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COMPUTATIONAL WEARABLES DESIGN: SHOE SOLE MODELING AND PROTOTYPING

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Abstract: Computational wearables design is based on the integration of algorithms into the design process. The use of computational design tools offers a series of advantages in the wearable product design modelling because a complete family of products can be produced with a limited effort from the designer, while at the same time geometries with high complexity can be dealt with a manageable way. The present paper aims to create the appropriate code for modelling shoe soles. The use of a visual programming language leads to a better understanding of the produced code and aims in controlling and optimising the output models. Following the proposed methodology, 3D scanning technologies and plantar pressure diagrams are used for introducing the sole customised geometry, and then the proposed algorithm creates a variety of alternatives of the final shoe sole geometry. As a result, both the customisation and the high number of alternative designs lead to increased creativity and customer satisfaction. Due to the complexity of the geometry produced, 3D printing technologies are incorporated for the prototype implementation.
Keywords: *Computational design, product design, wearables, algorithmic design, visual programming, 3D printing.*

1. INTRODUCTION

In the recent years, the use of computational design has been increasing in various sectors of the industry and a number of applications. Computational design is one of the modern tools that are based on programming through a mathematical framework. The automation offered and the reduced design time needed are the two main pillars on which computational design is based on. The term automation describes a series of predefined steps followed, combined with the appropriate values of all the parameters involved. When changing the parameters, the same steps run via the computer code and different solutions automatically appear on the screen. The second pillar mentioned is the design time which by using computational design tools is greatly reduced [1].
Another reason that computational design is used, is the ability to include a series of parameters and the result throughout the design process to be fully controlled. In essence, a series of different geometries are produced, based on the same algorithm and different parameters. In other words, a design generator is built based on specific parameters and coded commands. Each parameter is usually defined through a numerical value; however, it can also be a file type i.e., a 3D geometry, an image [2].
The use of computational design is used in the design of product brand identity also, through the appearance of industrial products. Based on various techniques, the designer/programmer is effectively the creator of products that belong to families. All this is implemented using product design algorithms that support not only the geometrical characteristics but their manufacturing and branding identity as well [3].
Nowadays, both researchers and shoe manufacturers deal with the analysis and the use of plantar pressure measurements for customized sole design. Deconstructing the traditional sole geometry and replacing it with a new unique structure for each user, promotes shoe customization and offers new opportunities for business success. Voronoi lattice is one of the most commonly used methods with an aim to create an unusual complex geometry. Computational design is a powerful tool for creating algorithms that can offer a variety of unusual geometries and topologies including Voronoi based algorithms as well. Use of a series of parameters can lead to a large number of geometrical variations produced by the same algorithm. In the case of the Voronoi lattice, the geometry built is related to a set of points spread in 2D or 3D space. As a result, finding the appropriate algorithm for controlling the point coordinates lead to a fully controllable 2D/3D geometry for a number of applications [4, 5, 6].
Pattern design both in 2D and 3D can be used with computational design tools, because they can take advantage of the parameters' value involved and their influence on the final geometry needed. Especially in the shoe making

sector, this can be further extended with an aim to offer shoe sole geometries that are unique and impressive for their customers. Repeating a controllable pattern design, offers a variety of geometric structures, that have numerous mechanical properties and affect the final sole geometry. Examining a set of separate topologies and their optimization, novelty can be introduced in the shoe sole design process and provide increased satisfaction to every customer involved, thus customized design is promoted without drastically increasing the cost of development [7, 8, 9, 10].
There are cases, where multiple mechanical properties are required from a specific geometry and this can be achieved with the use of meta-material structures (MMS). A meta-material structure can provide different mechanical properties in a number of geometrical regions. Such structures usually use a set of repeated geometries. Each geometry can have different mechanical properties so that they can locally change how a product behaves. The use of 3D printing as a means to fabricate the final geometries produced, is the most appropriate technology [11, 12].
Design and manufacturing of shoes and shoe soles by themselves receive a great deal of interest from the technical point of view. As an industry, shoemaking progresses towards digitization with modern Computer Aided Design and Manufacturing tools (CAD/CAM), Computerized Numerically Controlled machines (CNC) and modern digital fabrication methods. 3D scanning and foot measurements can lead to creating molds for the final sole design [13, 14, 15].
The current paper presents a framework that combines both methodologies together with technological tools in order to create customised shoe sole geometries. 3D scanning and computational product design was used for creating automatically the appropriate geometry based on plantar pressure measurements as well as sole unevenness. 3D Voronoi mesh was initially used for the sole geometry but then an algorithm was specifically built with an aim to optimise the customised sole. The algorithm spreads the points in 2D/3D space in a fairly uniform way in each area of pressure. When the plantar pressure is high the points density increases as well. As a result, the high density of points in certain (high pressure) areas increases the sole resistance to vertical forces.

2. METHODOLOGY

2.1. Point-based sole geometry

Shoe soles are geometries, which are capable of receiving various pressures from the human foot. The aim of this particular study is to design a sole structure, which would vary the distribution of the material in a controlled manner over its geometry. The term structure, refers to the generation of a network based on a set of points both in 2D and 3D. In the areas where the points have higher density, the network would be thickened. On the contrary, in the areas where the points would be sparse, the network would thin out. The main question raised was how to spread the points in space so that they change their density in a manageable way, based on the rules set by the designer. Figure 1 depicts the workflow of the proposed methodology. The aims were to design and fabricate shoe soles using a point-based approach and distribute these points in a controllable manner for improved performance. Computational design tools were used via Grasshopper™ visual programming language supported by Rhinoceros3D™ for the sole design and 3D printing offered prototypes for an early evaluation. The algorithms used for the point distribution in each area of the foot contact with the sole was one of the main contributions of this research.

2.2. Algorithm for the point distribution

The main purpose of the algorithm was to create points in 2D space as well as to control their density in predefined areas. Later, the 2D version was extended to cover 3D geometries as well. The algorithm built was based on two inputs. The first was related to the definition of the areas in which the point density would be differentiated. The process of defining these areas was based on the colour gradation provided by the pressure map of every user. The specific equipment that it was used for the paper's purposes is the foot scanner EPSR2® from the Comex® Company. The EPSR2® is a special rigid baropodometric platform which it is used for baropodometric and postural analysis, orthostatic and dynamics of the individual foot. The pressure map was converted into separate distinct areas that would receive the point generation with variable density. The number of regions could vary and it was controlled by the designer. The second input was related to the setup of the appropriate numerical values that would define the density of the created points in every area. The main goal was to decrease the point spacing in high pressure areas and increase the point spacing in low pressure areas. Figure 2 presents how the point distribution procedure works, making use of a simple geometry i.e. a square. The square was divided in two areas with different pressure applied. The blue depicts the area of low pressure, whereas high pressure was applied on the red side. Hence, the visibility of the generated points was facilitated according to their density. This

differentiation provides a solid basis for shoe sole geometry generation.

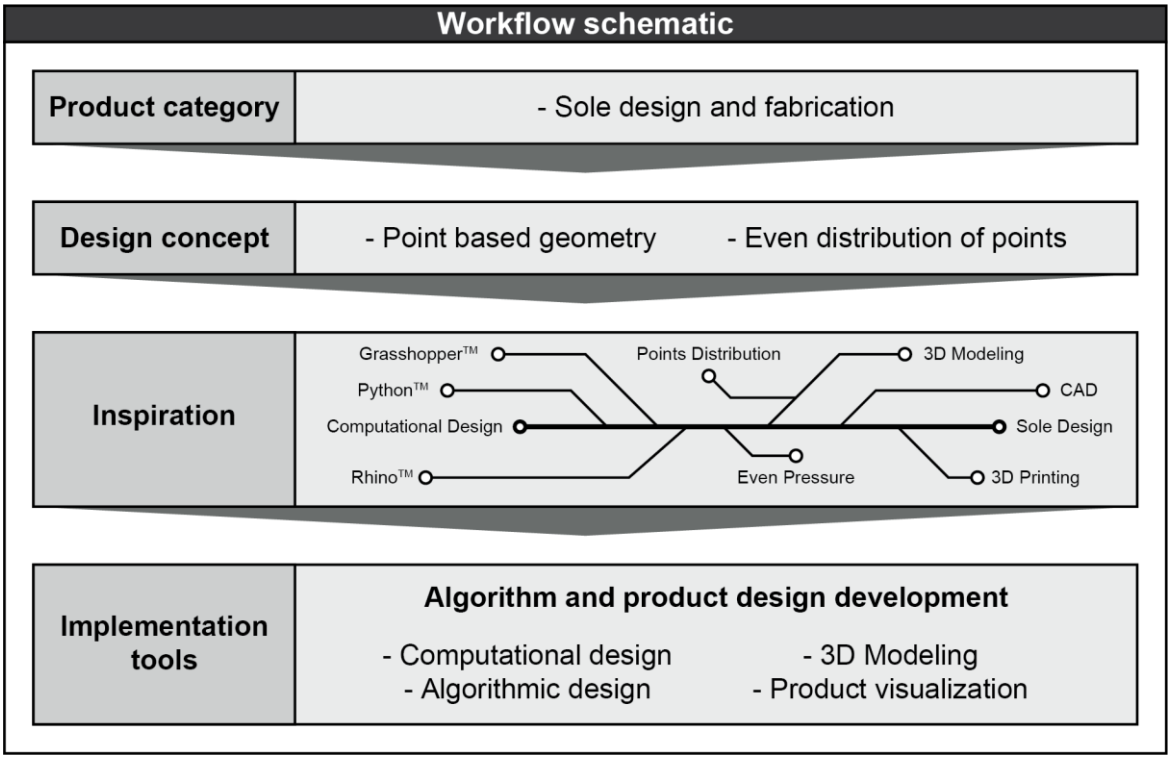


Fig. 1. Workflow of the shoe sole design and fabrication

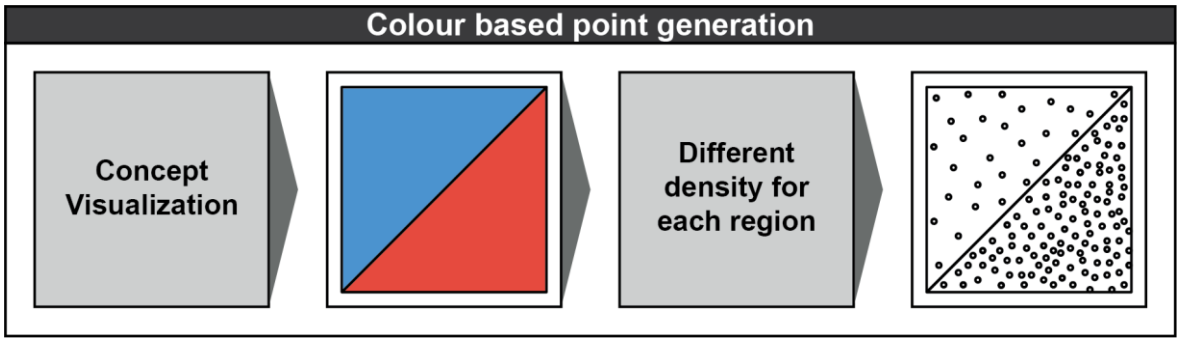


Fig. 2. The colour of each region is used for differentiating the density of the points generated

2.3. 2D strategies for points distribution

Two strategies for the point generation procedure were followed. Both start the insertion of points in each region based on concentric circles trajectories (Figure 3). In the first case, the circles of all regions have a common centre to start with. In both areas, continuous uniform curves were created, but the density was different. Nevertheless, the distance between the circles of each region was equal with the distance among the points positioned on each circumference involved. The algorithm of the first strategy was divided into four stages. The first stage begins with the creation of the circles and the definition of their distances separately in each area. In the second stage, the points were designated on the orbits of the circles according to the distances of each area. Then the Voronoi grid was introduced and the circles and points were hidden.

The algorithm of the second strategy follows a similar process, but differs in the way the circular geometries were introduced. More specifically, the centers of the circles were defined at the center of each region separately.

2.4. 3D strategies for points distribution

The next step was the transfer of the proposed strategies of the Voronoi grid generation from 2D to 3D. In this case, the algorithm was adjusted in working on 3D regions instead of flat 2D surfaces. The idea behind this, was to replace the 2D circular geometries with 3D spheres. Essentially, all concentric circles would turn into concentric spheres. The new points would be placed on the surface of each sphere. An extra parameter was added in order to introduce the altitude of the points in each region. The value of the elevation distance was set equal on all cases and equal to the distance among the points of the concentric orbits. Figure 4 depicts the steps followed in 3D and

indicatively for only one region, in order to increase the readability of the algorithm. A series of circles was created based on the initial sphere and then following the altitude parameter of the algorithm, the points were generated. Finally, the Voronoi grid was created using all these points and the final geometry was produced.

2.5. Comparison of 2D point distributions

Four distribution strategies were tested in 2D with respect to the shoe sole design (Figure 5). The square geometries incorporate two separate regions. The low pressure one that uses 25 points to create the Voronoi grid and the high-pressure region that uses 100 points for the same. The fixed ratio of the points in all cases assisted in visualising the quality and improvement achieved in each case. The same principles were applied in the sole geometries as well.

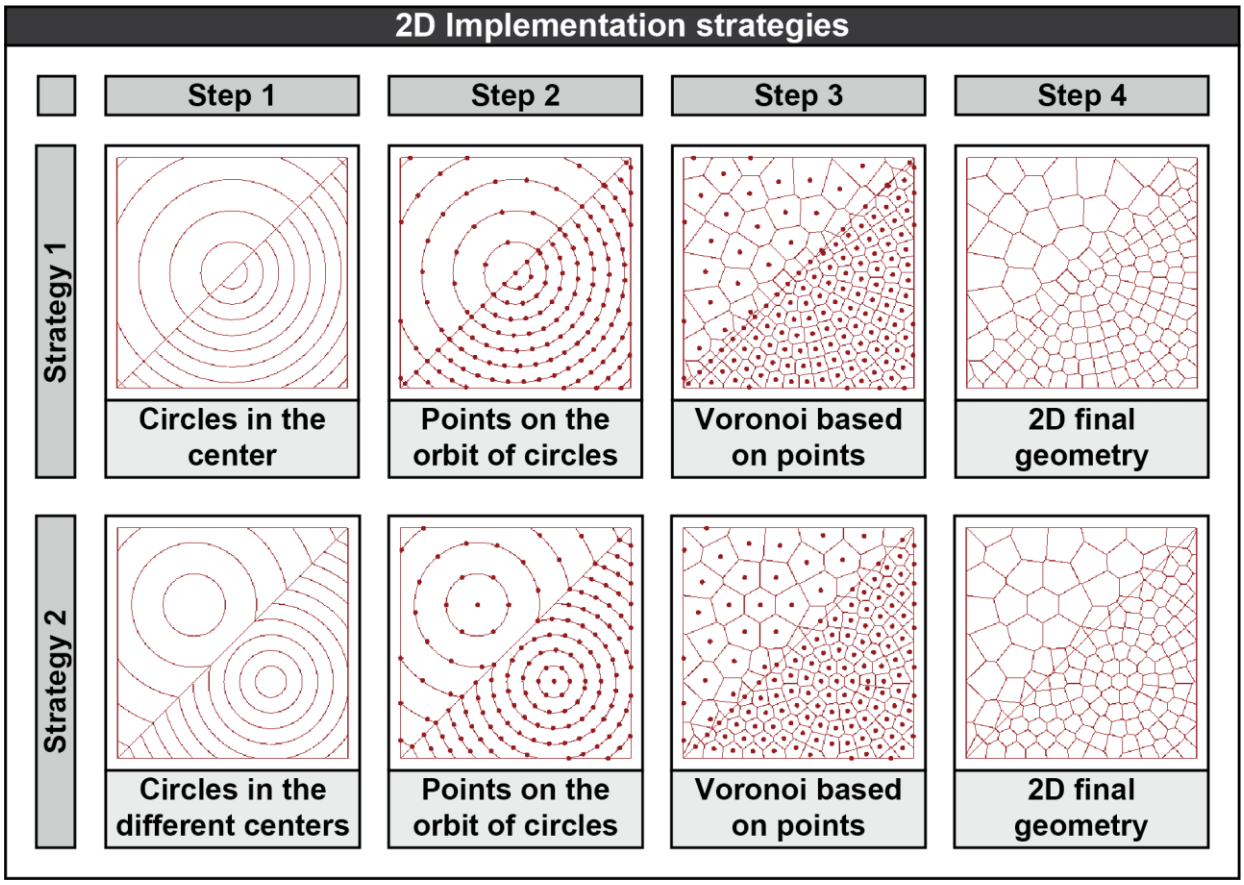


Fig. 3. 2D implementation of the Voronoi grid based on two strategies

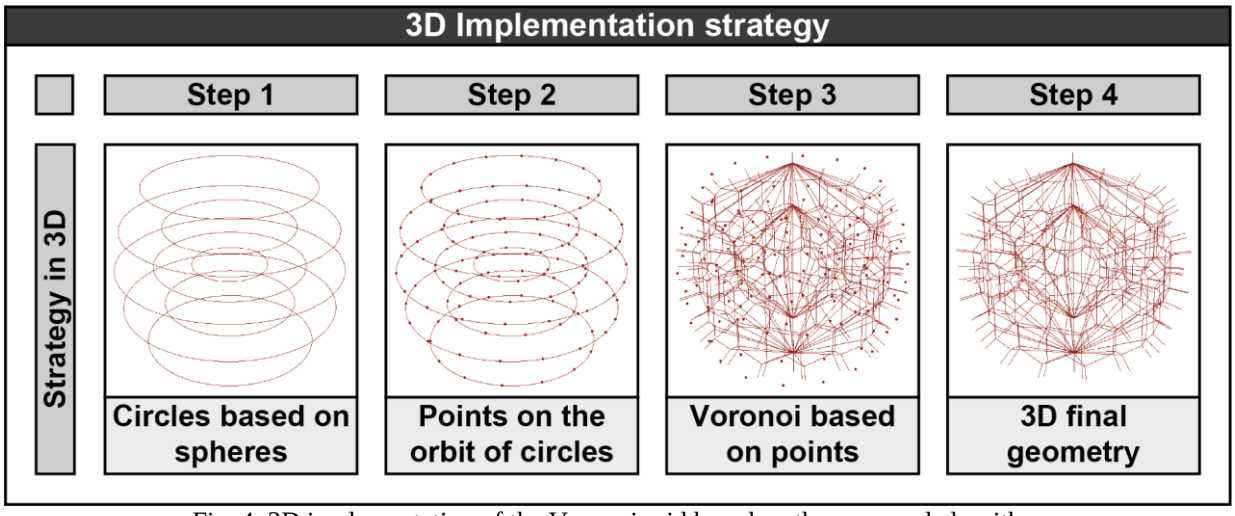


Fig. 4. 3D implementation of the Voronoi grid based on the proposed algorithm

In the first case called “Random”, a Python™ piece of code was developed within the Grasshopper™ environment. The code used an iteration structure that generates random coordinates via the *Random()* function (creates random points in a closed area). Based on these coordinates, the set of points was generated in the selected region. An important feature of the code was to define the number of points in the region. Controlling the number of points resulted the point density in each region to be controlled as well.
In the second case called “Population”, another piece of code was developed in a similar way via the *Populate Geometry* command. This command spreads a certain number of points over an area in a relative uniform manner. It uses an algorithm that through a set of iterations generates the points in space. With each iteration a large number of points were defined from which only one was selected to be generated (the selected point was the one that maintained the longest distances from its nearby points). The result of this method was to create the new points in the areas with the lowest density. This was also the reason that the result of this method produced points fairly evenly distributed in space.
In the last two cases, both strategies presented earlier were implemented.
The third case named Distribution 1, resulted in a high-quality mesh and very good continuation properties between the two regions. The same was true when comparing the meshes on the footprint geometry of reference. As a result, it was this algorithm that was selected to continue the development of the shoe sole model design and fabrication.

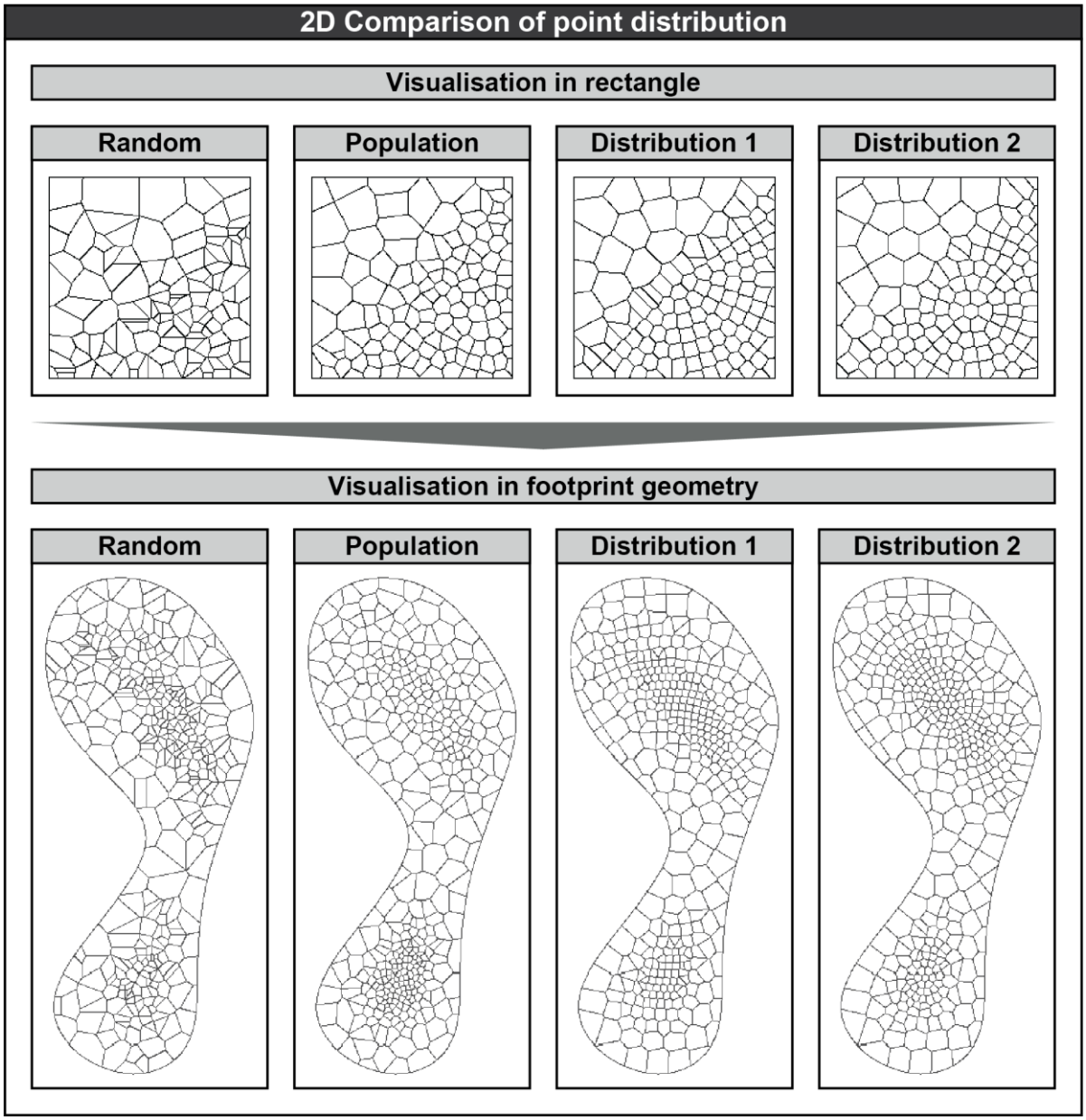


Fig. 5. 2D implementation of different algorithms in square and footprint geometries

3. RESULTS

Having selected the algorithm to be applied on the footprint geometry, a series of steps had to be programmed, in order to automatically create the mesh in all cases under study. The process started with the introduction of a plantar pressure map. A number of regions involved were created based on the colour read on each pressure map. Figure 6 depicts one of the case studies used and the coloured areas provided lead to the separation of the regions to be meshed. In this case, 3 colours were used (blue, green, red) and the 3 regions were recognised (low, medium and high pressure). With this automatic 2D geometry recognition, the areas with different level of pressure were detected. The next step of the procedure followed was to start inserting sets of points with respect to the properties of each region. When the pressure in the referred region was high, the density of the points inserted was high as well and more points participate in the set of points.

Based on the Distribution 1 strategy selected previously, a series of circles were created at a fixed point for all pressure levels. This resulted in sets of points with high density in the red area and as the pressure was reduced the point density was further lowered compare to the initial high pressure one.

Before converting the algorithm from 2D into 3D the total space that would be occupied by the geometry of the sole should be defined. In more detail, a 3D scan could be performed on the user foot and the surrounding area. Based on the scanned geometry, the final shape of the sole emerged. This shape was a customised geometry different for each user. A scanned full foot adds extra data (according to 3D scanning technologies), e.g., the entire morphology of the sole and the specific curviness of each main characteristic of the foot. Furthermore, through the 3D scanning strategy of the foot, authors can record the foot/sole imperfections and particularities for each individual user. Figure 7 provides a step-by-step presentation of how a full 3D final shoe sole geometry was created. First the user's foot is 3D scanned and the surface constructed offered the basis for a user customised geometry. The selected algorithm was modified with an aim to separate in the appropriate 3D regions the sole. The final volume of the sole could be divided into smaller volume-areas according to the pressure levels selected (three in this case). In these geometries, the selected algorithm was altered in order to create the appropriate points in 3D space and cover the complete shoe sole.

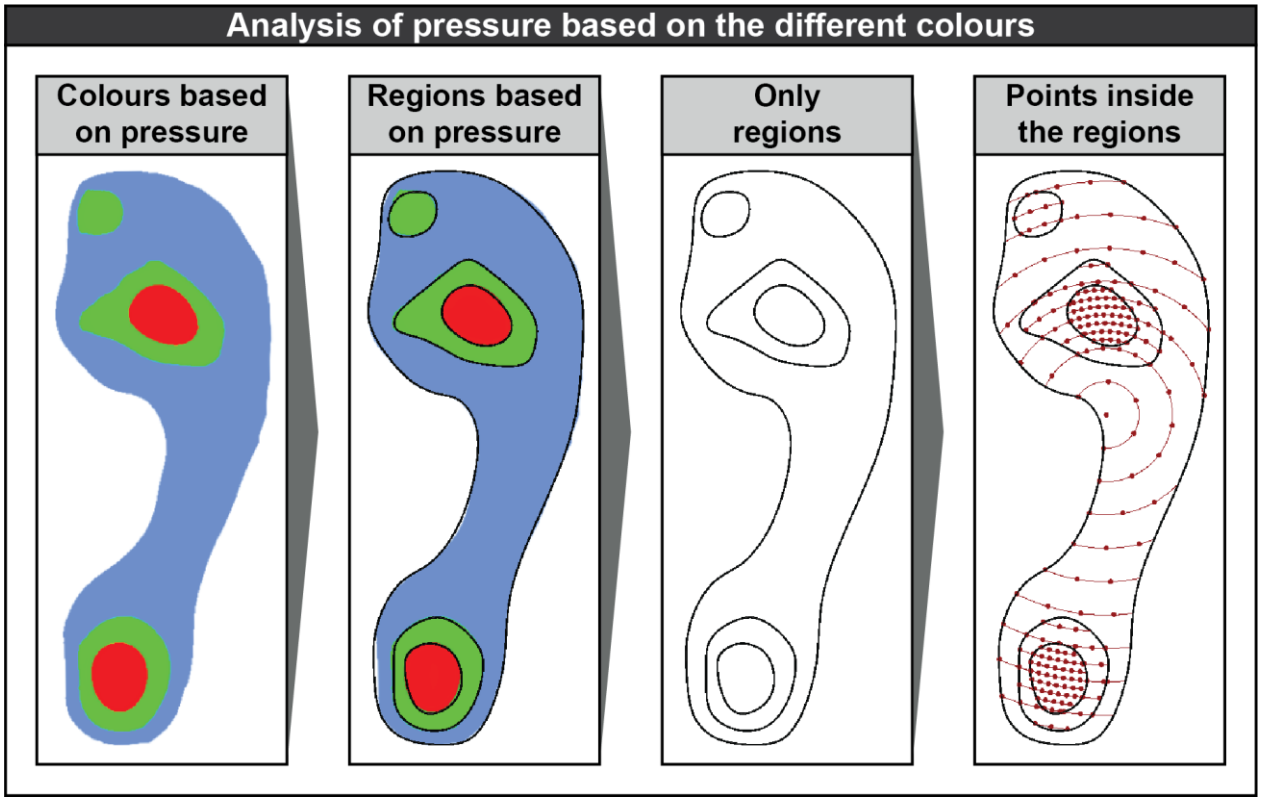


Fig. 6. Applying the region separation algorithm based on the colour of the plantar pressure map and generate point sets

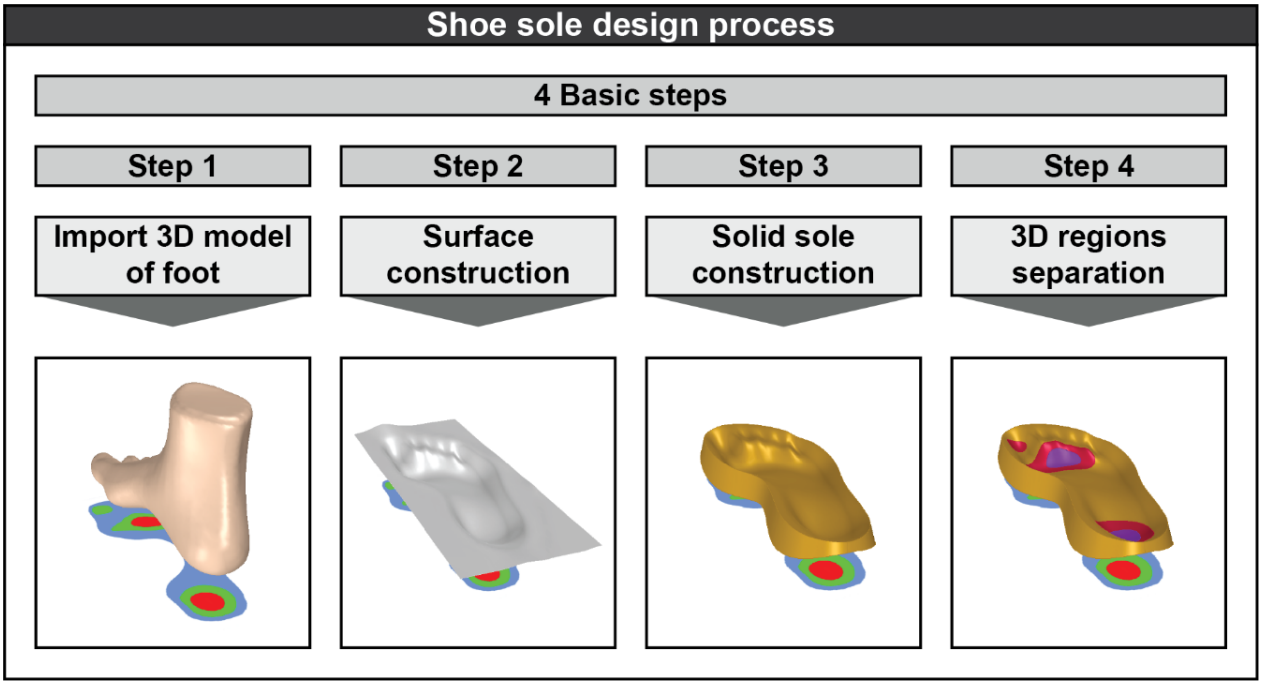
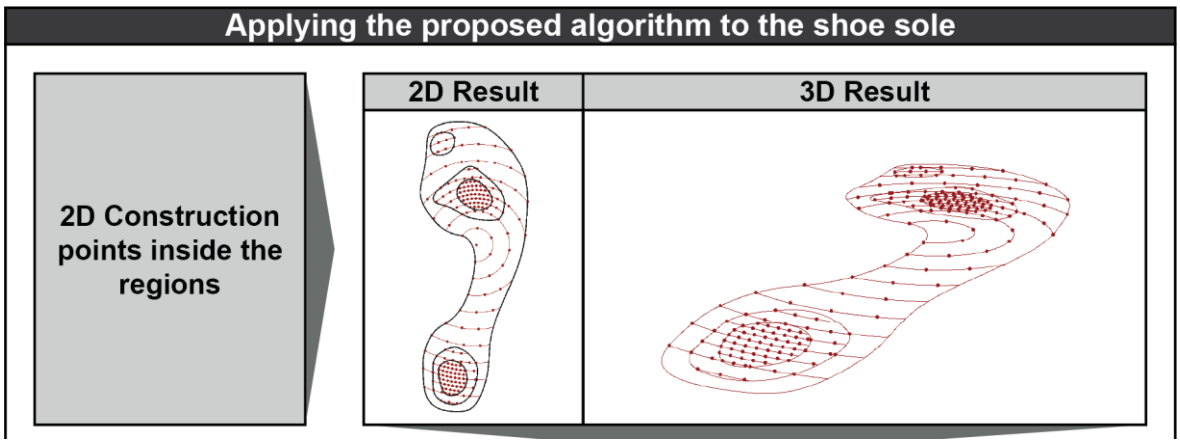


Fig. 7. 3D customised shoe sole design

In the last stage, the 3D version of the algorithm was applied to the geometries of the produced shoe sole with an aim to generate the 3D point sets. More specifically, based on a fixed point in the centre of the sole, a series of concentric spheres were created. According to the spheres and the geometries of the sole, the distances of the created points were defined. This process resulted in the creation of a set of points in each 3D region, that vary in density (the same approach as in 2D was used). The application of a Voronoi meshing resulted in a network of lines within the geometry of the designed shoe sole. The aforementioned network was converted into a volume in order to become 3D and encompass the appropriate mass. The final 3D Voronoi based geometry could be 3D printed with a variety of technologies and fabricate not only early-stage prototypes but final shoe soles to be incorporated into shoes (Figure 8).

Figure 9 presents the 3D printed fabrication of the geometry provided. Different 3D printing efforts were performed with Fused Filament Fabrication-FFF (Creatbot™ D600) and resin-based technology (Creality™ HALOT-LITE). The filament that was used for the final 3d printed sole is the PLA-EVO® from the NEEMA3D® Company. The resin-based model was used with an aim to optimize the structural support used during the 3D fabrication and the final FFF based model offered a great deal of help in manufacturing the real shoe sole. Authors propose a set of prototyping approaches that serve both functionality and ergonomics points of view, while focusing on the original design process followed.



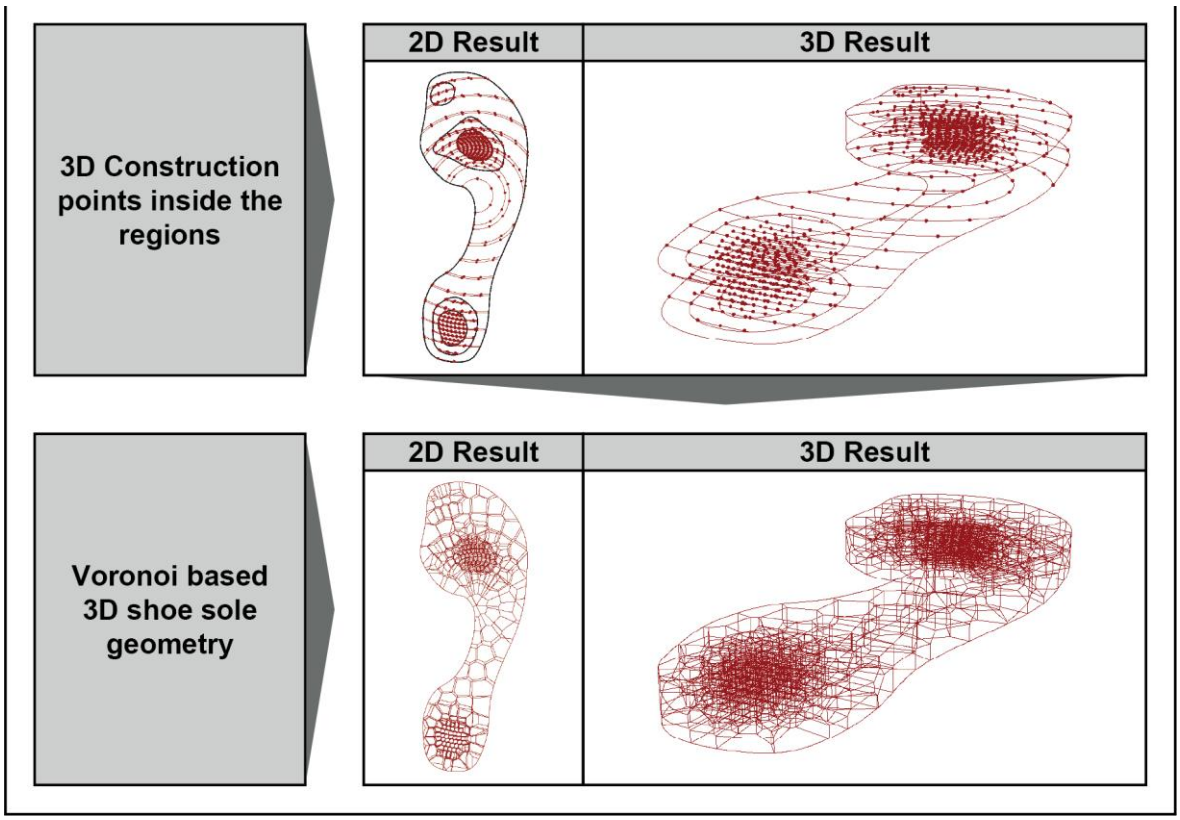


Fig. 8. 3D shoe sole geometry built based on a set of Voronoi network

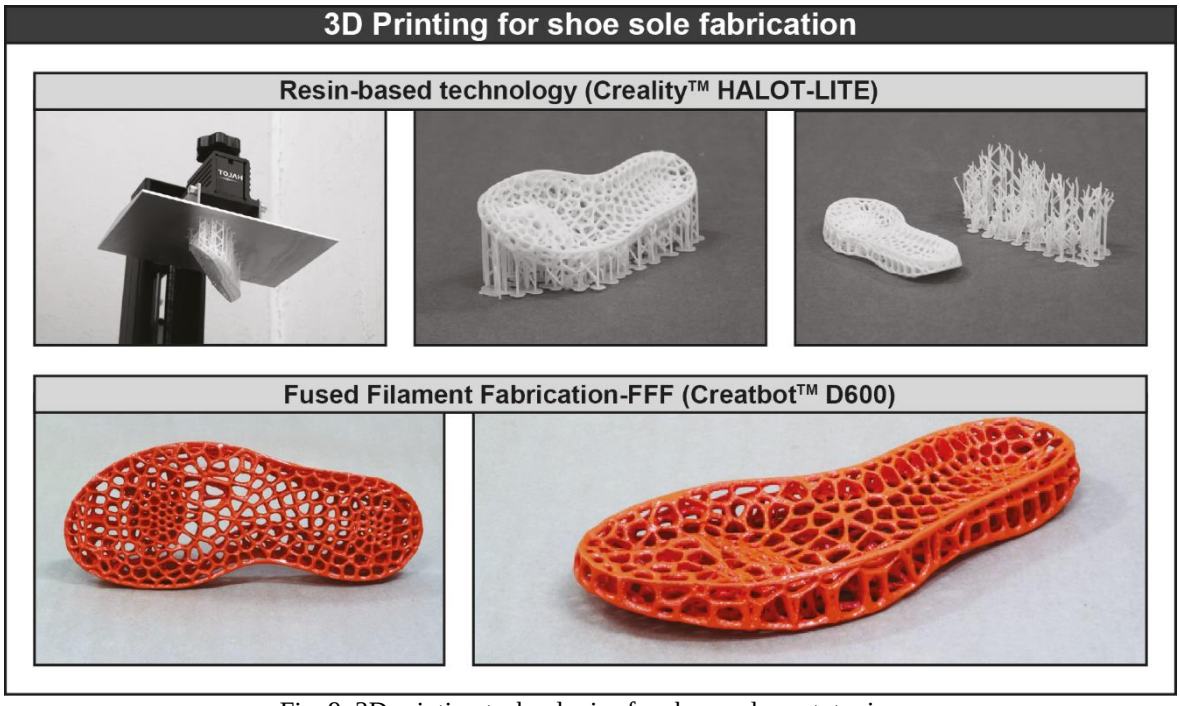


Fig. 9. 3D printing technologies for show sole prototyping

4. CONCLUSIONS

The literature survey provides a solid basis with an aim to prove that computational design becomes increasingly trendy for the design engineers. This is the case because with the algorithms implemented, the design process becomes automated and produces unusual geometries to a great extent. The use of CAD oriented design is directly linked to the use of tools such as Grasshopper™.

Those complex geometries are part of a family-based product design approach. This means that the algorithms

are able to provide a large number of alternative designs, all under the same umbrella and can satisfy the users with customized products for each individual. Additionally, the3D printing technologies become the means for manufacturing the required prototypes, as well as the final product.
A methodology was presented together with a step-by-step approach in creating the geometry, based on a fully controlled mesh for the design of customized shoe sole. The tool is fully automated with an aim to combine a 3D scan and the plantar pressure map of the user's foot and design the appropriate shoe sole geometry. The geometry produced was first developed in 2D and then was converted to 3D. The set of points created in each region of pressure had different density and the Voronoi network built aimed in customizing the output for each user. The algorithm applied offered very good continuation properties between the neighbored regions. The Voronoi based 3D geometry acquired was then 3D printed and early evaluation prototypes were delivered.
As a future work, the proposed algorithm could be used in other applications, where density variation is required. In addition, the mechanical properties of the structures can be digitally or physically studied.

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