Computer-Aided Design AND APPLICATIONS www.cadanda.com

A Digitally-enabled Integrated Approach to Design and Manufacture Shoe Lasts

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ABSTRACT

In the era of the fourth industrial revolution the efficient sharing and exploitation of information are key success factors for companies. In order to maintain competitiveness and to answer to the requests for highly customized products, shoe last producers need to innovate their processes, by adopting digital technologies. The present paper proposes an innovative integrated approach for shoe last design and manufacturing. The process is enabled by CAD/CAM technologies, which allow to integrate the design and manufacturing phases, and by haptic technologies, which allow to interact with the virtual models to simplify the successive planning and manufacturing operations. The final aim is to support traditional companies in the implementation of the Industry 4.0 paradigm. The test case about marking operation confirms that the adoption of the proposed approach leads to a sensible improvement in the company operational efficiency, thanks to the reduction in the number of repetitive tasks.

Keywords: Shoe Last Design, Industry 4.0, CAD/CAM Technologies, Haptic Interface.
DOI: https://doi.org/10.14733/cadaps.2019.593-610

1 INTRODUCTION

During last years, Industry 4.0 has emerged as one of the most discussed topics, from both academia and industry [23]. According to this new industrial paradigm, manufacturing processes need to be digitalized and physical items, such as devices and company assets, need to be efficiently connected each other [30]. To this aim, several key enabling technologies (e.g. sensors, cyber physical systems – CPS, Internet of Things devices – IoT, haptic devices) have been developed and integrated within the manufacturing processes [1][35]. The implementation of the Industry 4.0 paradigm impacts at different levels and requires a change in the business model, especially in the case of small and medium enterprises (SMEs) [22]. The product development process can be also positively affected through the integration and virtualization of design and production processes [27].

In this context, activities are becoming more data intensive and collaborative, thus data sharing is assuming a crucial role [34]. The efficient gathering, management and exploitation of information are key success factors for companies approaching Industry 4.0 [29]. This is true both in high-tech sectors, as electronics or automotive, and in traditional sectors, as the fashion or the footwear industries.

The manufacturing of shoes requires the involvement of several small companies that actively collaborate to realize the different materials (e.g. leather), semi-finished parts (e.g. sole, insole, upper, last) and components (e.g. laces, heel, accessories) [20]. In the last years, several studies aim to develop innovative technologies to support and improve the shoes development process, which is still grounded on traditional processes [18][5]. The main research topics are focused on product customization [10], design automation [24], human foot modelling and comfort simulation [28].

Shoe lasts can be viewed as 3D models of a human foot, used to mount footwears [19]. They are quite simple products, realized starting from a block of plastic or wood. However, they are essential for the shoe assembly, since the final shoe style, design and comfort strictly depend on the last. Currently the shoe last design and manufacturing are commonly based on artisanal processes and on the know-how of expert operators who manually realize and optimize the wood model used as a base for the realization of the plastic lasts in different sizes [18].

In order to maintain competitiveness in the global market and to answer to the requests for highly customized products [32], shoe last producers need to innovate their processes, by adopting digital technologies to improve their efficiency and fully exploit the available data [9]. Several literature studies are focused on the development of methods and technologies dedicated to the design of footwear products [8]. In particular, the design of customized lasts has been investigated by several authors who developed CAD-based approaches and tools [17][24][26][33], algorithms for the last grading [12] and methods for shoe last customization and personalization [14][16]. Another common research topic is related to the design of lasts for special user categories and applications [2][3]. However, none of these approaches/tools focus on the radical innovation of the operational processes (both design and manufacturing) of shoe last producers, according to the Industry 4.0 paradigm.

The present paper wants to overcome this lack by defining and testing an innovative integrated approach for shoe last design and manufacturing. The proposed process is enabled by Computer Aided Design (CAD) / Computer Aided Manufacturing (CAM) technologies, which allow to use design data (e.g. 3D models) to realize a horizontal integration among the design phase/department and the production phase/machines, according to the Industry 4.0 pillar regarding the system integration. In addition, haptic technologies are used to interact with the virtual models in order to simplify the successive planning and manufacturing operations (e.g. marking, drilling). The main aim is to support traditional and artisanal footwear companies in increasing the flexibility of their processes, in rapidly reacting to changes in demand or stock levels, in adapting their production to customer needs, in efficiently using the available data and in improving the workers' conditions (reduction in the number of repetitive operations). This study also represents one of the first examples of industrial use of haptic interfaces that are largely used in theoretical research studies, but currently have scarce application in real industrial contexts [7][31].

The remainder of the paper is structured as follows. Section 2 describes the current (i.e. traditional and AS-IS) design and manufacturing processes of shoe lasts, showing the main bottlenecks and criticalities. Section 3 presents the steps of the proposed (i.e. TO-BE) digitally-enabled approach, together with the developed software tool that acts as a link between the design and manufacturing phases. Section 4 presents the implementation of the proposed approach and technologies in the context of the shoe last marking task and the discussion of the obtained results. Finally, Section 5 reports conclusions and proposals for future developments.

2 THE TRADITIONAL AND AS-IS PROCESSES FOR SHOE LAST DESIGN AND MANUFACTURING

The shoe lasts design and manufacturing processes involve a combination of traditional/manual operations and digital/automatic technologies. Figure 1 shows the most important steps, classified by analyzing the modus operandi of different shoe last producers. Two variants can be defined: (a) Traditional process, in which the shoe last finishing (i.e. adding of required features, as holes or marks) are performed manually, and (b) AS-IS process, in which the shoe last finishing is supported by digital technologies and automatic machines.

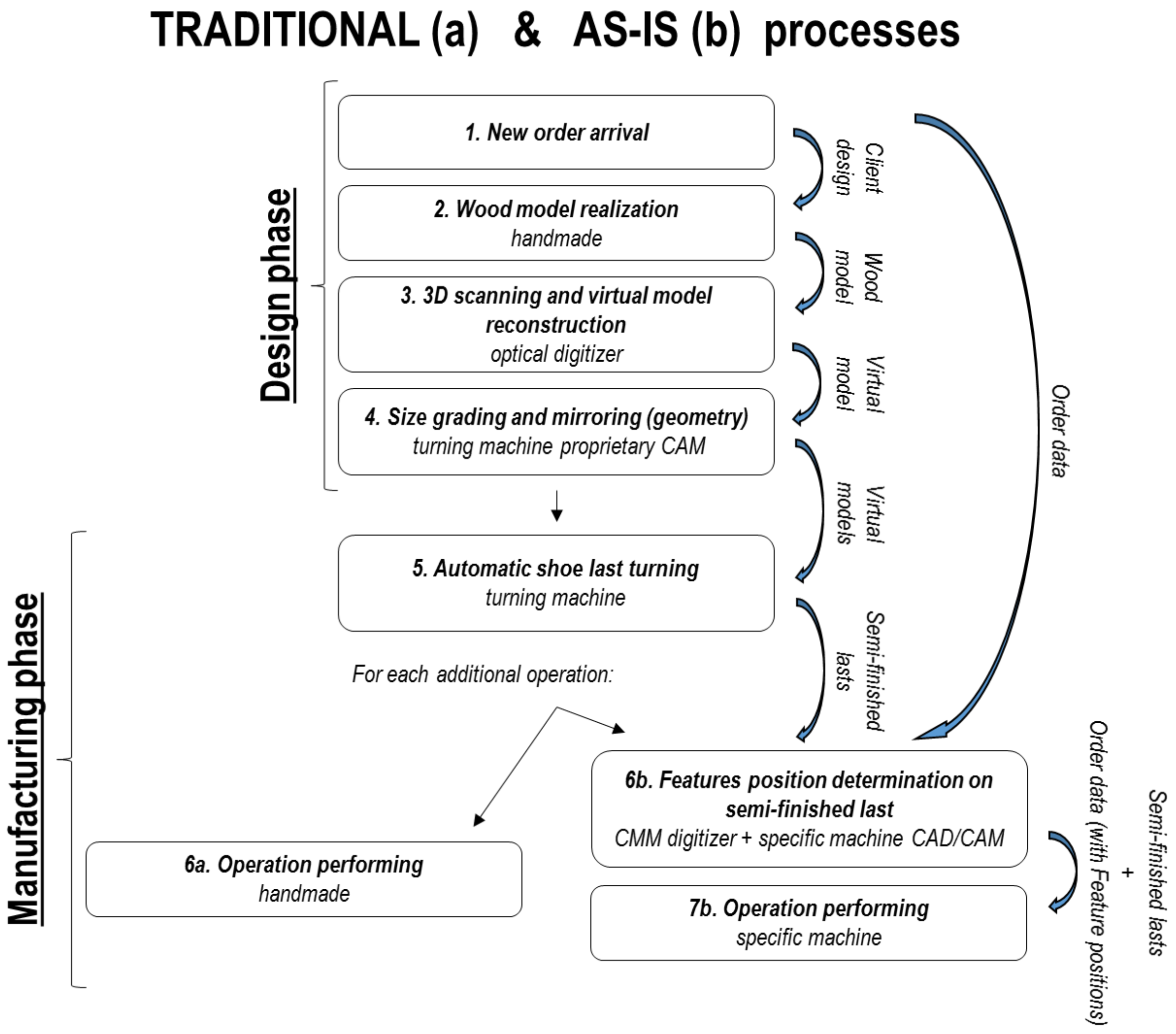

Figure 1: The TRADITIONAL and AS-IS processes.

The process begins with a new order, which consists in the definition of technical, economic and stylistic specifications on the basis of client requirements (Step 1 – *New order arrival*). In this phase, a preliminary documentation describing the order (called *Order data*) is generated to specify the product code and name, the required sizes, the number of required pairs per sizes, the typology and position of required additional features, etc.

The first operational step is the *Wood model realization* (Step 2). For each order, only one wood model for the right foot and for the base size (usually 37 for woman shoes and 40 for man shoes, according to the European size system) is manually realized by the factory's artisans. This certainly represents a critical operation, since it strictly depends on the ability of operators to correctly interpret and concretize the client requirements (especially in terms of style). However, currently, virtual technologies, such as 3D modelers, are not commonly adopted and "accepted" in the shoe last sector, thus the physical wood model still have a central role to preliminary evaluate the "stylistic rendering" of a new model.

After the final approval of the wood model, this latter is scanned in order to obtain a digital model, to be used in the successive phases (Step 3 – *3D scanning and virtual model reconstruction*).

At this stage, the base virtual model has to be mirrored and graded, to rebuild the left foot and all the required sizes (Step 4 – *Size grading and mirroring*). This task is generally carried out through the use of the proprietary CAM software tool installed in the specific turning machines, which only requires as input a STL model of the right foot of the base size. This represents the final step of the design phase in the traditional and AS-IS processes.

The complete set of virtual models is then used for the production of shoe lasts, which are realized by turning plastic bricks (Step 5 – *Automatic shoe last turning*). During this operation, the last is hold by the machine by means of a dovetail joint positioned in the upper part of the last (Figure 2).

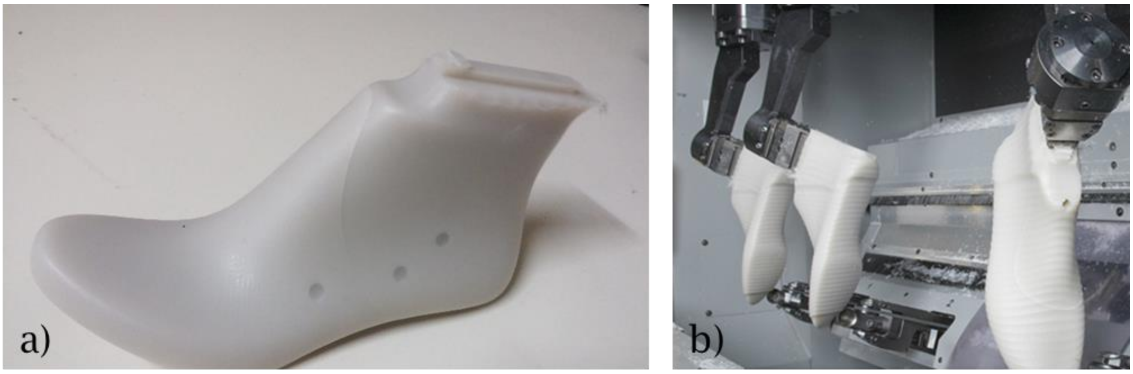

Figure 2: a) A turned shoe last, b) The shoe last turning machine with the detail of the hold system.

Once the geometrical shape is complete, other features must be usually added to finalize the last. For instance, several holes need to be added to hold the last during the shoe assembly. Furthermore, each last must be marked to add relevant information, such as collar's references and size.

In the Traditional process these operations are performed manually and need to be repeated for each last produced (Step 6a – *Operation performing*). The positions of some required features, in fact, are usually indicated by the artisan who produce the wood model by means of little bulges in the external surface of the last. For this reason, in order to retrieve their exact location, it is necessary to touch the last and to detect these bulges, as shown in Figure 3.

By implementing the AS-IS process, a first step toward automatization has been taken. According to this configuration, an operator manually defines the positions of the features on the semi-finished products, by using Coordinate Measurement Machine (CMM) digitizers, such as the MicroScribe® (Step 6b – *Features position determination on semi-finished last*). For instance, the marking process that was traditionally carried out by using manual ink stamps, is currently performed by using a laser technology (Step 7b – *Operation performing*). During the process, the last is handled by a robot which follows the paths defined by the operator through the CMM digitizer.

This operation is generally time consuming and not repeatable (different operators, different lasts, different machines, inefficiencies in identifying the correct position of bulges in the semi-finished last, etc.).

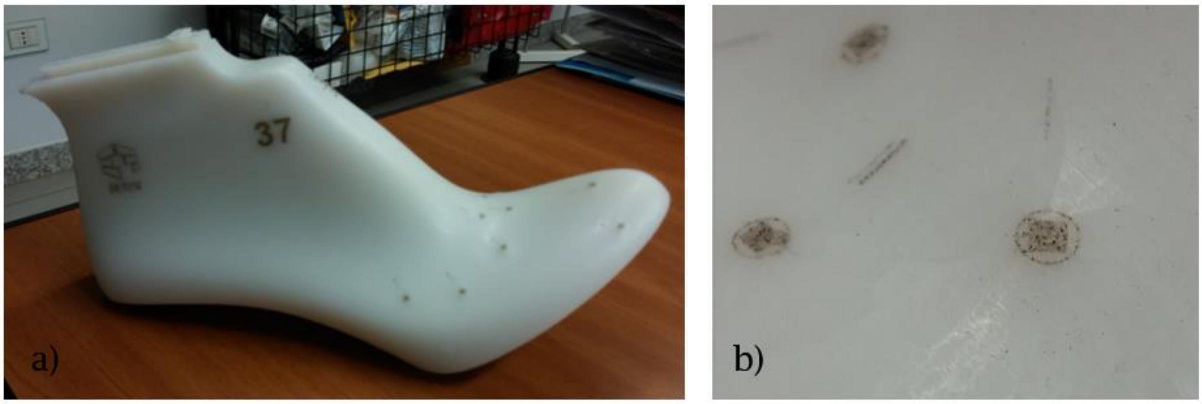

Figure 3: a) a shoe last with marks; b) zoom on the marks: each mark is located on the top of a bulge.

The main issues for automating the AS-IS process are related to the positions of the features needed in the lasts. CAD/CAM solutions with standard user interfaces (e.g. mouse, keyboard) are generally not enough accurate to define these positions, since they do not allow to "feel and touch" the last in order to identify the correct positions of the features (i.e. bulges in the external surface of the last). The use of a MicroScribe can be considered as an incomplete transition toward the process digitalization and efficiency improvement, since acquisitions must be repeated for each last model, pair and size in a production order. Furthermore, the final positions of the features on the actual lasts are still inaccurate. This is mainly due to the fastening system (i.e. the dovetail joint) used to fix lasts on the automatic machines supports. The joint position with respect to the last geometry is not known with sufficient accuracy, because of mechanical plays and differences between the different available turning machines. Finally, several machine regulations are often performed by operators before the turning. These operations cannot be easily traced since they are only based on the expertise of each operator, thus make the process not repeatable and are source of additional inaccuracies.

3 THE INTEGRATED DESIGN AND MANUFACTURING APPROACH

The core idea of the proposed process for shoe last production is to acquire the information required for operations, such as marking, drilling, etc. directly from the virtual model of the last, during the design phase. In order to correctly perform these operations, it is indeed necessary to define the positions where the additional features (e.g. marks, holes) have to be added. In this way, information is defined once for each production order, and can be scaled and processed together with the virtual model of the base size last. This allows reducing the number of repetitive and time-consuming operations needed during the manufacturing phase.

3.1 Digitalization of the shoe last design and manufacturing: The proposed TO-BE process

The steps of the proposed TO BE process are shown in Figure 4. The first three steps (*New order arrival*, *Wood model realization*, *3D scanning and virtual model reconstruction*) are exactly the same of the AS-IS process (see Section 2).

In the Step 4 (*Features position determination on virtual model*), the positions of the features are defined directly on the 3D virtual model of the last base size, through the adoption of a haptic device. As explained in the previous section, this operation represents a major issue for the automation of the traditional and AS-IS processes. Although the bulges are big enough to be picked by the scanner, the process of defining the feature positions cannot be fully performed by only using an algorithm. Human intervention and judgement are still required, in order to interpret and locate the bulges, which are not easily discernable from the last shape and which usually do not contain any information about the feature orientation. In addition, not all the features are identified by bulges (e.g. size mark, company logo mark). CAD/CAM solutions with standard user interfaces (e.g. mouse, keyboard), however, are generally not enough accurate to locate these positions. This issue can be solved by introducing in the process a haptic interface. A haptic interface can be defined as a device that enable the user to "touch" a virtual object by means of a force feedback. Some of the most common haptic interfaces, currently used only in the academic and research fields, are shown in Figure 5.

The output of the Step 4 is an "enriched" virtual model of the last containing also the coordinates of the position of each feature that has to be added on the last. These coordinates are referred to the frame of reference of the last virtual model, which is determined by the 3D scanning system during the Step 3 of the workflow.

In the Step 5 (*Size grading and mirroring*), the coordinates of the features and the virtual model of the last are scaled and mirrored. Through this elaboration [11][12], the geometries for all the sizes contained in a production order (according to the indications included in the *Order data* file) can be obtained. In addition, also the 3D models of the left feet are automatically derived. This operation can be automatized, as shown in literature. The last grading is usually anisotropic, with different coefficients for the length of the last and its width/height (see the sub-section 3.2.1)

After the shoe last has been turned (Step 6 – *Automatic shoe last turning*), the required additional operations have to be performed. Although the coordinates of the features in the virtual model reference system are already known, this information is still not enough, since the coordinates in the machine reference system are required. Unfortunately, the exact position of the shoe last on the machine support is not known with an acceptable degree of accuracy, because of mechanical plays and specific adjustments of the turning machines. This is mainly due to the fastening system (i.e. the dovetail joint) used to fix lasts on the automatic machines supports. For this reason, the physical shoe last needs to be scanned in order to find its exact position in the machine reference system (Step 7 – *Partial scan of the last on the machine reference system*).

At this stage, it is possible to align the virtual model used to define the positions of the features and the partial scan (Step 8 – *Alignment of partial scan and virtual model*). Efficient and well-known alignment algorithms could be used for this task (see the sub-section 3.2.2).

After that the alignment is completed, additional operations can be finally performed using the same automatic equipment of the AS-IS process (Step 9 – *Operation performing*).

3.2 Software tool

As explained above, different elaborations of the virtual models are necessary during the different steps of the proposed TO-BE process. To this end, a specific software tool with the following functionalities has been developed:

1. import the first virtual model (right foot and base size) obtained through the scan of the wood model;
2. import the production order data;
3. import the positions of the additional features in the base virtual model, detected by using the haptic interface;
4. scale and mirror the base virtual model (together with the features positions), by running a last grading algorithm;
5. import the partial scan of the last in the reference system of the machine;

6. align the virtual model (together with the features positions) with the reference coordinate system of the machine, recovered from the partial scan;
7. draft the instructions to guide the machine operations, on the basis of the aligned virtual model and of the production order data.

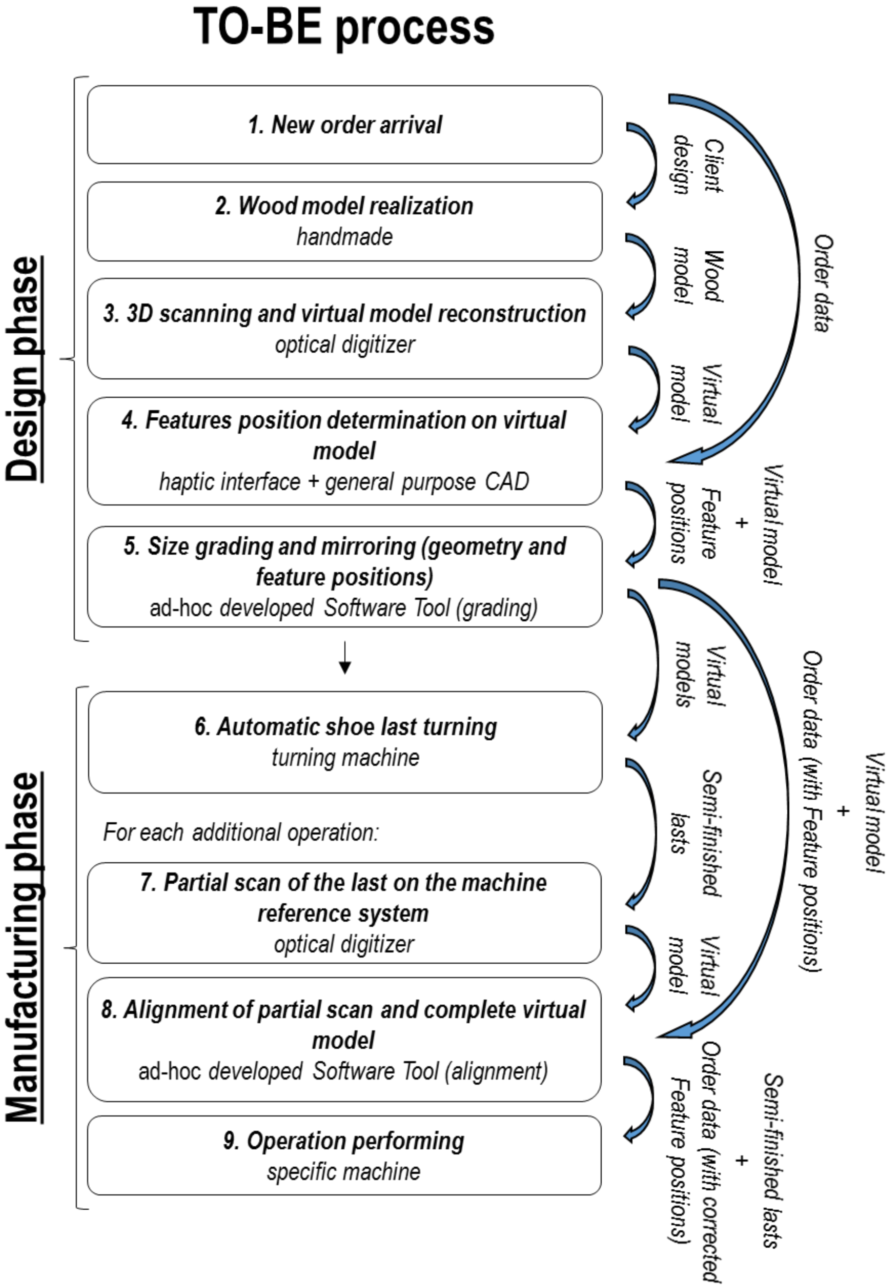

Figure 4: The proposed TO-BE process.

The software tool has been developed using the Matlab 2017a framework. This tool enables users to follow a wizard procedure to complete all the preparatory tasks needed before the operation performing. Therefore, the tool represents the joining link among the design and manufacturing phases needed to practically implement the digitally-enabled integrated process in real contexts. A screenshot of the tool interface is shown in Figure 6.

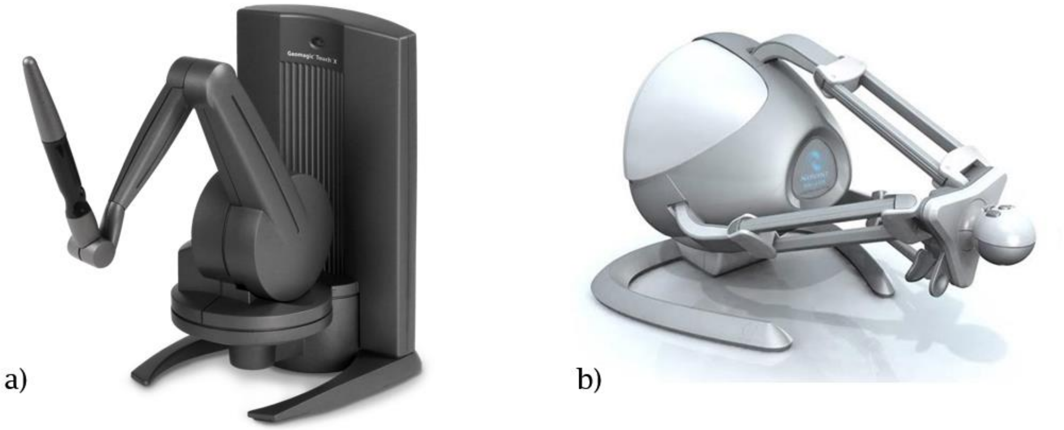

Figure 5: a) Geomagic Touch X ®; b) Novint Falcon ®.

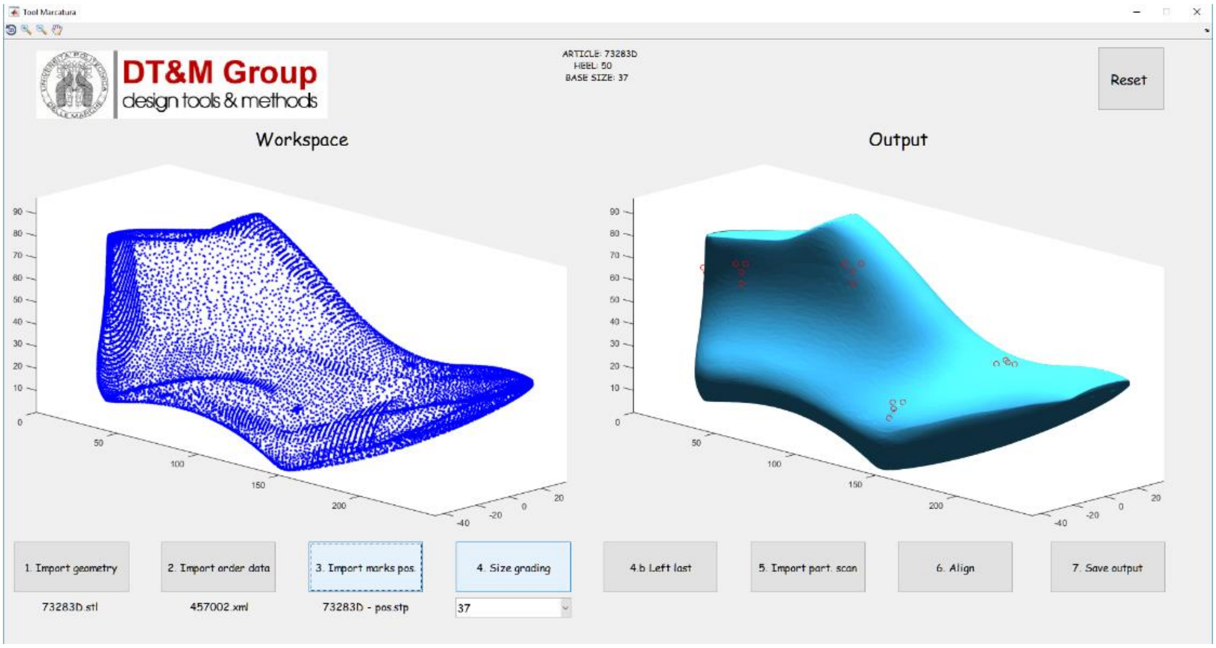

Figure 6: The software tool user interface.

3.2.1 Last grading

As explained in Section 2, since the grading algorithm currently used in the AS-IS process is not known and included in the proprietary CAM software of the turning machines, a simplified algorithm has been implemented in the developed software tool. This is based on literature studies and on a regression analysis, carried out on the basis of experimental tests.

According to Hinojo-Pérez et al [12], the grading equation can be defined as follows:

$$\boldsymbol{v_{i,n}} = \boldsymbol{v_i} \times \boldsymbol{T} = \boldsymbol{v_i} \times \begin{pmatrix} \boldsymbol{k_l} & \boldsymbol{0} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{k_c} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{k_c} \end{pmatrix} \tag{1}$$

$$\forall \boldsymbol{v_i} \in \{\boldsymbol{V}\} \; \forall \boldsymbol{v_{i,n}} \in \{\boldsymbol{V_n}\}$$

where $\{V\}$ is the set of points in the base virtual model, $\{V_n\}$ is the set of points in the n size graded virtual model, k_l and k_c are the grading parameters, which are unknown and have been defined as follows:

$$k_l = \frac{baseLength + lengthStep * (desiredSize - baseSize) * heelCorrection_l}{baseLength} \tag{2}$$

$$k_c = \frac{instepLength + instepStep * (desiredSize - baseSize) * heelCorrection_c}{instepLength} \tag{3}$$

where:

- $lengthStep$ = 6.66 mm is the length interval between sizes according to the European shoe size system;
- $instepStep$ = 4.5 mm is the instep interval between sizes according to the European shoe size system;
- $baseLength$ is the length of the base size last;
- $instepLength$ is the instep of the base size last;
- $baseSize$ depend on the base model;
- $heelCorrection_l$ and $heelCorrection_c$ are correction factors that depend on the heel height.

Thanks to a regression analysis, the values of k_l and k_c have been calculated by using the output virtual models scaled by the proprietary CAM software and inverting the equation (1). This operation has been performed for 30 different last models, using the sizes 35 and 41 (the smallest and the biggest available in the case of woman shoe lasts for), in order to have a sufficiently large sample.

At this stage, each parameter included in equations (2) and (3) is known except of $heelCorrection_l$ and $heelCorrection_c$, which depend on the heel height. Each equation has thus been solved, and mean values of $heelCorrection_l$ and $heelCorrection_c$ have been defined for five different heel height ranges. Results are shown in Table 1.

Heel height (hh) [mm]	$\boldsymbol{heelCorrection_l}$	$\boldsymbol{heelCorrection_c}$
0 < hh ≤ 15	1.002	1.0007
15 < hh ≤ 30	1.015	1.005
30 < hh ≤ 50	1.024	1.009
50 < hh ≤ 70	1.033	1.0012
70 < hh ≤ 100	1.039	1.015

Table 1: Calculated $\boldsymbol{heelCorrection_l}$ and $\boldsymbol{heelCorrection_c}$ for different ranges of heel height

Although its simplicity, the proposed approach has granted sufficient accuracy. This has been verified through a comparison between the virtual models graded by using the proposed approach and the virtual models graded by using the proprietary CAM software, taken as reference. Results have shown that the maximum error is inferior to 0.2 mm, which can be considered acceptable in the context of shoe last design and manufacturing, where the required tolerances are about 1 mm. Figure 7 shows an example of the comparisons performed for a last model with heel height = 50 mm, for sizes 35 (on the right) and 41 (on the left). It can be noticed that biggest errors are located on the heel and on the tip of the last, parts where generally no additional feature is positioned.

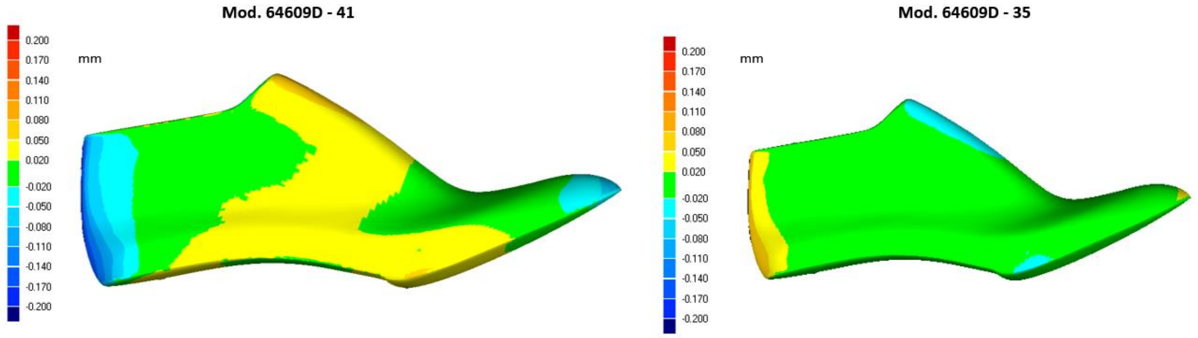

Figure 7: Error between the virtual model graded with the proposed algorithm and the virtual model graded by the proprietary CAM software.

3.2.2 Alignment between scan data

Step 8 of the proposed process requires the alignment between the complete virtual model mesh and a partial scan of the last, performed on the machine. For the alignment process, the Iterative Closest Point (ICP) algorithm has been implemented in the developed software tool. The ICP algorithm is widely used for geometric alignment of three-dimensional models, such as the outputs of 3D scanners. The algorithm was introduced in 1992 by Chen and Medioni [6] and independently by Besl and McKay [4]. Since then several variants have been also defined [25].

The implemented solution is based on the study of Kjer and Wilm [15]. According to the ICP algorithm, one cloud of points, called reference or target, is kept fixed. In our application the reference cloud corresponds to the scan of the last performed on the machine reference system. The second cloud of points, called source, corresponds to the mesh of the complete virtual model, calculated through the grading algorithm on the basis of the base virtual model. The source cloud of points is transformed, in order to match the reference cloud.

The basic steps of the implemented ICP algorithm can be briefly described as follows:

- the algorithm starts by estimating the relative rigid-body transformation between the two meshes that have to be aligned;
- successively, an iterative process refines the transformation by generating pairs of corresponding points and minimizing an error metric.

In order to guarantee the convergence to a solution in an acceptable time, meshes usually need to be pre-aligned. In the developed application, this operation has to be manually performed by the user.

It is worth to notice that in order to make the ICP work, it is not necessary to have two complete scans. The scan of the turned last on the machine reference system can be partial, and a single view is enough for the alignment. In this way, it is possible to speed up the scanning procedure, the alignment operations and thus the entire process.

4 APPROACH EXPERIMENTATION: THE SHOE LAST MARKING OPERATION

The proposed approach has been tested in the context of the shoe last marking task. This operation is usually performed using a laser beam, which marks the shoe last by burning its surface. The markings contain information about size, client, data, heel height and collar position, thus each shoe last must be marked in several positions. While the number and locations of collar position markings depend on the shoe last model, other markings usually remain in the same position. The shape of each marking is identified by a code. The number and the codes of the marking for each last model are saved in an XML file (i.e. Order data in Figure 4) at the moment of the order arrival. Figure 8 shows a finished shoe last with the details of each mark.

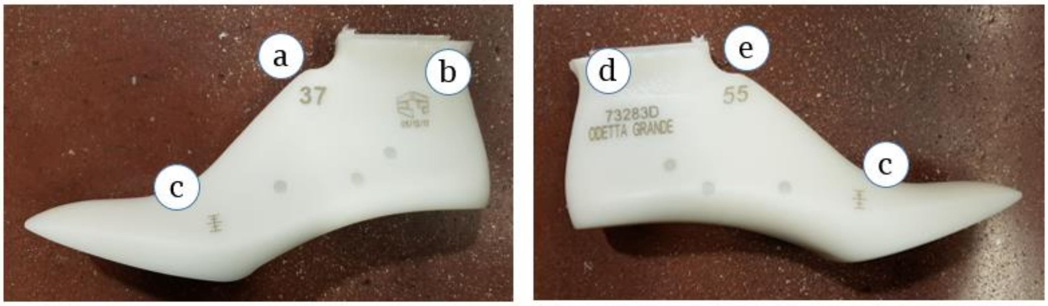

Figure 8: A marked shoe last: a) size; b) client; c) collar position; d) model name; e) heel height.

During the marking operation, an anthropomorphic robot moves the last, while the marking device is fixed. Figure 9 shows a picture and the layout of the work station used for the experimental tests.

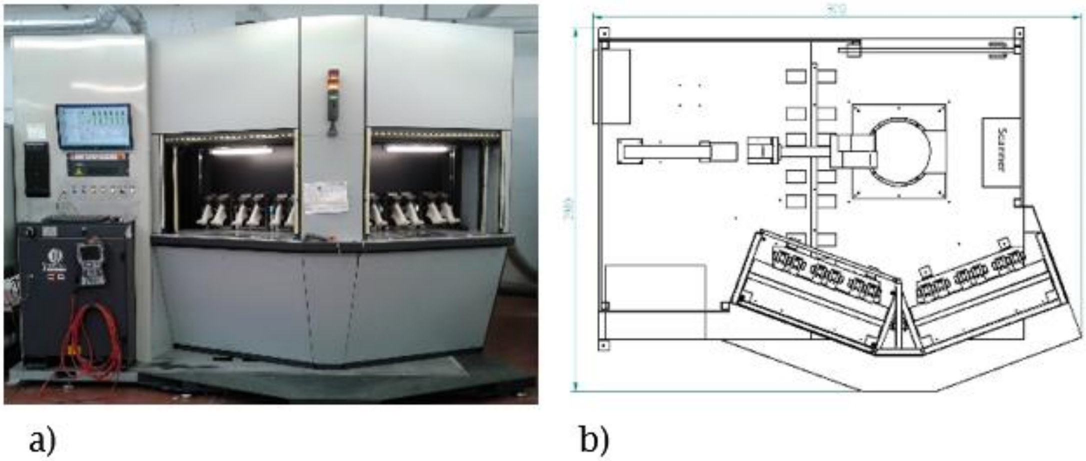

Figure 9: a) The work station used for the marking operation; b) layout of the machine

4.1 System calibration

The experimental setup has been designed in order to minimize the impact on the production processes of the company involved in the experimental phase. Although the MicroScribe has been eliminated in the TO-BE process, we decided to maintain the same input files for the marking robot, and thus the same reference system for the coordinates of the features (i.e. marks). In this way, the anthropomorphic robot did not need to be reprogrammed. However, by proceeding in this way, we had to determine the calibration matrix, between the MicroScribe reference frame and the 3D scanner reference frame, which is a 4x4 matrix containing information about the roto-translation between the two reference systems. This matrix is needed to correct the coordinates of the marks positions calculated by the software tool, after the grading, mirroring and alignment.

The calibration matrix has been estimated by using the modified shoe last shown in Figure 10 a. The modified last is a 41-size last, in which 12 reference holes have been performed on its upper surface, by using a manual drill. The holes, positioned randomly on the last surface, have been added in order to have more accurate references when acquiring the reference points coordinates with both the MicroScribe and the haptic interface. The size 41 has been chosen because it is one of the biggest sizes (lasts for woman shoes), and thus it ensures a wider distribution of the reference points to be compared.

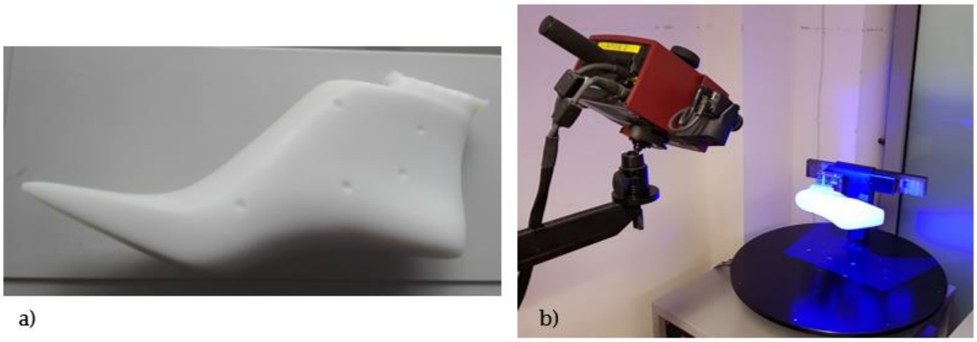

Figure 10: a) Modified shoe last used for the system calibration; b) 3D scanning of the modified last.

The last has been scanned by using a GOM Atos optical digitizer, to reconstruct a digital model (Figure 10 b). The reference frame of the digital model is located onto the fastening system used to grip the dovetail joint, by means of reference stickers positioned on its surface. The fastening system is the same used in all the production line.

Finally, the calibration matrix has been calculated by comparing the coordinates of the 12 holes determined in the two reference systems: (i) by using the MicroScribe, as in the AS-IS process, and (ii) by using the haptic interface, as in the TO-BE process An algorithm based on the well-known Horn's method has been used [13][21] to define the matrix.

4.2 Experimental setup

As described in Step 4 of the TO-BE process, the marking positions have been set by using a haptic interface. The device adopted in this case study is the "Geomagic Touch X", used together with the 3D software CAD "Geomagic Freeform by 3d System Inc." (Figure 11 a). Each marking position has been identified using 4 points positioned on the surface of the last: 1 point for defining the Cartesian coordinates, and 3 points for defining the Euler's angles (Figure 11 b). This latter information cannot be neglected, since during the marking the laser should be maintained perpendicular to the marked surface.

The coordinates of the point 1 correspond to the coordinate of the center of the marking. Unit vectors for reference frame of each marking can be calculated as follows:

$$\vec{u} = \frac{\overrightarrow{V_{34}}}{|\overrightarrow{V_{34}}|} \tag{4}$$

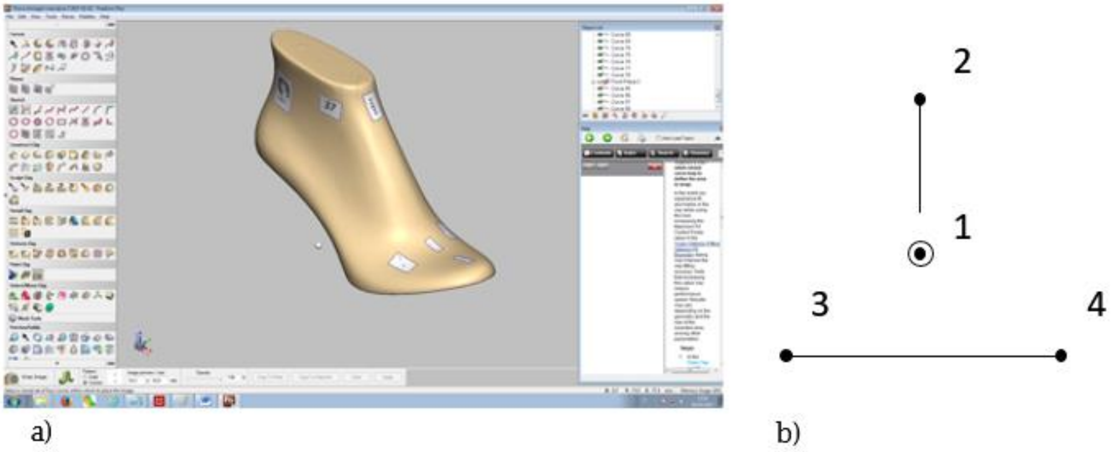

Figure 11: a) Definition of the marking positions using "Geomagic Freeform". In the picture, images of the marks have been projected on the last virtual model as a reference; b) Name convention for the points.

$$\vec{w} = \frac{\overrightarrow{V_{34}} \wedge \overrightarrow{V_{32}}}{\left|\overrightarrow{V_{34}} \wedge \overrightarrow{V_{32}}\right|} \quad (5)$$

$$\vec{v} = \vec{w} \wedge \vec{u} \quad (6)$$

Euler's angles that define the orientation of the plane $\vec{u}\vec{v}$ using the ZYZ convention can be derived from the components of the vectors $\vec{u}, \vec{v}$ and $\vec{w}$ as follows:

$$\varphi = Atan2(w_y, w_x) \quad (7)$$

$$\vartheta = Atan2\left(\sqrt{{w_x}^2 + {w_y}^2}, w_z\right) \quad (8)$$

$$\psi = Atan2(w_y, -u_z) \quad (9)$$

The virtual model, together with all the spots representing the positions of the marks needed in the considered production order, have been saved as STEP file, an ISO standard exchange format which can be thus interpreted without using proprietary software tools.

Successively, Steps 5, 7 and 8 of the proposed process have been carried out through the software tool developed using Matlab. In particular, the software allows the user to import:

- the complete mesh of the last in STL format;
- the STEP file containing the position of the markings;
- the XML file containing the codes of the markings (i.e. Order data);
- the STL file containing the partial scan of the turned last positioned on the marking machine. For this latter scan, the GOM Atom optical digitizer has been used.

Figure 12 shows the alignment performed between the partial scan and the complete 3D virtual model using the ICP algorithm. The algorithm proved to be effective also when the partial scan differed from the complete model in some details, such as the presence of part of the dovetail joint (on the top of the shoe last).

Once the alignment was completed, the coordinates of the marking positions have been "corrected" by using the calibration matrix, to refer the coordinates to the robot reference system. Finally, these coordinates have been exported in an .XML file and sent to the marking machine work station to guide the robot movements during the automatic performing of the marking process.

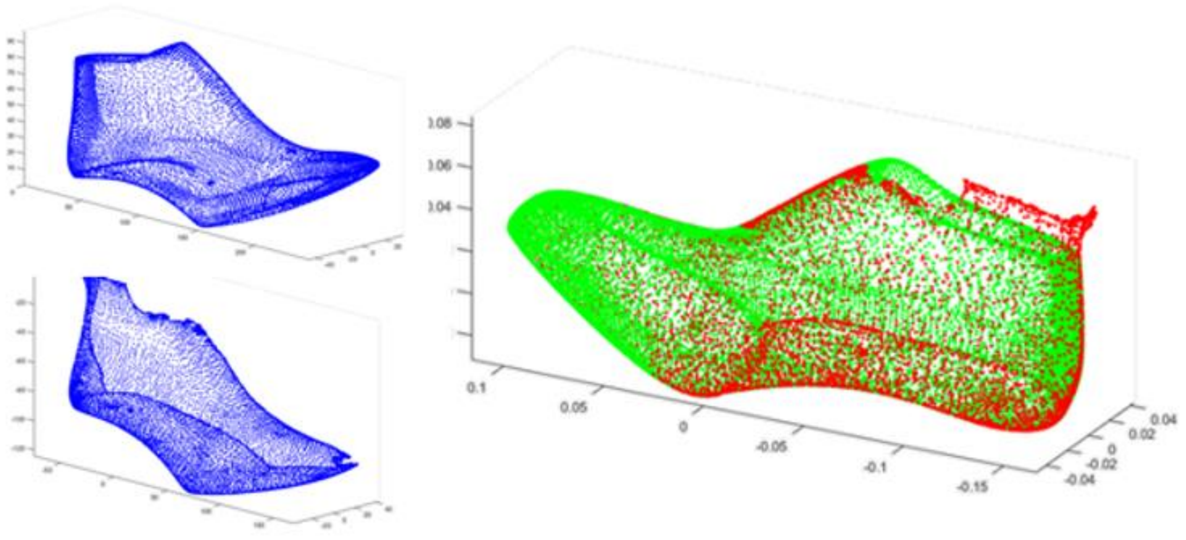

Figure 12: Alignment between partial scan and complete 3D virtual model, performed with the developed software tool.

4.3 Results

The experimentation confirmed the usefulness and the reliability of the proposed approach and of the developed software tool. Table 2 reports a comparison between the needed acquisitions of the marks positions to complete an entire production order by following the traditional, AS-IS and TO-BE processes.

Shoe last order	*Number of acquisitions of the marks positions*		
	Traditional process	*AS-IS process*	*TO-BE process*

 **Last code**: 732830 **Number of sizes in order**: 13 **Number of lasts in a pair**: 2 **Number of turning machines**: 4 **Total number of lasts:** 462	462 Features are manually detected in each physical last Marks are manually added in each last (ink stamps)	13 x 2 x 4 =104 Features are detected in the physical lasts through the CMM digitizer for each size for right/left feet and for each turning machine Marks are automatically added in each last (laser marking)	1 Features are detected through the haptic interface only for the base size virtual model Marks are automatically added in each last (laser marking)

Table 2: Comparison between the traditional manual, AS-IS and TO-BE processes considering the number of acquisitions of the marks positions.

The number of marking points acquisitions is reduced from 462 times of the traditional process (one manual identification for each physical last), to 104 times of the AS-IS process (one scan for each size for each pair for each turning machine, performed during the manufacturing phase), to finally 1 time of the proposed TO-BE process (one scan performed during the design process by interacting with the virtual model through the haptic interface). These relevant results have been obtained thanks to the adoption of the proposed integrated process and tool.

The consistent reduction of the number of operations has two main positive impacts. The first one is related to the time required for the information acquisition, which has been consistently reduced. As a direct consequence, also the time for producing a complete production lot is reduced, and thus the company productivity could increase. The second one is related to the quality of the final products. The TO-BE process better ensures the process repeatability, thus the effective locations of the marks in all the physical lasts of a production order are more aligned with the theoretical exact positions. The measured errors in the marks positioning are inferior to 0.5 mm. This value is on average lower than the typical positioning errors for lasts marked with the traditional or AS-IS processes, and thus can be considered acceptable for the use in the successive shoe assembly phases.

5 CONCLUSIONS AND FUTURE WORK

Analyzing the current design and manufacturing processes of companies belonging to traditional sectors (e.g. fashion, footwear), as shoe last producers, it is clear that they need innovations in order to maintain their competitiveness in the global market, increase their flexibility, reduce the time to market for customized products, and fully exploit Industry 4.0 technologies.

In this context, this study presents an innovative approach dedicated to shoe lasts design and manufacturing, based on the adoption and integration of digital, CAD/CAM and haptic technologies needed to transform the traditional isolated processes in a digitally-enabled integrated process. The approach is grounded on a dedicated software tool that allows to carry out specific operations (e.g. last grading and mirroring, features positions definition and grading, preparation of virtual models and data to guide the automatic machine operations) during the design process, by interacting with virtual models also through the use of haptic interfaces. The anticipation of these tasks represents a fundamental step to streamline the operational processes, reducing the number of manual and repetitive operations.

The test case about the marking operation confirmed that the TO-BE approach is applicable in real industrial context without heavily altering the modus operandi of critical phases (e.g. last stylistic design and manufacturing of the wood prototype). The obtained results showed a sensible improvement in the company operational efficiency, thanks to the reduction of the time needed to finalize a lot. In addition, the product quality is potentially improved, as a consequence of a major repeatability of the process.

Future work is needed at first to test the approach with other specific operations (e.g. application of the steel reinforcement in the last), as well as in other companies of the footwear sector (e.g. shoe producers) and in other sectors. Furthermore, the use of the haptic interface should be improved by integrating it in the developed software tool, in order to enable the user to define the location of the feature on the last without using a general-purpose CAD software such as Geomagic Freeform, which was not created for this kind of applications and thus showed some limitations.

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