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An approach to design reconfigurable manufacturing tools to manage product variability: the mass customisation of eyewear

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Abstract In Mass Customisation (MC), products are intrinsically variable, because they aim at satisfying end-users' requests. Modular design and flexible manufacturing technologies are useful strategies to guarantee a wide product variability. However, in the eyewear field, the current strategies are not easily implementable, due to some eyewear peculiarities (e.g., the large variability of the frame geometry and material, and the necessity to use specific manufacturing phases). For example, acetate spectacle-frames are bent through a thermoforming process. This particular phase requires dedicated moulds, whose geometry strictly depends on the frame model to be bent; consequently, changes of the frame geometry continuously require new moulds, which have to be designed, manufactured, used, and finally stored. The purpose of this paper is to propose a new strategy to transform a dedicated tool (i.e., a thermoforming mould) into a reconfigurable one, to optimise the tool design, manufacturing and use. First, how the frame features influence the mould geometry has been investigated, creating a map of relations. On the basis of this map, the conventional monolithic-metallic mould was divided into "standard" (re-usable) and "special" (ad-hoc) modules, where the "special" ones are in charge of managing the variability of the product geometry. The mapped relations were formalised as mathematical equations and then, implemented into a Knowledge Based Engineering (KBE) system, to automatically design the "special" modules and guarantee the mould assemblability. This paper provides an original example of how a reconfigurable thermoforming mould can be conceived and how a KBE system can be used to this aim.

Keywords Mass customisation; Eyewear; Thermoforming mould; KBE system

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1 Introduction

A mass customised product is a good whose aim is to fit specific customer's requests, in a context of large production volumes (Da Silveira et al., 2001). Thus companies have to manage families of products characterised by several variants. To perform this task, the implementation of modularisation strategies and/or flexible manufacturing approaches are widely adopted actions (e.g., see (Fogliatto et al., 2012; Koren et al., 1999)).

In last years, also the eyewear industry has started to follow the Mass Customisation (MC) paradigm (Gilmore and Pine, 1997; Barman and Canizares, 2015). Large eyewear companies manage the constant variability of the frame geometries (especially in terms of shape and texture due to the fashion nature of this kind of product) through the continuous optimisation of their product development cycles and thanks to the ability of their skilled and experienced operators. Notwithstanding the high final quality of their products, the management of the variability of the frame geometries still represents a challenge for eyewear companies (Montalto et al., 2018) also because the implementation of flexible tools within the manufacturing process is often tough. For example, one of the production phases of cellulose-acetate spectacle frames is the front thermoforming, accomplished by experts operators, using presses and moulds. This phase is performed to bend the front. Each thermoforming mould is created ad-hoc for each model of frame. This fact leads to the following issues: the mould design cannot start until the frame design is completed, because the geometry of the frames and moulds are strictly correlated; the current mould design requires time, since a monolithic metallic block should be properly shaped through milling and polishing; multiple moulds must be produced in parallel (especially for large batches); each mould must be stored to guarantee the future availability of spare parts. The design and manufacturing of these tools — like the thermoforming moulds — could thus generate bottlenecks in the development process of new products. The current thermoforming mould is a dedicated manufacturing tool. Consequently, any change of the frame shape implies the design-and-manufacturing of a new mould.

This paper describes a design approach to transform a dedicated manufacturing tool (i.e., the thermoforming mould of spectacles fronts) into a reconfigurable one to effectively manage the product variability. It also presents a Knowledge Based Engineering (KBE) system for the automatic design of non-standard parts of the tool.

After an analysis of the functional and topological relations linking the design variables determining the frame variability (i.e., the product) to the mould functional features (i.e., the manufacturing tool), it is then possible to retrieve the necessary insights upon which rethinking the AS-IS mould configuration. The final aim is to transform this one into a reconfigurable tool, made up of "standard" and "special" components. The spectacle-frame variability is, thus, uniquely managed through the "special" components of the mould. Furthermore, to guarantee their assemblability, the use of a CAD system controlled by a set of rules, implemented into a knowledge-based system, has been successfully tested. As it will be discussed in Section 2, such design approach has never been implemented in this specific industrial field (i.e., the eyewear) and it represents also an original contribution in the field of reconfigurable thermoforming moulds design. We also demonstrate that the implementation of the proposed approach could make the eyewear product development cycle more efficient by enabling the concurrent design of the product, and of the manufacturing tool.

The paper is structured as follows. In Section 2, the relationship between the eyewear sector and the MC paradigm as well as the necessity to introduce reconfigurable manufacturing solutions in this sector are analysed. The approach is discussed in Section 3 while, Section 4 describes the case study (i.e., the redesign of the thermoforming mould). Finally, conclusions are drawn in Section 5.

2 About some distinguishing features of the eyewear industry

The following Sections set the background of the research. Specifically, Section 2.1 provides a contextualisation of the eyewear industry with respect to the Mass Customisation (MC) paradigm while, Section 2.2 discusses the importance of looking for reconfigurable manufacturing solutions to more efficiently and easily manage the product variability.

2.1 The wide product variability and the importance of customers' involvement

The necessity to adapt the production to continuous and rapid changes of the market and to reduce costs, in years, has pushed companies and research communities to overcome the traditional mass-production paradigm. For example, the *Lean Production* paradigm aims to minimise wastes; the *Group Technology* paradigm — as a strategy of the *Lean Production* paradigm (Bowen and Youngdahl, 1998) — attempts to cluster products and processes to save time and efforts; the *Flexible Manufacturing* paradigm allows — thanks to the technology — to conveniently and rapidly react to product changes (e.g., see (Browne et al., 1984)). In the *Group Technology* paradigm, machines are physically grouped, while using *Flexible Manufacturing Systems* (FMSs) machines can be grouped logically, thanks to the use of handling systems, as explained in (Kusiak, 1985). However, despite their intrinsic differences, these paradigms (see also (Stump and Badurdeen, 2012)) can be seen as enablers of the Mass Customisation (MC) concept appeared in the late 1980s (Da Silveira et al., 2001), which has now become a dominant manufacturing approach (Fogliatto et al., 2012).

If the mass-production paradigm aims to produce identical products to reduce costs, the MC approach is focused on products able to satisfy — as much as possible — customers' needs (e.g., see (Zhou et al., 2013)), not renouncing to large production volumes. This target has been made possible implementing modular design strategies, flexible manufacturing processes, and building integrated supply chains (Fogliatto et al., 2012). The product customisation is widely available in many industrial areas (e.g., automotive, electronics, food, and also apparel (Fogliatto et al., 2012; Nayak et al., 2015)) and it is mainly based on the idea of producing assembled products, to wit products whose components are picked from a list of possibilities and then assembled together (Da Silveira et al., 2001; Fogliatto et al., 2012; Duray, 2011; MacCarthy et al., 2003). In this sense, FMSs are universally recognised as fundamental for industries implementing the MC paradigm (Da Silveira et al., 2001; Fogliatto et al., 2012; Smith et al., 2013).

However, there is also a growing interest in Additive Manufacturing (AM) technologies. Indeed, these technologies are capable of manufacturing e.g., small volumes batches without the need of dedicated tooling and — for this reason — they have the potentiality to fully exploit the possibility of providing highly-customised solutions for MC (Fogliatto et al., 2012; Deradjat and Minshall, 2017; Conner et al., 2014; Diegel et al., 2010). However, AM technologies could become competitive with respect to other manufacturing solutions in case of products characterised by a high level of complexity, a high degree of customisation, or by a combination of these two characteristics (Conner et al., 2014).

To better understand the relationship between the eyewear field, the *Flexible Manufacturing* paradigm, and the MC concept, it is useful to refer to the product-process matrix as discussed in (Ariss and Zhang, 2002). This two-dimensional matrix is a tool to analyse the relationship between the manufacturing processes and the market life cycle stages. Considering these two orthogonal axes, in the top left corner "low volumes and low standardised products produced in job shops" are placed while in the bottom right corner "high standardised products in continuous flows" are assigned. Along the diagonal of this matrix (from the top left corner to the bottom right one) the so-called *feasible region* (Ariss and Zhang, 2002), from the business point of view, is placed. FMSs contributed in enlarging this feasible region, decreasing the economic and technological constraints and enabling the manufacturing of products characterised by high variability and high volumes (Ariss and Zhang, 2002). Hence, the MC concept is looking for further extending this feasible region since it demands fully-customised products and high production volumes.

Two key attributes characterise the MC: the type of implemented modularity (i.e., how modules are used to customise the products); in which phase of the product development process the customers are involved (Duray et al., 2000). On the basis of these criteria, MC companies can be clustered as (Duray et al., 2000): *Fabricators*, if customers are involved since the initial phases of the process and the product modularisation influences both the design and the fabrication process; *Involvers*, if, again, customers are involved in the initial phases of the process but the modularity is adopted in the assembly and use phases of the product i.e., they do not fabricate customised modules; *Modularizers* and *Assemblers* if customisation requirements do not affect the design and fabrication phases but, in case of *Modularizers*, modularisation strategies are applied in the design and fabrication phases while *Assemblers* can be seen as *assemble-to-order manufacturers* (Duray et al., 2000).

Customisation in the eyewear field is cited in the literature (Gilmore and Pine, 1997; Barman and Canizares, 2015) and in recent years many new start-up companies have been proposing ad-hoc spectacle frames for their customers, often using AM technologies (Sharma, 2010). These start-ups embody the MC philosophy and they could be categorised as *Fabricators* or *Involvers*. Large/medium eyewear companies — which have in their portfolio several luxury brands — are characterised by a different business model, which could be considered as mass-production. However, the following aspects need to be also considered.

First, production volumes are of two kinds: batches (up to few tens of pieces) for exclusive collections, and mass-production (up to thousands of pieces) for popular models. The main customisation possibilities are related to colours/textures and sometimes the size of the frame: end-users' needs and preferences are satisfied simultaneously putting on the market a high number of collections, each one having its peculiarities. From a manufacturing point of view, a "standard" frame is always built assembling a front, two temples, two lenses and in some cases beautifiers. However — despite the apparent low complexity of the product architecture — the manufacturing process is challenging: the high product variability (Montalto et al., 2016; Montalto et al., 2018) and the seasonality which characterises the fashion-market (De Toni and Nassimbeni, 2003) implies the necessity to simultaneously and rapidly manage different product and manufacturing changes. Furthermore, these parts, once assembled, must properly match in order to guarantee the fulfilment of both aesthetic and functional requirements (Montalto et al., 2018) since spectacles are fashion accessories, but also medical devices. Another aspect to underline is that the customers of these companies are not spectacle users, but fashion brands that are continuously looking for product innovation, which should also follow/anticipate the evolution of fashion trends. Indeed, luxury fashion-brands guide the design of spectacle-frames, demanding shapes, colours, materials, and high-quality levels to strengthen the brand identity, and influencing/generating end-user's needs through the launch of new fashion trends. Furthermore, the fashion-market, due to these continuous and rapid product changes, and the strong customers' involvement, is also pushing these companies to pursuit an *Agile Manufacturing* vision, as defined e.g., in (Gunasekaran, 1999; Brown and Bessant, 2003).

These aspects strongly influence the classification of companies operating in this industrial sector, characterised by such a wide product variability, and by the necessity of involving customers since the beginning of the design process. Hence, these aspects validate the classification of medium/large eyewear manufacturers as *Fabricators*.

Despite this high product variability, the manufacturing process of spectacles is not fully automatic (further details about this process will be provided in Section 2.2). It is also characterised by a handcraft essence (Montalto et al., 2016) because, especially in case of high-luxury models and frequent production changes, the expertise and the knowledge of the operators are a guarantee of the high product quality and thus represent an added value for the product. On the other hand, the automation of a three-dimensional fabrication processes could be too expensive and not as flexible as required (Zipkin, 2001) especially in case of rapid product changes. AM technologies, for certain materials largely used in the eyewear industry, such as cellulose acetate, cannot be used yet, even if advancements in this field have been recently published (Pattinson and Hart, 2017). The current manufacturing process of acetate spectacles is the one able to guarantee various aesthetic effects (e.g., in terms of colours and textures). Indeed, together with the geometric variability, also the wide material variability has to be considered (e.g., using additives different types of cellulose acetate can be created) which, again, makes highly difficult and expensive the implementation of fully automatic manufacturing approaches. These issues together with the time constraints set by the seasonality of the market (De Toni and Nassimbeni, 2003) are successfully overcome thanks to the ability of experienced engineers and operators and a semi-handcrafting production. However, it is also fundamental to develop complementary strategies to overcome these issues and support the work of engineers and operators in all product-development phases.

Summarising, the main difference between small and medium/large eyewear companies, is the way end-users' customisation needs are satisfied. Small eyewear companies, like start-ups, are closer to the end-users and they can have direct relationships with them. For this reason, they can directly embed users' needs and requirements through an artisan, or semi-handcrafting manufacturing process, or fully automatic ones, making use of AM technologies. In this case usually, dedicated product lines and new fashion brands are created. On the other hand, the strategy of medium/large eyewear companies is different: they are in contact with fashion houses — which set the market rules regarding fashion trends — and tend to satisfy end-users' preferences through the development of a significant amount of different models for each season. Medium/large eyewear companies can be considered as suppliers of fashion brands, and they aim at making as much as possible agile their manufacturing process to effectively manage the issues previously mentioned.

2.2 The need for reconfigurable manufacturing tools for acetate frames

Acetate-frame fronts are shaped through two main phases: a CNC milling phase (fully automated and controlled through CAM systems) to obtain flat fronts from raw acetate boards, and a bending phase (i.e., a thermoforming phase) of the fronts performed, through a semi-automated process.

In the perspective of MC, CNC machines having modular tooling are Reconfigurable Manufacturing Systems (RMSs), in which both hardware and software instructions can be easily modified to be adapted to production needs and used to support the quality control check (Mehrabi et al., 2000). Indeed, compared to FMS, RMSs are a step ahead, since they allow a rapid change of the manufacturing process to address market changes (ElMaraghy, 2005; Mehrabi et al., 2000; Mehrabi et al., 2002).

On the other hand, the thermoforming phase consists in bending the heated fronts through a conformational press, equipped with an ad-hoc metallic mould. Due to the geometric variability, each frame model requires a specific mould, which must be designed and manufactured in multiple units and stored to guarantee the availability of spare parts. These moulds are shaped through the CNC milling of steel monolithic blocks, and can be considered as a dedicated tool. Such manufacturing approach is opposite to the necessity of implementing reconfigurable solutions for fulfilling the *agile* paradigm. An *agile* thermoforming phase would require re-configurable (and consequently re-usable) moulds. Consequently, the development of a re-configurable thermoforming mould should be considered.

Reconfigurable thermoforming moulds, especially pin-type metallic ones, have been deeply studied in years (Munro and Walczyk, 2007). Nevertheless, pin-type moulds do not guarantee the control of the smoothness of the mould surface (e.g., dimpling defects, (Sreedhara and Mocko, 2015)) while the standard CNC milling of steel blocks is still a reliable manufacturing solution.

Thermoforming moulds are in general less expensive and complex than injections ones. This is also the reason why frequent changes could be afforded. However, the continuous manufacturing of new thermoforming moulds can even saturate the production capacity of a workshop, affecting the efficiency of the whole product development process. The possibility to continue to quickly address product changes decreasing the number of mould parts to be manufactured, would not only result into a saving of resources but also into an increase of the company ability to be *agile*. Therefore a modular mould — based on a proper combination of ad-hoc and re-usable parts, and obtained through a standard CNC milling process — could represent an appropriate solution to make more efficient the manufacturing process of cellulose acetate frames.

In redesigning the front thermoforming mould, the need of linking the product characteristics (and their variability) to the one of the manufacturing tool (i.e., the mould), has been considered a priority; in this way, the new thermoforming mould configuration would have been able to support also deeps variation of the frame geometry. Hence, the redesign phase has been driven by the interest of exploring how to create the link between the mould and the frame design parameters. As module drivers (Erixon, 1996), we considered the need of identifying common physical units. However, in our cases these units are the ones of the manufacturing tool (i.e. the thermoforming mould) and not of the product (i.e., the spectacle frame). They have been identified starting from the functional/aesthetic features, and their degree of variability, which characterise a frame (more details will be provided in Section 4.1). However, up to now specific modularity methods or measures (Jiao et al., 2007; Campagnolo and Camuffo, 2010; Erixon, 1996; Jose and Tollenaere, 2005), have been not applied/evaluated, but they could be considered in a further engineering of the new mould configuration described in Section 4.3.

It is also worth underlying the reason why the focus of the redesign activity, is not the product (i.e., the spectacle frame), but rather the manufacturing tool (i.e., the thermoforming mould). When applying Design for Manufacturing and Assembly (DFMA) strategies (Boothroyd et al., 2011) the product is redesigned in order to guarantee the fulfilment of the settled manufacturing targets and requirements. The architecture of spectacle frames is already structured adequately for the manufacturing process. The point is that the front, as it will be explained in Section 4.1, is designed and manufactured as a unique part, but it is instead characterised by multiple aesthetic/functional features that are responsible for the continuous product changes. Decomposing the front into various modules, it is not currently an affective solution since it could significantly alter the front aesthetic characteristics (e.g., the continuity of its surface). Hence it has been decided, on the one hand, to redesign the thermoforming mould to properly manage these changes and, on the other, to redefine some aesthetic specifications, to enable the concurrent development of the product and, of its manufacturing tool.

As anticipated, for the design activity, a KBE system has been also used. This kind of systems can be used to automate *repetitive and non-creative design tasks* (La Rocca, 2012). A KBE tool is a Knowledge Based System (KBS) i.e., an expert system based on knowledge formalisation, which also integrates the functionalities of Computer Aided Design (CAD) systems, concerning geometry manipulation, and Computer Aided Analysis (CAA) tools (La Rocca, 2012). A properly conceived KBE application is stable, i.e., resilient to input errors and model inconsistencies and can be used by all experts involved in the design process (La Rocca, 2012). It is also worth underlying that several works are already available in the literature concerning the use of KBE systems to guide the design of manufacturing tools (e.g., see (Vosniakos and Giannakakis, 2013; Kakish et al., 2000)) and, specifically, of injection moulds (e.g., (Lou et al., 2004; Mok et al., 2008; Chan et al., 2003)). However, less examples exist concerning the automation of the design of thermoforming moulds (e.g., (van der Laan et al., 2004)).

Summarising, the aim of the research described in the paper is to transform the current spectacle front thermoforming-mould into a reconfigurable tool. It is evident that flexible and reconfigurable manufacturing systems/tools have been already described in the literature (e.g., (Koren et al., 1999; Gadalla and Xue, 2017; Müller et al., 2013)) as well as their design principles (e.g., (Katz, 2007)). However, the approach described in this paper still represents an original contribution, not only for the research context analysed (i.e., the eyewear field) but also because it is based on the product knowledge formalisation; this knowledge is used, on the one hand, to map the influence of the product variability on the design of the manufacturing tool, and, on the other, to automate the mould design and to guarantee the assemblability of the components of the new mould configuration. Indeed, an original aspect of this research is that the KBE system is used, not only to create variants, but also to guarantee, through mathematical rules that, the changes to be applied to the thermoforming mould, as a consequence of the product variability, do not affect the robustness of its architecture from the manufacturing point of view. Besides, the approach described in the paper could be extended to all industrial fields whose manufacturing processes require thermoforming moulds that need to be continuously updated or remanufactured to address frequent product changes. An example could be represented by the biomedical field where the thermoforming process is used and devices/products need also a high degree of customisation (Tugrul, 2016; Lusardi et al., 2013; Sansoni et al., 2015).

3 Linking the product design variables with the ones of the manufacturing tools

In MC, the product variability might need specific manufacturing solutions to be guaranteed. These ad-hoc solutions can cause inefficiencies since dedicated tools require to be designed, manufactured and finally stored (to guarantee the availability of spare parts). This paper, describes how this standard approach could be overcome starting from an analysis of the relationships existing among the design variables of the product and the ones of the manufacturing tools. Indeed, the rationalisation of the manufacturing process passes through making these relationships explicit. Despite this principle could be seen as obvious, its implementation is not easy especially in case of products, such as spectacles, whose design process requires the fulfilment of multiple and heterogeneous requirements (i.e., aesthetic, functional, technological/manufacturing) and whose correlation is not evident as discussed and demonstrated in (Montalto et al., 2018).

To reach this target, it is first necessary to explicitly identify those elements/features and design variables of the product, which undergo aesthetic or functional changes. Then, it is necessary to explore what elements and design variables of the related manufacturing tools are affected by these changes. This step allows creating a “map” of these relationships. This “map” is fundamental to stimulate a redesign of the manufacturing tools with the intent of localising as much as possible the effects of the product changes on the design of the manufacturing tools. Such redesign activity should be performed with the intent of clustering the components of each manufacturing tool into two main groups: “standard” vs. ”special”. The elements belonging to the first group can be re-used for the production of different models, whereas the latter have to be designed and manufactured anytime a change in the product is implemented.

Once the clustering of the elements has been performed, it could be useful to explore whether the design of the “special” elements could be carried out through the use of parametric models. These models are controlled by means of rules, which have to be conveniently inferred and expressed through equations and logic steps. This task could be performed using a CAD software matched with a KBE system. This one allows avoiding 3D model inconsistencies, which are more frequent in parametric CAD software when updating or modifying a model. These parametric models do not only enable the shortening of the design process, but they are also a guarantee of the proper matching/interfacing between “standard” and “special” components. Indeed, rules can be used to keep under control the fulfilment of the necessary boundary conditions.

In this paper, this reasoning has been applied to redesign a thermoforming-mould. The implemented procedure and the obtained results are discussed in Section 4.

4 The redesign of the thermoforming mould

4.1 The main geometric and functional elements of a frame

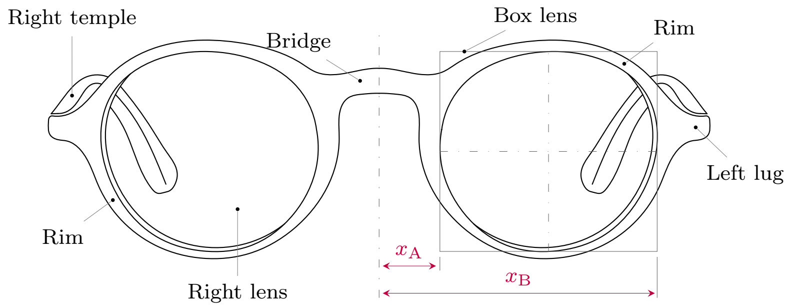
Although spectacles were born as medical devices, nowadays eyeglasses and sunglasses are also fashion products: functional and aesthetic requirements must always be simultaneously satisfied (Montalto et al., 2016). This paper is focused on spectacle frames in cellulose acetate because they often represent high-end and luxury frames while their production involves both automated and hand-crafted activities. The cellulose acetate is a material appreciated for its physical properties (e.g., weight, tactile sensation, possibility to be easily reshaped) and the great aesthetic freedom offered to the stylists (e.g., the acetate can be glued, dyed, and can contain various type of inclusions). From the manufacturing point of view, it is a challenging material due to the difficulty of accurately predicting its thermo-mechanical behaviour when it is used in thermoforming processes. Indeed, many factors can deeply influence its behaviour (e.g., dyes, inclusions, humidity, the quantity of absorbed solvents, material ageing, etc.). This thermoforming process is one of the key phases of the manufacturing process of a frame since it is the one in charge of bending it.

Spectacle frames are constituted by three main groups of components (Figure 1): a front (where the lenses are inserted); two lenses; two temples (to hook the frame to the right and left ears). The temples can assume different shapes-and-dimensions, and they can include various decorations, but most of the product variability is due to the front and lens geometries.

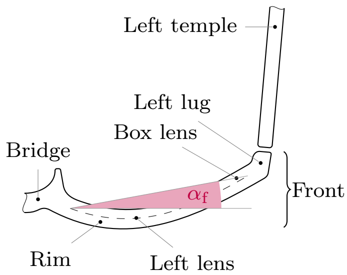
The front geometry can be split into different functional elements. They are (Figure 1): the rim; the bridge; the lugs. The rim is that part of the front around the lenses and could have different sizes, thicknesses or could miss in some parts (e.g., laterally, in the upper, or in the lower part, Figure 2) or completely (i.e., a rimless frame). The bridge is the connecting part of the front between the two rims (Figure 1) and can also variate (Figure 2) for geometry, length, curvature, or material (e.g., a metal bridge instead of acetate). Other differences can be identified in the vertical/horizontal positions of the lugs (Figure 2). They are at the two extremities of the front (Figure 1a), where there is the hinge connecting each temple to the front. Other minor aesthetic changes of frames (e.g., the presence of decorators and incisions) are not considered in the discussion. It has to be noted that, despite different functional elements concur in the definition of the geometry of the front surface (Figure 1), this one is represented as a unique element.

The lenses can potentially assume any shape (e.g., rectangular, oval, the so-called "pilot", "cat", and "butterfly"). Their geometry is one of the most important aesthetic features of a frame since it strongly influences its style lines (and thus also the product variability).

Finally, two more important features characterise the geometry of a spectacle frame: the face-form angle and the front-curvature. The face-form angle (α_{f}) i.e., the angle between the projection in the top view (Figure 1b) of the horizontal edges of the box-lens (Figure 1a) and the horizontal line representing the flat frame, is a fundamental parameter in the frame design since it guarantees the proper position of the lenses with respect to the eyes. The box-lens (Figure 1a) concepts derives from the boxing system (Brooks and Borish, 2006) used in ophthalmology to measure the lens whose vertical and horizontal dimensions are defined by the dimensions of the rectangular box (Figure 1a) surrounding the lens.



(a) *Front view*



(b) *Top view (partial)*

Fig. 1: A simplified representation of the front (a) and top (b) views of a spectacle frame. The main functional elements of the frame are highlighted (i.e., front, temples, lugs, rims, bridge, lenses). The x_A and x_B parameters are used to measure the horizontal dimension of the lens, considering the distance of the box vertical edges with respect to the frame central-axis. The box-lens is the rectangular box used in ophthalmology to measure the lenses dimensions. How the face-form angle (α_f) is measured is also shown (b). Images inspired by ISO 7998, pp. 23–24 (ISO, 2005).

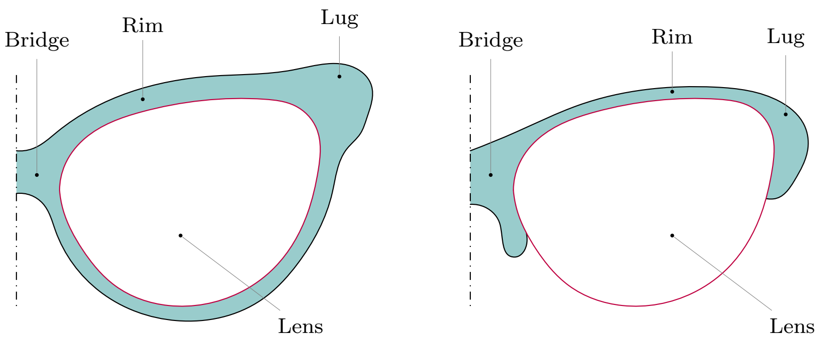


Fig. 2: The variability of a front is not only focused on the shape and dimensions of the lenses. For example, in these images two examples of front are represented. They have the same lenses but the following characteristics are different: type and dimensions of the rims; the sizes and the position of the bridge and of the lugs. Hence, they are two different fronts: a full front (left) and a half-front (right).

The front curvature is the three-dimensional curvature of the front. It guarantees that: the rims perfectly surround the lenses; the lenses are properly fastened to the front; a sense of continuity is created between the lens curvature and the front. This curvature determines the degree of envelopment of the front on the user's face, and for this reason, it has a strong aesthetic relevance. It can assume different three-dimensional configurations (e.g., spherical, cylindrical, flat). The values of the parameters controlling these configurations can vary among models.

Concerning the development process of a new frame, during the concept design phase the main functional and aesthetic requirements are set (Figure 3). The functional requirements guarantee that the spectacle can be considered not only as a fashion accessory but also a medical device (a detailed explanation of these requirements is provided in (Montalto et al., 2018)). The new frame-concept is re-elaborated during the detail design-phase, after which the final geometry of the new model is released. At the end of this phase, the frame design is fully defined. Therefore, the design of the thermoforming mould can start. All these phases are usually executed in series. Hence any delays will reflect in the entire chain.

4.2 The main geometric and functional elements of a front thermoforming mould

In the eyewear industry, the main functionality of a thermoforming mould for acetate frame is the imposition of the desired curvature to the frame front. This operation is accomplished laying down the heated cellulose-acetate front on the surface of the thermoforming mould and applying over it a pressure (Figure 4). Hence, the surface of the mould must follow the one of the front. Two portions of this surface are in charge of properly bending the rims and lugs of the front (Figures 1 and 4). These portions of the mould surface can be called as the *Rim/Lug surface*. The centring of the front with respect to the mould surface is guaranteed by those portions of the mould surface called jigs (Figure 4). Their shape must exactly reproduce the lenses shape and has to guarantee a fast insertion-and-removal of the front. Finally, the proper shaping of the bridge (see Figure 1) is guaranteed by the central part of the mould surface that can be called as the *Bridge surface* (Figure 4).

As the front surface, also the mould one is considered as a unique geometry, despite also this one can bee seen as the "sum" of multiple functional features (i.e., bridge surface, jigs, rims/lugs surface). The obvious consequence is that, nowadays, redesign and remanufacturing activities of the mould are needed, anytime a new frame model, and thus a new front surface, is released (see also Figure 3).

4.3 Mapping the frame variability on the mould features: identification of "standard" and "special" modules

As already discussed in Section 4.1, the front surface is considered as a unique feature, despite the frame front is made up of different functional elements (i.e., rims, lugs, and bridge, Figure 1a). Actually, from the geometric point of view, some simplifications can be made since, for example, rims and lugs (Figure 1a) always undergo the same curvature. On the contrary, such aspect is not guaranteed for the bridge (Figure 1a), which could be characterised by different aesthetic features. These considerations allow splitting the front geometry into three main regions (Figure 5): two lateral surfaces

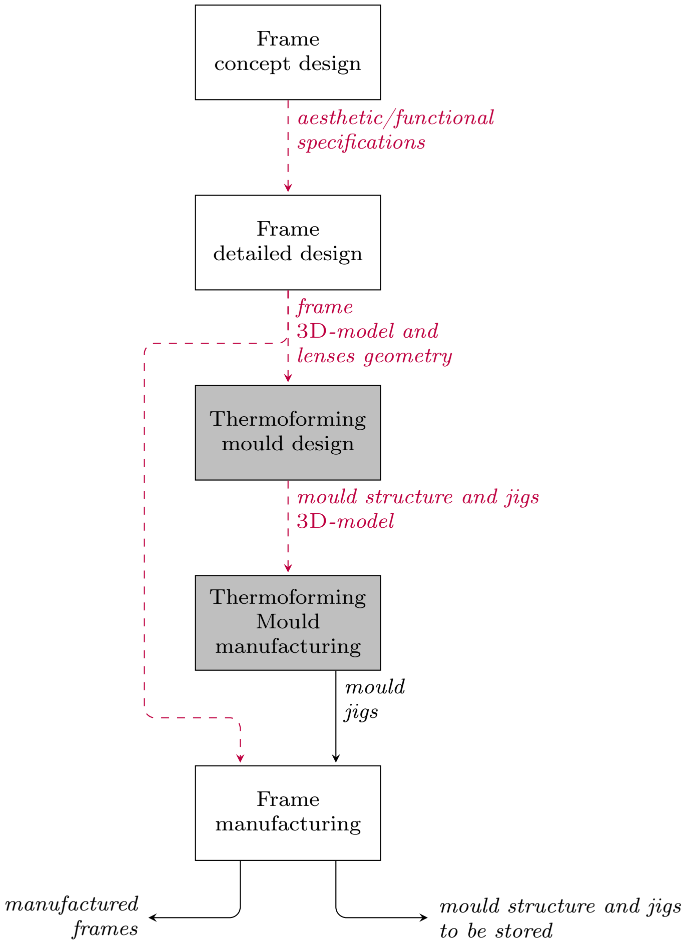
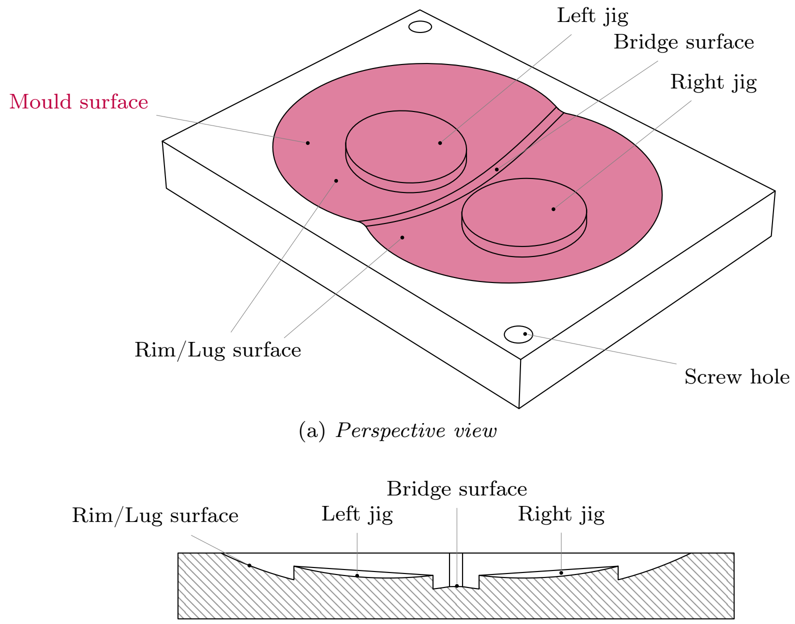


Fig. 3: The AS-IS development-cycle of a new model of frame. The white boxes are the activities of the process related to the frame while the grey boxes concern the thermoforming mould. Dashed and solid arrows respectively stand for the flow of information/data, and of the physical parts.

(they are symmetric) and a central one (for the bridge), which has also the role of both connecting and orienting the lateral surfaces, in order to get the desired face-form angle (Figure 1b). This one is thus a design variable (it is both a functional and an aesthetic requirement, Figure 3), not only for the front but also for the mould surface.

The lateral surfaces (Figure 5), which determine the curvature of rim and lugs, are the leading elements of the front and they can vary as described in Section 4.1. Their geometry depends on the stylist's decisions but — analysing the various collections over the years — they could be clustered in families (e.g., cylindrical, spherical, or flat).

The central surface (Figure 5) is characterised by a width and a curvature that can vary as described in Section 4.1 for the bridge. The stylist can decide the kind of connection to be implemented (e.g., through a sharp or a fillet edge or a planar surface, etc.) between the rims and the bridge (i.e., between the lateral surfaces and the central



(a) *Perspective view*

(b) *Transversal view*

Fig. 4: A simplified representation of the current thermoforming mould depicted in a perspective (a) and transversal (b) view. The current mould is a monolithic structure and its features (i.e., surface, jigs, and screw holes) are shaped through the milling of a metallic block. The main functional elements of the mould surface are highlighted (i.e., jigs, bridge surface, rim/lug surface)

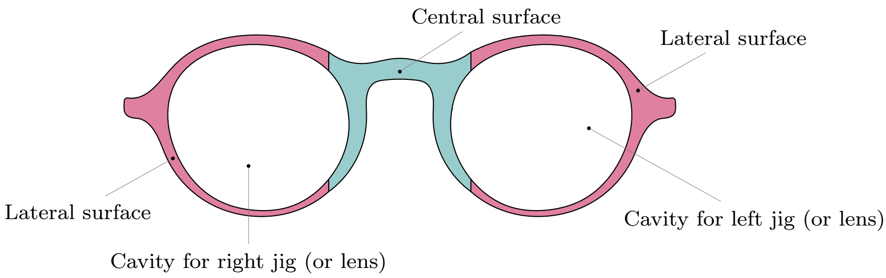
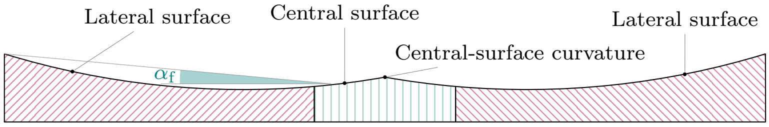


Fig. 5: The front surface can be split into three main regions: two lateral regions (in crimson) and a central one (in teal), with variable extensions.

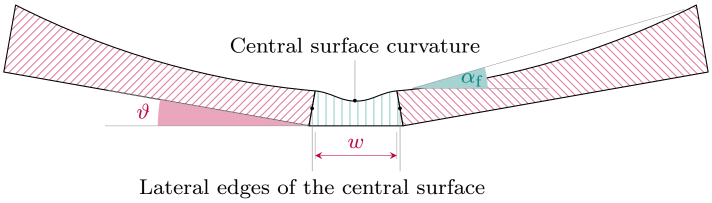
one). These aspects are all design variables, which will influence the mould surface design.

Finally, the empty area of the front needed to fix in position the two lenses (Figure 5) has also to be considered. This area must replicate the geometry of the lenses. This geometry represents a further design variable to be considered when designing the mould surface.

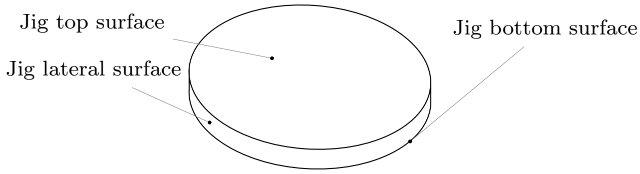
The same geometrical reasoning used for the front can also be applied to the mould surface, considering this one as made up of three main features: two lateral surfaces



(a) *Cross section view of a mould designed to fulfil a small face-form angle* α_f *and a sharp bridge. The cross-sections of the jigs are not represented.*



(b) *Cross section view of a mould designed to fulfil a positive face-form angle* α_f *and a curved bridge. The central surface is characterised by a width* w *while the lateral surface has a* ϑ *orientation. The cross-sections of the jigs are not represented.*



(c) *Perspective view of a jig having a circular lateral shape.*

Fig. 6: In Figures 6a and 6b, the same theoretical division performed on the frame in Figure 5 has been applied to the mould. The lateral portions of the mould are related to the lateral surfaces of the front. In these two images two possible configurations of mould are shown: they have the same lateral surfaces (i.e., the same lateral curvature) but a different central part (with teal hatching). In 6a the bridge will be sharp and the frame will have a small face-form angle while, in 6b, the frame (to bend) has a smaller and curved bridge with a different face-form angle. The central region also has to guarantee the continuity between the two lateral regions. In Figure 6c, the main geometric elements of the jig shape are shown; this jig is suitable for a frame with circular lenses (e.g., the frame represented in Figure 5).

(symmetric) and a central one (Figure 6). If the value of the face-form angle changes, the two lateral surfaces have to be properly oriented with respect to the central one as well as the lateral edges of this central surface (Figures 6a and 6b). The lateral surfaces of the mould can be re-used whether the same class of surfaces for the front geometry is selected (e.g., spherical, cylindrical, or flat) and these surfaces have the same dimensions (e.g., the same radius in case of spherical or cylindrical surfaces). Any change in the bridge geometry has to be also reflected on the one of the central surface of the mould in terms of width and curvature (Figures 6a and 6b). Finally, any change of the lens shape implies a change of the jigs geometry, since they have to be the same.

The central surface of the mould can be considered as an interface element (for the two lateral surfaces, Figures 6a and 6b): its geometry must guarantee a proper connection among all these elements. Also, the jigs could be considered as interface elements between the front and the mould. Since it could be possible to have two fronts having the same type of curvature (e.g., spherical, cylindrical, or flat) and dimensions,

Table 1: Mapping of the influence of frame features variability on the main mould elements (see also Figures 5 and 6).

Frame feature (design variables)	Mould feature directly involved	Change to be implemented on the mould
Face-form angle	Lateral & Central Surfaces	Orientation of the lateral surfaces (ϑ) and of the lateral edges of the central surface.
Front surface geometry	Lateral surfaces	Geometry of the lateral surfaces (they must be replaced unless the class of surfaces is the same and they have the same dimensions) and of the bottom surface of the jig.
Bridge length	Central Surface	Width of the central surface (w).
Bridge curvature	Central Surface	Curvature of the central surface.
Lens geometry	Jigs	Lateral surface of the jigs.

but different lens shapes, it could be more effective to consider them as separate elements of the mould surface. The proper interfacing among the mould lateral surfaces and their related jig (left or right) has to be guaranteed by the bottom surface of the jig (Figure 6c) which should have the same curvature of the lateral surfaces.

To hold in position all the elements of the mould surface a new structure has to be designed. This one should be no more a monolithic block since it has to allow a fast and easy: substitution of the lateral surfaces of the mould when they cannot be reused; orientation of these surfaces when it is necessary to tilt them in order to fulfil the value set for the face-form angle; substitution of the central surface; insertion and removal of the jigs.

In Table 1 all the aspects previously discussed, concerning the influence of the frame variability on the mould functional elements, are listed. These ones have been used to define the new architecture of the thermoforming mould which has been structured into the following modules (2 of them classified as "standard" and 2 as "special"):

- 2 symmetric modules representing the lateral surfaces of the frame ("standard");
- 1 central module representing the frame bridge ("special");
- 1 jigs module made up of two symmetric and removable jigs ("special");
- 1 structural module ("standard") that has the function of: holding all the components in position; orienting the lateral modules properly; guaranteeing an easy insertion of the central module; allowing the connection to the thermoforming press.

This new concept of thermoforming-mould could positively affect the development cycle of new models of spectacles. As represented in Figure 7, during the frame concept-design the stylist will provide information useful not only for the frame detailed design, but also (indirectly) for the mould configuration. Indeed, together with the aesthetic details, the stylist has to explicit also the type of surface to be used for the front (e.g., spherical, cylindrical, or flat), the face-form angle, the frame dimensions and the bridge curvature. This information is usually known but using the configurable mould it can be directly used to design and manufacture the central module and gather all the standard elements (whether these are already in stock). The design and manufacturing of the central part can proceed almost in parallel with the frame detailed design, while the design and manufacturing of the jigs have to start as soon as the lens geometry is released. Because of the simplicity of the jigs geometry, this fact should not represent an issue. Once jigs are manufactured, the mould can be immediately assembled and used for the front thermoforming.

As already underlined in Section 2.2, the identification of the main modules is a direct consequence of the choice of linking the intrinsic characteristics of the frame (and their variability) with the design parameters of the mould. In this way, also in the case of deep variations of the frame geometry, the new mould configuration can be still used just changing the *special* modules. Indeed, while the "standard" parts are re-usable for almost any frame model, the "special" ones have been conceived to fully manage the product variability. Stylists' requirements can be now used for the design of both the frame and the mould whose development could thus start before the frame geometry is finalised. For example, in case of two frame models differing just for the lens shape, the structural, the lateral and the central modules of the mould are the same. The only difference is related to the jigs, which can be easily designed and manufactured as soon as the lens shape is defined. Instead, in case of two frame models differing for everything, i.e., lens shapes, sizes, face-form angles and front surface curvatures (for example spherical and cylindrical), only the structural module of the mould is the same. The main advantage is that the lateral modules of the mould can generally have only a few possible configurations (e.g., big spherical, small spherical, large cylindrical, flat), consequently once the lateral parts of the mould (in charge of creating the lateral front-surfaces) are built, they can be re-used for all fronts which share the same type of surface and with the same dimensions. If the face-form angle is different the only change to apply is the ϑ orientation (Figure 6b) of the lateral surfaces (this change can be manually or automatically controlled) and the geometry of the central module of the mould (whose dimension is quite small). This new configuration of the thermoforming mould makes easier to switch from a frame model to another.

It is worth underlying that a further tuning of the new architecture of the mould could be performed, as already anticipated in Section 2.2, especially for what concerns the standard modules (e.g., the structural modules) and their potential sub-modules in order to keep under control the impact of this new architecture on the whole manufacturing process.

4.4 The design of the "special" modules through a rule-based engineering system

As already discussed in Section 4.3, the central part of the mould and the jigs can be considered as "special" module and interfacing elements. They are both connected to the lateral surfaces: the jigs through their bottom surface, while the central surface through its lateral surfaces (Figure 6). The relations between the lateral and central modules are regulated through mathematical equations (easy to infer), which depend on the surface family selected for the lateral modules (e.g., spherical, cylindrical, or flat). The width, the height and the slope of the lateral surfaces depend on several factors (Table 1), and they can be evaluated through mathematical relationships. The relation between the lateral module and the bottom surface of the jig is easy: they must have the same curvature. Furthermore, they have to be fixed to the lateral-surface modules and in the same position of the lens "cavities" in the bent front. Hence, the design of the "special" modules (i.e., the central module and the jigs modules) is the result of the proper combination of mathematical equations (necessary to guarantee the proper

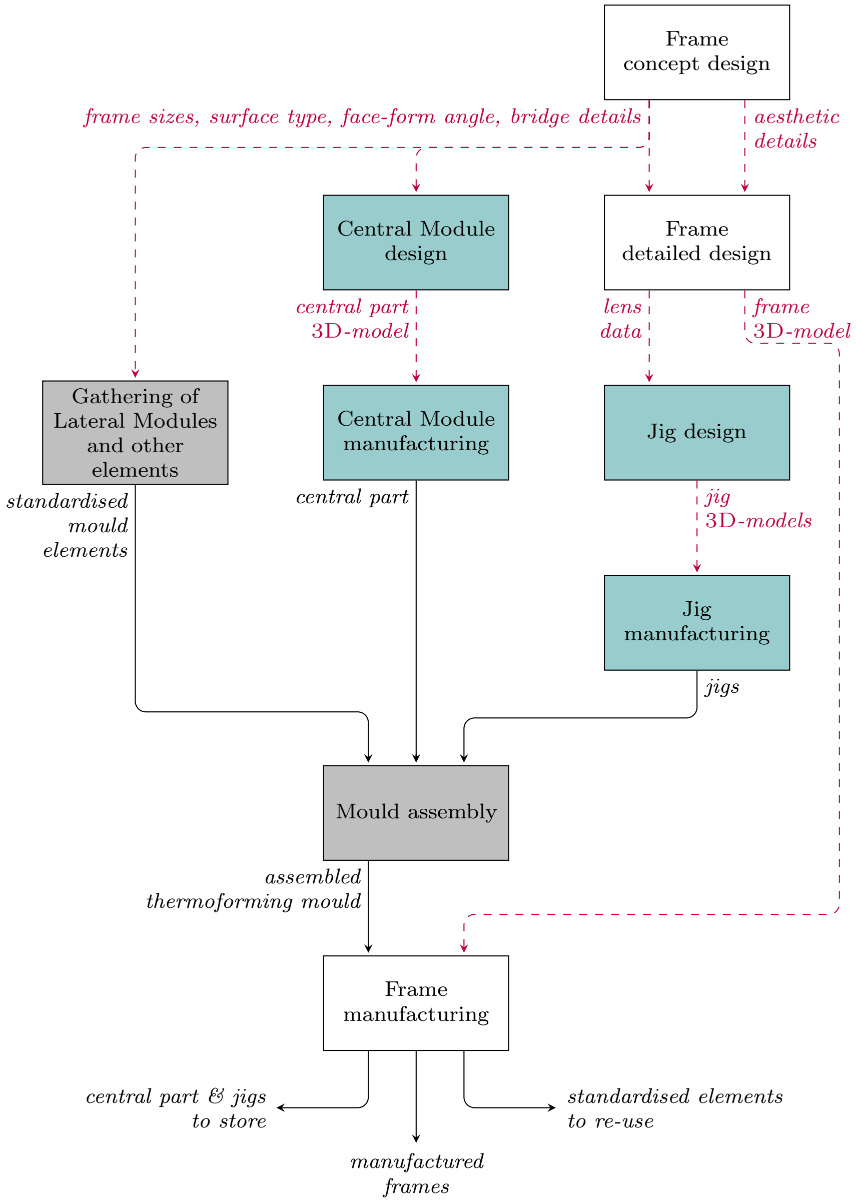


Fig. 7: The TO-BE process of the frame-development cycle using a reconfigurable thermoforming mould. The white boxes concern the frame cycle, the teal boxes define the new phases for the development of the "special" mould modules, and the grey one stands for the gathering of all "standard" parts of the mould and their assembly with the ad-hoc components. The dashed arrows represent information or data.

interfacing among the modules) and the specifications set by the stylist (i.e., the lens shapes for the jigs, the bridge length and the curvature for the central module, the geometry of the lateral surfaces for both the central and the lateral modules). Based on the previous considerations, the design of each part of the new mould configuration can be guided.

To speed up and support this design task, the use of a KBE system was experimented. This kind of tool can implement knowledge and procedures through rules and — basing on them — execute specific operations (e.g., the automatic generation of CAD models). Their robustness allows avoiding the generation of non-manifold geometries, and the scripting code necessary to implement the design activity can be easily debugged and updated. Also, their implementation, within industrial contexts, is positive since it pushes the formalisation of the company knowledge. In this research, the commercial software ParaPy® was used (www.parapy.nl).

The ParaPy® KBE system provides scripts for the generation and the managing of CAD models. Consequently, parts can be generated following a procedure similar to the one that would be used in a standard CAD environment (e.g., extrusions, cuts, rotations, etc.). However, as already underlined, the scripting allows a more robust control of the geometry. In addition, ParaPy® provides a Graphical User Interface (GUI) for engineers to set the inputs for the part generation (Figures 8 and 9). In real time, the software adapts the model from the values set for the inputs, and it exports the generated model using a neutral format (e.g., a `*.step` file). In this way, the user can verify the parts within an assembly environment together with the 3D models of the standard parts.

The automatic generation of the "special" modules was tested using, as an example, two lateral modules having spherical surfaces. Obviously, the new mould configuration can also be used with different type of front curvatures (e.g., cylindrical or flat), but it is necessary to create new scripts with the suitable equations for the part design and to link the different inputs to mathematically define the surfaces and the geometrical relations among "standard" and "special" parts. A structural module and several lateral modules with different radii were designed, using the CAD system SolidWorks® (www.solidworks.com). Two different scripts were instead implemented for the design of the central module and the jigs. The script for the generation of the central module takes as inputs: the lens-base curve, the frame thickness, the desired face form angle, and the distances `x_A` and `x_B` of the box lenses (Figures 1 and 8). Through the Python scripts used in ParaPy®, a 3D-model of the part is generated. The script for the jigs generation uses as inputs only the lens-base curve and the frame thickness (Figure 9), while the lens shape is provided through a textual `*.dat` file with the coordinates of the lens border. The lateral surface of the jigs is designed through the mathematical rules embedded in the ParaPy® script.

It is worth underlying once again that, a change of the class of the lateral surface (e.g., from spherical to cylindrical, or flat) would require a substantial modification of the mathematical relations determining both the geometry of the modules and the interfacing constraints. Consequently, also the scripts (i.e., the ones implemented in ParaPy® to design the central parts and the jigs) need to be changed. Nevertheless, the general approach would remain the same.

In Figure 10, the new configuration of the thermoforming mould (with a double spherical surface) is shown. The assembly has been generated using the CAD software SolidWorks®. Obviously, this new configuration represents a solution that is con-

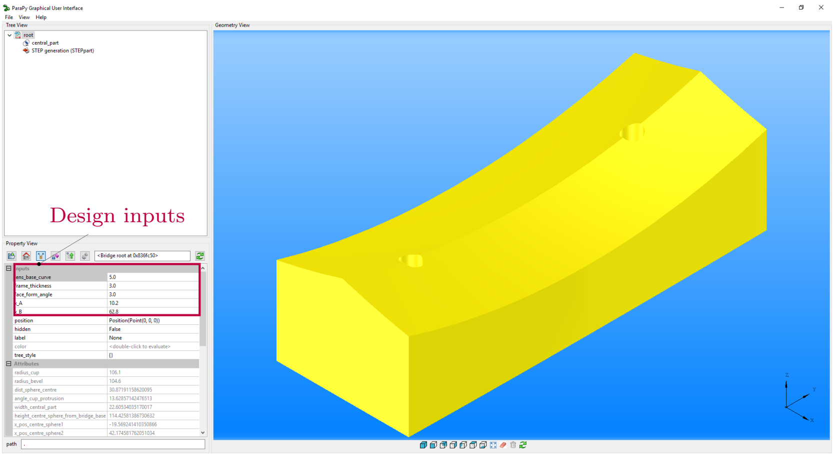


Fig. 8: 3D model of the central-part of the mould, visualised through the GUI of ParaPy. This "special" part is necessary to create the continuity between the two lateral modules and the bridge shape. The part is modelled on the basis of the implemented design-rules and the inserted inputs (highlighted with the crimson box) in case of a surface generated by two spheres and a sharp bridge.

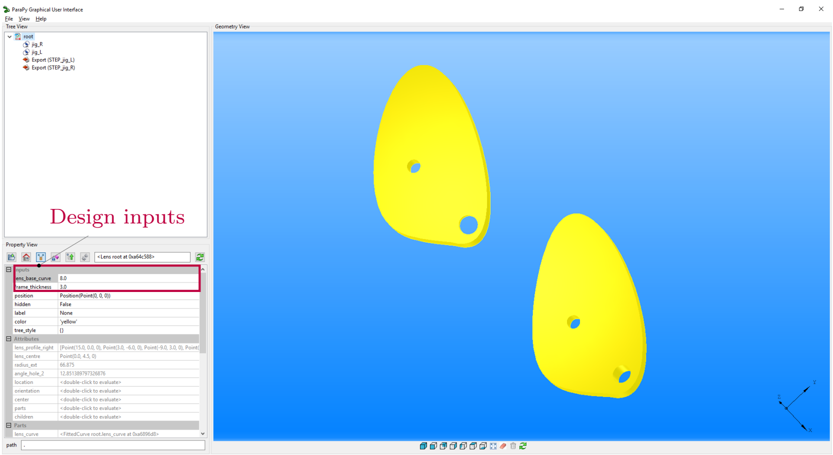


Fig. 9: The 3D model of the jigs visualised through the GUI of ParaPy. These parts are two "special" parts of the -mould; they hold in the right position the front during the thermoforming phase and they have the same shape of the lenses. The holes are used to fix the jigs to the mould lateral surfaces. Inserting all necessary inputs (highlighted with a crimson box), the jigs 3D model is automatically updated.

ceptually valid, but not engineered yet. Indeed, the objective of this case study was to test the effectiveness and validity of the approach in a real industrial context.

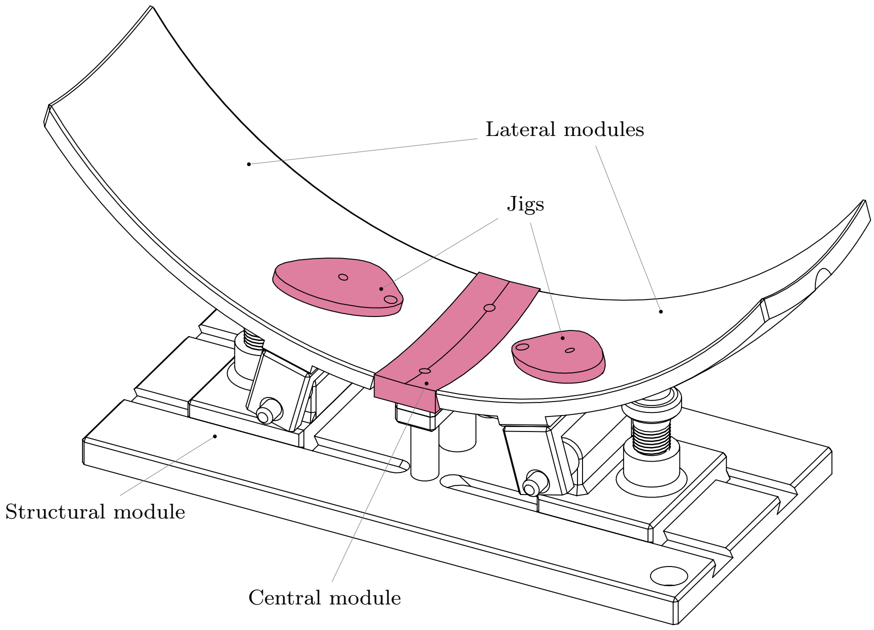


Fig. 10: The 3D model of the new mould configuration created within the assembly environment of SolidWorks®. The crimson parts (i.e., the jigs and the central module) are the "special" ones modelled using the ParaPy® KBE software (Figures 8 and 9) and then, imported into the CAD environment. The other components are the "standard" modules.

5 Conclusions

In this paper, a design approach to transform a manufacturing tool (a thermoforming mould) into a reconfigurable one is discussed. The objective is to propose a strategy for making manufacturing processes ready to address fast and continuous product changes. The research context is the one of the eyewear industry even if, the proposed approach and the considerations derived, can also be transferred to all those industrial fields where a thermoforming phase is part of the manufacturing process and the product undergoes continuous changes. An example could be represented by the biomedical field.

The proposed design approach is based on the following reasoning. For making a manufacturing tool able to guarantee the high product variability, it is fundamental that its design process would be grounded on the same design parameters determining the variability of the product. In this way, it is possible to distinguish those elements of the tool that can be considered as standard from those that need to be always updated anytime a change is performed on the product. Hence, it is fundamental to map the variability of the product structure onto the architecture of the manufacturing tool.

This reasoning has been applied to redesign the thermoforming mould used to bend the fronts of spectacle frames. In the current development processes, this tool is designed and manufactured once the detailed design of the new frame is released. This mould is usually conceived as a unique monolithic block, whose bending surface reflects the one of the frame. Hence, anytime a new frame is released a new mould has to be manufactured. This situation leads to the following consequences: several mould variants need to be produced but also stored to guarantee spare parts availability; any delay in the design of the frame as well as in the design and manufacturing of the tool will affect the whole development cycle.

Starting from the identification of the main design variables leading the variability of the frame front, the thermoforming mould was split into "standard" and "special" modules. The "special" modules are those elements of the mould in charge of guaranteeing the product variability. Actually, also the "standard" modules concur in guaranteeing this variability but the range of the possible needed variants could be a priori defined. This strategy allowed generating a reconfigurable thermoforming-mould to make the company able to manage rapid production changes in an *agile* way.

This new mould configuration is adaptable to any spectacle frame. The frame design requirements are used to select or design the "standard" parts and to design the "special" ones that need to be manufactured. In addition, to guarantee the proper interfacing among "standard" and "special" modules, a KBE system has been used. Through this one it is possible to automatically design the "special" modules using the data available also before the detailed design phase of the frame is completed, implementing a concurrent engineering approach. The KBE system has allowed formalising the mathematical constraints that need to be fulfilled to guarantee the assemblability of the mould.

The outcome of this research — performed in collaboration with an eyewear industry — is a conceptual study based on a real industrial problem. Apart from the eyewear industry, this strategy could be used in all those fields where the product undergo continuous geometric variations, the aesthetic requirements are as important as the functional ones, and the manufacturing process involves a thermoforming phase. By identifying and formalising the rules, that link the variability of the product to the one of the mould geometry, a company could increase its ability in rapidly and efficiently fulfilling customers' requests.

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References

Ariss, S. S. and Zhang, Q. (2002). 'The impact of flexible process capability on the product–process matrix: an empirical examination'. In: *International Journal of Production Economics* 76.2, pp. 135–145. DOI: 10.1016/S0925-5273(01)00146-3 (cit. on p. 4).

Barman, S. and Canizares, A. E. (2015). 'A survey of mass customization in practice'. In: *International Journal of Supply Chain Management* 4.1, pp. 65–72 (cit. on pp. 2, 4).

Boothroyd, G., Dewhurst, P. and Knight, W. A. (2011). *Product Design for Manufacture and Assembly*. Third Edition. CRC Press (cit. on p. 7).

Bowen, D. E. and Youngdahl, W. E. (1998). '"Lean" service: in defense of a production-line approach'. In: *International journal of service industry management* 9.3, pp. 207–225 (cit. on p. 3).

Brooks, C. W. and Borish, I. (2006). *System for Ophthalmic Dispensing-E-Book*. Elsevier Health Sciences (cit. on p. 9).

Brown, S. and Bessant, J. (2003). 'The manufacturing strategy-capabilities links in mass customisation and agile manufacturing–an exploratory study'. In: *International Journal of Operations & Production Management* 23.7, pp. 707–730 (cit. on p. 5).

Browne, J., Dubois, D., Rathmill, K., Sethi, S. P., Stecke, K. E. et al. (1984). 'Classification of flexible manufacturing systems'. In: *The FMS magazine* 2.2, pp. 114–117 (cit. on p. 3).

Campagnolo, D. and Camuffo, A. (2010). 'The concept of modularity in management studies: a literature review'. In: *International Journal of Management Reviews* 12.3, pp. 259–283 (cit. on p. 7).

Chan, W. M., Yan, L., Xiang, W. and Cheok, B. T. (2003). 'A 3D CAD knowledge-based assisted injection mould design system'. In: *The International Journal of Advanced Manufacturing Technology* 22.5, pp. 387–395. DOI: 10.1007/s00170-002-1514-9 (cit. on p. 7).

Conner, B. P., Manogharan, G. P., Martof, A. N., Rodomsky, L. M., Rodomsky, C. M., Jordan, D. C. and Limperos, J. W. (2014). 'Making sense of 3-D printing: Creating a map of additive manufacturing products and services'. In: *Additive Manufacturing* 1, pp. 64–76 (cit. on p. 4).

Da Silveira, G., Borenstein, D. and Fogliatto, F. S. (2001). 'Mass customization: Literature review and research directions'. In: *International Journal of Production Economics* 72.1, pp. 1–13. DOI: 10.1016/S0925-5273(00)00079-7 (cit. on pp. 2, 3).

De Toni, A. and Nassimbeni, G. (2003). 'Small and medium district enterprises and the new product development challenge: Evidence from Italian eyewear district'. In: *International Journal of Operations & Production Management* 23.6, pp. 678–697. DOI: 10.1108/01443570310476672 (cit. on pp. 4, 5).

Deradjat, D. and Minshall, T. (2017). 'Implementation of rapid manufacturing for mass customisation'. In: *Journal of Manufacturing Technology Management* 28.1, pp. 95–121. DOI: 10.1108/JMTM-01-2016-0007 (cit. on p. 4).

Diegel, O., Singamneni, S., Reay, S. and Withell, A. (2010). 'Tools for Sustainable Product Design: Additive Manufacturing'. In: *Journal of Sustainable Development* 3.3, p. 68 (cit. on p. 4).

Duray, R. (2011). 'Process Typology of Mass Customizers'. In: *Mass Customization: Engineering and Managing Global Operations*. London: Springer London, pp. 29–43. DOI: 10.1007/978-1-84996-489-0_2 (cit. on p. 3).

Duray, R., Ward, P. T., Milligan, G. W. and Berry, W. L. (2000). 'Approaches to mass customization: configurations and empirical validation'. In: *Journal of Operations Management* 18.6, pp. 605–625. DOI: 10.1016/S0272-6963(00)00043-7 (cit. on p. 4).

ElMaraghy, H. A. (2005). 'Flexible and reconfigurable manufacturing systems paradigms'. In: *International journal of flexible manufacturing systems* 17.4, pp. 261–276 (cit. on p. 6).

Erixon, G. (1996). 'Design for modularity'. In: *Design for X*. Springer, pp. 356–379 (cit. on pp. 6, 7).

Fogliatto, F. S., Da Silveira, G. J. C. and Borenstein, D. (2012). 'The mass customization decade: An updated review of the literature'. In: *International Journal of Production Economics* 138.1, pp. 14–25. DOI: 10.1016/j.ijpe.2012.03.002 (cit. on pp. 2–4).

Gadalla, M. and Xue, D. (2017). 'Recent advances in research on reconfigurable machine tools: a literature review'. In: *International Journal of Production Research* 55.5, pp. 1440–1454. DOI: 10.1080/00207543.2016.1237795 (cit. on p. 7).

Gilmore, J. H. and Pine, B. J. (1997). 'The four faces of mass customization'. In: *Harvard business review* 75, pp. 91–101 (cit. on pp. 2, 4).

Gunasekaran, A. (1999). 'Agile manufacturing: A framework for research and development'. In: *International Journal of Production Economics* 62.1, pp. 87–105. DOI: 10.1016/S0925-5273(98)00222-9 (cit. on p. 5).

ISO (2005). *ISO 7998: 2005 Ophthalmic optics – Spectacle frames – Lists of equivalent terms and vocabulary*. Standard. Geneva, Switzerland (cit. on p. 10).

Jiao, J. R., Simpson, T. W. and Siddique, Z. (2007). 'Product family design and platform-based product development: a state-of-the-art review'. In: *Journal of Intelligent Manufacturing* 18.1, pp. 5–29 (cit. on p. 7).

Jose, A. and Tollenaere, M. (2005). 'Modular and platform methods for product family design: literature analysis'. In: *Journal of Intelligent Manufacturing* 16.3, pp. 371–390. DOI: 10.1007/s10845-005-7030-7 (cit. on p. 7).

Kakish, J., Zhang, P.-L. and Zeid, I. (2000). 'Towards the design and development of a knowledge-based universal modular jigs and fixtures system'. In: *Journal of Intelligent Manufacturing* 11.4, pp. 381–401. DOI: 10.1023/A:1008978319436 (cit. on p. 7).

Katz, R. (2007). 'Design principles of reconfigurable machines'. In: *International Journal of Advanced Manufacturing Technology* 34.5-6, pp. 430–439. DOI: 10.1007/s00170-006-0615-2 (cit. on p. 7).

Koren, Y., Heisel, U., Jovane, F., Moriwaki, T., Pritschow, G., Ulsoy, G. and van Brussel, H. (1999). 'Reconfigurable Manufacturing Systems'. In: *CIRP Annals - Manufacturing Technology* 48.2, pp. 527–540. DOI: 10.1016/S0007-8506(07)63232-6 (cit. on pp. 2, 7).

Kusiak, A. (1985). 'The part families problem in flexible manufacturing systems'. In: *Annals of Operations Research* 3.6, pp. 277–300 (cit. on p. 3).

La Rocca, G. (2012). 'Knowledge based engineering: Between AI and CAD. Review of a language based technology to support engineering design'. In: *Advanced Engineering Informatics* 26.2, pp. 159–179 (cit. on p. 7).

Lou, Z., Jiang, H. and Ruan, X. (2004). 'Development of an integrated knowledge-based system for mold-base design'. In: *Journal of Materials Processing Technology* 150.1–2, pp. 194–199. DOI: 10.1016/j.jmatprotec.2004.01.037 (cit. on p. 7).

Lusardi, M. M., Jorge, M. and Nielsen, C. C. (2013). *Orthotics and Prosthetics in Rehabilitation-E-Book*. Elsevier Health Sciences (cit. on p. 8).

MacCarthy, B., Brabazon, P. G. and Bramham, J. (2003). 'Fundamental modes of operation for mass customization'. In: *International Journal of Production Economics* 85.3, pp. 289–304. DOI: 10.1016/S0925-5273(03)00117-8 (cit. on p. 3).

Mehrabi, M. G., Ulsoy, A. G. and Koren, Y. (2000). 'Reconfigurable manufacturing systems: Key to future manufacturing'. In: *Journal of Intelligent Manufacturing* 11.4, pp. 403–419 (cit. on p. 6).

Mehrabi, M. G., Ulsoy, A. G., Koren, Y. and Heytler, P. (2002). 'Trends and perspectives in flexible and reconfigurable manufacturing systems'. In: *Journal of Intelligent Manufacturing* 13.2, pp. 135–146. DOI: 10.1023/A:1014536330551 (cit. on p. 6).

Mok, C. K., Hua, M. and Wong, S. Y. (2008). 'A hybrid case-based reasoning CAD system for injection mould design'. In: *International Journal of Production Research* 46.14, pp. 3783–3800. DOI: 10.1080/00207540601103100 (cit. on p. 7).

Montalto, A., Graziosi, S., Bordegoni, M. and Di Landro, L. (2016). 'An inspection system to master dimensional and technological variability of fashion-related products: A case study in the eyewear industry'. In: *Computers in Industry* 83, pp. 140–149. DOI: 10.1016/j.compind.2016.09.007 (cit. on pp. 4, 5, 9).

Montalto, A., Graziosi, S., Bordegoni, M. and Di Landro, L. (2018). 'Combining aesthetics and engineering specifications for fashion-driven product design: a case study on spectacle frames'. In: *Computers in Industry* 95, pp. 102–112. DOI: 10.1016/j.compind.2017.12.003 (cit. on pp. 2, 4, 5, 8, 11).

Munro, C. and Walczyk, D. (2007). 'Reconfigurable pin-type tooling: A survey of prior art and reduction to practice'. In: *Journal of Manufacturing Science and Engineering, Transactions of the ASME* 129.3, pp. 551–565. DOI: 10.1115/1.2714577 (cit. on p. 6).

Müller, R., Esser, M. and Vette, M. (2013). 'Reconfigurable handling systems as an enabler for large components in mass customized production'. In: *Journal of Intelligent Manufacturing* 24.5, pp. 977–990. DOI: 10.1007/s10845-012-0624-y (cit. on p. 7).

Nayak, R., Padhye, R., Wang, L., Chatterjee, K. and Gupta, S. (2015). 'The role of mass customisation in the apparel industry'. In: *International Journal of Fashion Design, Technology and Education* 8.2, pp. 162–172. DOI: 10.1080/17543266.2015.1045041 (cit. on p. 3).

Pattinson, S. W. and Hart, A. J. (2017). 'Additive Manufacturing of Cellulosic Materials with Robust Mechanics and Antimicrobial Functionality'. In: *Advanced Materials Technologies* 2.4, 1600084–n/a. DOI: 10.1002/admt.201600084 (cit. on p. 5).

Sansoni, S., Wodehouse, A., McFadyen, A. K. and Buis, A. (2015). 'The aesthetic appeal of prosthetic limbs and the uncanny valley: The role of personal characteristics in attraction'. In: *International Journal of Design* 9.1 (cit. on p. 8).

Sharma, R. (Sept. 2010). *Custom Eyewear: The Next Focal Point For 3D Printing?* URL: https://www.forbes.com/sites/rakeshsharma/2013/09/10/custom-eyewear-the-next-focal-point-for-3d-printing/#6b5cdf4f7ed7 (cit. on p. 4).

Smith, S., Smith, G., Jiao, R. and Chu, C.-H. (2013). 'Mass customization in the product life cycle'. In: *Journal of Intelligent Manufacturing* 24.5, pp. 877–885. DOI: 10.1007/s10845-012-0691-0 (cit. on p. 3).

Sreedhara, V. S. M. and Mocko, G. (2015). 'Control of Thermoforming Process Parameters to Increase Quality of Surfaces Using Pin-Based Tooling'. In: *ASME. International Design Engineering Technical Conferences and Computers and Information in Engineering Conference,* vol. 4: 20th Design for Manufacturing and the Life Cycle Conference; 9th International Conference on Micro- and Nanosystems. ASME, V004T05A016. DOI: 10.1115/detc2015-47682 (cit. on p. 6).

Stump, B. and Badurdeen, F. (2012). 'Integrating lean and other strategies for mass customization manufacturing: A case study'. In: *Journal of Intelligent Manufacturing* 23.1, pp. 109–124. DOI: 10.1007/s10845-009-0289-3 (cit. on p. 3).

Tugrul, Ã. et al. (2016). *Biomedical devices: design, prototyping, and manufacturing.* John Wiley & Sons (cit. on p. 8).

Van der Laan, T., Weteringe, B. and van Tooren, M. (2004). 'Automatic generation of rib mould for rubber forming of thermoplastic composites, using knowledge based engineering'. In: *Proceedings of the 11th European Conference on Composite Materials*. Rhodes, G. (cit. on p. 7).

Vosniakos, G.-C. and Giannakakis, T. (2013). 'A knowledge-based manufacturing advisor for pressworked sheet metal parts'. In: *Journal of Intelligent Manufacturing* 24.6, pp. 1253–1266. DOI: 10.1007/s10845-012-0664-3 (cit. on p. 7).

Zhou, F., Ji, Y. and Jiao, R. (2013). 'Affective and cognitive design for mass personalization: Status and prospect'. In: *Journal of Intelligent Manufacturing* 24.5, pp. 1047–1069. DOI: 10.1007/s10845-012-0673-2 (cit. on p. 3).

Zipkin, P. (2001). 'The limits of mass customization'. In: *MIT Sloan Management Review* 42.3, pp. 81–87 (cit. on p. 5).