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Parametric Patternmaking of Shoe Last Bottom Based on AutoCAD for Mass Customization

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Abstract: To solve the conflict between the low production efficiency of shoe patternmaking in the footwear industry and the increasing requirement for customization of shoe goods, this paper aims to explore a parametric patternmaking technology to promote the efficiency of patternmaking for customization of female leather shoe last. Through an experimental study, a parametric patternmaking model of the shoe last bottom has been established based on the parametric drawing function in AutoCAD. In this patternmaking model, the flat geometric shape of the shoe last bottom has been modelled through the tool of graphic constraint in AutoCAD, while the essential measures and their proportions have been parameterized by the tool of dimensional constraint. A series of tests to this parametric patternmaking model demonstrated that the original model can be modified in shape and dimensions automatically and quickly according to changes in parameters' values controlled by foot sizes. Depending on the results of this study it can be concluded that parametric drawing technology can be employed to create various patterns of the shoe last bottom for customization of shoes' patternmaking to meet various individual requirements with relatively high efficiency. The achievement of this study can also be employed in the patternmaking of the shoe upper and even other kinds of products for customization.

Keywords: Mass Customisation, Shoe Last, Patternmaking, AutoCAD, Parametric Design

1. Introduction

Currently, there is a tendency for some traditional labour-intensive industries, such as the apparel and footwear industries, to transform from mass production to mass customization because of the development of technology, increasing diversity of customer needs and globalization of industries [16]. Mass customisation has become a competitive strategy to offer various products and services to meet individual customer needs and wants in nearly mass production costs and lead time [14]. Regarding the footwear industry, mass customization might be able to be achieved by offering shoe customisation on the style or dimensions without an increase in prices and delivery time [24].

According to the process of footwear product development [19], increasing the efficiency of shoe pattern making based on shoe last is the key to achieving mass customisation in the footwear industry [3]. Shoe patternmaking is fundamental for the manufacturing of shoes in the footwear industry. Traditionally, a set of shoe patterns for production are normally created based on a range of shoe lasts, which are three-dimensional stylized foot-shaped forms with certain specifications [2]. Through a set of processes of style line drawing on, peeling off and flattening out of the masking tape attached to a shoe last, master shoe patterns can be created as a representation of the last's three-dimensional surface (Figure 1). These processes need to be manipulated by technicians elaborately in a way of time-consuming and experience-based.

Figure 1. *Process of shoe-last-based footwear product development [2].*

As fitting and comfort-sensitive products [2], each pair of shoes with a specific set of sizes needs certain shoe last with specific measurements. The method of shoe last-based patternmaking often leads to an extension of the product development cycle. The complexity of processes and an increase in cost result in low efficiency. While shoes are also fashionable commodities with intrinsic characteristics of frequent changes across different sale seasons. Thus, the footwear industry often meets the conflict between the requirement for fast-paced changes in shoe styles and the long lead time.

Along with the quick development of digital technologies, the traditional footwear production industry which majors in hand-made manufacturing have made a progress through the adoption of new digital technologies such as CAD/CAM/CAE. Shoe last virtual 3D models can be generated by the application of laser scanning and parametric [16, 21]. Based on the virtual 3D shoe last, a few companies have published specialist application software such as Rhinoceros that can offer a tool for shoe style design in which shoe designers can carry out shoe design within a 3D virtual context [15].

However limited by the traditional patternmaking principle of the last-oriented shoe patternmaking, many kinds of literature for digital technology applications in footwear production are concentrated on the research about 3D modelling shoe last through scanning [17] and its adoptions in foot measuring, customization of shoe last [8] and shoe last parametric design [20]. Regarding digital techniques applied in shoe patternmaking, only a few pieces of literature investigate the application of digital technologies in the digitalisation of shoe patterns for mass production [9]. There is a lack of research about feasible techniques able to be applied in shoe patternmaking to improve the efficiency of shoe production.

To solve the problems mentioned above, a parametric shoe patternmaking technology was proposed as an approach to the achievement of mass customization. Through an experimental study based on parametric drawing techniques of AutoCAD, a digital parametric model of a shoe's last bottom pattern was developed which can vary in geometry and dimensions automatically according to individual sizes input. The flexibility of this parametric shoe last bottom pattern model can provide an approach to mass customisation in the footwear industry.

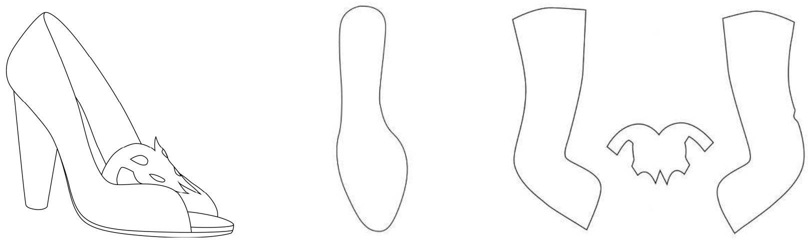
2. Principles of Parametric Shoe Patternmaking

Shoe last parametric patternmaking concerns shoe last patternmaking principles and techniques of parametric drawings. Traditionally shoe patterns are normally attained by transforming the shoe last 3D surface into flat patterns. Different from the traditional way, generating shoe last patterns with parametric technology works according to the modelled flat patterns of shoe last rather than the shoe last. Parametric patterns of a shoe last are parameterised as models which can be quantified by certain parameters. The changes in parameter values can trigger the changes in dimensions of the shoe-last patterns but maintain similar geometrical forms. To explore this new approach for customisable shoe last patterns, it is necessary to understand the principles and process of shoe last patternmaking and the technologies of parametric drawing.

2.1. Shoe Last-Based Patternmaking

Shoe patterns consist of many parts but can primarily be classified into two main groups: the upper and the sole [2]. The upper concerns everything on the shoe above the bottom, while the sole is the bottom of shoes supporting the upper. The upper is normally attached to the bottom around the contour curve of the bottom (Figure 2).

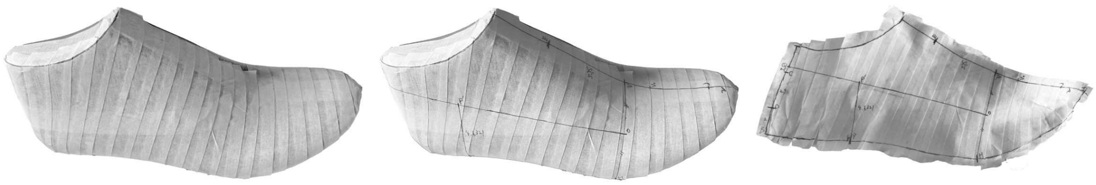
There are two approaches to developing shoe patterns named shoe-last-based patternmaking and flat pattern design [19]. Shoe-last-based patternmaking is a shoe patternmaking technology through which shoe patterns are created by draping processes on certain shoe lasts. It is suitable for producing basic shoe patterns for prototype production or individual shoes for customisation. Oppositely, flat pattern design is a shoe patternmaking technology through which a range of shoe patterns with a series of various sizes are created based on a scaling process of shoe basic patterns. Flat pattern design is often used in shoe mass production to meet mass-market needs for standard styles but diverse measurements.



(a) Shoe product (b) The bottom pattern (c) The upper patterns

Figure 2. *A shoe with its patterns.*

Shoe-last-based patternmaking normally includes a series of steps from selecting a shoe last, copying the three-dimensional surface of the shoe last through to flattening it into two-dimensional geometrics [2]. First, a type of shoe last is selected according to the shoe style and measures desired.



(a) (b) (c)

(a). Next, the shoe last is tapped up with masking tape or covered by heat-moulded plastic material on which the shoe design is drawn; (b). After that, the tape or plastic material is cut, peeled and flattened into flat pattern blocks; (c). This process of shoe patternmaking is carried out by integrating multiple factors: the shoe shape, style and dimensions. The set of patterns is one-to-one matched with an individual shoe. Thus, the patterns made in this way are merely suitable for a particular shoe style and sizing but unable to satisfy the variation of shoes in styles and dimensions.

Figure 3. *The process of last-based shoe patternmaking.*

To meet the mass consumption of shoes, many footwear manufacturers implement a mass production strategy through which the shoes are produced on scales based on standards in shoe styles and dimensions. Under the mass-production strategy, modelling and grading techniques are adopted in shoe patternmaking to improve the productivity of shoe products in various sizes. Through modelling techniques, basic shoe patterns are created by translating the shoe's last three-dimensional surface into two-dimensional geometrics blocks from which various shoe styles are derived. In the first phase of this process, the technique of the shoe-last-based patternmaking is used to create a set of basic shoe patterns (formes) composed of the insole and inside and outside upper patterns. Then, the patterns responding to various shoe types and styles are constructed by certain flat structural designs on the basic shoe patterns [19]. These patterns are special for some classical shoe designs which concern the men's Oxford shoe, Derby shoe, Monk shoe and Chukka boot as well as the ladies' Court shoe and the Ghillie shoe [19]. Since the processes are primarily manipulated in a two-dimensional context this technology can be named shoe flat pattern design.

2.2. Parametric Technology

As mentioned above, shoe last patterns are constituted of geometric figures with certain dimensions. Shoe last patternmaking is a process of definitions of geometric figures and constraints of dimensions. Even though various dimensions of shoe last patterns respondent to different sizes of shoes, geometric figures for a certain shoe style are similar and embody the same architectural framework. This attribute renders it possible to create shoe last patternmaking through parametric drawing.

Parametric drawing is a technology of constraint-based modelling offered by AutoCAD [13]. Using parametric drawing tools in AutoCAD, a drawing shape can be defined as a certain geometric object(s) based on geometric constraints and dimensional constraints. The geometric constraints define the drawing object shapes and set up linkages among different objects while the dimensional constraints control the dimensions of drawing objects by parameters or formulas. Once a parametric drawing object has been created, it can be quickly modified with merely a change of one or several dimensions rather than actual editing the shapes to respond to various needs on dimensions [13]. This technology applied in shoe last patternmaking would raise the efficiency of personalisation of the pattern dimensions.

Along with the development of parametric drawing technology in AutoCAD, higher efficiency of parametric drawing technology has been demonstrated in a few pieces of literature in garment patternmaking [23, 22]. Similar to garment patterns the shoe last patterns can also be produced through parametric drawing technology. Comparing the processes between garment and shoe last patternmaking, the patterns of a garment or shoe last can be obtained through draping on a mannequin or shoe last to translate 3D model to 2D flat patterns [7, 2]. Then these patterns can be modelled as basic patterns for further modification according to values of one or several parameters assigned to meet various individual sizes.

Based on the parametric drawing principles, this study was proposed to explore a parametric shoe last bottom patternmaking approach to satisfy the requirement of mass customisation of footwear production. Through the parametric drawing technologies in AutoCAD, the hand-made pattern was modelled as a parametric model [19] on which the shoe-last bottom pattern [2] can be modified quickly and automatically according to the changes in primary parameters (normally the shoe primary sizes) to respond to individual foot measurements. This technology can be used in shoe last patternmaking to achieve mass customisation in footwear manufacturing.

3. Methods

Shoe patterns are primarily composed of upper and sole parts which are traditionally created relying on patterns of shoe last upper and bottom parts. This study focuses on the exploration of parametric modelling methods of underlying shoe's last bottom patterns for shoe sole patternmaking. We conducted an experimental exploration based on parametric drawing tools on the platform of an engineering drawing software AutoCAD. This experimental study methods incorporate modelling of shoe last bottom pattern, digital parameterisation of the models and validation of the shoe last bottom parametric patternmaking methods.

3.1. Modelling Shoe Last Bottom Pattern

Modelling shoe last bottom patterns is a technology of flat pattern design. Differing from shoe pattern making by shoe-last-based dropping, modelling shoe patterns through flat patternmaking develops the shoe patterns based on foot measurements and scale [18]. The measurements are obtained directly by measuring feet while the scale is used to calculate those measurements which are difficult or time-consumed to establish. Scale for shoe patternmaking is based on analyses of a set of measurements of feet referring to the shoe patterns obtained through dropping. The principle of scale relies on the assumption that people's feet are generally proportionate. For example, a foot with a longer length will usually have wider toe width and vice versa. Thus, some detailed dimensions can be scaled by primary ones with appropriate proportions derived from statistical analyses of various measurements. Based on the shoe last flat patterns along with feet measurement standards, templates of shoe last patterns can be created as models for shoe pattern making.

Similar to the engineering drawing, modelling the shoe-last patterns entails two key elements: geometric figures and their dimensions [12]. To simplify the modelling of irregular shapes of the shoe last patterns, an entire shoe last pattern was divided into several sections suitable to be fitted by simple geometric objects such as lines, arcs and ellipse curves. The dimensions of each geometric object are determined by direct measurements or calculations according to the scale relationship with the primary dimensions. Therefore, modelling of shoe last patterns can be attributed to the nature of geometric objects and their dimensions. The process of modelling contains defining geometric objects, constraining the geometric relationships among the objects and constraining the dimensions of each object.

3.1.1. Defining Geometric Objects

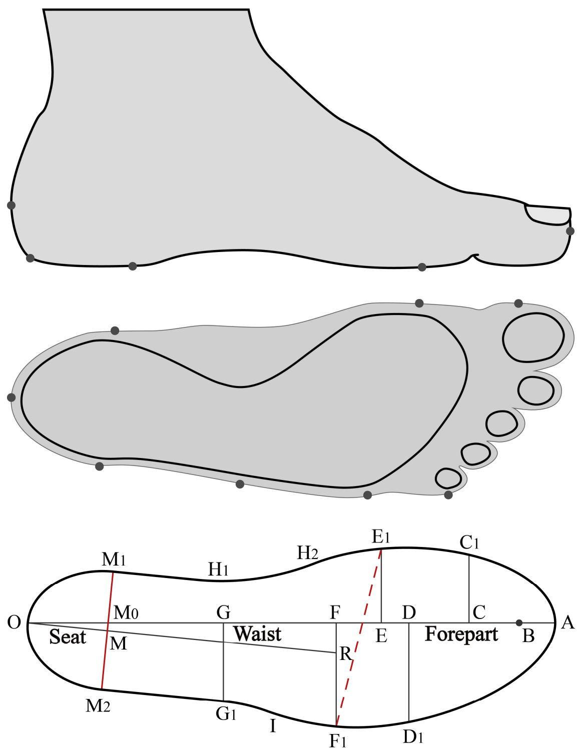


Figure 4. *The geometric features of the shoe last button [24].*

According to the observation of the patterns of shoe-last bottoms created by the shoe-last-based 3D dropping method, it is evident that the shoe-last bottom patterns always manifest complex irregular shapes. Under the software CAD technical situation, the entire contour of the shoe-last patterns is normally constructed by non-uniform rational basis spline (NURBS) which is determined by a set of feature points [10]. However, NURBS curves are impossible to be evolved accurately according to the changes in shoe last primary dimensions [5] even though they can accommodate the outline of shoe last bottom flat patterns.

To enable parametrisation of shoe last bottom pattern making, the whole pattern of the shoe last bottom is divided from toe point to heel into three sections: forepart, waist and seat (Figure 4). From the rear heel point (O) to the front toe point (A), the centre line (OA) passing through the shoe-last bottom pattern splits the pattern into inside and outside sections. In this template of the shoe last bottom pattern, besides the rear heel point O and the front toe point A, a set of other feature points are also used to define an explicit contour of the pattern.

In the section forepart, point C_1 represents the salient point of the big toe and point D_1 represents the little toe tip. Point E_1 represents the first metatarsal bone and F_1 means the fifth metatarsal bone that the ball girth can be measured passing through these two points. Regarding the waist section, M1 and M2 are respectively the medial and lateral feature points as the cut-off points between the sections of the seat and waist. In addition, point G_1 represents the salient of the outside base of the fifth metatarsal bone and point I is the curvature-changing point along the lateral waist curve, while H_1 and H_2 are the curvature-changing points of the medial waist curve. Thus, the outer contour of the shoe last bottom can be regarded as six parts and their geometric attributes are as follows: The curve of the forepart can be regarded as two elliptical arcs AE_1 and AF_1 starting from the front point of the last (A). Two curves of the rear heel M_1O and OM_2 can be regarded as one elliptical arc with the heel centreline OR as the axis of symmetry. The outer waist contour line from the head to the heel can be regarded as two arcs F_1I and IG_1 with opposite radians and a straight line G_1M_2. The inner waist contour line can also be regarded as two arcs E_1H_2 and H_2H_1 along with a straight line H_1M_1. The waist inner curve E_1M_1 and outer curve F_1M_2 connect the forepart and seat in continuity.

In sum, the pattern of shoe last bottoms can be modelled as a shape constructed by multiple geometric objects which are defined by a set of feature points. The collaborative dimensions among these feature points are depended on various measurements of the foot. Thus, to obtain a precise parametric model of the shoe-last bottom pattern it is necessary to constrain the dimensions among the series of feature points in parametric ways according to the primary measurements of a foot.

3.1.2. Assigning Dimensions

Assigning dimensions to shoe last bottom patterns can be conducted by defining the two-dimensional positions of the series of feature points. The process can be dealt with by the creation of an inner framework as the architecture of a parametric pattern of the shoe last bottom. As illustrated in Figure 4, the framework lines can be classified into two groups which are respectively concerned with length and width measurements of a foot. The original point O is positioned on the rear heel point while point A represents the front end point of the shoe last. D_{oa}, the distance between point O and point A, equals the length of the shoe last. Central line OA does not only determine the length of the shoe last but also plays a role as a longitudinal axis that facilitates the position of the feature points by longitudinal and latitudinal dimensions [11].

Besides points of O and A, the other feature points including points C_1, D_1 E_1, F_1, G_1, M_1 and M_2 along the contour of shoe last patterns can be positioned through their longitudinal and latitudinal dimensions according to the baseline OA. According to International Organization for Standardization [6], referring to the original point O the longitudinal dimensions of the feature points can be gained by calculations based on different scale relationships between the longitudinal dimensions and the foot length (Table 1).

Table 1. *Longitudinal dimensions of feature points for the shoe last bottom pattern (Unit: mm).*

Dimension	Description	Formula
Longitudinal dimension		
OA	Last bottom pattern length	FL + 16.5 - 4.5
OB	The corresponding position of the big toe tip point on OA	FL - 4.5
OC	The corresponding position of the big toe contact point on OA	0.9*FL - 4.5
OD	The corresponding position of the little toe contact point on OA	0.78*FL - 4.5
OE	The corresponding position of the first metatarsal-phalange point on OA	0.725*FL - 4.5
OF	The corresponding position of the fifth metatarsal-phalange point on OA	0.635*FL - 4.5
OG	The corresponding position of waist point on OA	0.41*FL - 4.5
OM_0	The central position of the heel area	0.18*FL - 4.5
Latitudinal dimensions		
CC_1	The inner width of the big toe of the last	0.3434*BW – 0.02*0.0466*BW
DD_1	The outer width of the little toe of the last	0.4978*BW + 0.09*0.0432*BW
EE_1	The first metatarsal-phalange inner width of the last	0.3606*BW + 0.18*0.0694*BW
FF_1	The fifth metatarsal-phalange outer width of the last	0.5161*BW + 0.16*0.0539*BW
GG_1	The outer width of the waist of the last	0.3953*BW + 0.01*0.0717*BW
M_1M_2	Width of the heel area of the last	0.5077*BW + 0.48*0.093*BW+ 0.59*0.0763*BW

In addition, corresponding to the baseline OA, the latitudinal dimensions of the feature points can be gained by calculations depending on various scale relationships between the latitudinal dimensions and the tread width of the shoe last [6] (Table 1).

To sum up, the parameters required to define the length and width dimensions of the model are foot length (FL) and basic width (BW). The basic width is calculated from the proportional relationship with the ball girth. The foot length and the ball girth can be directly measured by users.

After clarifying the geometric figures and the dimensions of the shoe last bottom pattern, the drawing and parametric tools in AutoCAD were used to express them and completed the internal frame lines and contour profiles below. After connecting and constraining the contour profiles according to the endpoints of the frame lines, the parametric model of the shoe last bottom pattern would be established.

3.2. The Digital Parameterisation of the Models in AutoCAD

Under the condition of the definition of geometric objects and assignment of dimensions to the objects, a parametric model of the shoe last bottom pattern can be created by the drawing tools and parametric manager in AutoCAD. The process of the creation of the parametric model includes three steps: creating a geometric framework and constraints, dimensional constraining and creating parametric patterns of shoe last bottom.

3.2.1. Creating a Geometric Framework and Constraining

The digital parametric pattern of a shoe last bottom can be created based on a series of feature points along the contour of the pattern (Figure 4). The feature points can be positioned by an internal framework with dimensional constraints. As shown in Figure 5, the internal frame lines are composed of straight lines which can be created by the tool 'Line' in the AutoCAD as initial geometric objects for geometric and dimensional constraints assignment next.

The centre line OA is drawn parallel to the X axis on the AutoCAD's drawing panel and O is the orient point which can be positioned in any appropriate location. Then, the width framework lines A_1A_2, B_1B_2, CC_1, DD_1, EE_1, FF_1, and GG_1 can be drawn perpendicular to the centre line OA. To be convenient for selecting points M and M_0 to constrain with dimensions later, line M_1M_2 is divided into three sections including M_1M_0, M_0M and MM_2. GH is the extension of line G_1G and intersects with line M_1E_2 at point H. Besides the feature points, the dotted lines in the figure are reference lines for drawing contours.

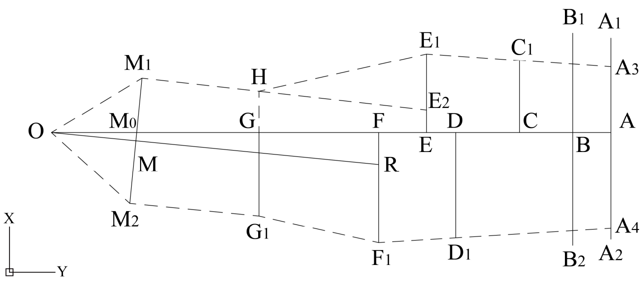


Figure 5. *The initial geometric objects of framework lines.*

Relying on the initial geometric framework lines of the shoe-last bottom pattern created above, appropriate geometric constraint tools in AutoCAD can be selected to define the geometric correlations among the framework lines. First, the centre line OA is defined as a horizontal line by the geometric constraint tool 'Horizontal' to ensure the orientation of the model. Then, the width lines A_1A_2, B_1B_2, CC_1, DD_1, EE_1, FF_1 and GG_1 are defined as lines perpendicular to centre line OA by the geometric constraint tool 'Perpendicular'. Further, the points C, D, E, F, G and M_0 are located on the centre line OA by the geometric constraint tool 'Coincident'. With the same tool and process, points M, R and E_2 are located separately on the lines OR, FF_1 and EE_1, while A, A_3 and A4 are located on line A_1A_2. The 'Collinear' and 'Coincident' constraint tools are selected to connect the lines M_1M_0, M_0M, and MM_2 and keep them coincident in direction and connected on the endpoints M and M_0. Furthermore, the same tools and processes are used to treat the framework lines next to the connecting points O, M_1, M_2, H, G_1, F_1, E_1, D_1 and C_1 to connect. Then, the geometric constraint tool 'Collinear' is used to assign the lines GG_1 and GH, lines A_3C_1 and C_1E_1 as well as lines A_4D_1 and D_1F_1 separately to make them collinear. Finally, line OR is set perpendicular to M_1M_2 by the geometric constraint tool 'Perpendicular', while line M_1E_2 is set parallel with line OR by tool 'Parallel'. In this case, the geometric correlations among a series of feature points and framework lines are defined and such discrete objects are integrated as a whole interrelated object.

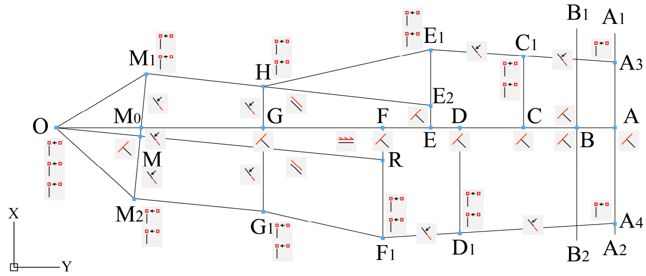


Figure 6. *The geometric constraints on the initial framework lines for the shoe last bottom pattern.*

3.2.2. Dimensional Constraining

Besides geometric constraints, dimensional constraints are the significant parametric tools in AutoCAD. Dimensional constraints along with geometric constraints allow drawing objects to be set and adjusted in dimension and geometric feature thereby easy to vary in size and even shape.

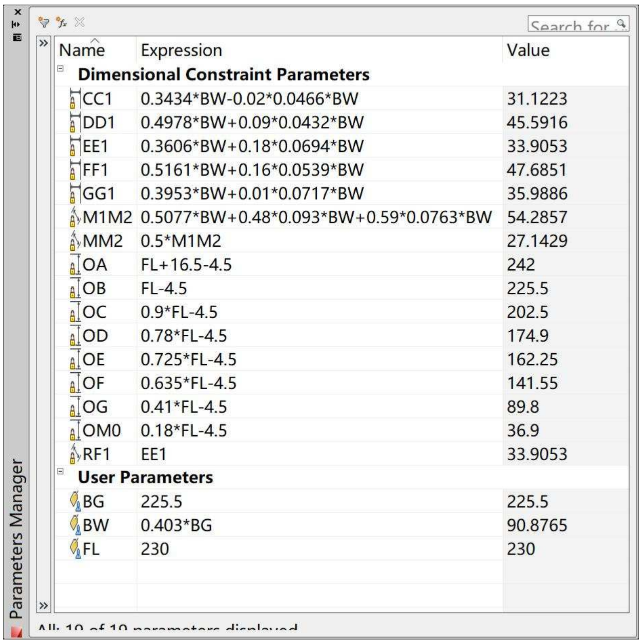
Dimensional constraints can be achieved by assigning constraints to certain dimensions or applying formulas to constraints of existing drawing objects through the Parameters Manager in AutoCAD [1]. Regarding the pattern of the shoe-last bottom, the basic dimensions such as Foot Length (FL), Ball Girth (BG) and Basic Width (BW) can be constrained with numeral values selected from shoe measurement standards or personal sizes (Table 2).

Besides the basic dimensions FL, BG and BW, the dimensional constraints to other dimensions of the shoe last bottom pattern can be treated by adding formula parameters since their values are the results of calculations according to certain formulas (Table 1). This kind of dimensional constraint is derived from the calculations of predefined formulas with independent variables of the primary dimensions including FL, BG and BW.

Table 2. *The primary dimensions and default constraints for the shoe last bottom pattern (Unit: mm).*

Name	Expression	Description
FL	230	Foot length
BG	225.5	Ball girth
BW	0.403*BG	Basic width

To create a substance of the parameterised drawing objects, the primary dimensions need to be assigned with default constraints. In this paper, FL and BG are assigned with respective default constraints of 230 mm and 225.5 mm (Table 2). The directly assigned constraints and formula parametric constraints can be added to the drawing objects through the Parameters Manager tool (Figure 7) in the Manage panel in AutoCAD [1].



Name	Expression	Value
Dimensional Constraint Parameters		
CC1	0.3434*BW-0.02*0.0466*BW	31.1223
DD1	0.4978*BW+0.09*0.0432*BW	45.5916
EE1	0.3606*BW+0.18*0.0694*BW	33.9053
FF1	0.5161*BW+0.16*0.0539*BW	47.6851
GG1	0.3953*BW+0.01*0.0717*BW	35.9886
M1M2	0.5077*BW+0.48*0.093*BW+0.59*0.0763*BW	54.2857
MM2	0.5*M1M2	27.1429
OA	FL+16.5-4.5	242
OB	FL-4.5	225.5
OC	0.9*FL-4.5	202.5
OD	0.78*FL-4.5	174.9
OE	0.725*FL-4.5	162.25
OF	0.635*FL-4.5	141.55
OG	0.41*FL-4.5	89.8
OM0	0.18*FL-4.5	36.9
RF1	EE1	33.9053
User Parameters		
BG	225.5	225.5
BW	0.403*BG	90.8765
FL	230	230

Figure 7. *The Parameter Manager with dimensional constraints and formula parameters.*

3.2.3. Creating Parametric Patterns of Shoe Last Bottom

Creating parametric patterns of shoe last bottom in AutoCAD concerns the contour definition, geometric constraining and dimensional constraining. Contour definition is carried out by drawing tools, geometric constraining is partly determined by geometric constraints of the feature points, while dimensional constraining is controlled by dimensional constraints of the framework lines.

To facilitate the fitting of the contour of the shoe last bottom pattern, the whole contour is divided into six sections. As shown in Figure 8, lines E_1F_1 and M_1M_2 divide the sole into forepart, waist and seat from front to back while line AO divides the sole into outside and inside. Each section is regarded as an independent geometric object and created by a certain drawing tool. The independent objects are positioned by passing them through the feature points defined previously. Then all the independent objects are connected by the geometric constraint tool 'coincident'. They are also drawn in smooth shapes by the geometric constraint tool 'tangent'.

In detail, the arc of the seat contour M_1OM_2 is drawn by the 'elliptical' tool that the arc starts from point M_1 to M_2 with point M as the centre point of the ellipse arc. Then, the axis points of the elliptical arc are positioned on the feature points O, M and M_2 by the geometric constraint tool 'coincident'.

For the forepart section, the outer-forepart arc F_1A is also drawn by the 'elliptical' tool that the arc starts from point F_1 to A with point F as the centre point. The inner-forepart arc AE_1 is drawn by the 'elliptical' tool from point A to E_1 with point E as the centre point. These two elliptical arcs are constrained by the tangent of vertical line A_1A_2 at point A to keep smooth with each other. After the tangent constraining, the positions of other endpoints of these two arcs may have slight shifts. In this case, the new endpoint of F_1A is named point J and the new endpoint of AE_1 is named point K.

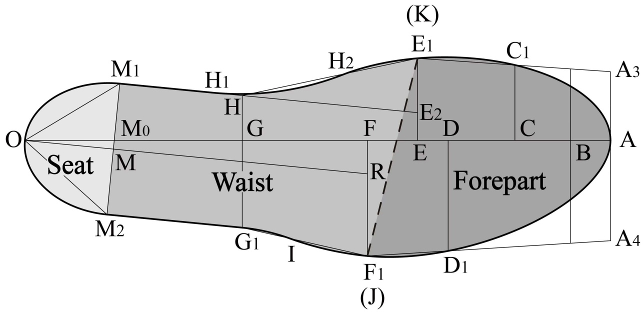


Figure 8. *The parametric model of the shoe last bottom pattern.*

Regarding the waist section, the inner waist contour line consists of line M_1H_1 and arc H_1H_2 and H_2E_1. It can be created as a polyline by the drawing tool 'Pline'. Line M_1H_1 is drawn in 'line' mode which starts from point M_1 to H_1 and then extended through point H_2 to point E_1 in 'arc' mode. Point H_1 is temporarily first located along the framework line M_1E_2 and then confirmed later subject to the 'tangent' constraint. Further, the inner waist contour line is respectively connected with arc OM_1 and AE_1 and fixed on the feature points M_1 H_1 and E_1 by the geometric constraint tool 'coincident'. Arc OM_1 and AE_1 are further set to be smooth by the geometric constraint tool 'tangent'. Repeating the processes and methods, the outer waist contour line can be created and connected with arc OM_2 and AF_1 smoothly. It can also be fixed on the feature points M_2 G_1 and F_1. At this point, the whole parametric model of shoe last bottom pattern has been established.

In summary, to create a parametric model of shoe last bottom pattern, the pattern is regarded as a compound geometric object which is decomposed into simply sections characterised by the feature points and framework lines. The primary process of creating shoe last bottom pattern includes establishing feature points and framework lines, drawing and connecting the initial contour lines and setting geometric and dimensional constraints. Through this process, a parametric model of shoe last bottom pattern can be created for flexible adjusting of sizes and shapes according to the values inputted to the parameters.

4. Validation of Parametric Pattern of Shoe Last Bottom

The advantage of the parametric pattern of the shoe last bottom is its ability to flexible adjustment in dimensions and shapes according to individual measurements. According to the measurement standard of the Chinese female foot, the essential dimensions of the foot such as the foot length (FL) and ball girth (BG) concern a series of the length and width dimensions of footwear. The range of female foot length is between 210 and 265 mm and the corresponding ball girth range is between 201 and 267.5 mm [24]. Thus, the assessment of the flexible adjustment ability of the parametric pattern of the shoe-last bottom is dependent on the effects of changing the essential parameters of the pattern such as the FL and BG.

In this case, three types of tests by changing the parameters of the parametric pattern were carried out based on the measurement standard of the female foot. To prepare for the tests, the two clusters of female foot measurements were selected to establish a matrix of foot dimensions as shown in Table 3. Three degrees of measurements from smallest, middle to largest in length and width dimensions were chosen for the tests. The first type of test is a width variation test in which the length size was kept constant (e.g. 265 mm) but variation in width sizes. Oppositely the second type of test is a length variation test in which the width size was kept constant (e.g. 267.5 mm) but variation in length sizes. The third type of test is a length and width variation test in which the length and width sizes were changed simultaneously.

Table 3. *Matrix of the Chinese female foot measurements (Unit: mm).*

Foot length \ Ball girth	201	234.5	267.5
210	✓		✓
237		✓	✓
265	✓	✓	✓

Whatever types of tests are conducted, the process of experiments concerns three steps. First, an initial parametric pattern of the shoe-last bottom is prepared with default values (e.g. 230 mm and 225.5 mm) assigned respectively to the essential parameters of FL and GB. Then, the initial parametric pattern is modified by changing the parameters' values according to the measurement standard in certain ways. Finally, assessments are made by observing the pattern shapes modified and measuring the essential dimensions. The criteria of quality assessment for the different patterns of the shoe last bottom include:

1. rational shape and geometric proportions,
2. continual and smooth contour,
3. and accurate dimensions.

4.1. Width Variation Test

Based on the parametric model of the shoe last bottom pattern opened in AutoCAD, the parameter FL was assigned in 265 mm and the BG was assigned respectively in 201 mm, 234.25 mm and 267 mm through Parameters Manager (Figure 7). After inputting new values to the essential parameters FL and BG in place of the default values, the initial parametric pattern of the shoe last bottom was modified automatically. Aligning the different patterns on the centre line results in the diagram shown in Figure 9. The diagram demonstrated that the three patterns had similar shapes with the same foot length size but different width sizes. According to the measurement of the patterns, the length and width sizes of the various patterns were coincident with the correspondent dimensions in the measurement standard.

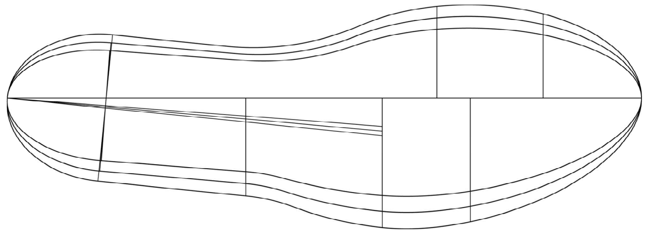


Figure 9. *The comparison of different parametric patterns in the width variation test.*

4.2. Length Variation Test

Based on the parametric model of the shoe last bottom pattern opened in AutoCAD, the parameter FL was assigned respectively in 210 mm, 237.5 mm and 265 mm and the BG was assigned in 267.5 mm through Parameters Manager (Figure 7). After inputting new values to the essential parameters FL and BG in place of the default values, the initial parametric pattern of the shoe last bottom was modified automatically. Aligning the different patterns on the centre line and centre point results in the diagram shown in Figure 10. The diagram demonstrated that the three patterns had similar shapes with the same width size but different foot length sizes. According to the measurement of the patterns, the length and width sizes of the various patterns were coincident with the correspondent dimensions in the measurement standard.

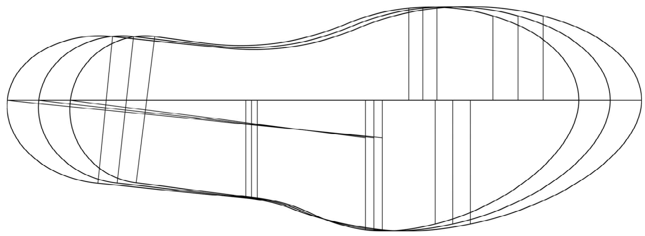


Figure 10. *The comparison of different parametric patterns in the length variation test.*

4.3. Length and Width Variation Test

Based on the parametric model of the shoe last bottom pattern opened in AutoCAD, the parameter FL was assigned respectively in 210 mm, 237.5 mm and 265 mm and the BG was assigned respectively in 201 mm, 234.25 mm and 267 mm through Parameters Manager (Figure 7). After inputting new values to the essential parameters FL and BG in place of the default values, the initial parametric pattern of the shoe last bottom was modified automatically. Aligning the different patterns on the centre line and centre point results in the diagram shown in Figure 11. The diagram demonstrated that the three patterns had similar shapes with different foot length sizes and different width sizes. According to the measurement of the patterns, the length and width sizes of the various patterns were coincident with the correspondent dimensions in the measurement standard.

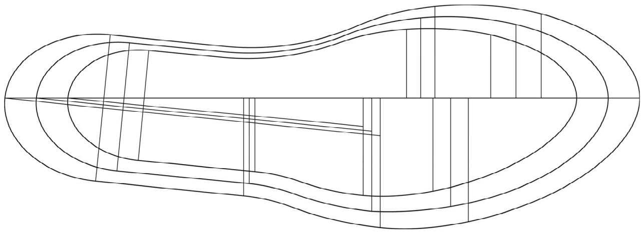


Figure 11. *The comparison of different parametric patterns in the length and width variation test.*

The three types of tests of the parametric pattern of the shoe last bottom demonstrated that the parametric model of the geometric shape for the shoe last bottom can be modified automatically according to the various input values of essential parameters of the pattern. The parametric pattern can be used to generate various patterns according to the different foot measures. The Parameters Manager can be used as an interface to control the parameter value inputting and modify the parametric pattern to respond to specifically required sizes quickly and automatically. By assigning certain values to essential parameters a parametric model of the shoe last bottom pattern can generate various patterns which can respond to different required sizes with rational shapes and geometric proportions, continual and smooth contours and accurate dimensions.

5. Conclusion

Facing the trend for the traditional labour-intensive footwear industry to transform from mass production to mass customization, many scholars and practitioners have paid attention to the study on 3D product development technologies. However, these studies are carried out under the traditional shoe-last-based product development methods. They have not yet offered feasible approaches to solve crucial technical problems such as effective and efficient patternmaking technologies of footwear products for mass customisation. In this study, we supposed a parametric patternmaking technology based on the parametric drawing technology in AutoCAD to achieve mass customisation of the shoe last bottom pattern. Based on an analysis of the geometric features of shoe last bottom patterns, the pattern architecture and dimensions were parameterised by the geometric and dimensional constraint tools in AutoCAD with a result in a parametric model of the shoe last bottom pattern. The process of parameterisation of the pattern primarily included three phases: contour definition, geometric constraining and dimensional constraining. The quality of the parametric model of the pattern was assessed by three types of tests in the process different values were assigned to the essential parameters (shoe sizes). The results of the tests demonstrated that the parametric pattern of the shoe last bottom could generate various patterns which can be controlled by the values input to the essential parameters in the model. In addition, the results also fulfilled the criteria of quality assessment including rational shape and geometric proportions, continual and smooth contours and accurate dimensions.

This study, therefore, indicates that parametric drawing technology can be an effective and efficient approach to achieving customisation of the shoe last bottom patternmaking for a quick response to the individual requirements of footwear product development. The flexibility of this parametric shoe last bottom pattern model can provide an approach to mass customisation in the footwear industry. Beyond the shoe last bottom pattern, this technology may also be suitable to be applied in other parts of footwear products such as the upper patternmaking and even other kinds of products (e.g. fashion garments).

Most notably, this is the first study to our knowledge to explore the effective approach to achieving mass customisation of footwear during the phase of the product development process. Thus, some limitations are worth noting. For example, the shoe's last bottom patterns vary since the changes in shoe styles such as the height of the heel or the shape of the forepart. In addition, shoe patternmaking mostly concerns upper patterns needed to be addressed further. These problems are merit to be addressed in the future.

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