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FROM PROTOTYPE TO PRODUCTION: USING PLASTIC 3D PRINTED PARTS IN FURNITURE

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1. Introduction

The choice of materials available to industrial designers in the development of new object solutions is only restricted by contextual factors such as; environment of use, manufacturing process and availability of resources. In theory this proposition is correct, however, in the context of objects designed for *small batch production*, the economies of scale are such that the selection of materials and processes reduces significantly. The recent emergence of additive manufacturing (AM) is providing industrial designers the opportunity to consider using materials previously not possible, such as plastic, a material synonymous with mass production. The issue with AM is that only the premium AM processes are capable of producing parts that are structurally sound and capable of high load bearing capacity, inferior processes such as Fused Deposition Modelling (FDM) have not been sufficiently tested in final production load bearing situations.

FDM is currently employed by designers to create production ready objects with minimal or no load bearing requirements. If FDM use could successfully expand into situations where structural integrity is mandatory the impact for industrial designers developing objects for small batch production would be significant.

The approach to addressing this issue is practice-based. The investigation is conducted by the author and the focus is on development of tangible objects that contribute towards a practical understanding of the operational limits of FDM parts and how they might be incorporated into production ready objects. The typology central to this study is domestic furniture, a domain familiar to design but as yet an area where limited FDM exploration has occurred.

The outcomes show that FDM parts are capable of withstanding loads, but are required to be designed to maximise inherent characteristics, such as the material grain which is governed by the build direction. Previous examples of commercialised FDM objects have shown that audiences have not rejected the slightly imperfect surface finish that FDM produces, similarly this study uses raw (unfinished) parts and has exploited the grain-like effect that is an inherent part of the FDM process.

2. State of the art review

Making objects is a significant contributor to export, innovation and productivity growth, and a reason why it is still of vital importance to both advanced and developing economies [Manyika et al. 2012]. The sector however is evolving, the once dominant model of manufacturing that originated in the mid 20th century that consisted of stand-alone workstations where machines were controlled by humans and work passed from one workstation to the next [Tassey 2014] is being supplanted by very different models. Significantly this shift is not restricted to large scale manufacturing, this change is being felt across the spectrum of object making. Additive manufacturing (AM) is part of the cutting edge of emerging technologies in manufacturing along with other elements such as; automation, robotics, advanced design and the internet of things. AM, also referred to as 3D printing, is unique in the manner it creates parts by depositing material layer-by-layer. This is a radical shift away from traditional methods of material subtracting, forming and joining [Conner et al. 2014]. Referred to as the third industrial revolution [Anderson 2012], [Markillie 2012], AM was first used as a tool to construct prototypes direct from a digital CAD model. This resulted in a streamlining of the product development process reducing time and costs. There is a diverse range of AM technologies that includes; material extrusion, powder bed fusion, binder jetting, material jetting, vat photo-polymerization, directed energy deposition and sheet lamination [Conner et al. 2014][1]. This diversification has been accompanied by an improvement in material selection, print, or build resolution and structural integrity. From product models, samples and test pieces, the fastest growing application for AM is the manufacture of parts for final products [Wohlers and Caffrey 2013] Impact on the production of real parts is across the product spectrum, initially AM was limited to premium manufacturing sectors [Petrovic et al. 2011], such as the aerospace [Edwards 2015], biomedicine [Adamson 2010], [Wohlers and Caffrey 2013] and high performance automotive [Halterman 2014], however, examples of AM parts are now evident in mainstream product segments such as optical and sunglass frames [Battistel 2012] and sports footwear [Zaleski 2015].

All the examples mentioned above use premium AM processes such as Selective Laser Sintering (SLS) and Direct Metal Laser Sintering (DMLS). These processes are used to create parts using polymers and metals and their most significant attribute is the ability to print parts with excellent structural integrity, this technology is highly sophisticated and more expensive than CNC machining centres [Wohlers and Caffrey 2013]. Injection moulding is a technology most suited to mass volume manufacturers, AM technology such as SLS and DLMS has been shown to be commercially feasible for applications of low to medium volume producers [Atzeni and Salmi 2012] or high value added producers such as in the biomedical and aerospace industries [Petrovic et al. 2011]. By reviewing the opposite end of the AM spectrum to where SLS and DMLS are located, it is the FDM process that dominates low cost 3D printers (livescience.com, dhubs.com).

FDM is a process where a small thread of plastic is fused together to form layers which are then built on, layer upon layer. This straight forward process has resulted in FDM machines becoming widely developed, with desktop versions readily available and costs reducing to being no more expensive than a desktop computer. FDM parts are used extensively for prototyping and appearance models, German automotive company BMW has gone one step further and is using FDM as a means to construct hand tools that assist production line operators in assembly and testing [Stratasys 2013] and 3D printer manufacturer Luzlbot has reached the one million mark in the production of a spare part. of small plastic components for 3d Printers [Objects 2016].

The simplicity of the extrusion process utilised as the material delivery system in the FDM process has encouraged widespread experimentation into new materials, although rigid plastics such as ABS, Polycarbonate, Nylon and Polystyrene remain the most common. FDM has afforded designers an opportunity to design forms and structures in plastic that previously would not have been possible, as plastic was a material commonly used by large scale manufactures using technologies such as injection moulding[2]. One remaining restriction is size. Large FDM machines are available and examples of large printed objects include a concrete house [Chang 2015], the body of a sports car [Kirkland 2014] and even a one piece chair [Sendin 2012], see Figure 1. These are extreme applications of the technology that is not reflected in the broader FDM community where the size of most machines print much smaller parts.

[1] Other terminology includes fused deposition modelling, solid ground curing, laminated object manufacturing and Selective Laser Sintering

[2] Other processes such as vacuum forming and rotational moulding still require tooling and specific machinery

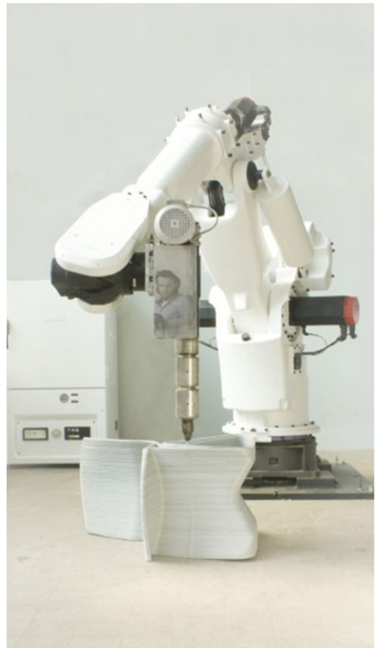

Figure 1. Dirk Vander Kooij, Domus Exhibition, Milan, 2012. Source: http://www.3ders.org/articles/20120501-3d-printing-robot-produces-satelite-lamp-from-recycled-cd-cases.html

Furniture that is manufactured in moulded plastic requires resources that support the funding and construction of tooling and the ability to access specialised machinery. The result is a field dominated by plastic furniture companies that can resource projects other small furniture manufacturers or designer-makers find challenging [Walden et al 2015]. Two examples include the Air Chair designed by Jasper Morrison which is constructed using gas assisted injection moulding technology and polypropylene garden furniture that necessitates tooling capable of producing hundreds of thousands of units. These two examples demonstrate that at both the high and low ends of the market, plastic moulded furniture necessitates a context that ensures a return on investment, either a premium is charged as in the case of the Morrison Air Chair, or, hundreds of thousands of chairs are manufactured and sold as is the case of the polypropylene garden chair.

Both these scenarios would be prohibitive to small furniture manufacturers or designer makers, even rotational moulding, which is another plastic processing method requiring less upfront expenditure than injection moulding is a significant barrier. There are other ways to integrate rigid plastic in furniture design, a popular method is to use plastic in sheet form and construct the furniture using conventional fabrication techniques, see Figure 2 and 3, this approach however, limits the possibility for complex geometric forms.

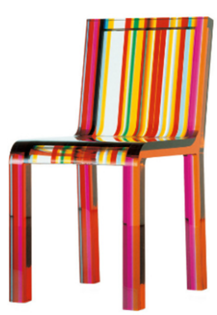

Figure 2. Rainbow Chair by Patrick Norguet for Cappellini, 2000. Source: http://cappellini.it/en/products/rainbow-chair

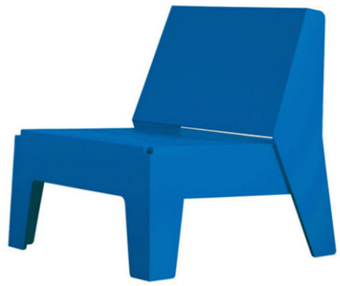

Figure 3. Butter Seat by Nick Karlovasitis and Sarah Gibson for DesignByThem, 2011. Source: http://www.designbythem.com/products/butter-seat

Synthetic plastic is a relatively new discovery, furniture on the other hand has a long history and although furniture has been constructed using almost every material known to man the most common is timber. In the context of small furniture manufacturers and designer-makers, the ease and flexibility in fabrication ensures timber continues to be a popular material choice. The ubiquitous nature of plastic in contemporary society is not reflected in the use of plastic in handcrafted or limited batch production furniture. Plastic emerged in the 19th century as a replacement for semi-precious materials such as ivory, mother of pearl, marble and tortoise shell [Catterall 1990]. Interestingly these materials were commonly used together with timber in the design and construction of a wide variety of objects including furniture [Payne 1985], [Lucie-Smith 1979], [Hinchman 2009]. But as plastics developed beyond their role as a material substitute, their use in combination with timber furniture did not. AM has provided for the opportunity to create hybrid objects where a combination of materials is used, examples include; a smart phone case made from a rigid plastic component and a knitted textile component [Artis 2015], a joining mechanism for timber legs in a table design [Maeda and Minale 2014]and a wood and plastic take-away cutlery set [Randi 2015]. These examples use the SLS process, which produce structurally and physically superior parts to FDM. The application of an FDM rigid plastic part as a functional element in a handcrafted timber product was identified as an opportunity to explore the potential for renewing this lost partnership between timber and other materials in furniture design.

The various options within furniture must be carefully considered as furniture can range in size and complexity from large wall storage systems to small foot stools. The project is developed within the small manufacturer or design-maker context and therefore the type of furniture will need to consider the size restriction that are imposed by conventional FDM machines. The side table emerged as a typology that satisfied the constraints and the specified context. Side tables are designed to hold artefacts such as bedside lights, books, alarm clocks, photographs etc. They are a small furniture item that reference the archetypical furniture piece; the table. Existing contemporary examples are not limited by any specific material or manufacturing process, see Figures 4, 5, 6 and 7.

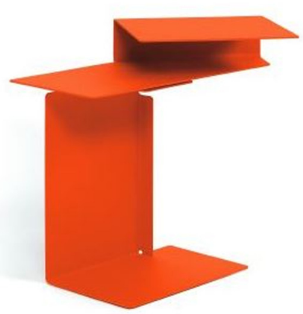

Figure 4. Diana by Konstantin Grcic for ClassiCon, 2002. Source: http://konstantin-grcic.com/projects/diana-a-f/

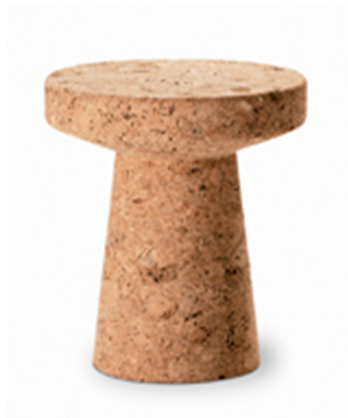

Figure 5. Cork Family by Jasper Morrison for Vitra, 2004. Source: http://www.jaspermorrison.com/html/50062475.html

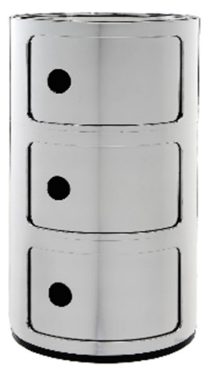

Figure 6. Componibili by Anna Castelli Ferrieri for Kartell, 1969. Source: http://kartellstorela.com/shop/componibili/

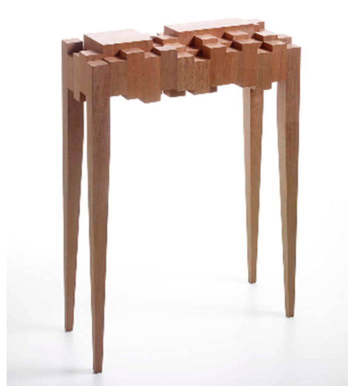

Figure 7. Blk, by author, Self Production, 2013, photo by Dieu Tan, property of author

3. Method

Complete understanding can be achieved through making, which is different to the knowledge a medical doctor may have about the human body or a motorbike mechanic may have about engines [Crawford

2009]. Making also produces proprietary knowledge which is attained through learning by doing [Fingleton 1999], making produces a type of knowledge that can only be accessed through the physical interaction with material, it precipitates ideas [Dobson 2013] and discoveries. The process of making is challenged by the tension that exists between the abstract idea inside the maker's mind and the physicality of materiality. Managing this tension in the context of an actual object confronts the maker in real terms, materiality is an arbitrator of truth and honesty. The rationale for undertaking this investigation through practitioner action is appropriate because the primary investigator engages with making as a way to access knowledge and understanding, which as part of the iterative design process, continually informs the dialogue that is established between investigator and object.

A side table requires a horizontal working surface and a leg/s to suspend the horizontal surface above the ground. Formulation of the project had previously determined that both timber and plastic would need to be incorporated into the design of the side table, and that the FDM component needed to be load bearing. To test FDM capacity it was decided that the legs should be 3D printed. Due to the maximum build dimensions of the FDM machines available for this study, printed parts could not be higher than 240mm. This restriction informed a design for the side table that utilised multiple short legs. Designs using short legs were investigated initially through 2D sketches. Numerous issues were considered, firstly, it was decided not to print the legs in solid material, this may have guaranteed structural integrity but would be a significant waste of material, unnecessarily expensive and make the build time exceedingly long. The first leg was designed as a hollow form with a 3mm wall section, 2.0mm wall section on the cross rib and 3mm wall section on the screw boss detail. The parts would be printed vertically, this ensured the layers would run perpendicular to the axis which would aid structural integrity of the part when placed under load.

4. Results

The first design was printed, it was dropped multiple times onto concrete flooring and then the part was placed under a static load, with a 3mm wall section it was structurally sound. A second design was created that incorporated a reduction of the main wall section to 2.5mm, the cross ribs and fixing detail remained unchanged. This second design was printed and also survived the rudimentary structural tests. Rather than continue testing one leg at a time, the next stage involved producing a full scale test prototype. Four legs were, a timber body was made and the parts assembled together. To push the testing a little further, the prototype was sat on by the author, an eighty kilogram static load. Surviving this test the focus now turned to the actual form of the timber component and legs.

Conventional manufacturing processes favoured (rewarded) repetition, and most legs used in furniture would hence use multiples of the same design. One of the unique features of the FDM process and AM more broadly is the ability to print different parts without being penalised. This opportunity to design different legs all following a predetermined theme was implemented. A number of themes were tested including designs reminiscent of traditional turned wooden legs. It was identified that the solution was not in forms derived from rotated revolutions, instead, a more complex geometry would exploit the capacity for free-form construction, another feature of the AM technology.

To contrast with the complex geometry of the river stone inspired legs, the timber body would adopt a somber and restrained design; straight sides, single radius corners and simple geometric form. Solid timber, as opposed to veneered or reconstituted timber, is synonymous with hand crafted objects and would contrast with the synthetic material used in the legs. Following material selection and acquisition the timber was carefully prepared and crafted into the desired forms. To accentuate the visual and tactile quality of solid timber it was worked and finished in accordance with standard wood working practice.

5. Conclusion

The side tables, see Figure 8 and Figure 9, demonstrate that FDM parts can be integrated into real life applications. The structural integrity is achieved by specifying a larger wall thickness than what would be used in an injection moulded part and by incorporating full length support ribs. The legs are printed with the layers positioned horizontally to maximise strength of the part when placed under load.

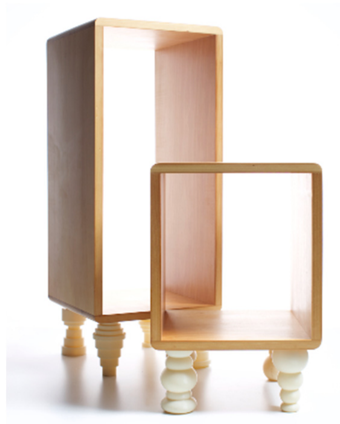

Figure 8. Mnd side table by author, 2015, photo by Dieu Tan, property of author

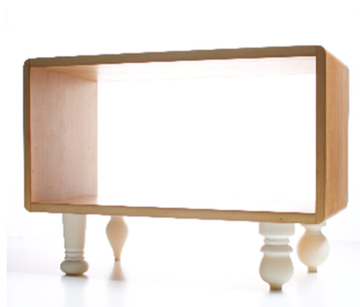

Figure 9. Mnd side table by author, 2015, photo by Dieu Tan, property of author

The aesthetics of the FDM part with the exposed layers of plastic and the various print imperfections contrasts with the precise and smooth finish of the timber part. The FDM part remains on display and is not hidden behind a facade or masked by a treatment such as painting. Plastic in furniture design has been widely utilised but incorporating FDM parts presents another possibility particularly useful for small furniture manufacturers and designer-makers and the flexibility of FDM part design allows for easy integration with other materials.

6. Further research

The structural integrity of FDM parts has been validated, however, destructive testing was not conducted which would have provided conclusive evidence regarding wall section, cross rib configuration and potential weak or fail points. Destructive testing would allow for a better understanding of the FDM part and its possible applications in other furniture objects that are more structurally demanding such as dining tables and chairs.

The side table succeeds in integrating the hand made with the machine made, however, the FDM part is physically much smaller creating an unbalanced visual result. An opportunity exists to investigate how a more aggressive or balanced integration between these two material, might enable a better understanding. Additionally, the timber component, although handmade, could very well have been made entirely by machine, another research enquiry could be established to investigate making the distinction between machine and hand, more explicit.

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