Title:

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

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Introduction:

In the era of the fourth industrial revolutions (i.e. Industry 4.0), the efficient gathering, management, sharing and exploitation of information are key success factors for companies [8][12][14]. This is true both in high-tech sectors, as electronics or automotive, and in traditional sectors, as the footwear industry.

The manufacturing of shoes requires the involvement of several small companies that actively collaborate to realize the different semi-finished parts and components (e.g. sole, insole, last) [11]. Shoe lasts are quite simple products (composed by a block of plastic or wood), but 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 mainly based on artisanal processes and on the know-how of expert operators who manually realize and optimize the wood models used as a base for the realization of the plastic lasts in different sizes [10].

In order to maintain competitiveness in the global market and to answer to the requests for highly customized products, shoe last producers need to innovate their processes, by adopting digital technologies to improve their efficiency and fully exploit the available data [5]. Different literature studies aim to develop methods and technologies dedicated to the design of footwear products [4][6], customized lasts [7] or even lasts for special user categories and applications [1][2]. However, none of them focus on the radical innovation of the shoe last producers operational processes (both design and manufacturing).

In this context, the present paper proposes 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 close the gap between the design and manufacturing phases, and by haptic technologies, which allow to interact with the virtual models in order to simplify the successive planning and manufacturing operations (e.g. marking, drilling). The final aim is to support traditional and artisanal footwear companies 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. In addition, this study represents one of the first examples of industrial use of the haptic interfaces that are largely used in research studies, but currently have scarce application in real industrial contexts [3][13].

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 the following Fig. 1, the traditional, the AS-IS and the proposed TO-BE processes are compared.

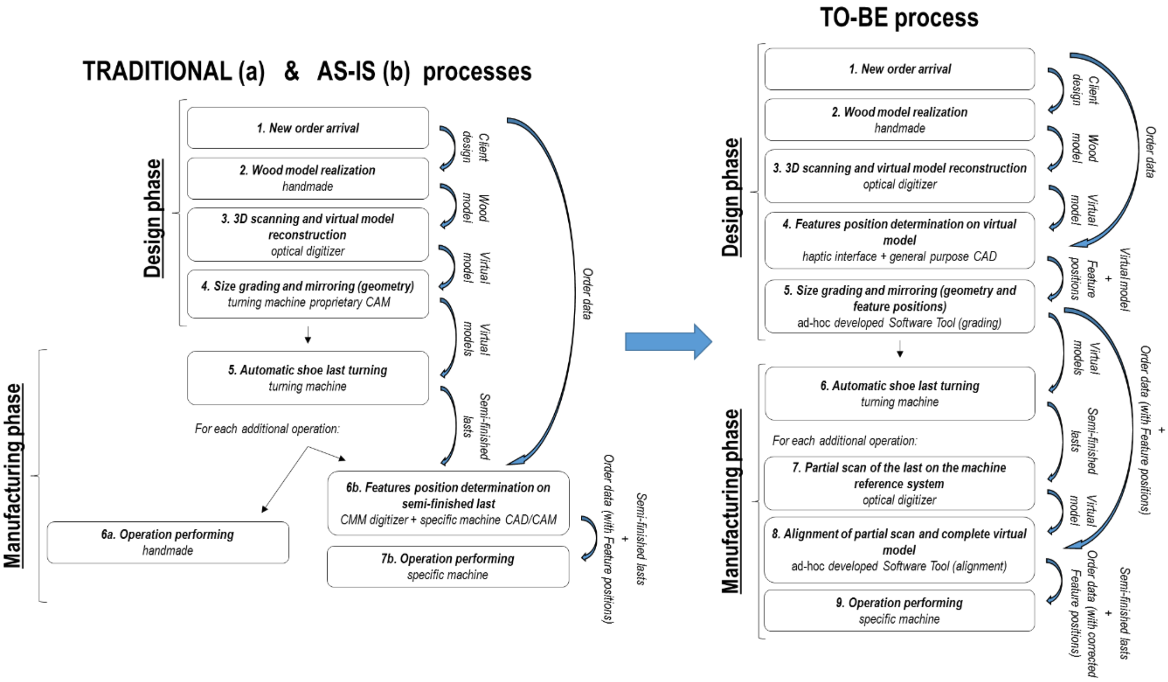


Fig. 1: Benchmark between the Traditional, the AS-IS and the proposed TO-BE processes.

The Traditional and AS-IS processes

The process begins with the arrival of a new order, followed by the realization of a wood model. For each shoe last type, only one wood model for the right foot and for the base size (usually 37 for women shoes and 40 for men shoes) is manually realized by the factory's artisans. After that, the wood model is scanned in order to obtain a digital model, which is thus mirrored and graded, to rebuild the left foot and all the required sizes. This is the final step of the design phase in the traditional AS-IS process.

The obtained virtual models are then used for the production of shoe lasts, which are realized through automatic turning machines, starting from pre-formed plastic blocks. During this operation, the last is hold by the machine by means of a dovetail joint positioned in the upper part of the last (Fig. 2). Once the geometrical shape is complete, other features must be added to complete the last. 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. While in the Traditional process these operations were completely manual, currently (AS-IS process) a first step toward automatization has been taken. For instance, the marking process that was traditionally carried out using manual ink stamps, currently is performed by using a laser technology. During the process, the physical last is handled by a robot, while an operator manually defines the positions of the marks on the semi-finished products by using Coordinate Measurement Machine (CMM) digitizers (e.g. Microscribe®). This operation is time consuming and not repeatable (different operators, different lasts, different machines, etc.).

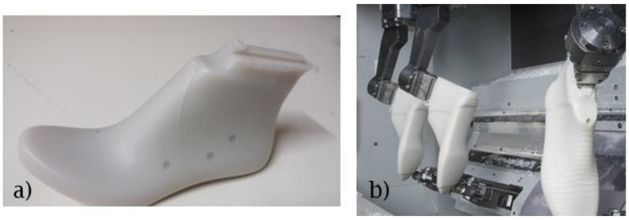


Fig. 2: a) A turned shoe last, b) The shoe last turning machine.

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

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 virtual model in order to identify the correct positions of the features (i.e. bulges in the external surface of the last). The adoption of a Microscribe can be considered as an incomplete transition toward the process digitalization and efficiency improvement, since acquisitions in the physical lasts 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 available turning machines.

In the proposed TO-BE process the information required for the realization of the additional features (e.g. marking) is directly defined on the virtual model of the base size of the last, obtained through the 3D scan of the initial wood model. This is possible thanks to the complete integration of a haptic interface, which enables the user to “feel” the last geometry, by means of a force feedback. This allows to set the features positions by detecting the markers in the virtual model. One of the main advantages of the proposed TO-BE process is related to the number of acquisitions needed for the setting of the features positions. This operation is done only one time for each shoe last virtual model, during the design process. Successively, the defined positions can be scaled and mirrored together with the virtual model of the base last to finally define the positions for all the lasts in a production order.

After that the shoe last has been turned, the required additional operations can be performed. In this case, the positions of the features are already known, since they have been previously set on the virtual model. However, the exact position of the shoe last on the machine support is not known with an acceptable degree of accuracy. The physical shoe last is thus scanned to find its position in the machine coordinate system. Finally, the virtual model used to find the positions of the features need to be aligned with the scan, using proper algorithms, such as the Iterative Closest Point [8].

A specific software tool has been developed to perform all the needed elaborations with the virtual models: (i) import the virtual model obtained through the scan of the base size wood model, (ii) set the positions of the additional features in the base virtual model, (iii) scale and mirror the base virtual model (together with the features positions), (iv) align the virtual model with the reference coordinate system of the machine, and (v) draft the instructions to guide the machine operations. More details about the developed software prototype functionalities are described in the context of the case study.

Approach Experimentation: the shoe last marking:

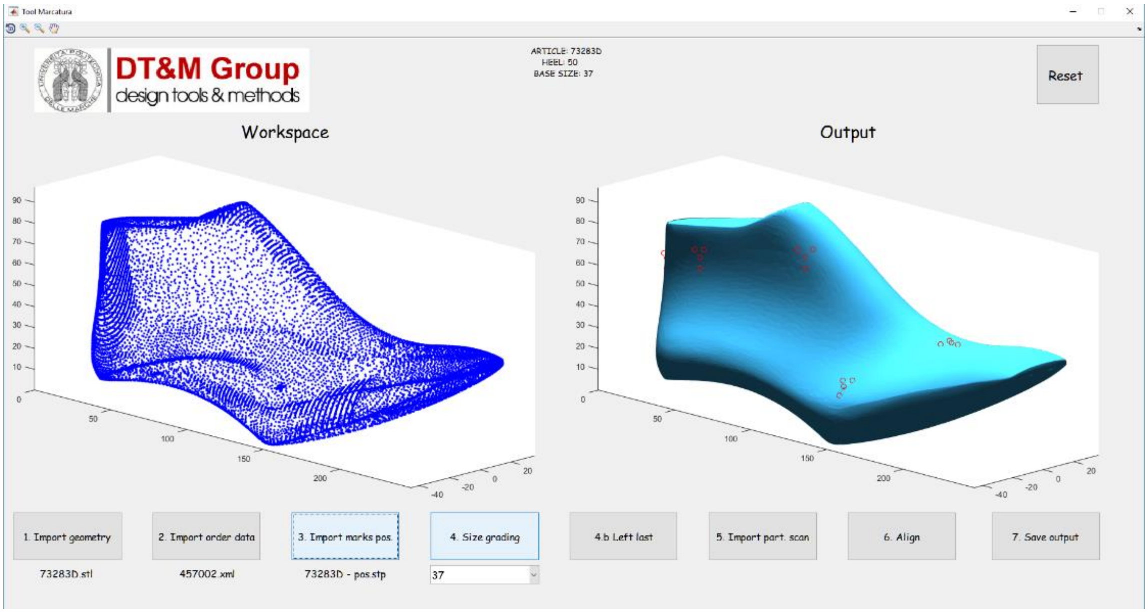
The proposed approach has been tested in the context of the shoe last marking task. This operation is performed using a laser beam, which marks the shoe last by burning its surface. The markings contain information about size, client, data and collar position, thus each shoe last must be marked in several positions. During the marking operation, an anthropomorphic robot moves the last, while the marking device is fixed (Fig. 3 a).

As described in the previous section (step 4 of the TO-BE process), the marking positions have been set by using the haptic interface “Geomagic Touch X” and the software tool “Geomagic Freeform by 3d System Inc.” (Fig. 3 b). 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. The virtual model, together with all the spots needed to set the positions have been saved as STEP file.

Fig. 3: a) The robot used for the marking operation, b) The shoe last virtual model with markings.

Step 5, 6, 7 and 8 of the proposed TO-BE process have been carried out through the software tool developed by using the Matlab 2017a framework (Fig. 4). This tool enables the user to follow a wizard procedure to complete all the preparatory tasks needed before the marking operation:

- To read the STEP file containing the coordinates of the points saved using the haptic interface;
- To read an XML file containing all the information about the last model and the order to be processed (e.g. order number, list of sizes, lists of marks to add);
- To scale and mirror the virtual model and the coordinates of the points (contained in the STEP file), to obtain the information required for the other sizes and pairs in the order;
- To read the STL file obtained with the scan of the physical shoe last fixed in the marking robot;
- To align the virtual model and the marking positions to the scan contained in the STL file, by means of a specific Iterative Closest Point algorithm [8];
- To export an XML file with the paths to be followed by the robot during the marking operations.


Tool Marcatura

ARTICLE: 73283D
HEEL: 50
BASE SIZE: 37

1. Import geometry: 73283D.stl
2. Import order data: 457002.xml
3. Import marks pos.: 73283D - pos.stp
4. Size grading: 37

Fig. 4: The software tool user's interface.

The experimentation confirmed the usefulness and the reliability of the proposed approach and of the developed software tool. Tab. 1 presents an extract of the obtained results.

Shoe last order	*Number of acquisitions of the marks positions*		
	Traditional process	***AS-IS process***	***TO-BE process***
 **Last code**: 732830 **Number of sizes**: 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 last Marks are manually added in each last (ink stamps)	**13 x 2 x 4 =104** Features are detected through CMM. Marks are automatically added in each last (laser marking)	**1** Features are detected through the haptic interface Marks are automatically added in each last (laser marking)

Tab. 1: Comparison between the traditional manual, AS-IS and TO-BE processes considering the number of acquisitions of the marks positions.

Tab. 1 reports a comparison between the needed acquisitions of the marks positions to complete an order by following the Traditional, AS-IS and TO-BE processes. The number of the marking points acquisitions is reduced from 462 (manual acquisitions for each shoe last), to 104 (one acquisition for each size for each pair for each turning machine, performed during the manufacturing phase by interacting with the physical lasts), to finally 1 (one acquisition performed during the design process by interacting with the virtual model), thanks to the use of the proposed integrated process and tool. The measured errors in the marks positioning are inferior to 0.5 mm in comparison with the exact positions. This value is on average lower than the typical positioning errors for lasts marked with the AS-IS process, and thus can be considered acceptable for the use in the successive shoe assembly phases.

Conclusions:

This study presents an innovative approach dedicated to shoe lasts design and manufacturing. The approach is 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. This represents an essential step toward the practical implementation of the Industry 4.0 paradigm within the artisanal footwear companies. The test case about the marking operation confirms that the adoption of the TO-BE approach leads to a sensible improvement in the company operational efficiency, thanks to the reduction in the number of repetitive operations needed to finalize a production order.

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