hull models and models of particular details. The boat was also printed at different scales: 1/100 and 1/50. The 1/50 model was larger then the maximum available build size of the 3D printer, therefore had to be printed in 3 sections which were then glued together.
3 Retroactive Modelling and Trial Projects

In order to provide proof of concept to company directors of this new technology and justify the purchase of a new machine, the SMG used 3D printer to produce models of many different projects, at many different scales, demonstrating different design intentions. This opportunity was also used to produce models of previous projects involving complex geometry. 3D printing provided the opportunity for modelling projects that had been too geometrically complex to model by hand. This proved to be a rewarding process, especially for those designers who work on complex and/or computationally developed projects. Designs that had previously been impossible to model could now easily and quickly be 3D printed. These projects, which previously could only be viewed on a screen, or on a paper print, could now be realized in three dimensions. These prints would always initiate a conversation about some unseen aspect of the project.

A computer program was written by the SMG that produced mathematical surfaces. Another series of custom digital tools could populate these surfaces with generated components. The forms created using these processes used simple algorithms, but produced complex forms. These forms were used to test the limits of complexity the 3D printer could handle. As long as the digital file was not corrupt, it would print. There was no limit to the complexity.

After these tests, Foster + Partners decided to purchase a 3D printer and integrate it into its design processes. At this point, even though 3D printing was not available to general projects, we were printing about five prints a week.
The formal introduction of 3D printing to the office began with a SMG lecture on rapid prototyping and the display of the best 3D printed models. Several project teams began to use 3D printing as a way to develop design options; these projects were often projects involving the SMG. 3D printing was a process that was at first looked at sceptically, then with amazement, soon became a standard part of the design process.

An extremely important aspect of the 3D printing process was that it was fast enough for the architectural design cycle. A design could be discussed in a review, changes could be updated in the CAD model, an STL file could be made from the 3D digital model, the file would be set to print overnight, and a new 3D printed model could be placed on the table for a design review the next day.

The SMG began to develop special digital tools and a series of standard techniques for 3D printing. It was necessary that CAD models were modelled in solids before being exported from Microstation into STL format. In order to print the same model at different scales, a strategy of using placeholder shapes and centrelines were used – these placeholder entities could then be thickened using the custom digital tools such as TubeMan and Thicken. A minimum thickness for structure, skin, and model bases was established. Techniques and workflow processes were developed to produce the best possible models without taking too much time.

The ZCorp Spectrum 510, the in-house 3D printer, is one of the few rapid prototyping machines on the market that can produce full colour prints; however, its colour capability was not the reason it was chosen as the rapid prototyping machine for the office. The
colour capabilities were later found to be a useful tool to display environmental analysis in three dimensions. Special computer programs were written to translate the environmental analysis data back into the CAD environment. Once the data was back in CAD, the geometric entities could then be thickened to solids and printed.

At this point the 3D printer was printing about ten prints a week. This was to be full capacity for one printer at that time. There were no dedicated personnel for the 3D printer; all work was undertaken by members of the SMG and by the individual architects using the process. This system did not work very well, the machine was not being maintained properly, and there was no chain of responsibility.

5 The Adoption of 3D Printing as a Standard Design Tool

Rapid prototyping has now been adopted generally by project teams in the office as a potential design tool. Many teams now use the 3D printer as an integral part of their design process. 3D prints are done at various stages in a project’s design: from early conceptual studies, to detail development, even to presentation models. Because CAD modelling for the 3D printer demands careful modelling, the rapid prototyping process has helped raise the quality of 3D CAD models in the office generally.

3D printing starts with a 3D digital CAD model, which is a representation of the design. Often this digital representation is only considered in terms of visual points: walls have no thickness, unrealistic cantilevers and structure does not node out. When digital models are 3D printed, the model is suddenly submitted to gravity. This informs architects about the feasibility of their designs as structural principles still apply. This also leads architects and
designers to do better CAD modelling: columns must meet the ground and the roof, floor planes must line up, and surface geometry must be clean in order to be thickened.

A design is often communicated through a series of plans, sections, perspectives, models, and animations. In a design process, the 3D digital model often lacks the details that exist in the rendered visualisations and plans. All of these representations are often not synchronised. With 3D printing it is much easier to keep everything synchronised as every representation is derived from the same digital model.

3D printing is relatively fast process. It is definitely fast when compared to traditional model making, which is a slow and laborious process. Even compared to sketch modelling, which is much quicker, 3D printing is still faster and gives you increased accuracy and precision. 3D printing has allowed for smaller project teams to produce more work faster. Instead of spending weeks in the sketch modelling shop, designers can be working up new designs in CAD, and outputting sketch models on the 3D printer. In this sense, the sketch model making process, in some cases, has become automated. When combined with the custom generative tools created by the SMG, teams can output 3D models of very complex geometries, and highly detailed solutions at very early design stages. However, even if the geometry isn’t that complex, the process has still be used simply because it is faster and more efficient that building the model any other way.

Foster + Partners has a staff of professional model makers. They were very sceptical of the introduction of 3D printing as an in-house process. They saw this as a direct threat to their positions. The need for traditional model making has not decreased with the introduction of 3D printing technology; if anything, it has created more work for the Model shop through in increased emphasis on the importance of the physical model for communicating the design, and by creating a need for more adventurous and detailed final models.

Foster + Partners now has a dedicated room and dedicated personnel for rapid prototyping. Because of the level of demand for 3D printing services, there has been the purchase of an additional printer. There has also been an increased awareness of other types of rapid prototyping technologies. Many more models are being sent out for Stereolithography (SLA) or Selective Laser Sintering (SLS) as these processes are more suitable to produce more robust presentation models. Through introduction of these high end rapid prototyping technologies, we have seen a shift in perception and attitude from our professional model shop. Due to higher complexity and increasing tighter deadlines, high end rapid prototyping often becomes the only way to produce a physical model. Compared to traditional models, rapid prototyped models often lack in diversity of materials, for example, woods, metal, perspex. On the other hand, traditional models often take weeks to produce, this in contrast with rapid prototyping models, which normally only take days. In this way, design changes are possible up to the last moment and in a design driven environment this is crucial.

One of the most interesting ways to use rapid prototyping in an architectural environment is when it is combined with traditional model making. A good example of this is shown in figure eight. this is a model of Faustino Winery where SLA (roof structure), SLS (factory equipment), laser cutting (walls and floors), 3-axis CNC routing (terrain) and hand modelling (assembly) have been used side by side. Each of these technologies has their own inherent weaknesses and strengths, for the Faustino model, each of these technologies has been used to its full potential.

6 Beyond Measure

Foster + Partners Specialist Modelling Group (SMG) was invited to participate in the show Beyond Measure: Conversations Across Art and Science at the Kettle’s Yard Gallery in Cambridge, United Kingdom. This show, curated by Barry Phipps, explores how geometry is used by artists and scientists – among many others – as a means to understand, explain, and order the world around us. The SMG collaborated with the artist John Pickering to create fourteen large 3D print models and one slide show of images. These models and images were based on the mathematical concept of the inversion principle, which is the concept that John Pickering has based much of his work on. The inversion studies were de-
developed during a series of experimental workshops. There was no formal brief for the project, which allowed the team to be guided by the surprise and delight of discovery. The SMG used this project to push forward its research into mathematical surfaces, extremely complex and data intensive structures, and the use of colour in rapid prototyping models. The mathematically derived surfaces were populated with adaptive architectural components and structure, and the inversion transformations were mapped by colour coding. Three examples of the 15 produced for the exhibit are shown in figure nine.

7 Experiments in Rapid Manufacturing

In the fall of 2006, Foster + Partners participated in the Festival of Trees, an annual charity event put on by Save the Children. The SMG was key part of the project team and chose to use this project as an opportunity to research the manufacturing capabilities of rapid prototyping technologies. The overall form of the Foster + Partners tree, called the Tree of Reflections, was that of a cone, the ideal form for a Christmas tree. The leaf geometry was generated by a custom computer program. This generative script allowed parameters to be easily changed to suit different manufacturing conditions. The tree was illuminated from within by a high-power LED light. This reflected out through a reflecting cone. The reflecting cone was manufactured with the assistance of Dr. Rupert Soar at Loughborough University, and was then electroplated in silver by Morganic Metal. This reflecting cone sat underneath the leaves and leaf structure, which were manufactured by EOS systems in Germany using the SLS process. As the tree was nearly two metres in height it was necessary to manufacture it in components. It was also crucial that these components could be efficiently nested within the rapid prototyping machine’s build chamber. Figure ten and eleven show the Tree of Reflections.

Through the design and fabrication of the Tree of Reflections project we have had a first
feel of what it could be like to design and direct layer manufacture the final product. A new set of construction and fabrication parameters have to be taken into account. The known solution space that is dictated by current fabrication, construction and assembly technology is no longer valid.

Through rapid prototyping technology, architects can start to experiment with rapid manufacturing, this might eventually shift not only fundamentally the way we construct buildings but also the way we design them. Through rapid prototyping a larger not yet explored application of layered manufacturing in architecture can be researched.

8 Conclusion

Foster + Partners has adopted rapid prototyping as a key component of its design process. 3D printing has become an essential part of the design development of many projects. The demand for 3D printing has led to the establishment of an in-house rapid prototyping facility with dedicated personnel. This facility now produces approximately 3500 rapid prototype models a year.

Rapid prototyping has given the office the ability to quickly produce sketch models from digital CAD models. Complex structures that previously could only be studied using 2D prints, can now be studied in three dimensions. Many types of models are produced using this process: structure, circulation, form, facade, detail, landscape, etc. This technology allows smaller teams to produce more, as team members do not have to produce physical models and can concentrate on design and only produce a 3D CAD model. The office’s use of rapid prototyping has pushed forward research in the areas of the solid modelling, the development of custom digital tools (for example, to automate thickening of elements), the integration of analysis results into the CAD environment, STL mesh editing, mathematical surfaces, and investigations into new rapid prototyping and rapid manufacturing technologies.

The use of rapid prototyping has meant an increase in the use of 3D CAD and in the quality of those models. The use of a single digital 3D CAD model to take drawings, renderings, and models from has increased the synchronisation of the design across these mediums, especially at early design stages. Different types of analysis can be visualised using the colour capabilities of the rapid prototyping machines. The use of rapid prototyping closes the loop in a digital design process in its recognition that key design decisions are still made from the study of physical models (Whitehead 2003).

The widespread use of 3D printing in the office has led to an increase in the use of other types of rapid prototyping. Stereolithography (SLA) and Selective Laser Sintering (SLS) technologies are now increasingly used not only for presentation models, but also to produce more robust study models. The use of rapid prototyping by design teams has also led to an increased interest in the potentials of rapid manufacturing. The office has experimented with using rapid prototyping technologies for rapid manufacturing in the Save the Children Tree of Reflections project. There is huge potential for growth in this area of the architecture design process.

9 References


