An internal combustion engine visualization physical prototype applying digital manufacturing

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Abstract. Nowadays computers have invaded all levels of production, thus improving the quality and quantity of products. Digital manufacturing involves all tools for design, simulate, and programming machine tools in order to manufacture prototypes or tools for production use. This project is a case study of digital manufacturing for prototyping of an internal combustion engine visualization model. Solidworks is used for 3D modeling of all parts of the engine. Fused filament fabrication (FFF) is used for physical modeling of the engine parts. Pros and cons of the manufacturing process are discussed. It is concluded that parameter optimization is needed in order to improve quality indicators of the 3D printed engine parts.

1. Introduction
Digital manufacturing is a manufacturing process which uses a variety of methods such as computer networks, rapid prototyping/additive manufacturing and database in order to analyze, organize and recombine the product, process and resource information [1]. Digital manufacturing has several advantages such as shortening of development time and cost, integration of knowledge coming from different manufacturing departments and manufacturing of parts and products in numerous production sites [2, 3]. In the future, it is expected that digital manufacturing will have the ability to generate and simulate more accurate alternative solutions for a number of product design activities [4-8].

Additive Manufacturing (AM) is a procedure of joining materials in order to manufacture parts from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing technologies [9]. AM is able to produce complex shapes and it has applications in various areas like automotive, aerospace, defense, medical, consumer products, architecture etc. [10]. A popular type of additive manufacturing method is Fused Filament Fabrication (FFF). The FFF process involves deposition of a filament of a thermoplastic material into thin layers which are cooled very fast (with cold fan) thus the next layer can be added into the previous layer [11]. Although traditional-subtractive manufacturing is preferred for producing high amount of similar objects, when a variety of materials is needed or the creation of large parts is aimed, 3D printing is preferred [12].

Many researcher reviewed pros and cons of using additive manufacturing methods for producing parts for various applications. Ngo et al. [13] reviewed 3D printing especially its benefits and drawbacks for future research and development. They included freedom of design, customization and ability to print complex structures as the main advantages in 3D printing and they mentioned high costs, limited applications in large structures and mass production, inferior and anisotropic mechanical properties and
limitation of materials and defects as major drawbacks. Camacho et al [14] provided an up-to-date review of experimental AM technologies in construction. They concluded that more research is needed to fully realize AM as a cost-effective and reliable option in the construction industry and its potential benefits. Niaki et al [15] mentioned in their work that companies have been benefited from potential opportunities of AM methods (i.e. distributed supply chain, light-weighting, integrated design, etc.) to improve their sustainability performance. Also, small percentage of companies adopted AM because of the environmental benefits.

This study is focused on the prototyping of an internal combustion engine visualization model. First all parts of the engine were designed using a CAD software and then they were constructed using 3D printing. The advantages and disadvantages of whole manufacturing process as well as future research perspectives and development of this work are discussed.

2. Technical details and experimental work
In this research Solidworks software was used for designing the internal combustion engine parts. Makerbot software was also used to guide and adjust the various parameters for the proper process printing. All designs were extruded in STL format and printed by Wanhao Duplicator 4X 3D printer (figure 1). The printing material which is used in this study is polylactic acid (PLA). PLA is a biodegradable, bioabsorbable and renewable thermoplastic polyester and has excellent mechanical strength and processability [16-17]. Suitable process parameters have been selected (table 1) trying to achieve the best quality of printed items. High printing temperature is associated with good surface finish [6], while it has been found that PLA material has better dimensional accuracy than ABS [18].

The whole manufacturing process consists of the following steps:
• Design of the 3D parts of the internal combustion engine in a CAD system.
• Preparation of the 3D printer by selecting suitable printing settings.
• Construction of the engine parts.
• Finishing of the parts after the construction.
• Assembly of the finished parts and visualization of the internal combustion engine model.

Three significant internal combustion engine parts designed, namely piston, connecting rod, crankshaft, cylinder block and head. As it mentioned in Section 2, in order to construct 3D models of parts, Solidworks software was used. Figures 2, 3, 4, 5 and 6 present all the engine parts designs.
Table 1. 3D printer parameters.

| Parameters                | Levels        |
|---------------------------|---------------|
| Extruder temperature     | 210 °C        |
| Platform temperature     | 60 °C         |
| Print speed              | 150 mm/sec    |
| Fill density             | 15 %          |

Figure 2. Connecting rod 3D design.

Figure 3. Piston 3D design.

Figure 4. Crankshaft 3D design.

Figure 5. Cylinder head 3D design.

Figure 6. Cylinder block 3D model.
After the proper printing parameters were selected (see table 1), all parts were constructed. Figures 7 and 8 present piston’s and cylinder block’s printing. Finishing and assembly of all parts was executed and the model of the engine took its final form. Figure 9 is shown the internal combustion engine model.

![Figure 7. Construction of the piston.](image)

![Figure 8. Construction of the cylinder block.](image)  
![Figure 9. The internal combustion engine model.](image)

3. Discussion
Designing and building this complex internal combustion engine using fused filament fabrication method has revealed a number of quality issues. The model has poor surface finish and dimensional accuracy, something that it can been seen in figure 9. Both these problems create an overall low quality product. The reasons are considered to be the process parameter values [19] as well as printer stiffness [20-21].

A plethora of 3D printers (also known as rapid prototyping machines or additive manufacturing equipment) that achieve better quality is existed in the market [22-23]. But, this is not an issue for this work. At this study a low-cost 3D-printing visualization prototype is attempted.

Optimization of the process parameters for these kind of parts is needed. Extruder printing temperature as well as different printing speed and fill density levels should be optimized in order to achieve the best quality product. However, this experiment is a first attempt for making complex shapes
using the process parameter values mentioned in table 1 and it is a benchmark for other experimental works like this one.

A plethora of 3D printers (also known as rapid prototyping machines or additive manufacturing equipment) that achieve better quality exist at the market, but at this study a low-cost 3D-printing visualization prototype is attempted. Moreover, other 3D printing methods such as Polyjet and Laser Stereolithography (SLA) are used by automotive and motorsport industries [24] and they are considered to give the best achievable quality. For example, Dolan et al. [25] used Selective Laser Melting – SLM (or Direct Metal Laser Sintering - DMLS), which is also a 3D printing method, to produce a piston for heavy-duty diesel engine and they showed that 3D printed pistons are an excellent choice for combustion development. In this research, the FFF method is utilized for producing the internal combustion engine parts in order to explore its results on making such complex models.

4. Conclusions
This study concerns the construction of an internal combustion engine visualization model using a popular 3D printing method, fused filament fabrication (FFF). All parts of the engine designed using a CAD software and printed one by one. It is revealed that the whole process has its advantages and disadvantages.

Using 3D printing for creating visualization models like this, can significantly reduce production time and cost. By means of use of additive manufacturing methods, it is possible to reduce essentially expenses on equipment manufacturing and material supplies and raise production efficiency. This is useful for all AM applications mentioned in the “Introduction” section.

On the other hand, the fabrication of this visualization model showed that 3D printing of complex shapes has poor performance at dimensional accuracy and surface roughness. This leads to bad surface finish and rough surface quality, which creates problems for fit and function models. More research is needed in order to fully determine which factors affect dimensional accuracy and surface roughness of complex models like the one that is fabricated in this work.

For future perspectives it could be mentioned that finite element simulation of this work can be used for searching the quality issues described above.

Acknowledgements
The Authors are grateful to Ilias Alexandridis and Apostolos Avranas for the digital drawings of the internal combustion machine parts.

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