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Original scientific paper

DESIGN PROCESS OF COMPLEX PRODUCT SHAPE WITH LATTICE VORONOI'S STRUCTURE USING CAx TOOLS

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A b s t r a c t: The aim of this paper is to present the design process of creating complex product shapes in industrial design with lattice Voronoi's structure using CAx tools. Complex product shapes have often been used in industrial design. Nowadays, the creation of products with complex shapes is possible using modern software package Fusion 360, using CAx tools and Additive Manufacturing (AM) technologies for rapid production and verification of prototypes. In this context, this paper focuses on a design process which incorporates the lattice Voronoi's structure as a topology optimization technique. The AM technology with Fused Filament Fabrication (FFF) 3D printing was chosen due to its ability to create products with rapid prototyping technology, as well as the complexity of the product shape. The design process includes conceptual design, 3D modeling and parametric design, preparation for production with 3D printing as well as testing to verify the product design. For prototyping of the product design an open-source system is used. The product model is designed and prototyped by the students with the use of 3D printing FFF technology.

Key words: design process; complex product shape; CAx; Fused Filament Fabrication (FFF)

ПРОЦЕС НА ДИЗАЈНИРАЊЕ СЛОЖЕНИ ОБЛИЦИ НА ПРОИЗВОД СО РЕШЕТКАВИ ВОРОНОИЕВИ СТРУКТУРИ И УПОТРЕБА НА АЛАТКИТЕ CAx

А п с т р а к т: Целта на овој труд е да се презентира процесот на дизајн за креирање сложени облици во индустрискиот дизајн со употреба на решеткава Вороноиева структура со употреба на алатките CAx. Сложените облици на производите често се употребуваат во индустрискиот дизајн. Денес креирањето на производи со сложени облици е овозможено со употреба на модерниот софтверски пакет Fusion 360, алатките CAx и адитивните технологии за брзо производство и верификација на прототипите. Во тој контекст, овој труд се фокусира на дизајнирање на процес кој вклучува решеткава Вороноиева структура како тополошка техника за оптимизација. Технологијата за адитивно производство со 3Д печатење со споени филаменти (FFF) е избрана како погодна да се креираат производи со технологија за брзо прототипирање, како и поради сложеноста на обликот на производот. Процесот на дизајнирање вклучува концептуален дизајн, 3Д моделирање и параметарски дизајн, подготовка за производство со 3Д печатење, како и верификување на дизајнот на производот. За прототипирање на дизајнот на производот се користи отворен систем. Моделот на производот е дизајниран и произведен од студент со користење на 3Д печатење со FFF технологија.

Клучни зборови: процес на дизајнирање; сложен облик на производ; CAx; 3Д печатење со споени филаменти (FFF)

1. INTRODUCTION

The complex shape of products with Voronoi structure inspired by nature has long been employed in the field of architecture, but today are employed in industrial design. The barrier for application of Voronoi structure in area of industrial design were software packages for 3D modeling and production technology of complex shape and surface. Today with the use of a several software packages such as Fusion360, Rhino & Grasshopper, Blender, nTopology, and others, as well as with application of additive manufacturing (AM) technology with FFF 3D printing, the product with complex shape can be easily fabricated. The software packages Fusion 360 and nTopology with its methodology is one of the best for generation of lattice and porous structure for different application areas. In this research software package Fusion 360 for 3D modeling of product with Voronoi structure is used. For fabrication of product the FFF 3D printing technology with Ender 3 V.2 printer and SuperSlicer software is used.

An interesting and useful way of improving the product design shape is by using the lattice Voronoi's structure. The Voronoi pattern can be implemented to reduce the mass of products while keeping the other product functionalities intact, to reduce the manufacturing time consumption and overall cost. Additionally, thanks to the unique and interesting nature of the Voronoi pattern itself, the aesthetic design of the product's shape will be increased, which will contribute to improving the overall product quality.

Recently, 3D printing FFF technology has emerged as an effective method to produce complex structures layer by layer [1, 2]. Reducing mass of products, material and time consumption problems are still challenges for 3D printing. Creating reliable and lightweight products can be obtained by replacing solid infill materials with Voronoi porous structures.

The AM technologies supported by advanced 3D modeling of complex shapes have opened a lot of new possibilities for product designing, creativity, ergonomics, custom design, aesthetics, and efficiency in the industrial design process. Product designs with aesthetic and complex shapes can be developed, prototyped, and fabricated. To benefit from the concurrent application of these technologies in the design process, industrial designers should be educated and trained in parametric design thinking and cooperation with computer programmers and production technology experts. On the other hand, the design process itself is highly dependent on personal creativity, sensory perception of form and material, and understanding of consumer product trends [3].

Nowadays, the CAx systems and CAx engineering applications are an inseparable part of industrial design. CAx tools such as: CAD, CAM, CAE, PLM, etc., are more significantly relevant in the development process of new products and industrial design. CAx tools significantly reduce the time and costs of a new product development and fast launching the product to the market [4–6].

In summary, FFF technology enhances the design freedom in creating complex shapes of products, with improved aesthetics and modern design while keeping intact the other product functionalities, compared to the traditional manufacturing processes. When properly designed for FFF technology, parts with complex shapes can be prototyped and/or produced directly. The power and adaptability which 3D printing provides can be used to create innovative and useful products.

2. BACKGROUND

Geometric Form/Organic Matrix is an AWOL trend based on lattice Voronoi's structures, which is a specific method of achieving dynamic balance between rational and natural worlds. Geometric form based on a primitive, such as a cube or rectangle, often defines an absolute outer boundary volume of which a cellular matrix of internal structures fills in the interior void. Nowadays, this technique has been primarily used in architecture and furniture (see Figure 1), with some inroads into the product category. Also, this trend is highly related to Organic Forms/Geometric Matrix, which inverts the relationship between form and interior structure [7].

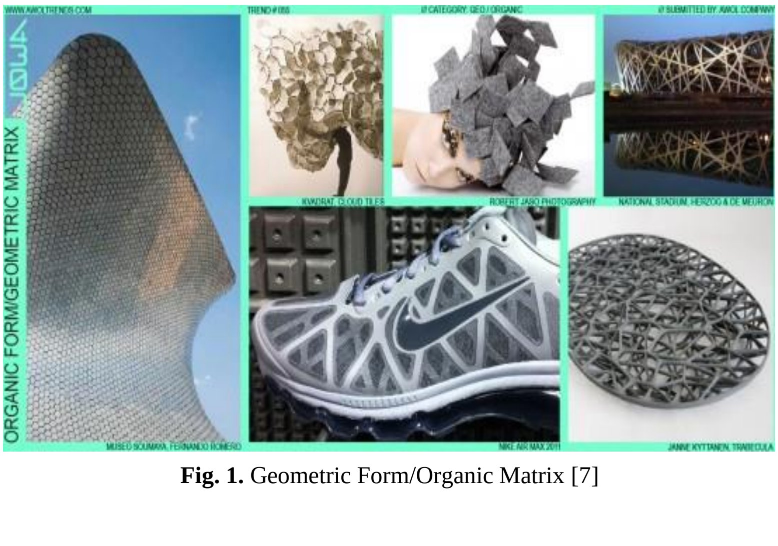

Fig. 1. Geometric Form/Organic Matrix [7]

Complex shapes and structures include complex surfaces, complex geometries, porous and lattice structures, etc., which are common in the natural environment. The most natural structures are complex structures with holes and porosities or irregular surfaces. These structures can be used as a lightweight infill, porous scaffolds, energy absorbers or micro-reactors. The novel rapid prototyping technology with 3D printing and application background is suitable to answer the current design methodologies in order to produce complex product shapes [8].

The product designers today have the possibilities to design complex geometries which can be produced with AM technology, considering there are less technological limits than before. In the research [9], Piros and Trautmann presented a new structure with complex geometries called Lightweight Voronoi Scaffold which is tested with multiaxial load case. The arrangement of Voronoi scaffold is not regular, random sampling-based Monte Carlo method is applied in order to provide proper distribution of generation of geometric instances. Piros *et al*. presented Lightweight Voronoi Scaffold which is compared to some common regular beam lattices, and results show that Lightweight Voronoi Scaffold was lighter in each case, which may open new opportunities in the field of additive manufacturing. Multilevel design for the interior of 3D fabrication is presented in the paper [10]. The aim of this work is to create lightweight 3D fabrications with lighter interior structures to minimize printing materials and supplementary to strengthen thin parts of objects. The approach allows for the composition of sparse and dense distributions of patterns of interior 3D fabrications in an efficient way, so users can fabricate their own 3D designs. Porous structures such as bone-like porous structures [10], porous Ti-based alloy prostheses [11], developed a density-aware internal porous supporting structure to improve the structural soundness of 3D fabrications [12]. The research of lattice Voronoi's structures are widely used for interior design supported with 3D print, due to its properties such as stress sustainable, lightweight, and cost-effectiveness.

The application of lattice Voronoi's structure method to construct controllable porous scaffolds is presented in the research of Wang *et al*. [13]. Their method was successful in obtaining the porous structures geometries, after which the specimens were prepared by selective laser melting technology for manufacturing and the specimens were tested with quasi-static compressive test. In the research of Lu *et al*. [14], Voronoi mesh is applied in order to reduce the material cost and weight of a given object, while providing a durable printed model that is resistant to impact and external forces.

Availability of AM technologies today has increased the application and popularity of 3D modeling of products with complex shape in industrial design to create parts with complex shape, structure, pattern, porous and lattice structures. AM technologies have applications in many areas, such as rapid prototyping and manufacturing of parts, orthopedic personalized devices [15] and others. Preparation time for AM production of parts with complex geometry is relatively short. Many industrial designers choose AM technologies as a tool for prototyping, especially for prototyping products with complex shapes such as Voronoi shapes implicated into product surfaces.

The main goal of this research is to present the design process which incorporates the lattice Voronoi's structure into the product complex shapes and the use of AM technology for prototyping of complex shapes. The design process includes identification of market needs, conceptual design, 3D modeling and parametric design, preparation for production with 3D printing FFF technology as well as testing to verify the product design. The applicability of this research is presented through illustrative example.

3. DESIGN PROCESS METHODOLOGY

The design process of a product is a complex process which consists of several phases [16]: identification of market needs, project planning, product definition or definition of the product engineering specifications, conceptual design and developing the product using CAD models, calculations, selection of materials, making technical drawings for the prototype production and defining all necessary information for manufacturing.

3.1. *Identification of market needs, product definition and project planning*

The project started at the Faculty of Mechanical Engineering in Skopje, in the study program in Industrial design. The project description was clearly defined with the set of general requirements. The project task was defined as a design of modern vase with application of AM technology and lattice Voronoi's structure. It was proposed the decorations of the vase to be focused on small led lights, powered by a battery. Additionally, in order to understand the design problem translation of customers' requirements into a technical description of what needs to be designed was made. The development of clear requirements is a key feature for an effective design process. The customers' requirements need to be translated to engineering specifications and the design team needs to understand the problem in order to write a good set of engineering specifications. The market research showed that there are already a lot of examples of 3D printed vases with lattice Voronoi's structure. They are designed with different shapes, functions, shell thickness, holes density, etc., intended for decoration with ambient light, others intended for office equipment, others for arranging and planting flowers. In Figure 2 vases with different lattice Voronoi's structures from many designers available on the market are presented.

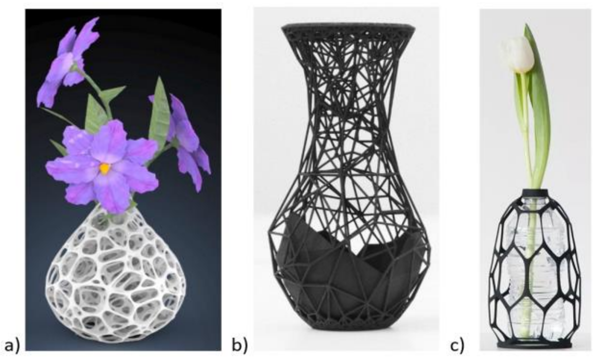

Fig. 2. a) Math Décor by Dizingof [17]. **b)** The Wire by Ivan Zhurba [18]. **c)** Knitted Vase Designlibero [19]

3.2. *Conceptual design*

A concept is an idea that is sufficiently developed to evaluate the physical principles that govern its behavior [16]. The concept of a vase with lattice Voronoi's structure is created with application of the software package Autodesk Fusion 360. Fusion 360 is CAx software for development of products with complex shapes and includes the module for creating lattice Voronoi's structures with an overall control of the mesh. The complex shape of the vase with lattice Voronoi's structures is created by the tools tessellate, reduce and pipe, incorporated in the Voronoi module. The created 3D model is parametric and the parameters which can be adjusted are Voronoi mesh, density, schedule of geometrical forms and diameter of mesh. The software Fusion 360 is not the simplest for creating lattice Voronoi's structure, but our requirements were fully satisfied. The product is intended for people who want a multi-functional eco product that can simultaneously be used as a decoration, ambient lighting, and flower vase. One concept of modern vase with lattice Voronoi's structure and complex shape was generated and is shown in Figure 3.

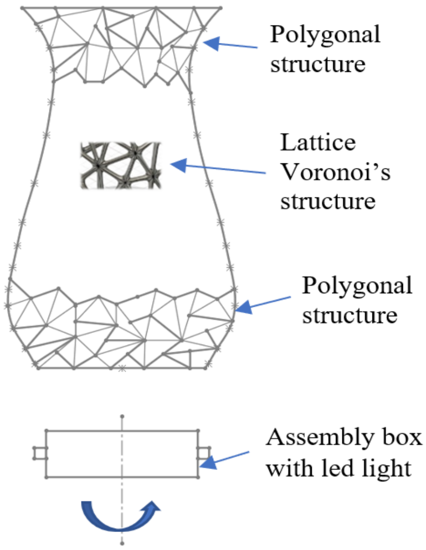

Fig. 3. Concept design of modern flower vase

3.3. *Product development*

The inspiration for the shape was a glass bottle, according to which the shape was modeled. The glass bottle inserted as an inner part of the vase with intention to achieve multi-functionality. The glass bottle in the vase serves as a flower vase.

The other function of the glass bottle in the vase is the excellent transparency and dispersion of light through the lattice Voronoi's structure. In the lower part of the vase electronics with led lights are inserted which serve as ambient lighting. The product design phase is focused on refining the concept into a hight quality product. The product's design is evaluated for its performance, robustness, quality, and cost. After all the important aspects were considered, such as performance, robustness, quality and cost, a novel design of a modern vase with lattice Voronoi's structure was created.

The vase was modeled with application of the Fusion 360 software, using the following modules: part, assembly, surface modeling, tessellate, reduce, Voronoi mesh, etc. Figure 4 presents the steps of creation of the modern vase 3D model with lattice Voronoi's structure using the Fusion 360 software.

3.4. *Prototyping*

The prototyping of the presented example, shown in Fgure 4, is with FFF 3D printing technology. For fabrication of the prototype the 3D printer Ender 3 V.2 was used, the G-code was created in the software SuperSlicer and PLA material was chosen as a prototype material. In the SuperSlicer a few parameters were adjusted, such as: printing orientation is vertical, infill is 20%, supports were used, and layer height is 0.2 mm. Printing time was 17 hours and 28 minutes.

Figure 5 presents the steps of the prototyping process: a) creating the g-code with the help of the software SuperSlicer, b) 3D printing process, c) 3D printed assembly and supports, d) the electrical circuit, and e) lower assembly with led light. The prototype of the final product of a modern vase with lattice Voronoi's structure is shown on Figure 6.

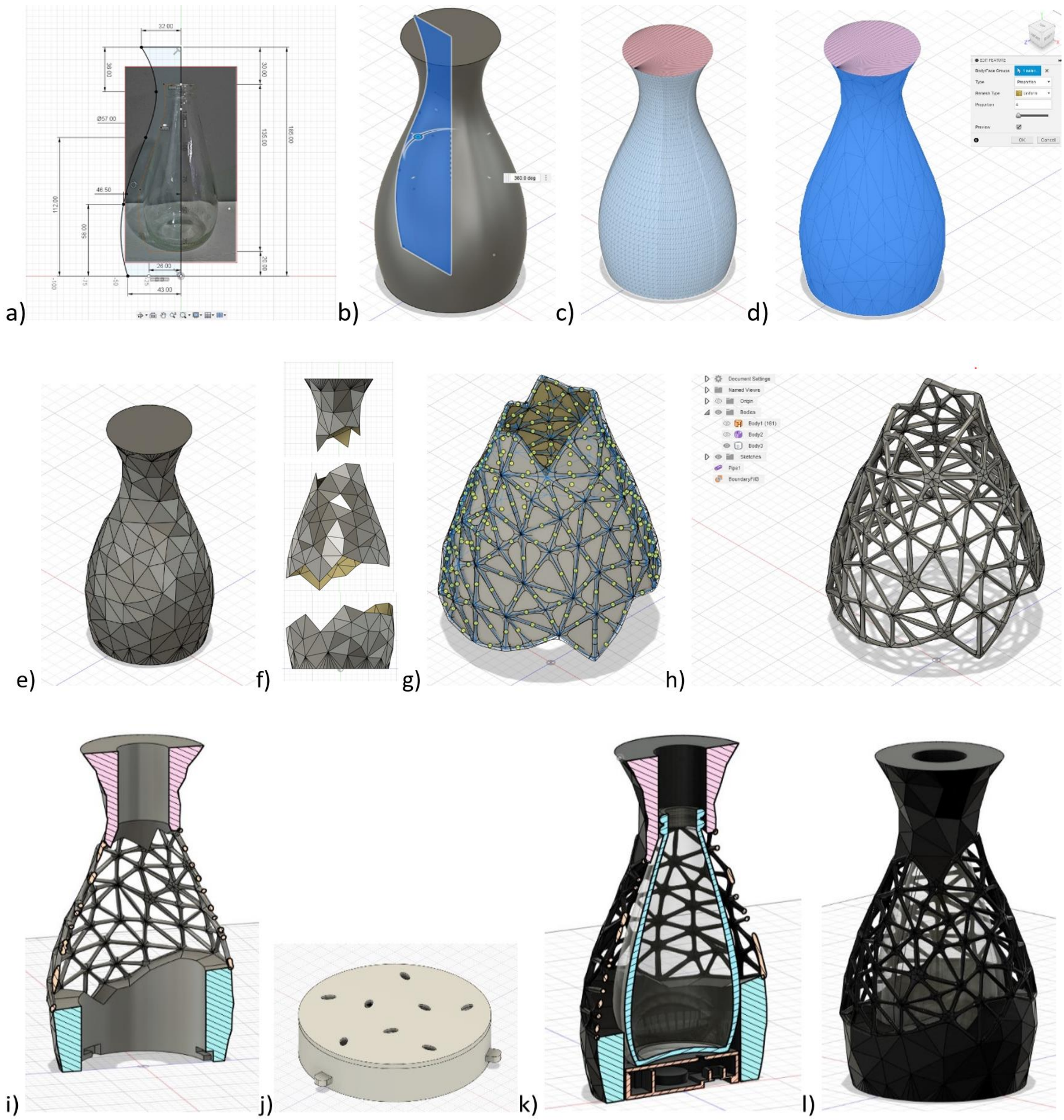

Fig. 4. Creating the 3D design of the vase with Fusion 360 in several steps: a) sketch, b) revolve, c) tessellate, d) reduce, e) create solid body, f) divide the body into 3 parts, g) lattice Voronoi's structure, i) section view of assembly, j) electronic plastic box, k) section view of vase, l) 3D model of vase assembly

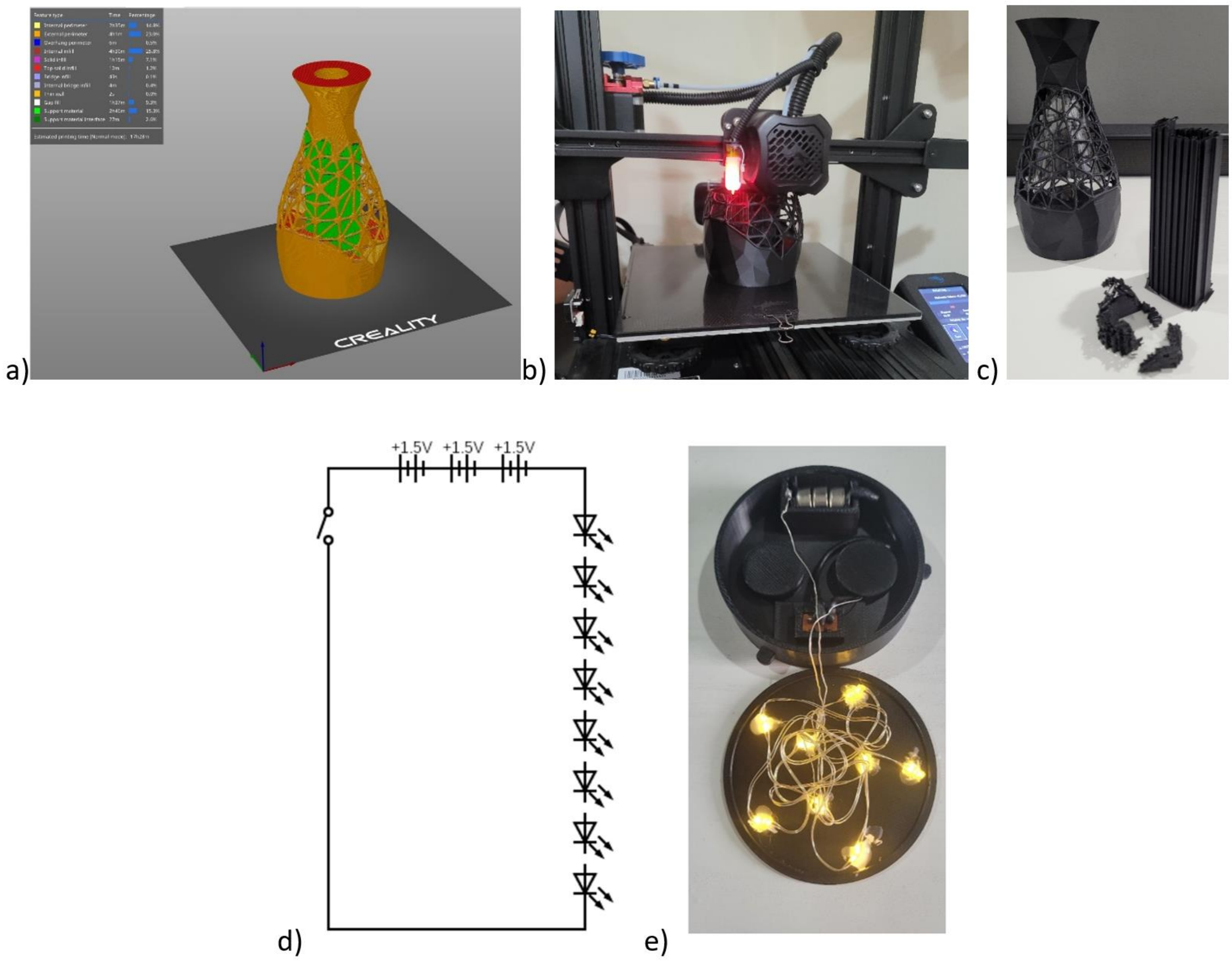

Fig. 5. Prototyping: a) creating g-code in super slicer, b) FFF process, c) the product and supports, d) electrical circuit, e) lower assembly with led ligh

Fig. 6. Final prototype of modern vase designed with lattice Voronoi’s structure

4. RESULTS AND DISCUSSION

The applicability of the design process of creating complex product shapes with lattice Voronoi's structure, using CAx tools and fabrication with 3D printing technology is presented through an illustrative example. The overall design process of creation and verification of product is presented in a few steps, such as: identification of market needs, product definition and project planning, conceptual design supported by handmade sketch of a product design (see Figure 3), product development using CAD and CAx tools for 3D modeling and analysis of model (see Figure 4), and rapid prototyping of product using 3D printing technology (Figure 5). The goal is for industrial designers to predict, evaluate, and improve owner designs as early in the design stage as possible by using CAx tools and rapid fabrication process with 3d printing technology. The final prototype of product modern vase designed with lattice Voronoi's structure is presented on Figure 6 in daily and night usage with ambient led light.

5. CONCLUSIONS

This paper presented the design process of creating complex product shapes with lattice Voronoi's structure in industrial design using CAx tools. Design process stages such as identification of market needs, product definition, project planning, conceptual design, product develop-ment, and prototyping, based on selected case study are described. The new design of the modern vase implements the use of lattice Voronoi's structure, decoration elements, and ambient led lighting. The complex shape is made by using the modern software package Fusion 360, CAx tools and 3D printing technologies for rapid production and verification of prototype. The verification of the prototype provides evidential proof of efficiency of the design process. The design process supported with AM fabrication and prototyping is aimed to encourage the industrial design students to fabricate their designs early in the design process, to evaluate and present their designs in a relatively short time.

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