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Using Rapid Prototyping Data to Enhance a Knowledge-Based Framework for Product Redesign

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Abstract

The particular characteristics of Rapid Prototyping technologies, both in terms of constrains and opportunities, often require the reconfiguration of the product model to obtain the best compliance with the product functionalities and performances. Within this field of research, a knowledge-based tool named Design GuideLines Collaborative Framework (DGLs-CF) was developed to support both the designers defining the product consistently with the manufacturing technologies and the manufacturers defining the building setup consistently with the product requirements. Present work is focused on enhancing the DGLs-CF knowledge base and on updating the DGLs-CF knowledge management by using the information gathered on some RP technologies. The added-value of this research is represented by an improvement in the Redesign/Reconfiguration Package, the final result of the DGLs-CF adoption. This is a list of actions to be performed on the product model and on the process parameters to avoid the limitations of the technology and to exploit at best its opportunities.

Keywords: rapid prototyping, knowledge-based engineering, product redesign, collaborative engineering

1. Introduction

The increasing complexity of design tasks and continuous developments in technology require the improvement of designers' problem-solving capabilities, through the development of Design for X (DfX) methods and tools accordingly. Moreover, they must be flexible enough to allow an easy customization according to the evolution of the technologies that they address. Up to now, several examples of DfX appeared in the research landscape, as described in [1–11] The next research step was to investigate the possibility of merging several DfXs together in an integrated framework able to generate design guidelines related to more than one phase of the product lifecycle. In this context, the Design GuideLines Collaborative Framework (DGLs-CF) was developed as a knowledge-based tool to help designers defining the product consistently with manufacturing and verification technologies. The aim of the DGLs-CF is to evaluate the feasibility of the product (model) with available manufacturing technologies, to exploit the particular characteristics of them and to measure the conformity of the product to the requirements with specific verification technologies [12].

Purpose of this work is enhancing the DGLs-CF knowledge base and updating the DGLs-CF knowledge management by exploiting the information related to several Rapid Prototyping (RP) technologies. The goal is to generate richer and more effective guidelines information for the designers. RP technologies build physical models starting directly from their CAD representations, as this way costs and times are drastically reduced. They are a very powerful tool in product development. New products normally develop in Concurrent Engineering environments where many actors play different roles; in these scenarios it is of great help having a physical prototype of the product, something tangible, which may help communicating different skills and developing new ideas [2,13–20]. The specific characteristics of the RP technologies, however, are not so widely known in depth and thus it is worthwhile customizing the DGLs-CF for them. This may be a good way of helping non-expert designers in exploiting the opportunities of RP technologies.

The paper opens with a short description of the DGLs-CF and then goes on to describe the four RP technologies selected for this research. The core section of the paper concerns the data collection and their elaboration to get compatibility with the knowledge base format inside the DGLs-CF. Some considerations about the use of these new pieces of information relating with specific classes of products close the paper.

2. The DGLs-CF

The DGLs-CF is a decision support methodology aimed at effectively helping and leading the activities of designers, manufacturers and inspectors for product redesign and process reconfiguration. The initial consideration is that designers are not necessarily experts in manufacturing and verification processes; likewise, manufacturers and inspectors are not experts in design. A detailed description of the DGLs-CF appears in [12,21–23]The DGLs-CF structure is shortly described in the next paragraph using IDEF0 formalism [24]. IDEF0 is preferred to more sophisticated description methods (UML, for example) because its simplicity makes it a good tool for sharing information in a concurrent engineering environment, especially for non-expert users.

2.1. The DGLs-CF Roadmap

Shortly speaking, the DGLs-CF considers the set of available technologies and the product to be redesigned and suggests a list of actions – the Redesign/Reconfiguration Package – to get the best compatibility.

The easiest way to describe this methodology is by using the so-called DGLs-CF roadmap. It puts in the correct logical order all the activities required by the DGLs-CF adoption as well as the related algorithms and modules. Figure 1 shows the main level of the IDEF0 diagram.

In the first setup phase (A1), the DGLs-CF is customized considering the characteristics of the class of the available manufacturing and verification technologies as well as the features characterising the product under study. Technological characteristics and product features are then related to each other using rules, which relate the limitations (but sometimes also the opportunities) of the technologies to each product feature. Rules are coupled with expressions, which are needed to evaluate

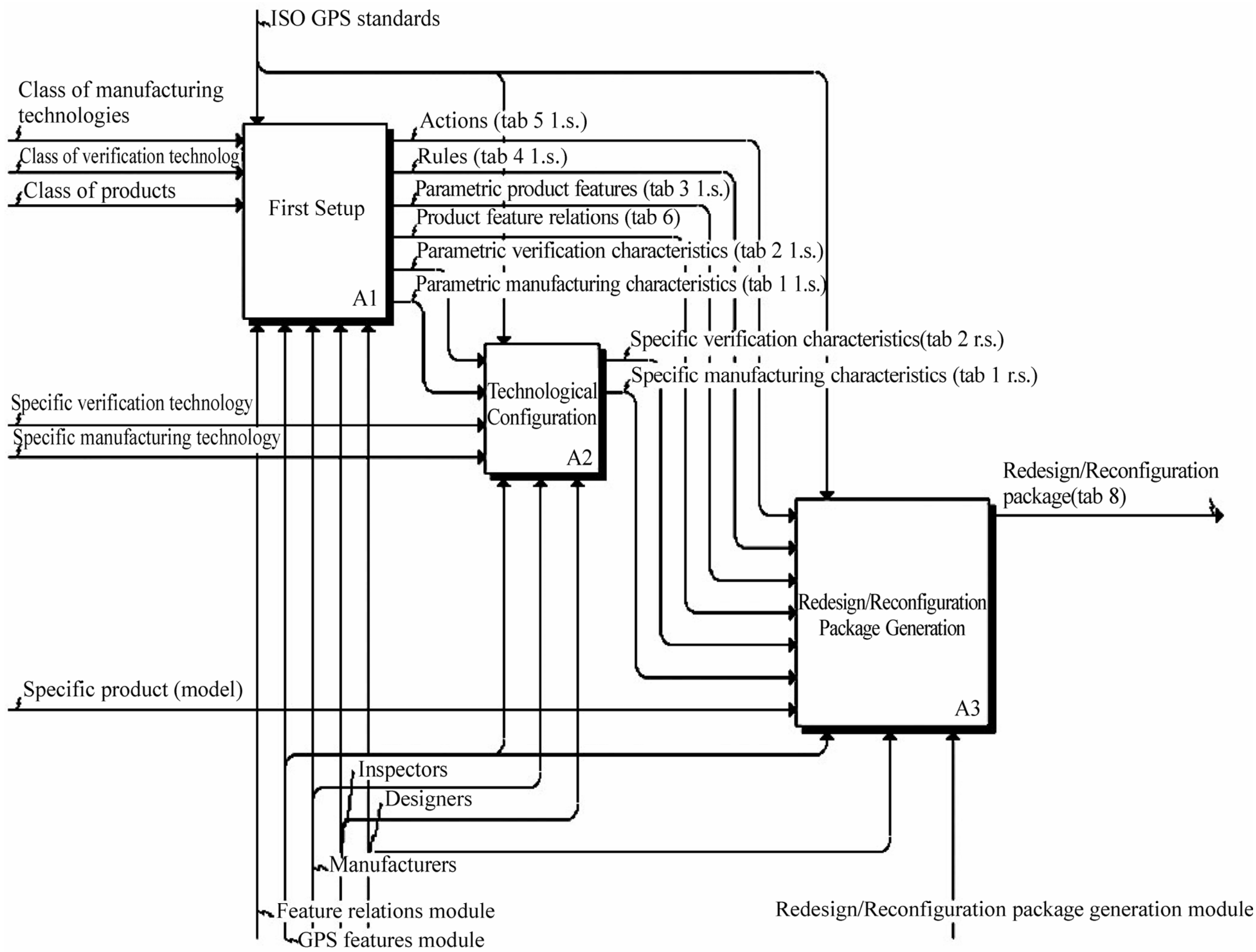

Figure 1. Main level of the IDEF0 diagram of the DGLs-CF roadmap

quantitatively the compatibility of the existing version of the product (model) with the available technologies. When the compatibility is not present, the rules suggest actions to be executed to overcome the limitations of the technologies and to exploit their opportunities. It must be noted that some actions may also affect different features when they are performed on a single feature to gain its compatibility. A "dynamic coefficient" is thus associated to the actions, with its value determined by the amount of features the action may affect. This value is decisive in defining the sequence of actions during the generation of the Redesign/Reconfiguration Package.

The Technological Configuration phase (A2) allows to set the parameter values of the manufacturing and verification characteristics, given the specific brands/models of the available equipments.

Finally, the Redesign/Reconfiguration Package Generation phase (A3) generates the list of actions (the Redesign/Reconfiguration Package) to be applied to the product (model) and to the technological process parameters by means of a recursive algorithm that evaluates time by time different product (model) configurations.

In this work the DGLs-CF knowledge base is enhanced with information related to some RP technologies; for this reason the main characteristics of the RP technologies considered here are described in the following.

3. RP Technologies

The RP technologies considered here are Fused Deposition Modelling (FDM), Stereolithography (SLA), Selective Laser Sintering (SLS), and Laminated Object Manufacturing (LOM). All of these systems build parts in multiple thin layers and their main characteristics, which are used in the DGLs-CF customisation, are summarised hereafter [25–27].

3.1. Fused Deposition Modelling (FDM)

This technology extrudes a molten thermoplastic filament (ABS, polyolefin, polyamide...) through a nozzle in the form of a thin ribbon and delivers it in computer-controlled locations appropriate for the object geometry, thus building the sections of the part. No high powered lasers are used. Typically, the delivery head moves in the horizontal plane while the support plane, where the part is built, moves vertically, so that each section is built over the previous one. The application temperature is such that the applied material bonds firmly with the previous layer. Some support material may be necessary to build the model, depending on the geometrical complexity of the part and on its orientation inside the workspace. The quantity and the shape of the support, which has to be removed from the final part, are calculated automatically. The first section is always built on a support plane, which section is slightly larger than the model to allow an easy removal of the part from the building platform. Precision and surface finishing of the parts are affected by the so-called"slicing" (the layering), which depends on the kind of equipment used, and can vary typically from 0.17 mm to 0.33 mm. The final parts do not need post-processing, except for support removal and some grinding for a better surface finishing.

3.2. Stereolithography (SLA)

A platform that can be lowered and elevated is usually located the thickness of a layer below the surface of a liquid photosensitive polymer contained in a tank. Each slice is etched onto the surface of the photosensitive polymer that solidifies when exposed to the laser beam. Once the laser has covered the whole surface of the layer, the platform lowers to a depth of another layer thickness, allowing the liquid resin to flow over the previously cured layer. A re-coating blade passes over the surface to ensure that a consistent layer thickness is present before the beginning of the next layer. Different building styles for the prototypes can be used with a SLA system. Normal style involves building full resin prototypes while other styles leaves some resin in the liquid state for different purposes (stresses minimization, generation of models for investment casting, etc.). Supports are required when islands (portion of a layer that is disconnected from any other portion of the same layer), overhangs, or cantilevered sections exist in the part being built. SLA parts have good surface texture and dimensional accuracy, however the orientation of the model in the workspace (due to the staircase effect) and the presence of support can influence the surface finishing. At the end of the building phase the model is carefully removed from the platform and a post-curing phase is performed, in a UV-beam oven, to completely solidify the part.

3.3. Selective Laser Sintering (SLS)

Here the object is built over a platform, where a layer of plastic, metal or ceramic powder (particle size approximately 50μm) is spread and kept heated. A laser beam melts the powder particles selectively. As the layer is finished, the platform moves down by the thickness of one layer (approximately 0.10–0.15 mm), and a new layer of powder is spread on the previous one. When the laser exposes the new layer, it melts and bonds to the previous one. The process repeats until the part is complete. Surrounding powder particles act as supporting material for the objects but in any case additional structures are needed during the building of overhangs. SLS parts have average surface texture and dimensional accuracy, the quality being mainly influenced by the powder particle size. On completion, the built volume has to cool down to room temperature after which the processed objects can be removed from the powder bed by brushing away excess powder. Sandblasting or other finishing manufacturing techniques are used to remove all un-sintered particles and to improve the final accuracy of the sintered objects. Of course in this case the support removal is not straightforward and requires special machining and tools.

3.4. Laminated Object Manufacturing (LOM)

In this technology, a sheet of thick paper (coming from a feed roll) with a polyethylene coating on the reverse side is placed on a platform. The coating is melted by a heated roller making the paper adhere to the building platform that, just like the technologies described before, can lower and lift along the Z axis. A laser then cuts the paper following the boundaries of the section of the object. The laser also creates hatch marks, which generate a collection of cubes in the final building volume of glued paper. These cubes behave as a support structure for the overhangs of the model. When the laser has finished the layer, a new paper sheet is applied. At the end of the job, the model is captured within a block of paper. When all of the surrounding cubes have been removed, the unfinished part is sanded down. In the case of cavities problems could be faced in the removal of the paper cubes.

The natural sensitivity of the paper to humidity and temperature can be reduced by coating the model. The surface finishing and the accuracy of the model are not to the same standard as the other methods, however objects have the look and feel of wood and thus can be worked and finished like wood.

4. DGLs-CF Knowledge Base Enhancement

4.1. Collection of Data

The aim of this work is the enhancement of the DGLs-CF knowledge base with pieces of information coming from the RP field. The attention is focused on the manufacturing characteristics, in order to determine the compatibility between the RP technologies and the products. Interviews with expert users and to equipment manufacturers, the previous experience of the authors, papers, user manuals and brochures, etc., have been the sources used for data collection. The goal of this task is to collect the characteristics of the four RP technologies described previously and to identify the related parameters that will be used afterwards by the DGLs-CF users to describe the available equipments [28–38].

4.2. Insertion of Data in the DGLs-CF

The DGLs-CF data structure is organized in tables. Those concerned with in this research have a left side where the characteristics of the class of technology and the related parameters are listed and a right side where the values of the parameters are set, given the specific available equipment. In this research, only the left side is considered, given that the goal is to characterize classes of RP technologies and not specific equipments. The information concerning the four RP technologies considered in this paper are inserted in the DGLs-CF data structure, the result is reported in Table 1 (FDM), Table 2 (SLA), Table 3 (SLS), and Table 4 (LOM).

Some characteristics are common to all the RP technologies considered, as they are intrinsic to the "nature" of the technologies themselves, these being the volume of the manufacturing workspace, the slicing (all the technologies build the models by layers) and the kind of material. Another important issue to consider in determining the compatibility between the RP technology and the product is the need for support for all of them, except for the LOM. SLA and SLS also allow the definition of the building style, as hatching and contouring style, and this characteristic also affects the product features.

5. Discussion

The outcomes of the activities described previously are presented here as an overview of the added-value of this result of this research inside the DGLs-CF. As seen before, in the DGLs-CF all the technological characteristics and the product features are expressed in terms of the related parameters. These features are described in the DGLs-CF data structure in another important table where again the left side contains the parameters allowing to describe a class of products, while the right side is filled by the parameter values of the specific product under study. The analysis of the RP parameters of Tables 1,2,3, and 4 suggests to identify some classes of products, which can be specifically considered here to highlight the enhancement in the DGLs-CF knowledge base. Table 5 shows the collected product features describing plastic front covers, Table 6 for headlights, Table 7 for moulds for headlights and Table 8 for dashboards. The right side of these tables is different from the technology-related ones as there is more than one column to highlight that the information processing in the DGLs-CF comes in an

Table 1. Parametric manufacturing characteristics for the FDM technology

Characteristic				
Label	*Name*	*Description*	*Parameters*	Parameter values of the specific available equipment
M1	Workspace	Volume of the manufacturing workspace	Workspace_x, Workspace_y, Workspace_z: dimensions of the manufacturing workspace	Workspace_x=… Workspace_y=… Workspace_z=…
M2	Material	Kind of material used	Material_ϕwire: diameter of the wire	Material_ϕwire=…
			Material_σ: mechanical properties of the material (minimum strength)	Material_σ=…
			Material_tx, Material_ty, Material_tz: dimensional tolerances related to the material	Material_tx=… Material_ty=… Material_tz=…
M3	Slicing	Material deposed slice by slice	Slicing_zmin: minimum thickness of the slice	Slicing_zmin=…
			Slicing_σx, Slicing _σy, Slicing _σz: mechanical properties (minimum strength in the three dimensions)	Slicing_σx=… Slicing _σy=… Slicing _σz=…
			Slicing_Ra_z: minimum obtainable roughness in z direction	Slicing_Ra_z=…
M4	Support	Support needed when building overhangs/ sloped surfaces or cavities	Support_x, Support_y, Support_z: support dimensions	Support_x=… Support_y=… Support_z=…
			Support_α: critical angle for supports removal (angle between the vertical wall and the overhang)	Support_α=…
			Support_Ra_xy: minimum obtainable roughness in xy plane	Support_Ra_xy=…

Table 2. Parametric manufacturing characteristics for the SLA technology

Characteristic				
Label	*Name*	*Description*	*Parameters*	Parameter values of the specific available equipment
M1	Workspace	Volume of the manufacturing workspace	Workspace_x, Workspace_y, Workspace_z: dimensions of the manufacturing workspace	Workspace_x=… Workspace_y=… Workspace_z=…
M2	Material	Kind of material used	Material_σ: mechanical properties of the material (minimum strength)	Material_σ=…
			Material_Ra_xy: minimum obtainable roughness in xy plane related to the material	Material_Ra_xy=…
			Material_tx, Material_ty, Material_tz: dimensional tolerances related to the material	Material_tx=… Material_ty=… Material_tz=…
M3	Slicing	Material deposed slice by slice	Slicing_zmin: minimum thickness of the slice related to slicing	Slicing_zmin=…
			Slicing_σx, Slicing_σy, Slicing_σz: mechanical properties (minimum strength in the three dimensions) related to slicing	Slicing_σx=… Slicing_σy=… Slicing_σz=…
			Slicing_Ra_z: minimum obtainable roughness in z direction related to slicing	Slicing_Ra_z=…
M4	Support	Support needed when building overhangs/sloped surfaces or cavities	Support_x, Support_y, Support_z: support dimensions	Support_x=… Support_y=… Support_z=…
			Support_α: critical angle for supports removal (angle between the vertical wall and the overhang)	Support_α=…
			Support_Ra_xy: minimum obtainable roughness in xy plane	Support_Ra_xy=…
M5	Building style	Different building styles	Building_style_σx, Building_style_σy, Building_style_σz: mechanical properties (minimum strength in the three dimensions) related to hatching and contouring style	Building_style_σx=… Building_style_σy=… Building_style_σz=…
			Building_style_Ra_xy: minimum obtainable roughness in xy plane related to hatching and contouring style	Building_style_Ra_xy=…
			Building_style_Ra_z: minimum obtainable roughness in z direction related to hatching and contouring style	Building_style_Ra_z=…

Table 3. Parametric manufacturing characteristics for the SLS technology

Characteristic				Parameter values of the specific available equipment
Label	*Name*	*Description*	*Parameters*	
M1	Workspace	Volume of the manufacturing workspace	Workspace_x, Workspace_y, Workspace_z: dimensions of the manufacturing workspace	Workspace_x=… Workspace_y=… Workspace_z=…
M2	Material	Kind of material used	Material_zmin: minimum thickness of the slice related to the particle size	Material_zmin=…
			Material_σ: mechanical properties of the material (minimum strength)	Material_σ=…
			Material_Ra_xy: minimum obtainable roughness in xy plane related to the particle size	Material_Ra_xy=…
M3	Slicing	Material deposed slice by slice	Slicing_zmin: minimum thickness of the slice related to slicing	Slicing_zmin=…
			Slicing_σx, Slicing_σy, Slicing_σz: mechanical properties (minimum strength in the three dimensions) related to slicing	Slicing_σx=… Slicing_σy=… Slicing_σz=…
			Slicing_Ra_z: minimum obtainable roughness in z direction related to slicing	Slicing_Ra_z=…
M4	Support	Support needed when building overhangs/sloped surfaces or cavities	Support_x, Support_y, Support_z: support dimensions	Support_x=… Support_y=… Support_z=…
			Support_α: critical angle for supports removal (angle between the vertical wall and the overhang)	Support_α=…
			Support_Ra_xy: minimum obtainable roughness in xy plane	Support_Ra_xy=…
M5	Building style	Different building styles	Building_style_σx, Building_style_σy, Building_style_σz: mechanical properties (minimum strength in the three dimensions) related related to hatching and contouring style	Building_style_σx=… Building_style_σy=… Building_style_σz=…
			Building_style_Ra_xy: minimum obtainable roughness in xy plane related to related to hatching and contouring style	Build-ing_style_Ra_xy=…
			Building_style_Ra_z: minimum obtainable roughness in z direction related to related to hatching and contouring style	Build-ing_style_Ra_z=…

Table 4. Parametric manufacturing characteristics for the LOM technology

Characteristic				Parameter values of the specific available equipment
Label	*Name*	*Description*	*Parameters*	
M1	Workspace	Volume of the manufacturing workspace	Workspace_x, Workspace_y, Workspace_z: dimensions of the manufacturing workspace	Workspace_x=… Workspace_y=… Workspace_z=…
M2	Material	Kind of material used	Material_zmin: minimum thickness of the slice related to the paper thickness	Material_zmin=…
			Material_σ mechanical properties of the material (minimum strength in the three dimensions)	Material_σ=…
			Material_Ra_xy: minimum obtainable roughness in xy plane related to the material	Material_Ra_xy=…
			Material_tx, Material_ty, Material_tz: dimensional tolerances related to the material	Material_tx=… Material_ty=… Material_tz=…
M3	Slicing	Material deposed slice by slice	Slicing_σx, Slicing_σy, Slicing_σz: mechanical properties (minimum strength in the three dimensions) related to slicing	Slicing_σx=… Slicing_σy=… Slicing_σz=…
			Slicing_Ra_z: minimum obtainable roughness in z direction related to slicing	Slicing_Ra_z=…

Table 5. Parametric product features for plastic front covers

Product feature				Labels	Parameter values of the product (model) (iterations)	
Label	*Name*	*Description*	*Parameters*		*I*	*II*
F1	Bounding box	Overall dimensions of the product	Bounding_box_X, Bounding_box_Y, Bounding_box_Z: maximum dimensions	Bounding_box_X	=…	=…
				Bounding_box_Y	=…	=…
				Bounding_box_Z	=…	=…
F2	Minimum dimensions	Minimum dimensions in the product	Minimum_dimensions_x, Minimum_dimensions_y: minimum dimensions in horizontal plane	Minimum_dimensions_x	=…	=…
				Minimum_dimensions_y	=…	=…
			Minimum_dimensions_z: minimum thickness	Minimum_dimensions_z	=…	=…
F3	Overhangs/ Sloped surfaces	Overhangs and protrusions	Overhangs/Sloped_surfaces_α: overhangs/sloped surfaces angle (angle between the vertical wall and the overhang)	Overhangs/Sloped_surfaces_α	=…	=…
F4	Cavities	Through and blind holes, undercuts and other cavities	Cavities_x, Cavities_y: minimum dimensions	Cavities_x	=…	=…
				Cavities_y	=…	=…
			Cavities_d: maximum depth	Cavities_d	=…	=…
			Cavities_β: angle between the vertical wall and the axis of the cavity	Cavities_β	=…	=…
F5	Surface finishing	Surface texture	Surface_finishing_Ra_xy_max: maximum allowable roughness in the horizontal plane	Surface_finishing_Ra_xy_max	=…	=…
			Surface_finishing_Ra_z_max: maximum allowable roughness in the vertical plane	Surface_finishing_Ra_z_max	=…	=…
F6	Mechanical properties	Main mechanical properties	Mechanical_properties_σx, Mechanical_properties_σy, Mechanical_properties_σz: minimum mechanical strength in the three directions	Mechanical_properties_σx	=…	=…
				Mechanical_properties_σy	=…	=…
				Mechanical_properties_σz	=…	=…
F7	Cylindrical shapes	Minimum curvature radius of cylindrical shapes	Cylindrical_shapes_rmin: minimum curvature radius	Cylindrical_shapes_rmin: minimum curvature radius	=…	=…
F8	Shrinkage	Shrinkage effect of the material	Shrinkage_tx, Shrinkage_ty, Shrinkage_tz: Dimensional tolerances	Shrinkage_tx	=…	=…
				Shrinkage_ty	=…	=…
				Shrinkage_tz	=…	=…

iterative way. The product (model) is analyzed for compatibility with the available technologies, some actions are performed and the resulting product (model) is processed from the beginning (new iteration).

Finally, Table 9, Table 10, Table 11, and Table 12 show the relations between the technological characteristics and the product features, expressed in a qualitative way, for each meaningful couple technology/product.

This result is important because, as stated in the section of the DGLs-CF overview, the following step of the DGLs-CF roadmap consists in generating the rules that will be the source of the actions to be performed on the product (model) to get the best compatibility. The values "Strong" and "Weak" drive the rule and action definition

Table 6. Parametric product features for headlights

Product feature				Labels	Parameter values of the product (model) (iterations)	
Label	*Name*	*Description*	*Parameters*		*I*	*II*
F1	Bounding box	Overall dimensions of the product	Bounding_box_X, Bounding_box_Y, Bounding_box_Z: maximum dimensions	Bounding_box_X	=…	=…
				Bounding_box_Y	=…	=…
				Bounding_box_Z	=…	=…
F2	Minimum dimensions	Minimum dimensions in the product	Minimum_dimensions_x, Minimum_dimensions_y: minimum dimensions in horizontal plane	Minimum_dimensions_x	=…	=…
				Minimum_dimensions_y	=…	=…
			Minimum_dimensions_z: minimum thickness	Minimum_dimensions_z	=…	=…
F3	Overhangs/ Sloped surfaces	Overhangs and protrusions	Overhangs/Sloped_surfaces_α: overhangs/sloped surfaces angle (angle between the vertical wall and the overhang)	Overhangs/ Sloped_surfaces_α	=…	=…
F4	Cavities	Through and blind holes, undercuts and other cavities	Cavities_x, Cavities_y: minimum dimensions	Cavities_x	=…	=…
				Cavities_y	=…	=…
			Cavities_d: maximum depth	Cavities_d	=…	=…
			Cavities_β: angle between the vertical wall and the axis of the cavity	Cavities_β	=…	=…
F5	Surface finishing	Surface texture	Surface_finishing_Ra_xy_max: maximum allowable roughness in the horizontal plane	Surface_finishing_ Ra_xy_max	=…	=…
			Surface_finishing_Ra_z_max: maximum allowable roughness in the vertical plane	Surface_finishing_ Ra_z_max	=…	=…
F6	Mechanical properties	Main mechanical properties	Mechanical_properties_σx, Mechanical_properties_σy, Mechanical_properties_σz: minimum mechanical strength in the three directions	Mechanical_properties_σx	=…	=…
				Mechanical_properties_σy	=…	=…
				Mechanical_properties_σz	=…	=…
F7	Cylindrical shapes	Minimum curvature radius of cylindrical shapes	Cylindrical_shapes_rmin: minimum curvature radius	Cylindrical_shapes_rmin: minimum curvature radius	=…	=…
F8	Shrinkage	Shrinkage effect of the material	Shrinkage_tx, Shrinkage_ty, Shrinkage_tz: Dimensional tolerances	Shrinkage_tx	=…	=…
				Shrinkage_ty	=…	=…
				Shrinkage_tz	=…	=…
F9	Influence of environment	Environment influence on materials (humidity, temperature, …)	Influence_of_environment_σx, Influence_of_environment_σy, Influence_of_environment_σz: minimum mechanical strength in the three directions	Influence_of_environment_σx	=…	=…
				Influence_of_environment_σy	=…	=…
				Influence_of_environment_σz	=…	=…
			Influence_of_environment_Δx, Influence_of_environment_Δy, Influence_of_environment_Δz: maximum deflection in the three directions	Influence_of_environment_Δx	=…	=…
				Influence_of_environment_Δy	=…	=…
				Influence_of_environment_Δz	=…	=…
			Influence_of_environment_K_{Ic}: fracture toughness index	Influence_of_environment_K_{Ic}	=…	=…
F10	Free-form surfaces	Complex shape surfaces	Free-form_surfaces_c: curvature	Free-form_surfaces_c	=…	=…
F11	Ribs/webs	Supports or net of supports	Ribs/webs_zmin:_minimum rib thickness	Ribs/webs_zmin	=…	=…
			Ribs/webs_γ: angle between the vertical wall and the rib inclination	Ribs/webs_γ	=…	=…
F12	Pins	Small structures with circular or prismatic section	Pins_ϕ_eqmin: minimum equivalent diameter of a section	Pins_ϕ_eqmin	=…	=…
			Pins_h/ϕ_eq: height/ equivalent diameter of a section ratio	Pins_h/ϕ_eq	=…	=…

Table 7. Parametric product features for moulds for headlights

Product feature				Labels	Parameter values of the product (model) (iterations)	
Label	Name	Description	Parameters		I	II
F1	Bounding box	Overall dimensions of the product	Bounding_box_X, Bounding_box_Y, Bounding_box_Z: maximum dimensions	Bounding_box_X Bounding_box_Y Bounding_box_Z	=… =… =…	=… =… =…
F2	Minimum dimensions	Minimum dimensions in the product	Minimum_dimensions_x, Minimum_dimensions_y: minimum dimensions in horizontal plane Minimum_dimensions_z: minimum thickness	Minimum_dimensions_x Minimum_dimensions_y: Minimum_dimensions_z	=… =… =…	=… =… =…
F3	Overhangs/ Sloped surfaces	Overhangs and protrusions	Overhangs/Sloped_surfaces_α: overhangs/sloped surfaces angle (angle between the vertical wall and the overhang)	Overhangs/Sloped_surfaces_α	=…	=…
F4	Cavities	Through and blind holes, undercuts and other cavities	Cavities_x, Cavities_y: minimum dimensions Cavities_d: maximum depth Cavities_β: angle between the vertical wall and the axis of the cavity	Cavities_x Cavities_y Cavities_d Cavities_β	=… =… =… =…	=… =… =… =…
F5	Surface finishing	Surface texture	Surface_finishing_Ra_xymax: maximum allowable roughness in the horizontal plane Surface_finishing_Ra_zmax: maximum allowable roughness in the vertical plane	Surface_finishing_Ra_xymax Surface_finishing _Ra_zmax	=… =…	=… =…
F6	Mechanical properties	Main mechanical properties	Mechanical_properties_σx, Mechanical_properties_σy, Mechanical_properties_σz: minimum mechanical strength in the three directions	Mechanical_properties_σx Mechanical_properties_σy Mechanical_properties_σz	=… =… =…	=… =… =…
F7	Cylindrical shapes	Minimum curvature radius of cylindrical shapes	Cylindrical_shapes_rmin: minimum curvature radius	Cylindrical_shapes_rmin	=…	=…
F8	Shrinkage	Shrinkage effect of the material	Shrinkage_tx, Shrinkage_ty, Shrinkage_tz: Dimensional tolerances	Shrinkage_tx Shrinkage_ty Shrinkage_tz	=… =… =…	=… =… =…
F9	Influence of environment	Environment influence on materials (humidity, temperature, …)	Influence_of_environment_σx, Influence_of_environment_σy, Influence_of_environment_σz: minimum mechanical strength in the three directions Influence_of_environment_Δx, Influence_of_environment_Δy, Influence_of_environment_Δz: maximum deflection in the three directions Influence_of_environment_KIc: fracture toughness index	Influence_of_environment_σx Influence_of_environment_σy Influence_of_environment_σz Influence_of_environment_Δx Influence_of_environment_Δy Influence_of_environment_Δz Influence_of_environment_KIc	=… =… =… =… =… =… =…	=… =… =… =… =… =… =…
F10	Free-form surfaces	Complex shape surfaces	Free-form_surfaces_c: curvature	Free-form_surfaces_c	=…	=…
F11	Pins	Small structures with circular or prismatic section	Pins _ϕ_eqmin: minimum equivalent diameter of a section Pins_h/ϕ_eq: height/ equivalent diameter of a section ratio	Pins _ϕ_eqmin Pins_h/ϕ_eq	=… =…	=… =…

Table 8. Parametric product features for dashboards

Product feature				Labels	Parameter values of the product (model) (iterations) I	II
Label	*Name*	*Description*	*Parameters*			
F1	Bounding box	Overall dimensions of the product	Bounding_box_X, Bounding_box_Y, Bounding_box_Z: maximum dimensions	Bounding_box_X Bounding_box_Y Bounding_box_Z	=… =… =…	=… =… =…
F2	Minimum dimensions	Minimum dimensions in the product	Minimum_dimensions_x, Minimum_dimensions_y: minimum dimensions in horizontal plane Minimum_dimensions_z: minimum thickness	Minimum_dimensions_x Minimum_dimensions_y: Minimum_dimensions_z	=… =… =…	=… =… =…
F3	Overhangs/ Sloped surfaces	Overhangs and protrusions	Overhangs/Sloped_surfaces_α: overhangs/sloped surfaces angle (angle between the vertical wall and the overhang)	Overhangs/Sloped_surfaces_α	=…	=…
F4	Cavities	Through and blind holes, undercuts and other cavities	Cavities_x, Cavities_y: minimum dimensions Cavities_d: maximum depth Cavities_β: angle between the vertical wall and the axis of the cavity	Cavities_x Cavities_y Cavities_d Cavities_β	=… =… =… =…	=… =… =… =…
F5	Surface finishing	Surface texture	Surface_finishing_Ra_xymax: maximum allowable roughness in the horizontal plane Surface_finishing_Ra_zmax: maximum allowable roughness in the vertical plane	Surface_finishing_Ra_xymax Surface_finishing_Ra_zmax	=… =…	=… =…
F6	Mechanical properties	Main mechanical properties	Mechanical_properties_σx, Mechanical_properties_σy, Mechanical_properties_σz: minimum mechanical strength in the three directions	Mechanical_properties_σx Mechanical_properties_σy Mechanical_properties_σz	=… =… =…	=… =… =…
F7	Cylindrical shapes	Minimum curvature radius of cylindrical shapes	Cylindrical_shapes_rmin: minimum curvature radius	Cylindrical_shapes_rmin	=…	=…
F8	Pins	Small structures with circular or prismatic section	Pins _ϕ_eqmin: minimum equivalent diameter of a section Pins_h/ϕ_eq: height/ equivalent diameter of a section ratio	Pins _ϕ_eqmin Pins_h/ϕ_eq	=… =…	=… =…
F9	Influence of environment	Environment influence on materials (humidity, temperature, …)	Influence_of_environment_σx, Influence_of_environment_σy, Influence_of_environment_σz: minimum mechanical strength in the three directions Influence_of_environment_Δx, Influence_of_environment_Δy, Influence_of_environment_Δz: maximum deflection in the three directions Influence_of_environment_K_{Ic}: fracture toughness index	Influence_of_environment_σx Influence_of_environment_σy Influence_of_environment_σz Influence_of_environment_Δx Influence_of_environment_Δy Influence_of_environment_Δz Influence_of_environment_K_{Ic}	=… =… =… =… =… =… =…	=… =… =… =… =… =… =…
F10	Free-form surfaces	Complex shape surfaces	Free-form_surfaces_c: curvature	Free-form_surfaces_c	=…	=…

Table 9. Relations between FDM manufacturing characteristics and the product features for plastic front covers

		F1	F2	F3	F4	F5	F6	F7	F8
		Bounding box	Minimum dimensions	Overhangs/ Sloped surfaces	Cavities	Surface finishing	Mechanical properties	Cylindrical shapes	Shrinkage
M1	Workspace	Strong							
M2	Material		Weak		Weak	Weak	Strong		Strong
M3	Slicing		Strong		Strong	Strong	Strong	Strong	Strong
M4	Support		Strong	Strong	Strong	Weak	Weak	Weak	

Table 10. Relations between SLA manufacturing characteristics and the product features for headlights

		F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12
		Bounding box	Minimum dimensions	Overhangs/ Sloped surfaces	Cavities	Surface finishing	Mechanical properties	Cylindrical shapes	Shrinkage	Influence of environment	Free-form surfaces	Ribs/ webs	Pins
M1	Workspace	Strong											
M2	Material					Strong	Strong		Weak	Strong			
M3	Slicing		Strong		Weak	Strong	Strong	Strong		Weak	Strong	Strong	Strong
M4	Support		Strong	Strong	Strong	Strong		Weak			Strong	Strong	Strong
M5	Building style		Weak		Weak	Weak	Weak	Weak	Weak	Strong	Weak		

Table 11. Relations between SLS manufacturing characteristics and the product features for moulds for headlights

		F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11
		Bounding box	Minimum dimensions	Overhangs/ Sloped surfaces	Cavities	Surface finishing	Mechanical properties	Cylindrical shapes	Shrinkage	Influence of environment	Free-form surfaces	Ribs/webs
M1	Workspace	Strong										
M2	Material					Strong	Strong	Strong		Strong		
M3	Slicing		Strong		Weak	Strong	Strong	Weak	Strong	Weak	Strong	Strong
M4	Support		Strong	Strong	Strong	Strong			Weak		Strong	Strong
M5	Building style		Weak		Weak	Strong	Weak	Strong	Weak	Strong	Weak	

Table 12. Relations between LOM manufacturing characteristics and the product features for dashboards

		F1	F2	F3	F4	F5	F6	F7	F8	F9	F10
		Bounding box	Minimum dimensions	Overhangs/ Sloped surfaces	Cavities	Surface finishing	Mechanical properties	Cylindrical shapes	Pins	Influence of environment	Free-form surfaces
M1	Workspace	Strong									
M2	Material		Strong	Weak	Strong	Strong	Strong			Strong	
M3	Slicing		Weak	Weak	Strong	Weak	Strong	Strong	Strong	Weak	Strong

Table 13. Reconfiguration package for a headlight to be produced by SLA

	Domain	Actions			Relationships		
		Name	Goals	Cost	Features	Technological characteristics	Weight
Reconfiguration Package	Design	Over-dimension on thin parts	to make them compatible with the need for supports, the slicing and the material	8	Minimum dimensions	Slicing	Strong
						Support	Strong
						Building style	Weak
	Manufacturing	Orient the model	to avoid the need for support on surfaces requiring best roughness	5	Surface finishing	Material	Strong
						Slicing	Strong
						Support	Strong
						Building style	Weak
	Verification	Rotate and incline the measuring head	to obtain best accessibility to the overhangs and the minimum re-positioning	2	Overhangs/Sloped surfaces	Support	Strong

by weighting the importance of the pieces of information inside the DGLs-CF data structure, thus leading to a more effective Redesign/Reconfiguration Package generation.

Table 13 shows an example of Redesign/Reconfiguration Package generated using the DGLs-CF during the redesign of a headlight to be built with SLA. The strong-weak classification - degree of correlation - of the relationships between technological characteristics and product features has been exploited by the DGLs-CF algorithm used to generate this package. Moreover, the classification has been explicitly added to the package as a further help for the DGLs-CF users.

6. Conclusions

This paper describes the knowledge base enhancement and the knowledge management update of a method for product redesign and process reconfiguration named Design Guidelines – Collaborative Framework (DGLs-CF). Information collected using different strategies and from different sources (interviews, previous experiences, documentation, etc,) is formatted according to the data structure of this framework. These additional pieces of information enrich the knowledge base content of the method and make it tailored on the specific technologies. The specific characteristics of the RP technologies are in fact related to the product features and their relationships are weighted, thus allowing to privilege the actions determined by strong relationships in achieving the final result of the framework. Moreover, the analysis of these pieces of information suggested some interesting improvements of the knowledge management inside the DGLs-CF. An example of application of the DGLs-CF is shown: the Redesign/ Reconfiguration Package - a list of actions to be performed on the product (model) and/or on the process to get the best compatibility between the product and the manufacturing technology - related to a headlight to be produced by SLA.

In the future the same activities will be used for gathering data related to other technologies. In the meantime, this work suggests to evaluate all the parameters in the four tables of the technologies with respect to those in the four tables of the product features. In doing this, the affinity between some classes of technologies and some classes of products coming from experience could be confirmed or not.

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