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Cost modelling for fabrication of custom-made foot orthoses using 3D Printing Technique

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Abstract: Rapid manufacturing (RM) techniques construct the products guided through computer aided designing systems through various fabrication methods involving extrusion; sintering and photo polymerisation through deposition of material guided by CAD designed information of the parts. The rapid manufacturing techniques have the advantages of design freedom, increased part accuracy and consistency in production of final part. Recently the adoption of these techniques in various manufacturing sectors for direct production of the parts has been moved from 4% in year 2003 to nearly 20% in year 2011. This is driven by continuous reductions in material and machines costs which are the important factors that have increased the trend of application of rapid manufacturing techniques in different manufacturing sectors. Applications of rapid manufacturing techniques require productivity analyses that ultimately influence the manufacturer's decision for commercial scale applications of these techniques for low-volume production and production of custom-made parts; especially in medical sector. The requirement of production of custom-made parts, rehabilitation aids and devices in medical sector is explicitly higher in comparison to other manufacturing sectors. In this papercost and lead-time modelling is conducted for one of the rapid manufacturing technique named 3D printing for fabrication of custom-made foot orthosis. The results showed that fabrication cost £288.55 per pair of foot orthoses. The techniques also showed the advantage of reduced product lead-time.

Keywords: Foot orthosis, rapid manufacturing**,** 3D printing technique, cost and lead-time modelling.

1. INTRODUCTION

The layer manufacturing techniques are the extension of rapid prototyping (RP) which have emerged over last two decades (Hague *et al.,* 2003). These techniques create directly the 3D parts guided by CAD design information through addition of material layer by layer. The fabrication processes require no tooling or moulding and offers a greater design freedom for production of highly complex designed parts (Phillip and Wendell, 97). In rapid manufacturing fabrication process a virtual model of the part is designed through a computer aided designed (CAD) system and then the file is converted into (.STL) file format. The digital information of the part in .stl format is sent to rapid manufacturing systems for direct fabrication of 3D parts (Chen *et al.,* 1999).

2. STATE OF THE ART

2.1Orthotics and typical production methods

Foot orthoses (FO) are used for in treatment of foot pain improving gait stability in patients (Crabtree *et.al,* 2009). Custom made foot orthoses helps the patients in terms of reduction in foot pain while walking, improved fit, comfort and aesthetics (Jumani and Dalgarno, 2008; Pallari *et al.,* 2010). However, the fabrication of custom made orthoses incurs higher fabrication cost and time in manufacture at the orthoses. Conventionally the foot orthoses are produced manually or produced through vacuum forming of thin shell plastics (Crabtree *et.al.,* 2008). With the applications of technological advancements Numerically Controlled (NC) milling machines are applied in production of custom made orthoses with some more attempts by rapid manufacturing techniques based production of custome made foot orthoses are possible (Footprint, 2012).

2.1 Manual/handcrafted fabrication method

Fabrication of custom foot orthoses traditionally is based on manual activities and craft based processes. The fabrication process begins with placing the thermoplastic sheet which is slightly larger than anticipated orthoses in a pre-heated convection oven (Hunter *et al,* 1995). The sheet of plastic is placed in the oven for five minutes in a correct temperature until the plastic become pliable. In the next step, heated plastic sheet from the oven is taken out and draped it over the developed positive mould and then manually smoothed and pressed to get full contact with the positive mould. In the next step cutting lines are marked on the draped plastic. The last step is cutting of the shell according to drawn lines and smoothing the edges of the orthoses with grinder to get measurements accuracy and finishing in the final product (Pratt, 1995; Doxey, 1995). **(Fig. 1)** shows the thermoplastic piece (a) and orthoses draped over the positive mould of the foot impression cast.

2.2 Vacuum forming method

The other way of fabricating the custom orthoses is use of vacuum press or vacuum former instead of

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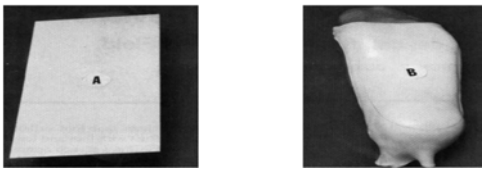


Fig. 1 (a) Plastic sheet and (b) heated plastic sheet draped over the positive mould

manually pressing the heated plastic sheet over the positive mould. It has been recognised by the many authors that vacuum press fabrication of orthoses shell bring more uniform and better results compared with manually draping for orthosis fabrication (Brown and Smith, 1976; Pratt, 1995; Doxey, 1995). The process requires high skills and expertises in fabrication process of orthoses to get the accuracy in measurements in final product (Hunter et al, 1995). Figure 2shows the vacuum press and the typical process steps in orthosis shell fabrication process. The process starts with (a) placing master wooden mould in the press and placing the heated sheet onto the top surface mould, (b) forming under the vacuum pressure while shaping the contours by hand, (c) cooling with air and spray mist and (d) release and trimming

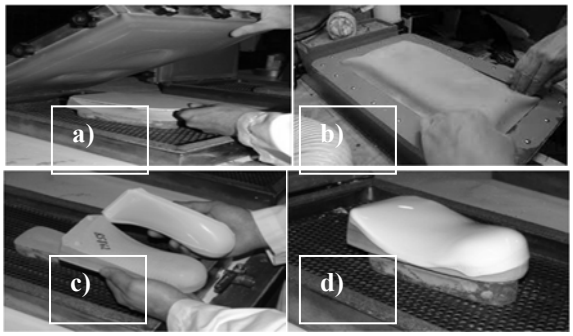


Fig. 2. Typical vacuum-forming process. (Source: Paris orthotics, VA, Canada).

2.3 CAD/CAM fabrication method

In 1960s numerically controlled (NC) milling machines were introduced for production of custom – made orthoses. Currently the technological advancements and computer aided designing (CAD) based systems are used for production of custom made orthoses (Lasurdi and Nielson, 2000). The present systems for production of custom foot orthoses are combination foot geometry capture using dgital scanning equipment, CAD orthoses design with specific software developed for orthoses designing (Davis, 1993) and automated CNC machine for milling the orthoses (Lasurdi and Nielson, 2000).The first commercial digital manufacturing system was "Orthoscan system" developed by American Digital Technology in the year 1988. Another system developed byAmmon Corporation named as "Ammon Production system" and was introduced by Bergmann Orthotic Laboratory. The both systems were using digital technology for capturing foot geometry (Grumbine, 1993). **(Fig 2)** shows the process flow for CNC based foot orthoses manufacture. The process starts with (a) 3D scanning of plantar surface, (b) Software for insole design, (c) NC milling of EVA block and (d) Retrieval and trimming. CAD/CAM processes based on milling are currently considered the closest solution to fully customised-on site manufacture of foot orthoses. Milling systems are usually part of proprietary CAD/CAM solutions that comprise: a 3D foot scanning system, orthotic modelling software and CAD/CAM manufacturing station.



Fig. 3. CAD/CAM process (Source: DelcamPlc.healthcare solutions).

3. 3D PRINTING TECHNIQUE

The 3D printing is a rapid manufacturing technique which was developed at Massachusetts Institute of Technology (MIT), USA used for prototyping of parts and tools directly from computer aided designed (CAD) parts. In 3D printing technique a removable material cartridge that contains ultra violet (UV) curable resin is loaded inside the printer. The production process starts in a cartridge containing ultra violet (UV) curable resin and a system for deposition of material in layer by layer on the build pad. A plastic sheet constructed in the cartridge extends from the cartridge and is coated with liquid resin uniformly. Once the liquid resin is coated, the build pad is moved downward with the coated sheet which deposits another layer of resin treated by a flash of focused UV light rays. The ultra violet light rays solidify the deposited layer of the resin material. The sheet of the plastic is retracted and is re-coated with another layer. The process is continued until the fabrication of final part. Figure 4 shows (a) V-flash 3D printer and (b) door open printing process in V-Flash 3D printer (3D systems.com)



(a) (b)

Fig. 4(a) V-Flash 3D printer and (b) door open printing process in V-flash 3D printer

4. 3D PRINTING TECHNIQUE FOR ORTHOSIS FABRICATION

4.1 Methodology.

An orthosis model designed in a CAD based system presented in **(Fig. 5)** was sent for 3D printing system to produce the orthosis model using 3D V-Flash printing system.

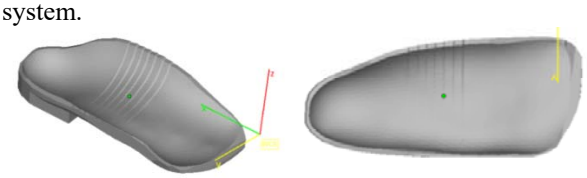


Fig.: 5 Orthosis model developed in CAD based design system

Table: 1 Orthosis model measurements and material used.

Measurements of orthosis and consumed material	
Measurements of orthosis model	Height 50.81, Width 179.51, Depth: 79.91 mm
Time of fabrication	10 hours
Consumed material	V-FlashFTI Resin
Model material (FTI-GN material)	52 grams
Support material consumed	29 grams

4.2 Fabrication of orthosis model

A V-Flash® 3D printing system manufactured by 3D systems Inc, USA was used for orthosis model fabrication. 3D V-flash™ software was used to transfer the design of the orthosis model developed through CAD based system into (STL) file. Fabrication process starts with conversion of CAD based orthosis model into .stl file format through systems proprietary 3D V-flash™ software. A size of orthosis model measuring of 230 (L), 170 (W) and 200 mm (H) (9 × 6.75 × 8 inch) was used in the 3D system. The system has consumed 10 hours of time per build in fabrication process.

5. RESULTS AND DISCUSSIONS

The cost and the lead-time for the production of orthosis was analysed and modelled. The production costin rapid layer manufacturing techniques are classified in four main types;the cost of production and administrative overheads, operational cost and cost of 3D system machine, material and labour cost (Gibson *et al.,* 2010). For calculating the productivity of the 3D printing machine an important assumption was made on the basis of (i) production time per run and (ii)number of total runs per year. The assumption for operational life of the machines was assumed for 5 years.

5.1 For 3DP technique using V-Flash system modelling of the cost and lead-time.

By using the V-Flash system, an assumption was made that one machine has to bein operation for one run of 10 hours of time per day for 220 working days per year in the basic operating model. The volume of total production was computed by the total estimated volume of production. The machine controlling software V-Flash™ gave a fabrication time of 10 hours for one part assuming the machine to work for 220 days per year. The model gaveper year a total of 2200 machine hours for 10 hours of fabrication time per day; approximately 25% of utility of machinetime. A The total cost of £87839 for production of 110 pairs per year; costing a pair of orthoses for of £798.53 using V-flash 3DP system is presented in Table 2. The computation of machine cost per year was estimated through cost of depreciation of machine per year. The maintenance cost per year was added with the 10% of the total cost of the machine. For the machine the depreciation cost was assumed for 5 years. This has given a total cost of £4640 per year for machine cost. The calculation of material was estimated by weight of consumption of material in orthosis model and in the structure for supporting the orthosis model. The weight of the total material used in the orthosis model was then calculated by the actual material cost per gram. In the fabrication process a material of 52 grams and 29 grams was consumed in orthosis model and support structure respectively. This gave a total of 81 grams of material consumption in model fabrication and in support structure per part. This gave an estimated cost of the material for £36.45 per part andper pair cost of £72.90.The building space at the cost of £120/m^2 per year was estimated as the production overhead. A cost of consumption of energy for the machine at the cost of £1.5 per hour was added as the overhead. This gave a calculated total of £32880 per year as the production overhead which was combined with administrative overhead at rate of £2320 per year.

The cost of labour was estimated by the required time of the labour for running of the machine. The one run operation of on V-Flash system needs the estimated time of one hour as the labour time. This is based on setting of the machine for 30 minutes consumed in loading of the material cartridge and 30 minutes of time for getting the fabricated part and post processing. However, a cost of £39980 was computed as the yearlycost of labour for the operatorin the basic model with use of one machine and labour of one operator.

5.2. Mathematical calculation in cost modelling

The method for calculation of fabrication cost is presented in equation 1

$C_{total} = C_{machine} + C_{material} + C_{overheads} + C_{labor}$ Equation -1

For calculation of machine cost $C_{machine} = E/5 + M$ Equation 2

For calculation of material cost $C_{material} = V_{mod:} + V_{sup:}$ x (material cost £/kg) Equation 3

For calculation of production overhead $C_{overheads} = C_{prod:\ overhead} + C_{admin\ overhead}$ Equation 4

For calculation of labour cost C_{labour} = Annual Salary of Technician Equation 5

Total cost per pair was calculated by $C_{per\ pair} = C_{total}$ / Total no. of pairs produced Equation 6

Table 2 Calculations of cost per pair using V-Flash system in 3DP technique

Cost calculations using V-Flash system in 3D printing method		
Volume of the production per year		
Total parts/run	N	1
Fabrication time of run	T	10 hours
Fabrication rate for one hour	R = N/T	0.1 hours
Total operational hours per year	HY	2200
Total number of production per year	V = HY x R	220 parts
Number of total pairs per year		110 pairs
Total cost of machine per year		
Machine and associated equipment	E	£15465*
Cost of depreciation/year	D = E/5	£3093
Cost of maintenance of machine/year	M	£1546
Total cost of machine/year	MC = M+D	£4640
Total cost of material per pair		
Consumed material/part	52 grams @£0.45/grams	£23.40
Consumed supporting material/part	29 grams @£0.45/grams	£13.05
Cost of material for model/kg		£453*
Cost of support material/kg		£453
Cost of material/part		£36.45
Total cost/pair		£72.90
Production overhead per year		
Area of the Building	246.5/m^2 @ £120/m^2 per annum**	£29580
Consumption of the energy by machine	@ £1.5/hour x 2200 operational hours of the machine per year	£3300
Total cost/year		£32880
Administrative overhead per year		
Hardware		£2175***
Cost of software		£2175***
Cost of utilities/year		£1450
Costof depreciation for the hardware/year		£435
Cost of depreciation for the software/year		£435
Total cost/year		£2320
Cost of labour per year		£39980/year
Total cost	110 pairs per year	£87839
Total cost/pair	£87839/110 pairs	£798.53

* Cost quotation for material from Print IT 3D Ltd, UK, 2010.

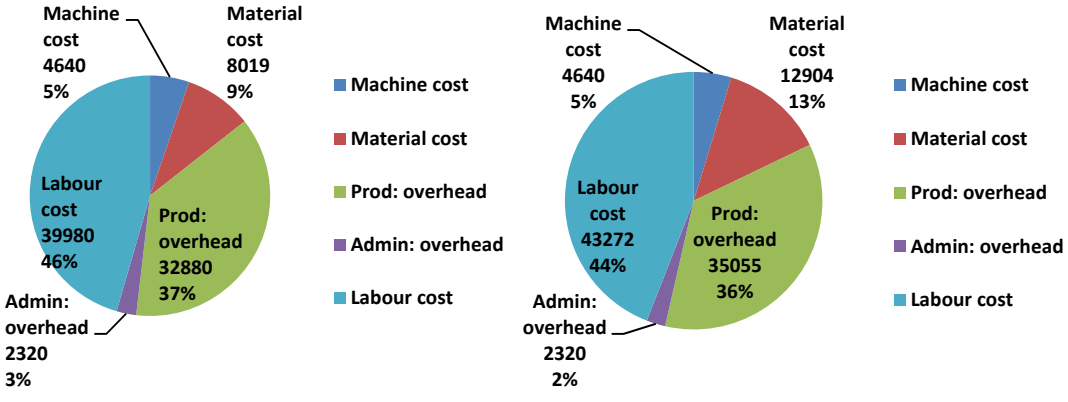


Fig. 6 Costing elements in basic operational model for 220 and 365 working days per year

5.2 Analysis of the model

Scenario 1-Increase in the operational hours of machine per year

An assumption was made that a machine to work for 365 days per year for basic operating model which was comprised working for 220 days per year. For working of 365 days a year; the cost elements in assumed basic operating model are shown in **(Table 3).** This was included with a part time technician required to work for one hour of time per day for 145days; which resulted in raised the volume of the production per year from 110 to 182 pairswhich gavecost of £541.50 per pair; resulted in 32% lower in total cost per pair with compared to basicoperating cost model.

Table 3 Cost per pair in the basic operational model for 365 working days/year

Total cost per pair using V-flash system		
Cost of the machine		£4640
Cost of material for 182 pairs	@ £72.90/pair	£13267
Production overhead		£35055
Administrative overhead		£2320
Cost of labour	Full time + part time operator	£43272
Total cost	182 pairs per year	£98554
Total cost per pair	£98554/182 pairs	£541.50

(Fig. 6) represents the different breakdowns of costing elements in (a) basic operating model for 220 working days and (b) operating model based on 365 working days respectively. In the model the indirect costs are 91% and 87% of the total cost. This cost is included with 5% cost for machine cost and 5% production and administrative overheads 40% and 38%and 46% cost for labour and 44 % of the total cost in the model. Cost of material stands for 9% and 13% respectively as direct cost of the total cost

Scenario 2- Establishment ofthe low cost operational model

By using V-Flash 3D system for production of foot orthosis; a low-cost" operational model was established for one run of 10 hours of fabrication time per day. In order to obtain optimal productivity from the model; 2 technicians were included operating with 10 machines in order to for balance the machines operational hours and working hours of the labour. In the established model one run of 10 hours of fabrication time per day on one machine was assumed to work for 365 days year. This gave a calculation of 3650 hours of machine time per year for each machine and a total of 36500 machines working hours per year for 10 machines which gave 58% machine utilisation time per year.

For the "low cost" operating model the Table 4 represents the totalhours of the running of machines and totallabour hours required per year for the technicians. One hour of labour time is required for operation of one run on one machine as mentioned in the **(Table 4).** The running of 365 runs per year needs 356 hours of labour time per year. This makes a computed total of 3650 machine labour hours per year for running of 10 machines. The total labour time in hours per year for one technician are based on 1760 labour hours per year which makes a total of 3520 hours per year for 2 technicians. A total of 182 pairs per year are assumed to be fabricated from the operating model based on one run of 10 hours of fabrication time per day on one machine. This makes an total annual fabrication volume of 1820 pairs of orthoses for 10 machines.

Table 4 Required labour hours for machine and technicians/year in "low-cost "model

No: of machines	Total of machine operational hours per year	No: of technicians	Labour of echnicians hours per year
1	365	1	1760
2	730	2	3520
3	1095	3	5280
4	1460	4	7040
5	1825	5	8800
6	2190	6	10560
7	2555	7	12320
8	2920	8	14080
9	3285	9	15840
10	3650	10	17600

(Table 5) presents the cost elements in "low cost" model based on working of 2 technician son 10 machines. A building space cost of 6m^{2}at the cost of £120/m^2 for each machine added with the cost of energy consumption at the rate of £1.5 per hour for extra machine was included. It is further included the cost of machines buying and operational cost of 10 machines and cost of consumed material per year. The cost of labour for 2 technicians was computed for £79960 per year. The model showed the computed total of £372988 for production of 1820 pairs per year giving the cost of £288.55per pair; 64% lowering the cost per pair comparison with basic operating model for 220 working days.

Table 5 Total computed production cost per pair in "low cost" V-Flash based cost model

Low cost operating model based 10 machines with2 technicians		
Cost of machine per year		£46400
Cost of material for 1820 pairs	@ £72.90/pair	£132678
Production overhead per year		£90750
Administrative overhead per year		£23200
Cost of labour per year	Full time + part time operator	£79960
Total cost	1820 pairs per year	£372988
Total per pair cost	£372988/1820 pairs	£288.55

(Fig. 7) represents the details of the costs in "low cost" model. The indirect cost makes a total of 64% of the total cost. This comprised of cost of the machine 13% over-heads 30% and cost of labour as 21% of the total cost in the model. The material cost stands as 36% of the total cost as the incurring direct cost.

For the production of custom-made foot orthoses; layer manufacturing approach is an alternative route to traditional manufacturing techniques. Figure 7 showed that material cost for resin is one of the higher costing element in the low cost established operating model. The low cost operating model gave the cost of 288.55 per pair of foot orthoses.

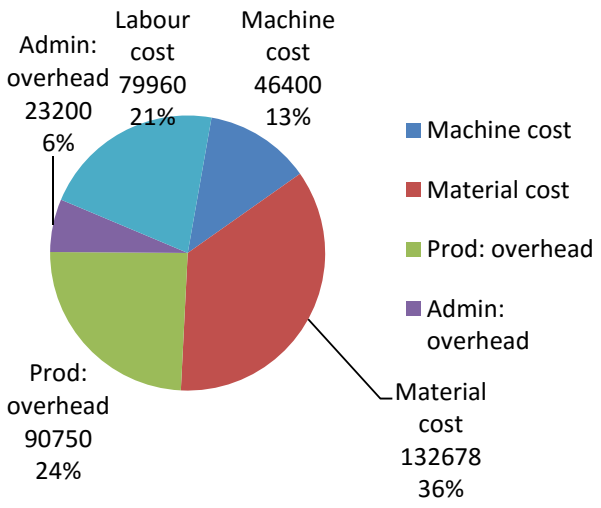


Fig. 7 Cost categories in "low cost" operating model

6. CONCLUSION

The cost modelled developed using V-Flash 3D printing technique initially showed a higher cost of £798.53 per pair of foot orthoses. The cost was reduced to £ 541 per pair by increasing the total working time of the machines per year. Further by balancing the operational time of the machines per year and required time of labour per year; the model gave a cost of £ 288 per pair. The estimated cost per pair given by the model is higher in comparison with present cost of custom made orthoses using traditional manufacturing using CNC machines which gives an estimated cost of £150 to £250 per pair. The other main factor in production of custom-made foot orthoses is lead-time that takes two to three weeks of delivery time. As the applications of rapid manufacturing techniques for production of parts and prototyping are increasing with the advancements in speed and materials in rapid manufacturing the newer and faster machines with introduction of low cost and improved quality materials enhance the applications of these techniques in fabrication cost effective custom made orthoses.

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