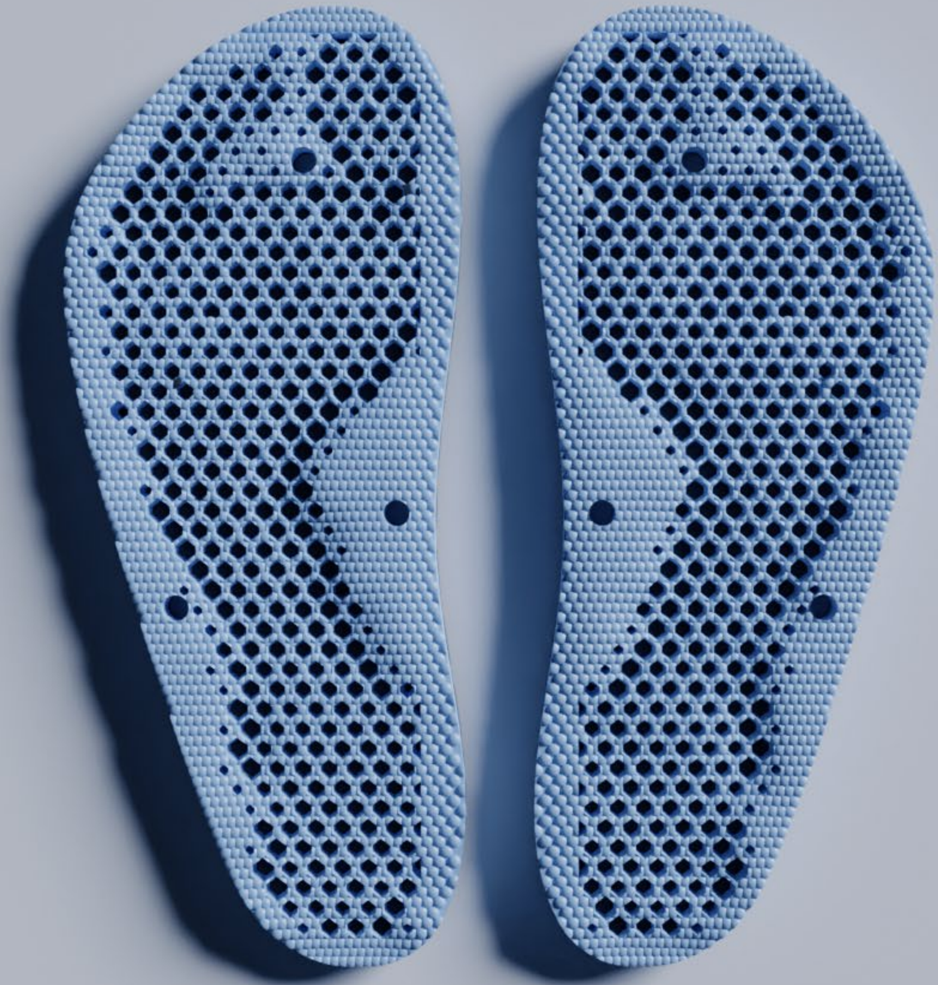
DFAM Individual report

Using additive manufacturing in the injection moulding process



Alfie Thompson

CID: 01216995

Introduction

Mass customisation is the process of creating products and goods customised to specific user's needs on a large scale. Traditional manufacturing has struggled to achieve mass customisation of products, despite increasing demand from consumers. [1]

Injection moulding can output thousands of parts per hour with reliably high quality and low failure rates. Automated injection moulding tools can cost anywhere from £10,000 to £100,000 [2][3]. Mass customisation of injection moulded parts has, therefore, traditionally been prohibitively expensive.

Additive manufacturing has the potential to overturn this, making mass customisable of products economically viable. This can mean that every user can have parts created just for them at much lower prices than previously possible (figure 1).

Figure 1 – Geometry customised to a specific user through generative design and pressure mapping.

Concept

Simple injection moulding tools can be 3D printed out of common materials and with almost any 3D printer. Challenges from the extreme pressure and temperatures can be overcome by plastics such as Nylon, PETG and ASA, and resins with high temperature resistance. These cheap, 3D printed parts are inset into simple aluminium or steel casings that reinforce the printed inserts (figure 2 & 3)[2]. These can withstand a small, but a not insignificant number of injections before breaking. This opens the injection moulding process to the benefits of 3D printing.

Figure 2 – An example of small production run injection moulded parts. Resin parts are inset into an aluminium frame. [2]

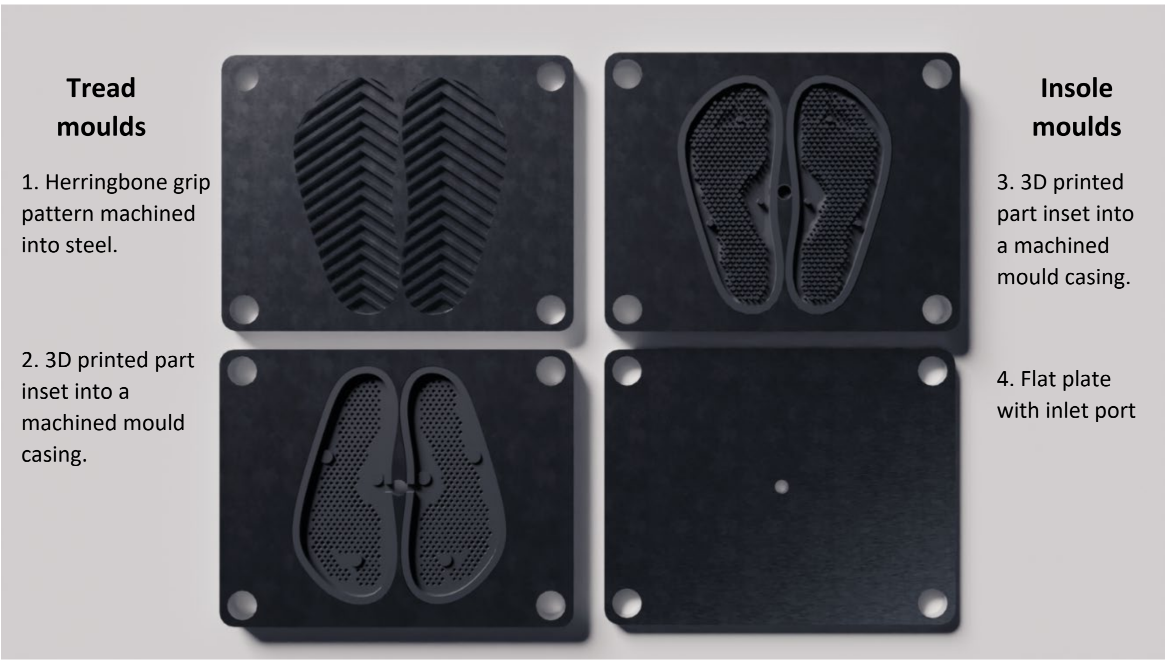


Figure 3 – Proposed moulding tools for the design outlined in the report. Swappable 3D printed parts are inset into simple generic machined steel cradles.

Proposed design

Figure 4 - Final Flip flop design, shown with blue TPU insole and Black Rubber Treads.

The proposed design takes advantage of additive manufacturing for improved personalisation, whilst aiming to make mass customisation more approachable by using a fusion of additive and traditional manufacturing.

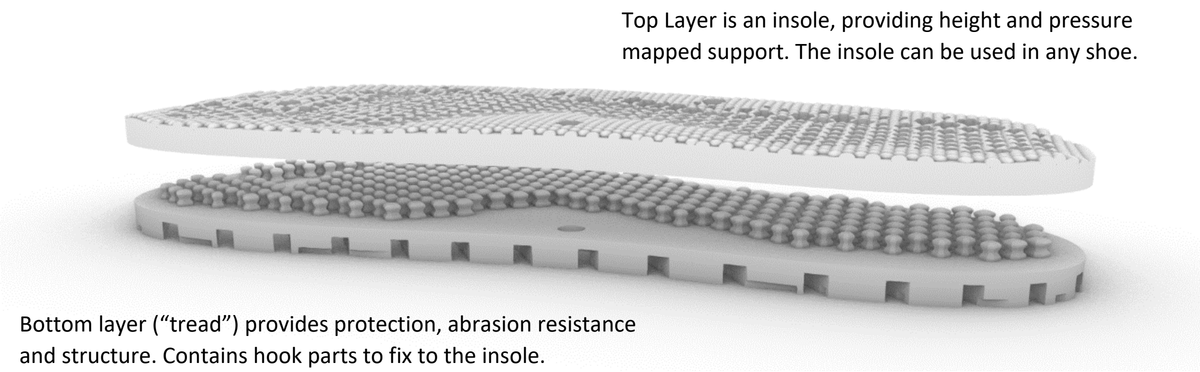


Figure 5 – Diagram showing the two parts of the flip flop design.

A shoe is proposed with a removable custom insole, designed with compliance and support at key areas defined by a pressure map (figure 1). Higher pressure areas are made softer and lower pressure areas are firmer. In addition, the insole is height mapped to provide additional support in areas of low pressure and fitting more perfectly to the shape of the user's foot.

The flip-flop is split into two sections. A customised insole provides support to the user's specific pressure map. The tread protects against heat, abrasion and sharp objects.

Re-entrant geometries create snap joints that connect the insole and tread together (figure 6). The socket is integrated into the hex holes. This means that the insole can also be disconnected and transferred to be used in normal shoes. The shoe can easily be pulled apart and put back but will stay together when in use.

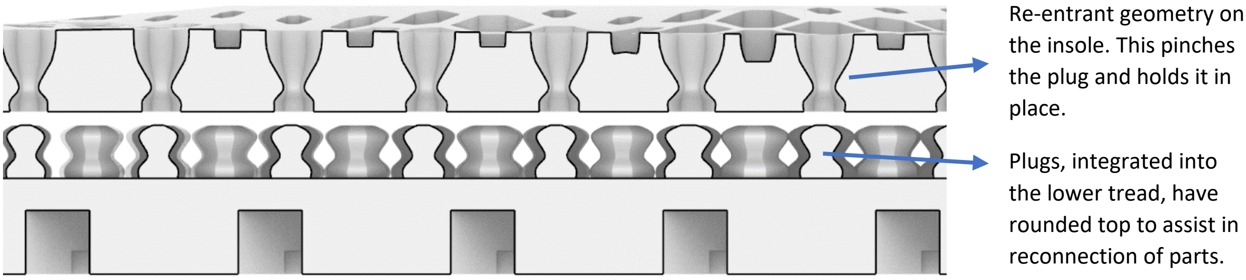


Figure 6 – Annotated Sectional view of two parts.

Additional micro-geometries increase grip and reduce strain through stimulation of muscles (figure 7) [4][5]. Micro dots can help to reduce pain in the sole of the foot. This a common technique used in orthepaedic shoes, particually for children and the elderly (figure 8).

Figure 8 - Child's orthopaedic insoles showing discrete microgeometries. [5]

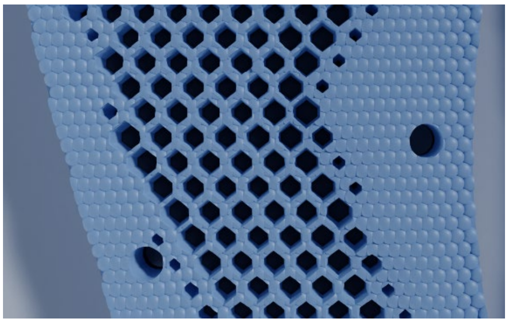


Figure 7 - Micro-geometries cover the top surface of the insole. This matches the feature commonly used in orthopaedic shoes.

Value added from additive manufacture

Through pressure mapping, data can be generated. This can be converted through generative design techniques, such as coding and visual programming, into the perfect shoes for a user, custom designed at a fraction of the cost of custom orthotic insoles, which can cost £200 to £800 per pair [6][7]. These designs can then be injection moulded in a range of materials, from memory foams to soft TPUs, into 3D printed tools made of temperature resistant plastics.

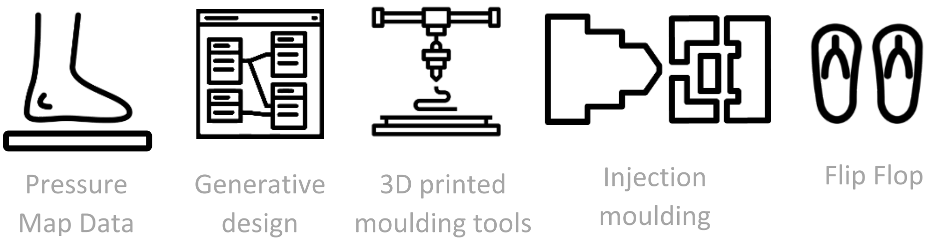


Figure 9 – Proposed production methodology of parts.

Subtractive manufacturing techniques such as CNC machining could provide similar benefits of low-cost customised parts. A key limitation of CNC machining, however, is that overhangs are not easy to produce, this precludes the use of re-entrant geometries such as the plug and sockets used in this design. CNC machines also struggle with small and intricate geometries, as small milling bits need to be used, increasing manufacturing time. Effective designs for shoes require a manufacturing process not limited by these constraints.

Advantages of fusion manufacturing

3D printing has fewer limitations and works effectively in the customisation of products with short lead times, relatively low cost and few limitations on geometry. Key issues, however, obstruct mass customisation. There is currently a limited selection of desirable materials that can be used such as TPUs (Thermoplastic polyurethane) and foams, whereas injection moulding can use a wider range of materials.

The cost breakdown of the proposed manufacturing method (table 1) was completed. This looks at the raw material and labour costs of 3D printing shoes or 3D printing injection moulding tools and then injection moulding the part. It shows that even a single unit is cheaper when produced through injection moulding.

Table 1 - Results of a simplified cost breakdown of parts. The left columns show the cost per unit of 3D printed parts, and the right show injection moulded parts using 3D printed moulding tools.

Unit cost by type of production				
Quantity	**3D print**		**Injection mould**	
	FDM	SLA	FDM	SLA
1	£ 32.35	£ 71.11	£ 8.92	£ 32.44
5	£ 32.35	£ 71.11	£ 3.37	£ 8.92
25	£ 32.35	£ 71.11	£ 1.30	£ 2.41
10000	£ 32.35	£ 71.11	£ 0.83	£ 0.88

Generic, high-performance materials such as Nylon and PETG are inexpensive, making the cost of reusable, high quality moulding tools very low. Additionally, TPU processed for injection moulding can be bought in small 25kg batches for only £2 per kg and in larger batches for less [8].

The cost of flexible materials filaments such as TPUs, is high in comparison to stiffer and more common materials, with TPU filament costing anything from £30 to £80 per kg, and SLA (stereolithography) resin costing £200 per kg [2]. In addition, FDM (fused deposition modelling) printing of Flexible parts has a higher failure rate than stiffer materials.

Injection moulding tool insets capable of producing up to 100 parts can be produced on consumer grade 3D printers. These can be swapped out for different insets in just a few seconds. This increases manufacturing speed and reduces labour costs, particularly if multiple parts are made off a single mould.

See appendix A for a full cost comparison of manufacturing methods.

Considerations for additive manufacture

Anisotropy of the parts is difficult to consider due to the size of the part. Ideally, the print should be angled so the z-axis is orientated along the length of the thin extrusions of the mould, this is uneconomical, however, due to the greatly increased print time. To counteract the weakness from the print orientation, sockets are integrated into the top mould, these hold the plastic extrusions and stop them from breaking off, although if the mould is not being used again this is not an issue.

The moulds are designed to be self-supporting, meaning that no support material is necessary. This reduces print time, and post processing time. Angles on all overhangs were limited to 45°, the most common limit of self-supporting structures.

Injection mould material flow was considered by positioning the inlet port into the centre. The part thickness is considered against the total volume. With thin parts of high volume, high pressure is used for the injection which puts a strain on the printed moulding tools. Parts were therefore kept quite thick to reduce this pressure. Additional inlet ports into the parts can also reduce the necessary pressure.

Materials

The insole of the shoe can be made of many materials; however, a soft TPU-silicon mixture provides support and impact resistance [9]. The melting temperature is approximately 210°C [10]. Another common material is memory foam. This can be over moulded over the TPU into specific areas with a simple mould (figure 10). In addition, the TPU can be bonded to materials without altering the injection mould tool, increasing comfort.

The tread of the shoe is made of rubber. This provides stiff and durable performance. Most importantly, rubber is abrasion resistant.

Figure 10 - Insole with memory foam and fabric.

The mould will ideally be printed in Nylon. It can withstand the limited production runs of less than 10 parts and is low-cost and relatively easy to print. Along with being inherently lubricating, it can also be treated using silicon spray to reduce the ability for injection moulded parts to stick. A disadvantage of nylon is its hydrophilic nature, it must be kept relatively dry. The outer mould is made of steel, providing the strength needed for the high pressures. A high temperature resin could also be used, providing the higher quality SLA printed parts at a higher cost.

Users

This design will work well for many different types of users. With the cheaper parts, a user can buy many shoes and insoles for the price of one. This provides obvious benefits for users with orthopaedic problems. Orthopaedic shoes are designed specifically around the internal structures of the foot and help people who have abnormalities in these structures [11]. As people age, these become very common, making the elderly a key potential user group. Orthotic insoles, using the same key principle as those outlined in proposed design, help elderly people to walk more easily, through support and cushioning in key areas. Although many potential users could be elderly, orthotic insoles are beneficial to those of all ages as all sizes of foot are accommodated.

Methodology

The design was created initially by prioritising the performance of the shoes through the customisation of geometry. The design was then adapted to fit the proposed manufacturing process.

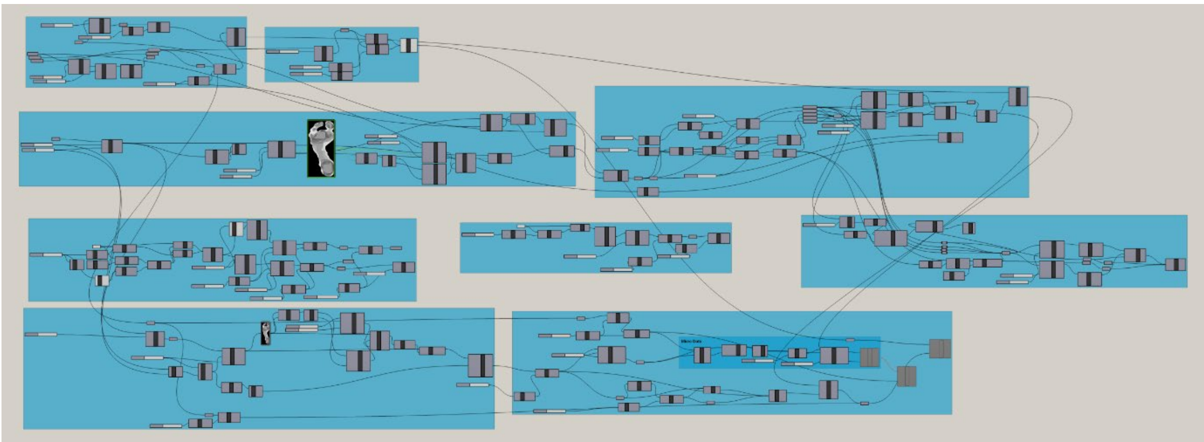


Figure 11 – Basic overview of the code used to generatively create the flip flop design.

A generative program was set up in grasshopper (figure 11), a plugin made for Rhino. It takes basic dimensions of the feet, passes them through a pressure map and simplifies the shape for the sole. The grasshopper code is split into modules, each tackling specific aspects of the design.

A full breakdown is provided along with the CAD files.

Conclusion

The proposed design uses additive manufacturing to enable economically viable mass customisation. A manufacturing method is presented which uses a fusion of additive and traditional manufacturing to create customised shoes at a lower cost than either method on their own. 3D printed tool inserts, printed using FDM or SLA techniques, made using Nylon or high-temp resin are inset into simple generic steel moulding tools. 3D printing increases geometric freedom with smaller features and more complex parts, without an increase in production time that is seen with CNC machining. Injection moulding decreases cost of materials and of duplicate parts.

The flip flop design itself introduces inbuilt functionality in the form of transferability between shoes using compliant snap fittings. This is only possible using additive manufacturing and presents a strong value addition. The shoe is customised to the user, increasing comfort and providing unrivalled support. Additional features commonly found in orthopaedic shoes are also included which also increase comfort without increasing cost by taking advantage of the benefits of 3D printing.

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Appendix A

Economic comparisons of Manufacturing processes					
Manufacture Method	**3D print**		**Injection mould**		
Print Type	FDM	SLA	FDM	FDM	SLA
Mould manufacture - if applicable					
Print type	-	-	FDM	FDM	SLA
Mould material	-	-	ABS	ABS	High Temp resin
Cost / kg	0	0	30	30	204
Density (kg/m^3)	0	0	1070	1070	1070
Volume per unit (mm^3)	0	0	0.000103813	0.000103813	0.000103813
Mould Mass (kg)	0	0	0.11107991	0.11107991	0.11107991
Print time (hr)	0	0	8	8	15
Labour cost	0	0	£ 4.80	£ 4.80	£ 9.00
Mould cost per unit	0	0	£ 8.13	£ 8.13	£ 31.66
Shoe Manufacture					
Material	TPU	TPU	TPU	Memory Foam	TPU
Density (kg/m^3)	1070	1070	1070	800	1070
Volume / mm^3	0.000309868	0.000309868	0.000309868	0.000309868	0.000309868
Mass (kg)	0.33155876	0.33155876	0.33155876	0.2478944	0.33155876
Cost £/kg	83.0922944	200	2	10	2
Unit cost (pre labour)	27.5499781	66.311752	0.66311752	2.478944	0.66311752
Time (hr)	8	8	0.01	0.01	0.01
Labour	£ 4.80	£ 4.80	£ 0.12	£ 0.12	£ 0.12
Price per unit	£ 32.35	£ 71.11	£ 8.92	£ 10.73	£ 32.44

Small Batch					
Quantity	5	5	5	5	5
Total Time (hr)	40	40	8.05	8.05	15.05
Labour	£ 24.00	£ 24.00	£ 5.40	£ 5.40	£ 9.60
Total Cost (Small Batch)	£ 161.75	£ 355.56	£ 16.85	£ 25.93	£ 44.58
Price Per unit	£ 32.35	£ 71.11	£ 3.37	£ 5.19	£ 8.92
Larger Batch					
Quantity	25	25	25	25	25
Total Time (hr)	200	200	8.25	8.25	15.25
Labour	£ 120.00	£ 120.00	£ 7.80	£ 7.80	£ 12.00
Total Cost (large Batch)	£ 808.75	£ 1,777.79	£ 32.51	£ 77.91	£ 60.24
Price Per unit	£ 32.35	£ 71.11	£ 1.30	£ 3.12	£ 2.41
Industrial Batch					
Tools	-	-	100	100	100
Quantity	10000	10000	10000	10000	10000
Total Time (hr)	80000	80000	900	900	1600
Labour	£ 48,000.00	£ 48,000.00	£ 1,680.00	£ 1,680.00	£ 2,100.00
Total Cost (large Batch)	£ 323,499.78	£ 711,117.52	£ 8,319.31	£ 26,477.57	£ 8,762.84
Price Per unit	£ 32.35	£ 71.11	£ 0.83	£ 2.65	£ 0.88

Labour is assumed to take place for only 5% of print time (checks, maintainance, ect) at £12 per hour. *A Unit is a pair of shoes. Excluded fixed costs, operating costs of equipment, ect.*

Figure 13 - Full breakdown of costs associated with different manufacturing methods of the flip flop. Both FDM and SLA printing techniques are taken into consideration.