DESIGN FOR MANUFACTURING AND ASSEMBLY OF A FINGER SUBASSEMBLY FOR A PROSTHETIC DEVICE

Florin - Felix RĂDUICĂ[1], Ionel SIMION[2]

Over the years, prosthetic design has evolved with the technology development. In recent years an emergence of additive manufacturing technologies has led to a wide variety of prosthetic designs. Our study uses Design for Manufacturing and Assembly (DFMA) to develop a methodology for the design of low-cost 3D printed upper-limb prosthetic devices. The aim was to adapt an existing DFMA methodology to be used for prosthetic design. The initial design was modelled in open-source software and improved with DFMA software with the proposed methodology. The resulting design led to a better performing prosthetic at a lower price. This research can be used to further develop existing devices using the proposed methodology.

Keywords: upper-limb prosthetic device, low-cost, 3D printing, DFMA, concurrent engineering.

1. Introduction

The human hand has a large number of degrees of freedom, but trauma may lead to function loss. Hand motor function loss initially puts patients in social-economic distress, then it forces adaptive attitudes and finally make them turn to a prosthetic device. Prosthetics are bespoke and patients need to visit the clinic several times before getting fitted with a device. While this type of devices belongs to the traditional way, new prosthetic devices have seen a lot of improvements and during the past 20 years, the development of 3D printed prosthetics, that require less handling, has experienced an exponential growth. This growth coupled with the part customization capabilities has led to an insertion of 3D printing technology into many fields. In the field of bioprinting, the 3D printing technology meets medicine. Bioprinting progress has been made to the point that small, unexpensive and bespoke medical assistive devices are highly available to patients. Patients benefit from a design process that considers the manufacturing and assembly of these assistive devices. A device design is optimized to consider the material properties of which the prosthetic is made, and the performance characteristics are enhanced by design intent. Design evolution is aided by the presence of online

[1] PhD Candidate University POLITEHNICA of Bucharest, Romania, e-mail: felix.raduica@upb.ro
[2] Prof., University POLITEHNICA of Bucharest, Romania e-mail: ionel.simion@upb.ro

databases filled with prosthetic design files that are available to be used, redesigned, and customized.

2. Literature review

There have been few studies regarding Design for Manufacturing and Assembly (DFMA) [1] integrated into the prosthetic field. However, there seems to be an established theoretical and fundamental basis for the general approach for DFMA [2]. While in prosthetics there is a lack of literature, in the industrial engineering field, welding is done using Design for Welding DFW strategies [3], in the construction field, Design for Deconstruction/Disassembly DFD is used [4], [5] and in the product design field, Design for Reliability DFR is used [6]. A classical approach to prosthetic design is described in [7] where the performance of several composite materials are compared for a proposed design. The design is undertaken using the following stages: (i) a modeler software is used to define the geometry, (ii) FEA software is used to analyse stress distribution, (iii) the parts are manufactured using injection moulding and (iv) the parts are tested using physical testing apparatus to validate the design. A more modern approach is described in this study [8] the authors use DFMA and FEM to design a 6-bar mechanism knee prosthetic. Initially they use DFMA software to increase the DFA index by 5%, then they use DFM to further refine the injection moulding manufacturing process and finally they use FEA to develop a new design. Additionally, this study [9] describes an in-depth Design for X (DFX) optimization using DFMA, FEA and DFE in biomedical products such as orthotic knee joints. The authors used a methodology based on (a) iterative designs, (b) CAD model enhancement, (c) FEA analysis, (d) DFM with CNC milling optimization and (e) Design for Environment (DFE) to enhance Cycle time reduction and manufacturing time reduction using robust design tools.

Although customization may be expensive this is not the case for 3D printed prosthetics. There are several types of prosthetic devices available for hand function recovery. Usually we think of these as (1) passive devices, where the prosthetic has just a cosmetic function and (2) active devices where the device has multiple motor functions. Furthermore, the active devices are subdivided into (a) body powered, where the motion is done through the movement of the residual limb or other body part, (b) external powered devices, where the movement is done through sensors that trigger motors on muscle tensioning and (3) mixed actuation devices where one segment of the arm is body powered and the hand is externally powered.

The multidisciplinary approach to the field of low-cost upper-limb prosthetics, permits case studies on implementing new techniques from other areas of research. In the case presented in the paper, not much had been done yet to improve this type of product in the DFMA approach. The novelty of the present work introduces DFMA to the field of low-cost upper-limb prosthetic device design. Although some multidisciplinary approaches are discussed in the literature on additive manufacturing, thermoforming, casting [10] and on integrating artificial intelligence and virtual reality [11], not a lot has been said about incorporating DFMA into the process. The improvements are usually either for optimizing biomimicry [12] or being functional like in the extreme case of energy return-based sports prosthetics [13].

During initial design of the prototype finger the dimensions were added to have a base point for the design. The product is part of a bigger assembly, but for the study only the finger was considered. The 3 segments are destined to be used as bars in a mechanism meant to move as to grasp objects.

Although much work has been done to date, more studies must be done to establish a design methodology in the field of prosthetic devices. The lack of such information represents a gap in our knowledge of design methodology for upper-limb prosthetic devices.

The purpose of this study was to develop a design methodology for prosthetic devices based on the DFMA principles. Specifically, the work focused on the redesign of a low-cost 3D printed upper-limb prosthetic device.

This topic was identified as being of importance to patients with upper limb loss and researchers looking to expand the field of prosthetic design. It is hoped that information from this study may be useful in identifying areas of lack of knowledge to those who are responsible for designing prosthetic devices.

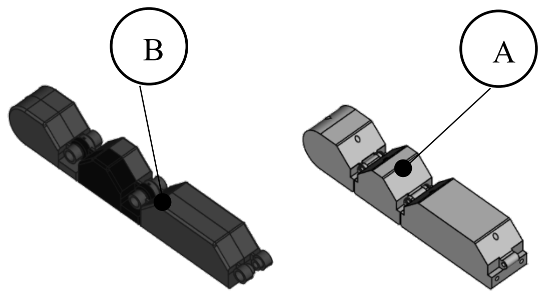

Fig.1. Design A (right) and Design B (left)

Although a method for Design for Additive Manufacturing (DfAM) described in [14] the concept is applied with a finite element analysis in the context of metal parts manufacturing. However, the basic elements may be considered for inclusion in prosthetic design. Thus, further research may include the DfAM in the context of concurrent engineering for fused filament fabrication (FFF) of prosthetics.

The aim of the study is to improve 3D printed upper-limb prosthetic designs using the DFMA methodology. A case study is presented of a finger prosthetic design. The design is analysed and improved using the DFMA approach. Consequently, the purpose of the present work is to propose a novel design methodology.

2. Materials used for virtual prototyping

The DFMA software (Boothroyd Dewhurst, Inc, Rhode Island, USA) licensed by University POLITEHNICA of Bucharest, was used to perform analysis on an existing design of a finger prosthetic. The computed results are presented in subsequent sections of the present work.

The redesign of the prosthetic finger was done using FreeCAD (Freecad Project Association, Brussels, Belgium). The software allows free license use as it is on open-source project.

The computer used to run DFMA and FreeCAD has an Intel Core i7 processor with 16 GB of RAM system memory. The graphics card is a NVIDIA GeForce GTX 1660 with 6 FB of video RAM.

3. DFMA Methodology for design improvement

The finger subassembly of an upper-limb prosthetic device with both body powered and external actuation for patients with partial hand loss was redesigned. The 2 prosthetic device variants were considered for comparison with the following naming convention: (A) is a generic design and (B) is the redesigned variant. The redesigned device had to be low-cost and 3D printable with little complexity regarding assembly. Design (A) was altered regarding improving performance. Initial performance was tested and the performance of what become device (B) was also tested. In the end a comparison of the 2 variants gives the performance increase of Design (B) over Design (A). The investigation was performed virtually, on the lab computer with Computer Aided Engineering software as seen in Figure 1. Using the DFMA software the analysis for assembly and design for manufacturing were conducted on the initial design and the design variation.

Both designs are wire/cable driven. In the case of prosthetic devices, there are 2 ways of actuation either through wire/cable or through bar mechanisms. The system of cable/wire was chosen because of its lightweight design and the elastic capabilities. Although the bar mechanisms are much more robust and are highly studied in the literature, the increased complexity and larger volume displaced led us to choose the cable/wire system.

Although the sample is small, this provides an opportunity to better characterize the performance of the two devices. Furthermore, this also gives the chance to include more criteria. However, this does not mean that the restrictions do not apply. Additionally, our study applies to low-cost prosthetics but does not apply to commercial prosthetics. In each case there were two broad categories of analysis (1) Design for Assembly (DFA) and (2) Design for Manufacturing (DFM) as described in [15]. In Equation 1 the DFA index is defined by the relationship between N_m - theoretical minimum number of parts, t_m - minimum assembly time per part and finally t_a - estimated total assembly time.

$$DFA_{INDEX} = \frac{N_m \cdot t_m}{t_a} \cdot 100 \quad (1)$$

The initial design, Design (A), was selected from recently published literature and was developed in a previous study by the authors, to introduce a new method of actuation. The study considered only low-cost prosthetic devices. This criterion was employed to assure understanding of design intent for both devices. The list of parts is described in Table 1.

Table 1

Parts of the finger subassembly

	Part name	Print time [min]	Weight [g]	Filament length [m]
Design A	Index distal	105	11	4.26
	Index middle	98	11	3.88
	Index proximal	195	22	8.14
	2 x M3 screw	-	-	-
	2 x M3 washer	-	-	-
	2 x M3 nut	-	-	-
Design B	Index distal ½	42	4	1.43
	Index distal 2/2	40	4	1.33
	Index middle ½	45	4	1.45
	Index middle 2/2	41	3	1.25
	Index proximal ½	56	5	1.97
	Index proximal 2/2	65	6	2.23
	2 x bearings	-	-	-

The virtual testing instrumentation in this study employed the DFMA software (Boothroyd Dewhurst, Inc, East Greenwich, Rhode Island, USA), which permits the assessment of cost of assembly, duration of assembly, manufacturing costs and a custom cost spreadsheet for estimating production cost of 3D printing described by equations from 2 to 5 and in Figure 2.

Both designs were tested in the environments described previously. The designs were brought individually into the testing software environment where they were analysed for DFA and DFM. For design (B) the performance characteristics were derived after the redesign of Design (A). For each design we compared the output of the DFA and DFM software components of DFMA and the results derived from our spreadsheet calculator.

The parts designed in each case were inserted into the DFA component of the DFMA software. Table 2 shows the parts with their respective operations that are considered in the DFA study.

In general, prosthetic devices are bespoke. At least the interface between the amputee and the device is personal to everyone. In the case of the presented work, the methodology considered a reference model, and no other variations were considered to avoid high complexity.

A tabular analysis was used to test performance differences. Furthermore, charts were drawn to better establish the differences between the two variants of the prosthetic device.

$$U_c = \frac{c_p + u + m}{a_l} + r_p \cdot e_p \quad (2)$$

$$M_{pc} = m_c \cdot p_w \quad (3)$$

$$P_{dc} = d_t \cdot d_c \quad (4)$$

$$T_c = M_{pc} + p_t \cdot U_c + P_{dc} \quad (5)$$

Where U_c – usage cost, c_p- cost of printer, u- upgrades, m- maintenance, a_l- average lifetime, r_p- rated power, e_p- energy price, M_{pc}- material part cost, m_c- material cost, p_w- part weight, P_{dc}- part design cost, d_t- design time, d_c- design cost, T_c- total cost and p_t- printing time.

Table 2

DFA considerations included in the study.

Design A		Design B	
Part	Count	Part	Count
01_index_distal	1	01_index_distal_01	1
02_index_middle	1	01_index_distal_02	1
Threaded fastening	1	Snap/push fitting	1
03_index_proximal	1	02_index_median_01	1
Threaded fastening	1	02_index_median_02	1
29_bolt	2	Snap/push fitting	1
30_washer	2	03_index_proximal_01	1
31_nut	2	03_index_proximal_02	1
Feed wire/cable through aperture	6	Snap/push fitting	1
Lace harness	1	Bearing	2
Feed wire/cable through aperture	3	Snap/push fitting	2
Lace harness	1	Feed wire/cable through aperture	6
-	-	Lace harness	1
-	-	Feed wire/cable through aperture	3
-	-	Lace harness	1

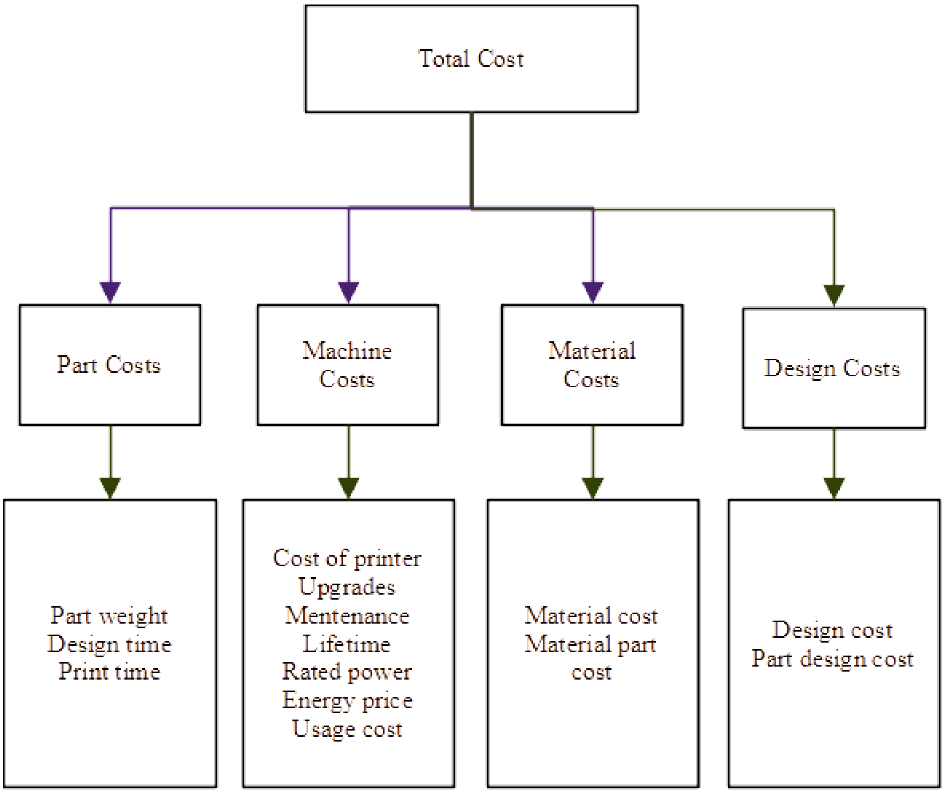

Fig.2. Diagram for 3D printing cost estimation

The prosthetic was developed to regain lost motor function of the human hand. It was intended for adults of all ages and could be provided on request. It was designed for use in undertaking activities of daily living. The prosthetic operated in two positions, either open or closed. Its operation permitted the user to grab objects. The prosthetic consisted of five fingers, with three segments each except for the thumb, that were attached to the palm with screws. The palm was linked to a socket with a hinge and on the socket 3 motors that pulled on cables from the fingers were attached. Tensioning of the cables by motor actuation of wrist contraction provided the motion of the prosthetic. We considered the index finger and its redesign here.

The CAD software FreeCAD (Freecad Project Association, Brussels, Belgium) was made for mechanical engineering design. It was intended to replace drafting and generate mechanical parts and assemblies with easier implementation and management. It was designed for use in typical engineering design offices. It operated on the lab computer. The design engineer provided input data and the software would return the output design model. The export operation permitted further analysis and improvement by other software packages. The software relied on computers with powerful graphics cards that can render complex geometries on screen.

The DFMA software package was developed to improve engineering design by considering multiple methodologies at once. It was intended for design optimization and cost reduction. It was designed for industrial applications that used production machinery to make parts. The DFMA software is divided into two smaller packages. The DFA package is used for assembly process optimization while the DFM package for manufacturing optimization. The software takes the CAD model, assembly processes and manufacturing processes as inputs and outputs optimization proposals based on assembly and manufacturing methodology improvements. Although the DFM software can analyse many technologies, 3D printing is not considered. To solve this issue, we compiled a spreadsheet calculator to determine the performance characteristics necessary to compare the two designs.

Implemented through case studies like presented in [16] the DFMA methodology is developed in this work alongside the redesign of a prosthetic finger device. We have improved a 3D printed upper-limb prosthetic design using the DFMA methodology with novel particularities presented in section 3 on DFMA Methodology for design improvement.

4. Results

Figure 3 displays the cost per part comparison between Design A and Design B using additive manufacturing for an upper limb prosthetic device subassembly. The cost per part for Design B is significantly lower than Design A's part costs. Manufacturing costs for the 3D printed parts of Design B outperform the Design A parts by a factor of 2, making the redesign an obvious improvement in this case. For example, in the case of the distal segment of the finger, the Design A part would cost $1.14 while in the Design B variant this would cost $0.72 less. Clearly, the findings indicate that Design B is the better choice for manufacturing of the prosthetic parts. It appears that the high customization aspect of the device makes it hard to be manufactured in technologies other than 3D printing. Conversely, the same situation appears for the middle and proximal segments of the finger subassembly. Ultimately, shape drives costs down and leads to improvements based on the DFM methodology.

Design A had several screws, nuts and bolts which had potential for removal as the analysis concluded. DFA indices were derived from the analysis study and are given in Figure 4. The DFA index was computed, and the results can be seen in Figure 4.

The DFA index difference shows that the proposed design, Design B, has an improved performance in the assembly process as compared to Design A. The difference is cause by for example, the removal of fasteners. The fasteners were replaced with snap joints. Similarly, to the DFM, we can say, that the design has been improved in the DFA methodology as well.

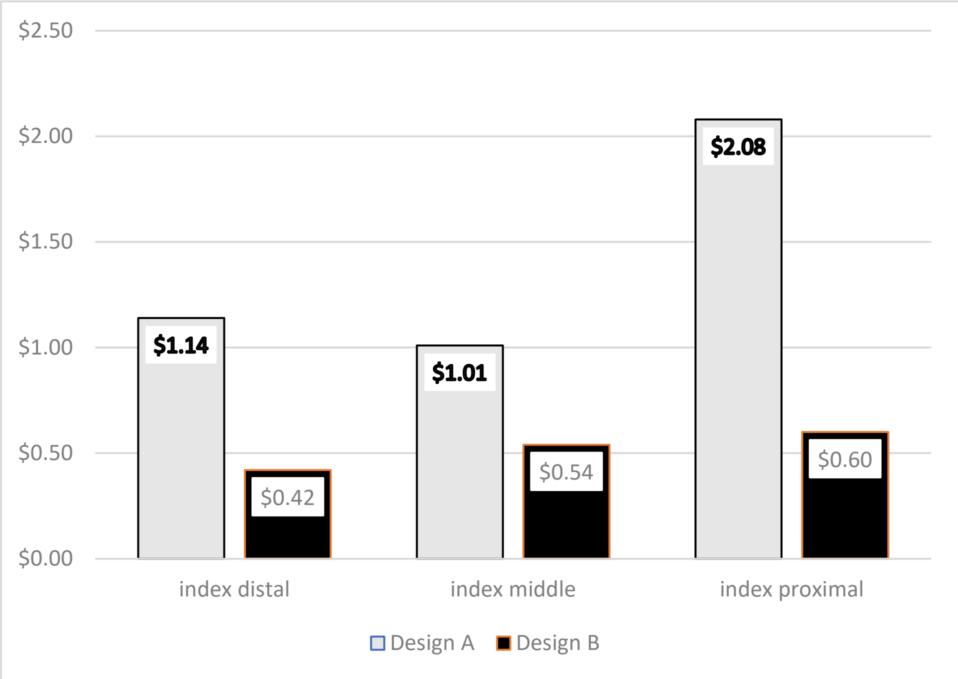

Fig.3. DFM cost comparison between 3D printing of Design A and Design B

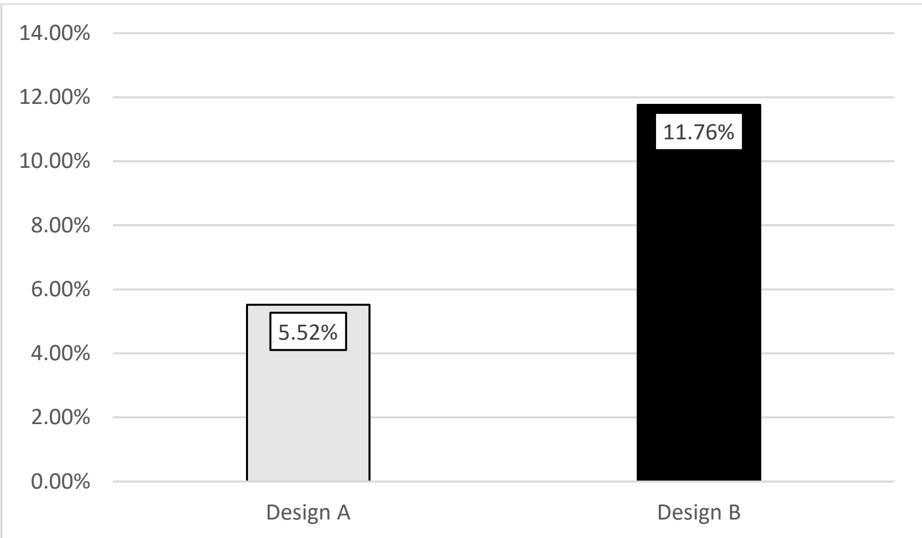

Fig.4. DFA index **comparison** between Design A and Design B

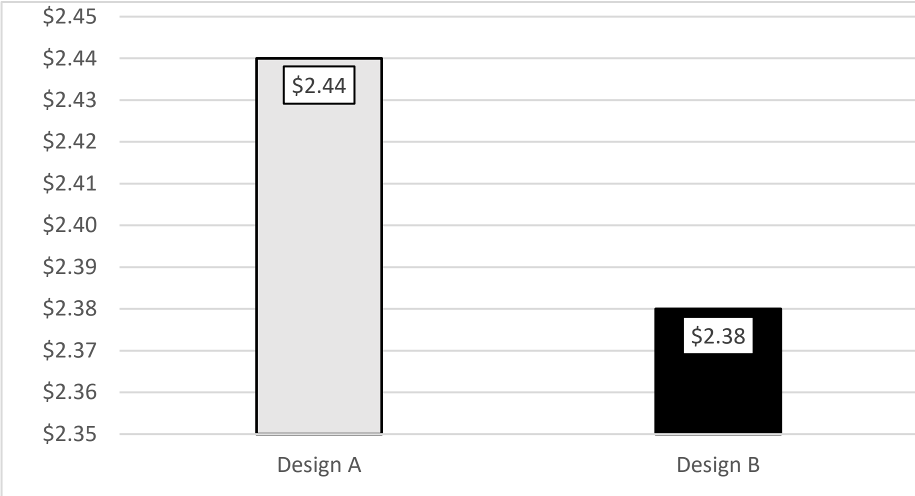

Fig.5. DFA total cost comparison between Design A and Design B

The total cost and total time comparison between Design A and Design B are displayed in Figure 5 and Figure 6. While the printing parameters are compared in Figure 7 and Figure 8.

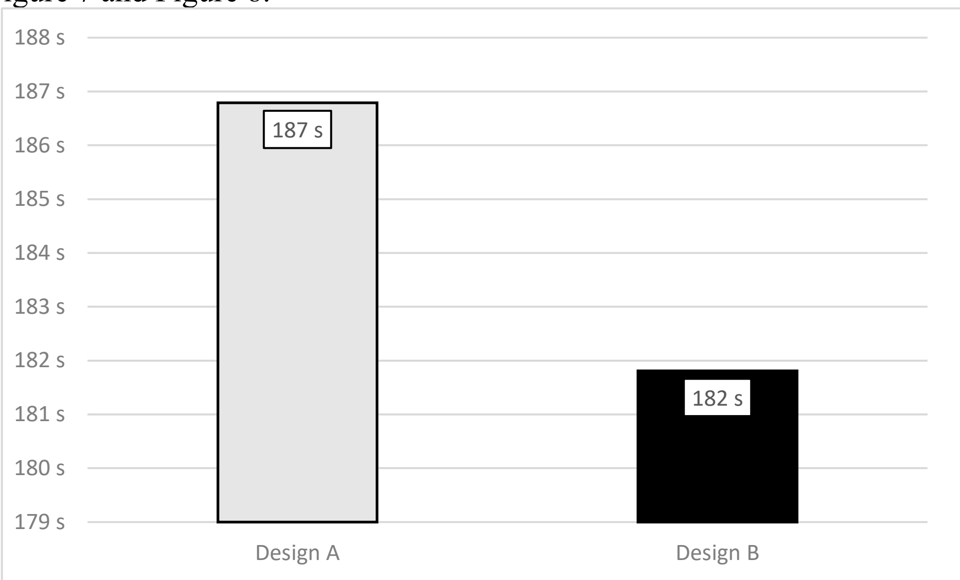

Fig.6. DFA total time comparison between Design A and Design B

Although the DFA index of our methodology results in a 6.24% efficiency gain, in this case study on knee prosthetics [17] the efficiency increases with 13.6%. In the case of this study [8] 16.48% was possible. Nevertheless, our methodology achieved an improvement.

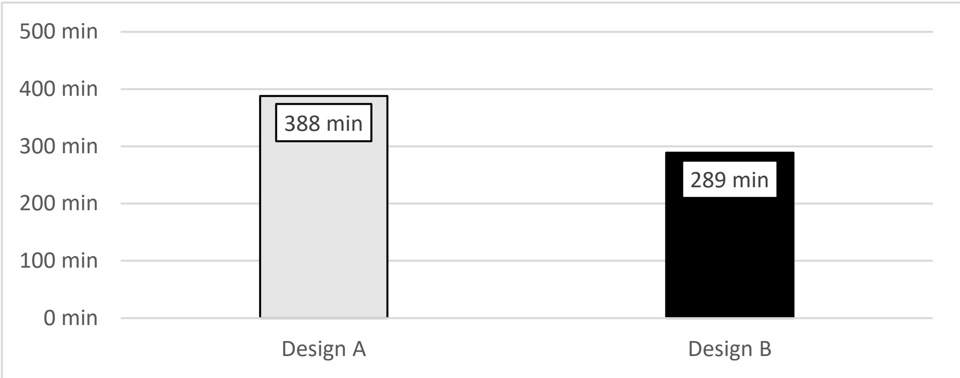

Fig.7. Printing time estimation **comparison** between Design A and Design B

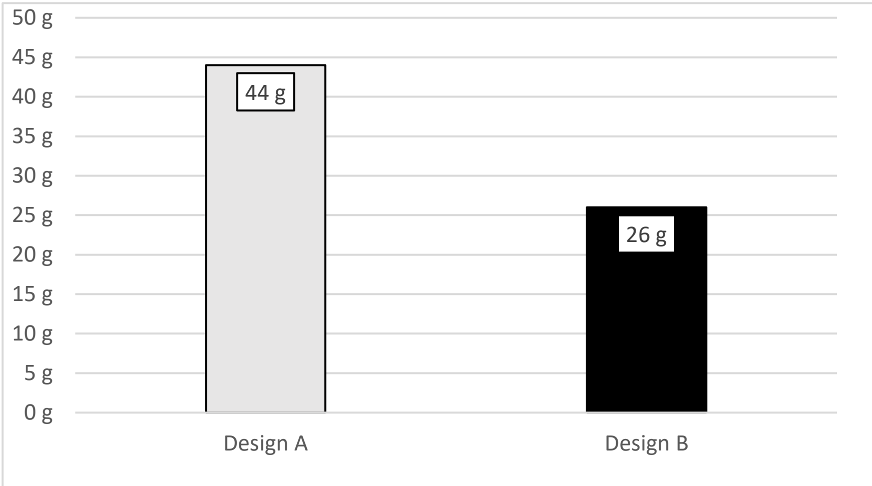

Fig.8. Weight of 3D printed parts estimation comparison of Design A and Design B

5. Discussion

The DFMA methodology implies that a positive engross improvement can be made upon the product if assembly and manufacturing factors are considered during the design stage. Consequently, the methodology is used in design strategy. Moreover, to improve the design efficiency, software like the DFMA considered in this work are used. Finally, both the methodology and software are introduced in the field of low-cost upper-limb prosthetic design by the present work.

The emerging additive manufacturing technologies coupled with the DFMA process led us to derive that existing generic designs of prosthetics have great potential if adapted to the new processes. The findings show that adapting generic designs to new technologies and using concepts like DFMA, can lead to improved prosthetic designs. One possible conclusion is that the design requirements for the new technologies are less demanding and have an impact on the performance of the design.

The DFA index shows an improvement in the design by more then 6% which results in a faster and cheaper assembly process for the proposed changes to the generic design. The total cost and total time shown in Figure 2 and Figure 3 gives evidence of improvement in cost and time reduction for the assembly process.

The DFM methodology outlined in Figure 4 reflects through Figure 6 3 cost reduction with manufacturing per segment. The reduction in printing and weight time shown in Figure 7 and Figure 8 demonstrate improvements in the DFM component of the study.

Extracting the cost and time parameters from the DFMA software gives the opportunity to compare cost and time for the 2 variations. The results in figures 5 and 6 suggest that Design B has a lower total cost and time associated with it.

This study has taken a step in the direction of defining a design methodology for low-cost, upper-limb prosthetic devices. It is possible of course that the commercial prosthetics industry may not benefit from this methodology as much as the low-cost open-source industry.

Low-cost prosthetic devices have seen a breakthrough with the rise of additive manufacturing. The presented designs are simplified, and the study does not address complex commercial devices. Usually, functionality in these types of prosthetics is sacrificed along with mechanical reliability and fit [18]. This is to provide a low-cost transitional device to aid amputees as they wait for their commercial variant.

The approach outlined in this study should be developed and applied to different parts of prosthetic devices to improve upon the proposed methodology and design process.

Although the results seem to indicate a performance increase of the design, no actual physical tests have been done to verify the validity of the results. No practical test has been conducted. Moreover, this might constitute the basis for further research.

Similar to [19] which presents a DFMA and sustainability approach the originality of this work is the illustration of the integration of DFMA into upper-limb prosthetic design for improved product design. Using the DFMA methodology in addition to rapid prototyping is a useful way to accelerate product development [20]. In the case of prosthetic device design development, we detailed the process on how this methodology might be applied to prosthetics.

The matter of conversion of time-to-money is considered and has been extracted from the DFMA software once every assembly step has been inserted and corelated with the cost of doing set operation. Despite this, an overall total cost was not established. Furthermore, an overall total cost of the product may depend greatly on the local technology and equipment used. Moreover, total cost may include non-engineering topics and items not related to the current work going as far as branding and marketing costs.

Socially, 3D printed upper-limb prosthetic devices improve quality of life for amputees. The present research is devoted to improving prosthetic design to empower people with low access to healthcare insurance. There are estimations of 3-4 people out of 100,000 that suffer from limb loss due to amputation [21]. Although these prosthetics are usually used as transitional devices, low-income households have no choice then to use them as final devices. Furthermore, the 3D printed prosthetics are also used in underdeveloped countries and war zones. Although neither sufficient research nor policy is enough, the research effort tries to improve devices through efforts like the present work.

In the current work the authors outlined a new design methodology approach for prosthetic devices. The presented case study and its highlighted experimental results show an encouraging outcome. Although the work of [1] covers a lot of manufacturing technologies, it does not offer a prosthetic device DFMA methodology. This leaves room for further research opportunities in the field.

6. Conclusion

The aim of this study has been to develop a methodology to improve generic designs of upper limb prosthetic designs. As the figures show, by using 3D printing and applying DFMA the design performance is increased from the DFM and DFA point of view. The relationship between using 3D printing and applying DFMA is quite strong and leads to innovation in high customization industries like the low-cost prosthetic device industry. These findings support the conclusions of other studies that DFMA included among other processes may enhance designs in the industry where it is applied.

We have presented a case study of a finger prosthetic design. The initial generic design was improved using the proposed DFMA variation for prosthetic devices proposed in section 3 on DFMA Methodology for design improvement. The novel design methodology regarding prosthetic design using a variation of the DFMA methodology and additive manufacturing. This has led to a gain of more than 6% in efficiency.

R E F E R E N C E S

[1] G. Boothroyd, P. Dewhurst, and W. A. Knight, *Product Design for Manufacture and Assembly*, Third Edition. CRC Press, 2010.

[2] D. Dobre, *Product development Basic theory and case studies*. Bucharest: Bren, 2014.

[3] C. Favi, R. Garziera, and F. Campi, ‘A Rule-Based System to Promote Design for Manufacturing and Assembly in the Development of Welded Structure: Method and Tool Proposition’, *Appl. Sci.*, vol. 11, no. 5, Art. no. 5, Jan. 2021, doi: 10.3390/app11052326.

[4] S. Abrishami and R. Martín-Durán, ‘BIM and DfMA: A Paradigm of New Opportunities’, *Sustainability*, Art. no. 17, doi: 10.3390/su13179591.

[5] K. Chen and W. Lu, 'Design for Manufacture and Assembly Oriented Design Approach to a Curtain Wall System: A Case Study of a Commercial Building in Wuhan, China', *Sustainability*, vol. 10, no. 7, Art. no. 7, Jul. 2018, doi: 10.3390/su10072211.
[6] A. I. Juniani, M. L. Singgih, and P. D. Karningsih, 'Design for Manufacturing, Assembly, and Reliability: An Integrated Framework for Product Redesign and Innovation', *Designs*, vol. 6, no. 5, Art. no. 5, Oct. 2022, doi: 10.3390/designs6050088.
[7] H. S. Mohammed and J. M. Salman, 'Design and Modeling the Prosthetic Foot from Suitable Composite Materials', *Am. J. Eng. Appl. Sci.*, vol. 13, no. 3, pp. 516–522, Sep. 2020, doi: 10.3844/ajeassp.2020.516.522.
[8] F. Ferryanto, K. A. Muhammad, T. Rubiyanto, S. Mihradi, A. I. Mahyuddin, and T. Dirgantara, 'Design Modification of an Affordable Prosthetic Knee Based on DFMA and Static Analysis', in *2017 5th International Conference on Instrumentation, Communications, Information Technology, and Biomedical Engineering (ICICI-BME)*, Nov. 2017, pp. 125–130. doi: 10.1109/ICICI-BME.2017.8537726.
[9] O. Castiblanco and I. Shareef, 'Optimization of StepLock® Orthotic Knee Joint Design', *Procedia Manuf.*, vol. 10, pp. 622–633, Jan. 2017, doi: 10.1016/j.promfg.2017.07.065.
[10] A. Manero *et al.*, 'Evolving 3D-Printing Strategies for Structural and Cosmetic Components in Upper Limb Prosthesis', *Prosthesis*, vol. 5, no. 1, Art. no. 1, Mar. 2023, doi: 10.3390/prosthesis5010013.
[11] K. Xu and S. Qin, 'An Interdisciplinary Approach and Advanced Techniques for Enhanced 3D-Printed Upper Limb Prosthetic Socket Design: A Literature Review', *Actuators*, vol. 12, no. 6, Art. no. 6, Jun. 2023, doi: 10.3390/act12060223.
[12] S. Narumi, X. Huang, J. Lee, H. Kambara, Y. Kang, and D. Shin, 'A Design of Biomimetic Prosthetic Hand', *Actuators*, vol. 11, no. 6, Art. no. 6, Jun. 2022, doi: 10.3390/act11060167.
[13] J. W. Park, B. Greenspan, T. Tabb, E. Gallo, and A. Danielescu, '3D Printed Energy Return Elements for Upper Limb Sports Prosthetics', *Prosthesis*, vol. 5, no. 1, Art. no. 1, Mar. 2023, doi: 10.3390/prosthesis5010002.
[14] S. Hällgren, L. Pejryd, and J. Ekengren, '(Re)Design for Additive Manufacturing', in *Procedia CIRP*, in 26th CIRP Design Conference, vol. 50. Jan. 2016, pp. 246–251. doi: 10.1016/j.procir.2016.04.150.
[15] N. Valter, *Design for manufacturing and assembly DFMA*. Bucharest: Bren, 2019.
[16] K. M. Antony and S. Arunkumar, 'DFMA and Sustainability Analysis in Product Design', in *Journal of Physics: Conference Series*, IOP Publishing, Feb. 2020, p. 012028. doi: 10.1088/1742-6596/1455/1/012028.
[17] T. Mangera, F. Kienhöfer, K. Carlson, M. Conning, T. Purkis, and G. Govender, 'Design for manufacture and assembly of a polycentric paediatric prosthetic knee', *Proc. Inst. Mech. Eng. Part B J. Eng. Manuf.*, vol. 233, no. 14, pp. 2566–2576, Dec. 2019, doi: 10.1177/0954405419840555.
[18] J. Zuniga *et al.*, 'Cyborg beast: a low-cost 3d-printed prosthetic hand for children with upper-limb differences', *BMC Res. Notes*, vol. 8, no. 1, p. 10, 2015, doi: 10.1186/s13104-015-0971-9.
[19] A. Subbaiah and K. M. Antony, 'Integration of DFMA and sustainability - A case study', *Int. J. Sustain. Eng.*, vol. 14, no. 3, pp. 343–356, May 2021, doi: 10.1080/19397038.2020.1871443.
[20] J. Raplee, 'DFMA to RP, ASAP', *Mech. Eng.*, vol. 121, no. 09, pp. 72–74, Sep. 1999, doi: 10.1115/1.1999-SEP-5.
[21] D. Latour, 'Advances in Upper Extremity Prosthetic Technology: Rehabilitation and the Interprofessional Team', *Curr. Phys. Med. Rehabil. Rep.*, vol. 10, no. 2, pp. 71–76, 2022, doi: 10.1007/s40141-022-00342-x.