ISSN 1392 - 1207. MECHANIKA. 2012 Volume 18(5): 600-604

Development of decision support system for fused deposition modelling manufacturing cost estimation

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crossref http://dx.doi.org/10.5755/j01.mech.18.5.2705

1. Introduction

Additive layer manufacturing has been known for many years. But the development of electronic and computer technologies has dramatically changed its processes and products. In addition, the global market counts new and new rapid prototyping technologies that allow fulfilling growing consumer requirements [1]. Rapid prototyping is a reliable technology that allows developing complex prototyping models and checking their design in early manufacturing stage. More over, rapidly developing technologies and the variety of new materials made it perfectly suitable not only for serial production of small complex parts, but also for such specific areas as biomedicine, aviation, and aerospace industry [2, 3]. In contemporary global competition environment, various rapid prototyping technologies find their place. More over, today we use the term “rapid manufacturing” that overwhelms the entire product design and manufacturing cycle, and is charactersised by the use of extremely sophisticated designing and manufacturing tools and processes. Thus we can maintain that rapid manufacturing became one of the most important elements of virtual manufacturing, which might be successfully used not only in traditional manufacturing, but also in rapid prototyping, teaching, and other areas [4]. Meanwhile, virtual manufacturing might be described as a process when physical manufacturing processes are designed with a help of artificial intelligence techniques leading to the reduction of production costs [5]. Thus, product designer must keep tight connection with the manufacturer, understand manufacturing processes used, and apply design for manufacturing (DFM) principles. Constant cooperation of various functional divisions, design and improvement of technological processes, and the application of optimisation and decision support processes lead to digital manufacturing [6]. Recent progress in computer aided design (CAD) and rapid prototyping technologies gave designers the tool to rapidly create an initial prototype from the concept only [7]. In order to fulfil growing consumer requirements, manufacturers must take into account not only functional characteristics of materials, but also such features of prototypes as aesthetic look, preciseness, and colour. Manufacturing costs, i.e. manufacturing time, model and support materials consumed, post-processing time, and similar expenditures, play an extremely significant role too. However, the system that might be capable of evaluating manufacturing costs of all rapid prototyping technologies in general is almost impossible; as such technologies and their manufacturing costs extremely differ. Slovenian scientists revealed technical features, especially, manufacturing rate and preciseness, of various rapid prototyping systems in their numerous publications. One of their conclusions states, that precise evaluation of manufacturing rate is impossible without the pre-testing of the machine [8]. The variety of materials, processes, and systems do not allow making conclusions on all technologies. However, 40% of all rapid prototyping systems of the world are marked with *Stratasys* brand. Such systems use fused deposition modelling technology. Fused deposition modelling is a solid-based rapid prototyping process where thermoplastic semi-finished products are extruded layer by layer in order to build functional models [9]. This technology has several advantages, but probably the most important one is simple and user-friendly environment [10]. We can outline few factors influencing the popularity of fused deposition modelling technology all over the world. First and the most important one is the variety of materials capable for being used in various industries.

Therefore, this article will concentrate on the analysis of fused deposition modelling processes. It has been noticed, that scientists lack for the information in regards to the calculation of manufacturing costs using fused deposition modelling technology, especially, in early stage of manufacturing process. This article will reveal such features of prototype construction and manufacturing process that have the greatest influence on manufacturing costs. Decision support system (DSS), created by the authors should help designers to evaluate alternative prototypes and allow manufacturers to optimally prepare manufacturing process already in early manufacturing stage.

2. Methodology

Fused deposition modelling technology has been widely described in a large number of scientific publications [11-13]. However, few facts, showing why it is so special, are worth to mention. First of all, this technology differs from the other technologies since it uses melted thermoplastic as model material; it might be recyclable production-grade thermoplastic acrylonitrile butadiene styrene (ABS); polycarbonate (PC), which has better mechanical properties than ABS; and polyphenylsulfone (PPSU/PPSF) featuring good strength, heat, and chemical resistance properties necessary for aerospace, automotive, and medicinal applications. Acrylonitrile butadiene styrene (ABS) is the most popular thermoplastic with such application, since it is ideal for the purpose of conceptual prototyping through design verification and is available in a variety of standard and custom colours [14]. Fused deposition modelling requires two types of material: model and support materials. Model and support material are melted in a plastifying unit and extruded through a die onto a platform to create a two-dimensional cross-section of the model. Subsequently, the platform is lowered and the next layer is extruded and fused onto the previous layer. A strand of melted plastic forms a frame of one layer obtained after decomposing part's CAD model to the layers. Model decomposition to the layers is performed using special software, which is acquired together with the machines involved. Here it is important to mention, that strands of overlapping layers are positioned with a turn at 90°. Layer images are presented in Fig. 1, disclosing also layers "N" and "N-1" what ensures better homogeneity and mechanical properties of the prototype. One of the main weaknesses of fused deposition modelling is surface roughness, which happens due to some specialities of the technological process. Of course, there are methods that help making surface quality better, but they need additional work and other expenditures [14, 15].

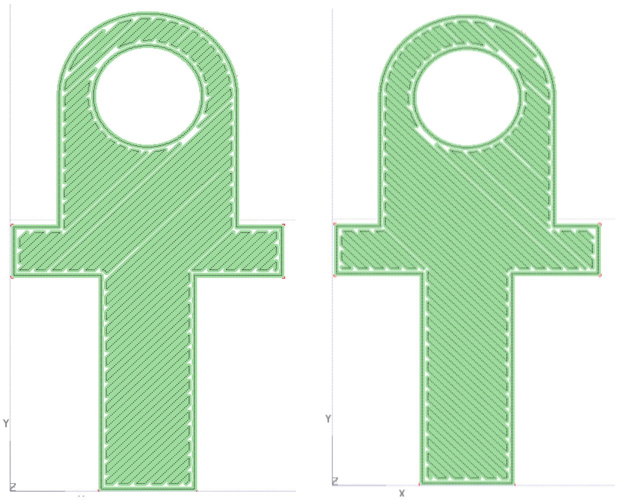

Fig. 1 Model decomposition to layers

Using fused deposition modelling technology, manufacturing costs depend on various parameters. Before going into details of the process, it is worth defining its three stages: preparation, manufacturing, and post-processing. Then manufacturing time may be calculated as follows

$$T_t = T_p + T_m + T_{post} \quad (1)$$

where T_{p} stands for the preparation time, T_m stands for the manufacturing time, T_{post} stands for support time. The preparation involves designing, converting data to "stl" format, searching and correcting errors, transmitting data to the machine, and preparing the machine. Support time encompasses prototype's taking out of the machine, removing support materials, and preparing for work. The author of the article does not take into account the preparation and the support times of the model provided herein, since they greatly depend on human factors and the structure of the part. Thus, the manufacturing time may be calculated as follows

$$T_m = \sum_{i=1}^{n} \left(tm_i + ts_i + tc \right) + th \quad (2)$$

where tm_i is the time of spraying one layer of model material, ts_i is the time of spraying one layer of support fill, tc is the time spent on cleaning a nozzle end for one layer, and th is the time necessary for the machine to reach work temperature. Although th is easily found and usually depends on the type of the machine used, other variables are not so easily assessed and controlled. Designers can modify product's structure and reduce the volume of model material with a help of traditional 3D CAD modelling systems and DFM principles. However defining the quantity of support fill is extremely difficult or it required additional software. On the other hand, the estimation of manufacturing costs also needs additional software. Therefore, designers, aiming to check several constructional alternatives and their manufacturing costs, must use special software or their own experience [16]. Prototype's manufacturing time depends on model and support materials consumed. Fig. 2 shows the dependence of manufacturing time on quantity of the materials. However, it also obvious that manufacturing time differs up to several hours even when the material quantity is very similar. Thus, the manufacturing time also depends on other parameters, such as positioning of the prototype, layer thickness, support fill, and model interior.

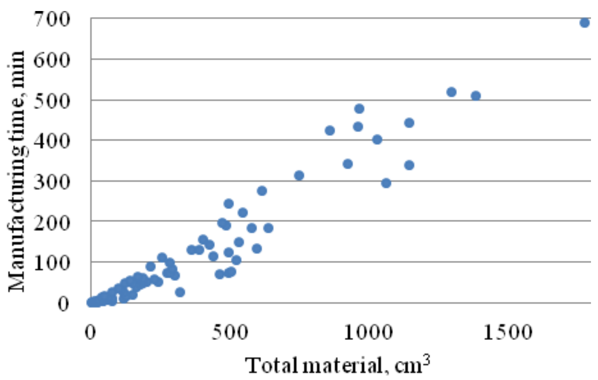

Fig. 2 Dependence of manufacturing time on quantity of the material

One of the objectives of this article is to identify the main parameters that affect manufacturing costs and propose a decision support system that would allow minimising manufacturing costs in early manufacturing stage. Another objective is to check whether the algorithm used by the program "CatalystEX" always rationally chooses positioning of the prototype. Prototyping was performed with a help of 3D CAD modelling system "SolidWorks". The CAD data were converted into standard triangular language (STL) format.

Table

Design parameters for the decision support system

Design parameter	Parameter range
Model material, cm^3	0.08-657
Support material, cm^3	0.12-65.09
Material type	ABS
Layer thickness, mm	0.254, 0.3302
Support fill	Basic, sparse, minimal, break-away, surround
Model interior	Solid-normal, sparse

Manufacturing costs' modelling was performed using fused deposition modelling manufacturing preparation program "CatalystEX". The research involved one hundred prototypes of various geometrical shapes and sizes that are commonly available in plastic parts. Table delivers marginal parameters of parts used for the creation of decision support system. Other important parameters, such as prototype's preciseness and roughness as well as hardness of prototype surface, are not analysed in this article. Fig. 3 shows percentage distribution of model and support materials. It is important to note that the parts were ranged by quantity of the model material in ascending order. We can see that bigger prototypes need less quantity of support material, while smaller prototypes may need up to 60% of support material. The quantity of support material may be reduced by changing positioning of the prototype during the manufacturing process. In addition, certain prototype design rules must be obeyed.

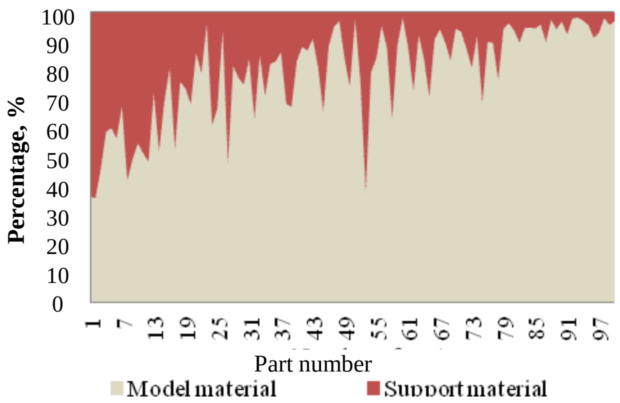

Fig. 3 Percentage distribution of model and support material

Also, it is important mentioning that the results shown in Fig. 2, where obtained using standard parameters of program "CatalystEX", when layer thickness is 0.254 mm, model interior is solid normal, support fill is sparse, and prototype positioning is performed with a help of function "auto orient".

Of course, when aiming to reduce the manufacturing time, it is necessary to reduce prototype's height in the direction of Z axis, but the experiments show that prototype's positioning in X-Y plane is important too. Here, the manufacturing time greatly depends on parameters of the machine. It was defined that the machine performs greater work movement in the direction of X or Y axis than when it's moving by a curve. However, the software does not always assess it properly, thus the manufacturing time and material expenditures become non-rational. The experiments were performed using fused deposition modelling machine BST 768. It is a middle-class machine with mechanically removed support material.

3. Results

The analysis of the manufacturing time in relation to layer thickness was performed first. In the first case, we have used standard thickness of 0.254 mm and then modelled the same parts with layer thickness of 0.3302 mm. Positioning was not changed, i.e. we used function "auto orient" in both cases. Fig. 4 clearly shows that the manufacturing time was reduced by 20-40% after the increase of layer thickness. Data shown in Fig. 4 are ranged by the quantity of model material in ascending order. The figure also shows the presence of some parts that did not feature the change of manufacturing time after changing the layer thickness. This is characteristic to parts with small volume and height in the direction of Z axis. Two parts distinguish by the decrease of their manufacturing time by 50–60%.

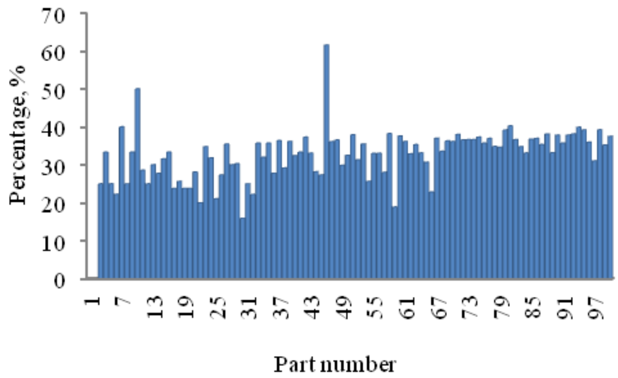

Fig. 4 Percentage distribution of the manufacturing time

These prototypes are of cylinder shape with two large openings. As for manufacturing of larger prototypes, the change in layer thickness reduces manufacturing time at greater extend. However, this experiment showed that the changed layer thickness influence the change in quantities of model and support materials. If model material changes at minor extend (decreases after the increase of layer thickness), the quantity of support material changes greatly and, in most cases, it increases. This might be explained by the fact that the parts need better support systems after reduction of layer thickness. Fig. 5 shows the consumption of model and support materials when the layer thickness is 0.3304 mm. The results are compared to the basic, when layer thickness is 0.254 mm. Fig. 5 shows that model material might be saved up, however support materials lacks, i.e. it will be used at greater extend when the layer is thicker. Although, the fluctuations are not large, they should be taken into account when designing and manufacturing the prototype. In this case, model and support materials have the same price, thus the most important figure is material consumption rate. Total material consumption rate of 82 parts was negative, since they needed more materials. After changing the layer thickness, 2 parts needed the same amount of materials, but the rest of them needed less.

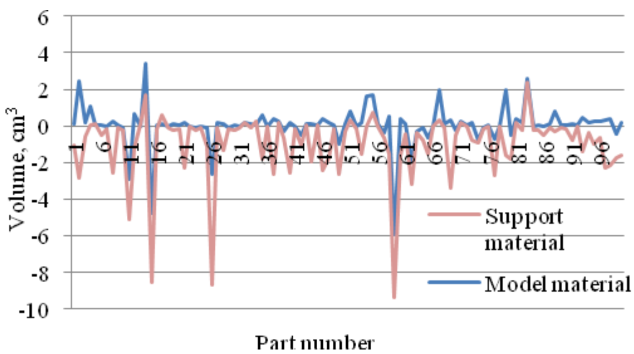

Fig. 5 Material consumption when layer thickness is 0.33 mm

The decision support system created was employed for the analysis of manufacturing costs. The experiment involved 100 parts. As it was mentioned before, manufacturing costs mostly depend on the manufacturing time and material consumption. The reference point was the automatic positioning performed with the help of the program "CatalystEX". Then, the positioning was repeated employing the rules defined. The research of model material consumption disclosed that the model material is consumed almost without changes. In addition, the research disclosed the interrelation between the consumption of model material and the positioning of parts. There is a tendency that the quantity of model material of small parts changes at greater extend, and it may constitute up to 3% of total quantity of the model material. While, the change in model material consumption of bigger parts (with volume above 35 cm^3) does not exceed 1%or remains unchanged in most cases. Changing positioning of the parts discloses more clear tendencies when comparing the quantities of support material. Fig. 6 shows changes in support material followed by the changes of positioning.

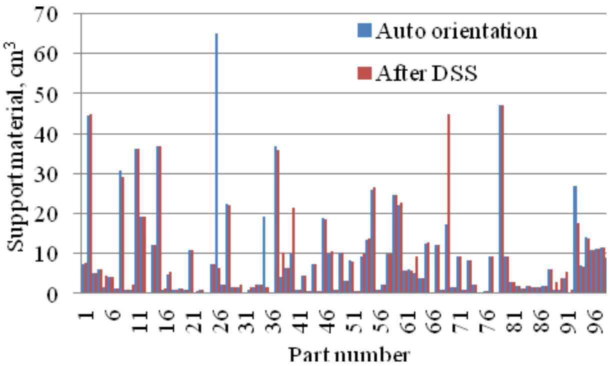

Fig. 6 Change of support material

After the change of part positioning, the quantity of support material slightly increased or remained the same in most cases. However the figure shows a few parts where the quantity of support material increased significantly. This might be explained by the fact that DSS was aimed at minimisation of manufacturing time. The increase in quantity of support material should not necessarily lead to the increase of the manufacturing time. On the other hand, the Fig. 6 shows a presence of the parts with significantly decreased quantity of support material. Extremely outstands part 26. However, the analysis shows that it was a part of cylinder shape with a big opening inside.

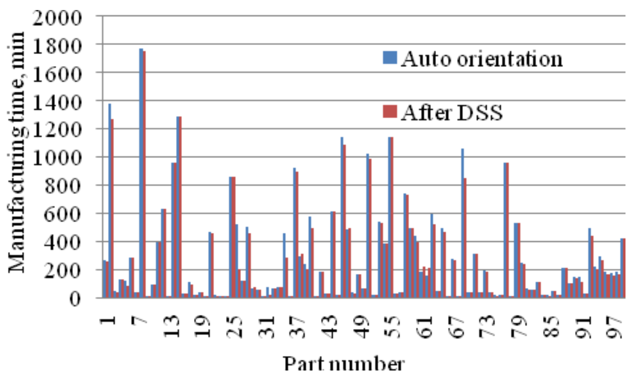

Fig. 7 The comparison of the manufacturing time using DSS

One of DSS rules maintains that interior openings of the parts shall be oriented vertically, if possible. Thus, in the first case, when the part was laid horizontally, all its openings had to be filled with support material, what is not necessary in this case. While the main objective of the article is to create a DSS that would enable rational choice of the best manufacturing alternative using fused deposition modelling technology, the focus should be on the optimisation of manufacturing time. Fig. 7 shows the manufacturing time before and after the use of DSS. Thirty nine parts of one hundred used showed equal manufacturing time in both cases. After a closer look at the structure of these parts, it was noticed that they are mostly small cylindrical parts. Fifty three parts needed less manufacturing time after the application of DSS. In eight cases, manufacturing time increased after the application of DSS. In total, the manufacturing time of one hundred parts decreased by 1554 minutes. Twenty six parts reduced their manufacturing time by 315 minutes; the consumption of support material significantly decreased too. Thus, we can conclude that the manufacturing time was reduced due to the difference of materials consumed in this case. However, the manufacturing time of other parts decreased by 1.4-30% in comparison to the manufacturing when the DSS was not used. In regards to the increased manufacturing time, there was only one part with the increase of 19%, and the other seven showed not greater increase than 7%. The biggest part of them were small sized parts.

4. Conclusions and discussions

The article analysed the impact of various parameters on manufacturing costs when using one of rapid prototyping technologies – fused deposition modelling. Manufacturing costs were forecasted in early manufacturing stage, and the DSS created will enable engineers choosing the best solution in real manufacturing processes. The article identified the most important parameters that influence the manufacturing costs; they are: material consumption, structure of the parts, and manufacturing parameters (layer thickness and positioning during the manufacturing). The presented methodology and DSS provide a solution that fills the research gap and might be helpful for making decisions in everyday practice. Performed research enables to make following conclusions:

1. The manufacturing time decreases from 20 to 40% after the increase of layer thickness from 0.254 to 0.3303 mm. The manufacturing time changes when the height of the part in direction of Z axis is small.

2. The change in layer thickness leads to greater consumption of support material and less consumption of model material; however, it does not have significant impact on manufacturing costs.

3. The manufacturing time of 53 parts used within the research decreased by 1.4-30% after the use of DSS, 39 parts remained unchanged and of 8 parts increased.

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SPRENDIMŲ PRIĖMIMO SISTEMOS SUKŪRIMAS GAMYBOS SĄNAUDOMS ĮVERTINTI TAIKANT LYDŽIOS MASĖS FORMAVIMO TECHNOLOGIJĄ

R e z i u m ė

Straipsnyje pateiktas sprendimų priėmimo sistemos modelis, skirtas gamybos sąnaudoms optimizuoti taikant lydžios masės formavimo technologiją. Pirmiausia nustatyti parametrai, kurie turi didžiausią įtaką gamybos sąnaudoms – sunaudotos medžiagos kiekis, detalės konstrukcija, sluoksnio storis, pozicionavimas gamybos metu. Straipsnyje pateikti rezultatai leidžia patikrinti sukurtos sprendimų priėmimo sistemos tikslumą.

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DEVELOPMENT OF DECISION SUPPORT SYSTEM FOR FUSED DEPOSITION MODELLING MANUFACTURING COST ESTIMATION

S u m m a r y

The article delivers a model of decision support system aimed at the optimization of manufacturing costs using fused deposition modeling technology. First, it identifies parameters that influence the manufacturing costs; they are: material consumption, the structure of parts, and manufacturing parameters (layer thickness and positioning during the manufacturing). The article delivers the results that allow assessing the preciseness of decision support system created.

Keywords: rapid manufacturing, cost estimation, fused deposition modelling.

Received August 23, 2011
Accepted October 19, 2012