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HOW RAPID PROTOTYPING PROCESS PARAMETERS COULD AFFECT THE PRODUCT DESIGN PHASE: A KBS APPROACH

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ABSTRACT

Considering the whole product life-cycle, product model is usually defined during the design phase, given a set of requirements and constraints belonging to the same domain. The use of different manufacturing and verification technologies may, however, profoundly affect the characteristics of the product, so that a re-design phase is often necessary. In previous work, a Knowledge Based System named Design GuideLines (DGLs) was developed, aiming to help the designers make the product model compatible with the requirements and constraints of the specific manufacturing and verification domains.

During the DGLs development, the possibility emerged to exploit them in order to identify possible relations among product features. This aspect seems very important, further helping the designer to better understand the consequences of the modifications suggested by the DGLs and applied to the product model during the re-design phase.

The present work aims to identify these relations among product features. The result of DGLs exploitation has been critically analyzed to highlight the link between manufacturing characteristics and product features, and, further, among features themselves. Unpredictable relations among the product features, given a particular Rapid Prototyping technology as manufacturing technology, have been discovered and exploited.

Keywords
Knowledge Based Systems, Process Parameters, Product Features, Rapid Prototyping, Fluid Deposition Modeling

1. INTRODUCTION

The development of new products and the optimization of existing ones deal, by necessity, with the definition of specifications, which must match product functionalities and performances [1 - 5]. On the other hand, the characteristics of products are profoundly affected by the different technologies determining the product life-cycle, so that great emphasis is placed on concurrent engineering, particularly aiming to bridge the gap between design and manufacturing. When a product is designed, all feasible manufacturing processes must be compared, in terms of production costs, time cycle, product quality and so on [6 - 10]. Much information, not exclusive to the designer, has thus to be considered starting from the design or re-design phase.

The approaches may be different: some authors focus their attention on tools helping in an early detection of design inadequacy [11], also addressing the problem of obtaining a sufficiently reliable evaluation of costs without the need for detailed design information [12]; others consider the need for re-design and optimization of existing components, through the evolutionary refinement of the design parameters [13]. In any case, in the design optimization, a central role is played by systems, which allow effective management of the several pieces of information, generally known as Knowledge Based Systems (KBS). Knowledge management is often assigned to the design phase with a direct link to specific manufacturing technologies, due to their particular characteristics.

Present work goes ahead on this scenario, concerning a KBS developed to help the designers in dealing with particular manufacturing and verification technologies. This work aims, in fact, to evaluate how the modifications applied in the re-design phase (to improve the product compatibility with particular manufacturing and/or verification technologies) may affect the characteristics of the final product. Particularly, the topic addressed here is the highlighting of possible links among different product features, given a particular class of manufacturing technologies. In fact, it is important to know how the modifications affecting a feature may affect or alter other features not directly related to it (for instance, the modification of the overall dimensions of an object, by way of a simple scaling action, could alter the manufacturability of thin walls, given the class of Rapid Prototyping technologies called Fluid Deposition Modeling). The goal is to provide the designers with more help, drawing their attention to the consequences of a local modification in a very simple and usable way. This goal is pursued by exploiting the Design GuideLines (DGLs), a Knowledge Based System developed by our research group in the last years. DGLs, allowing both the knowledge formalization and the organization of the relationships between product features and technological characteristics, become the perfect tool to discover the existing relations, more or less predictably, among the product features. With no doubt, this further information is very valuable in enriching the designers' knowledge about the whole product life-cycle.

This paper begins with a short description of the DGLs and the Fluid Deposition Modeling (FDM), as this is the manufacturing technology used to carry out the research and to test and validate the results of the proposed approach. Next, the whole procedure for the highlighting of the relation among product features is described in detail. A few considerations on quality and applicability of the results conclude the paper.

2. THE DESIGN GUIDELINES (DGLs)

The most obvious aspect in the relationship between design, manufacturing, and verification activities is the need/possibility to modify the 3D digital model in order to avoid critical situations in the manufacturing and verification processes and to optimize manufacturing in terms of times and quality of results. These operations will be collectively referred to under the term re-design. The development of the Design Guidelines (DGLs), which the Knowledge Based System used as a key-point for this research, started with two premises: 1) it is not "safe" to let the manufacturing operator carry out re-design operations (this is what happens today) because he may affect the model functionalities [14]; 2) design rules in existing literature [15], which now serve as the only guide in modifying the 3D digital model, show limitations that severely reduce their effectiveness and functionality during the design phase.

The DGLs are a KBS containing a set of design rules that completes the existing set and increases the likelihood of their use as an effective guide for the modification of a 3D digital model directly by the designers during the design phase. Modifications must guarantee not only that the model can be built with a particular manufacturing technology, but also that the building process is advantageous when compared to other technologies. The latter implies that times and post-processing work must be minimized and that the capabilities of the particular technology must be exploited. Moreover, the DGLs can take into consideration the characteristics of the verification methods and tools, helping the designer during the modification of the product model accordingly [16 - 18].

The knowledge structure inside the DGLs is complex and precise. It comes from a thorough investigation of knowledge generation, the cause-effect paradigm, the relationships between the various domains and the different pieces of information involved. A multi-level structure has been derived-the DGLs building-with five floors: Compatibility floor (used to evaluate the compatibility of the product with manufacturing and verification technologies), Rules floor (containing all the Rules determined by connecting the technological characteristics of manufacturing and verification with the features used to characterize the product), Design domain floor (containing all the Actions related to the design stage of the product), Manufacturing domain floor (same as the previous one but related to the manufacturing domain), and Verification domain floor (same as before, but related to the verification domain) (Fig. 1). Generally speaking, the use of the DGLs occurs as follows: once the product features and the characteristics of the manufacturing and verification technologies are defined, some Expressions are used to quantify the compatibility between the product and the technologies (i.e., the dark cell of the Compatibility Floor in figure 1 could contain the information "The compatibility between product overall dimensions and manufacturing technology workspace is equal to 0.7" - in a normalized range [0..1]). Then, for each cell containing compatibility values less than 1, one ore more Rules are activated in the Rules Floor. Each Rule leads to the activation of Actions (things that must be done when the compatibility value is 0 – in other words when the product, as it is, can not be produced or measured) or Hints (suggestions to increase the compatibility) to be performed in the different domains (Design, Manufacturing, Verification), placed in the corresponding Floors. Finally, DGLs collect Actions and Hints to generate one or more Reconfiguration Packages - a sort of to-do-list - with costs associated to them. At this point, the end user of the DGLs could select the package that best fits his skills and capabilities.

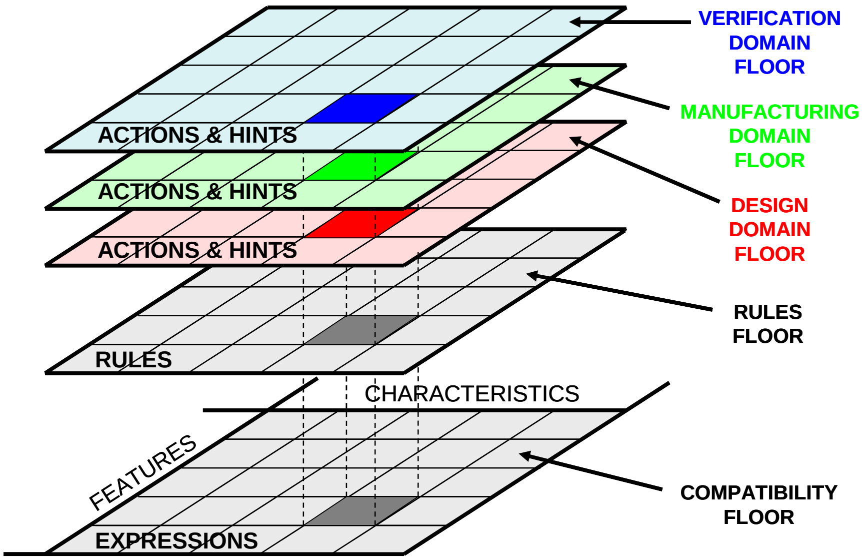

Figure 1: The five-floor DGLs building

Up to now, nothing has been said of knowledge generation; nevertheless, the issues related to the information transfer among the actors involved in the whole process have not been addressed yet. As it will be made clear in the following, these topics are heavily dependant upon the timing of the DGLs usage during product development. Three separate phases may be distinguished in adopting the DGLs: a Setup Phase, where the DGLs are assigned to a particular class of products and manufacturing and verification technologies, but not to specific configurations, brands, models, etc.; a Configuration Phase, where the DGLs are customized using the data of the specific technologies; and a Usage Phase, the only one dependant on the specific product analyzed. Given the precise structure of the DGLs and the presence of many components with very different meanings and operations, a roadmap was developed to organize all the steps in sequence. What follows is the roadmap structure. For each step, an example is given, together with the actor(s) involved.

DGLs setup phase

1. ***Identification of the technological characteristics***. (Characteristic: Workspace size; Parameters: WSx, WSy, WSz. Actors: Manufacturing and Verification experts).
2. ***Identification of the product features.*** (Feature: Max dimensions; Parameters: Xmax, Ymax, Zmax. Actors: Design experts).
3. ***Generation of Rules***. (Rule: "Product max dimensions must be confined in the workspace extent". Actors: Manufacturing and Verification experts).
4. ***Generation of Expressions to evaluate compatibility***: (Expression: "if Xmax<WSx AND Ymax<WSy AND Zmax<WSz then compatibility = 1 else compatibility = 0". Actors: Design, Manufacturing, and Verification experts).
5. ***Generation of Actions and Hints and related costs***. (Action: "Split the model", cost=8; Hint: "Change the orientation of the product in the verification workspace to get a better accessibility during the measurement", cost=2. Actors: Manufacturing and Verification experts).

DGLs configuration phase

6. ***Quantification of the technological parameters***. (Values: WSx=250 mm, WSy=250 mm, WSz=200 mm. Actors: Manufacturing and Verification experts).

DGLs usage phase

7. ***Product characterization***. (Values: X=160 mm, Y=260 mm, Z=120 mm. Actors: Design experts).
8. ***Calculation of the compatibility values and knowledge activation***. (Actors: none - this step is performed automatically, based upon the Expressions set up during the step 4).
9. ***Generation of the re-configuration packages***. (Actors: none - this step is performed automatically).
10. ***User choice of a re-configuration package and implementation***. Actors: Design experts.

The distribution of the actors in the roadmap highlights and confirms the fact that knowledge is transferred from the Manufacturing and Verification Domains to the Design Domain. In fact, while manufacturing and verification experts are the protagonists during the setup and configuration phases, designers are the only actors present in the usage one.

To date, all experiences with the DGLs have given encouraging results. For example, DGLs have been used in re-designing a coffee machine for its generation with the Rapid Prototyping technology named Direct Metal Laser Sintering (DMLS) [19] and to optimize the product model of a mechanical spacer to be produced with the Rapid Prototyping technology named Fused Deposition Modeling (FDM) and verified with a Coordinate Measuring Machine (CMM) [20]. A comparative study on how DGLs are used by their developers, as well as by designers and manufacturers with and without personal knowledge about the particular technologies, is currently underway. The ultimate goal is to test both the effectiveness of the knowledge content of the DGLs and their usability.

3. FDM TECHNOLOGY

Fused Deposition Modeling (FDM) systems build parts in multiple thin layers, as is the case with all current Rapid Prototyping and Manufacturing (RP&M) methods. In FDM, spools of thermoplastic filament are used as the basic material for the part fabrication: the material is heated to just above its melting point in a delivery head. The molten thermoplastic is then extruded through a nozzle in the form of a thin ribbon and applied in computer-controlled locations appropriate for the object geometry, thus building the sections of the part. 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 automatically calculated considering the orientation of the part. The first section is, in any case, built on a support plane, the section of which is slightly larger than that of the model, to allow easy removal of the part from the building platform [21, 22].

Precision and surface finishing of the parts are affected by the so-called ”slicing” (the layering), which depends on the kind of machine used, and can vary typically from 0.17 mm to 0.33 mm. A wide array of thermoplastic materials can be used to build models, i.e. ABS, polyolefin and polyamide.

The final parts do not need post-processing, except for support removal and some grinding for a better surface finishing. Another advantage of the FDM system is that it can also be used in an office, and not just in a laboratory: no high powered lasers are used; moreover the materials are supplied in spool format and present neither special handling nor environmental concerns [23].

4. DISCOVERING THE RELATIONS AMONG PRODUCT FEATURES DETERMINED BY PROCESS PARAMETERS

Given the descriptions of DGLs and FDM, the goal is now to develop and execute the procedure in order to discover the relations among product features determined by the technological characteristics. As DGLs are essentially a tool to prove the aforementioned relations, the verification aspects are ignored here, focusing the attention on the steps related to design and manufacturing.

The procedural steps, running accordingly with the DGLs roadmap, are shortly described in the following.

Identification of the technological characteristics

In this step, the analysis of the particular aspects of FDM Technology, previously described, lead to the identification of the whole set of its characteristics and related parameters. The experts of the FDM technology provide the information to fill the DGLs database as shown in Table 1 (in this table and in the following ones the content is only partially supplied, as an example to explain the procedure used; the whole data-base will be presented in further work).

Table 1: Technological characteristics with related values

Label	Characteristic	Description	Values	Meaning
M1	Manufacturing workspace	This characteristic represents the volume of the manufacturing workspace	xMmax, yMmax, zMmax	Maximum dimensions
M2	Support	This characteristic represents the need for support when building overhangs or cavities	xSmin, ySmin,	Minimum dimensions in horizontal plane
			αSmin, αSmax	Angles between vertical and walls
M3	Slicing	This characteristic represent the way of deposing the material slice by slice	Zmin, Zmax	Minimum and maximum thickness of the slice
…	…	…	…	…

Identification of the product features

Here the product is described in terms of features, mainly geometrical features, described and established in their values. The designer performs this task to provide the information to fill the DGLs database as shown in Table 2.

Table 2: Product features with related values

Label	Feature	Description	Values	Meaning
F1	Bounding box	This feature represents the overall dimensions of the product	Xmax, Ymax, Zmax	Maximum dimensions
F2	Minimum dimensions	This feature represents the minimum dimensions in the product	Xmin, Ymin, Zmin	Minimum dimensions
F3	Dimensions ratios	This feature represents the critical dimensions ratios	(X/Y)min, (Y/X)min, (X/Z)min, (Y/Z)min	Minimum dimensions ratios, on horizontal and vertical planes
F4	Overhangs	This feature represents the presence of overhangs and protrusions	αmin, αmax	Overhangs angle, measured to the respect of vertical plane
F5	Cavities	This feature represents the presence of blind holes, undercuts and other cavities	xCmin, yCmin, dCmax, β, dxmin, dymin	Minimum dimensions, maximum depth, orientation, and position of cavities
F6	Surface finishing	This feature represents the surface texture	RaX-Y max, RaX-Z max,	Maximum roughness measured on horizontal and vertical planes
…	…	…	…	…

Generation of the Rules

Product features are affected by the manufacturing characteristics; this can be expressed by Rules, established with consideration to each pair of characteristics/features. The FDM technology expert finds the Rules by analyzing the data collected during the previous task. He uses his own experience and knowledge in performing this task, again to provide the information to fill the DGLs database as shown in Table 3. Rules in Table 3 may appear to be rather simplistic, but they are just a tool for activating Actions and Hints and considering their interactions; they are the key to discovering the relations among the product features, in other words, to obtaining the results of this research. Naturally, all the Rules used here apply in the real world in daily working situations.

Table 3: List of Rules generated by the expert of the FDM technology

Label	Rule	Origin
R1	Dimensions defining the bounding box of the product must be minor than maximum dimensions of the building room	M1 vs. F1
R2	Minimum dimensions of the product must be greater than minimum dimensions related to the presence of Support	M2 vs. F2
R3	Dimensions ratios must be evaluated considering the need for Support	M2 vs. F3
R4	The presence of overhangs must be evaluated considering the need for Support	M2 vs. F4
R5	The dimensions, depth and orientation of cavities must be compatible with the need for Support	M2 vs. F5
R6	Roughness must be evaluated considering the presence of Support	M2 vs. F6
R7	Minimum dimensions must be greater than minimum dimensions related to the slicing	M3 vs. F2
R8	Dimension ratios must be evaluated considering the slicing	M3 vs. F3
R9	The position of cavities must be evaluated considering the slicing	M3 vs. F5
R10	Maximum roughness of the product must be compared with the Minimum roughness related to the slicing	M3 vs. F6
…	…	…

Generation of Expressions to evaluate compatibility

In this phase, a set of Expressions is defined, allowing for the identification of compatibility values between the manufacturing characteristics and the product features, both at the beginning of the evaluation procedure and after the Rules application. As before, the resulting Expressions are collected in the corresponding table of the Knowledge Matrix. These Expressions do not strictly concern the relations we are looking for in the present work, so Table 4 reports some of these Expressions merely as an example. For what concerns the actors, in this phase design, manufacturing and verification experts work together to develop the Expression set.

Table 4: List of expressions to evaluate the compatibility

Label	Expression	Meaning	Origin
E1	E1=1 IF Zmax<zMmax AND Xmax<xMmax AND Ymax<yMmax E1=0 IF Zmax> zMmax OR Xmax> xMmax OR Ymax> yMmax	Compatibility between model maximum dimensions and Workspace dimensions	M1 vs F1
E2	E2=1 IF Zmin>zSmin AND Xmin>xSmin AND Ymin>ySmin E2=0 IF Zmin<zSmin OR Xmin<xSmin OR Ymin<ySmin	Compatibility between model minimum dimensions and need for support	M2 vs F1
E3	E3=1 IF α≥αSmax E3=1-(1/(1+(((α-αSmin)/(αSmax-αSmin))/0.5)^4) IF αSmin< α<αSmax (*) E3=0 IF α<αSmin	Compatibility between model overhangs and need for support	M2 vs F3
E4	E4=1 IF MIN(Xmin, Ymin)>3*MIN(xSmin, ySmin) E4=0,5 IF MIN(xSmin, ySmin)<MIN(Xmin, Xmin)<3*MIN(xSmin, ySmin) E4=0 IF MIN(Xmin, Ymin)<MIN(xSmin, ySmin)	Compatibilities between cavities and need for support	M2 vs F4
…	…	…	…

Generation of Actions (and related costs)

In this step, the technology experts define the Actions determined by the Rules. Each Rule may determine different Actions, generally characterized by different costs (here reported in the range 1-10). Some Actions are collected in Table 5. If an Action necessitates another one, the link between them is shown as well. Please note the uniform format of the Action: "verb-accusative-goal".

Table 5: Actions

Label	Action	Domain	Cost	Link	Origin
A1	Split the model to make dimensions compatible with the workspace	Design	8	A2	R1
A2	Post-process the model to merge the split parts	Manufacturing	5	A1	
A3	Scale the model to get it smaller	Design	5		
A4	Over-dimension thin parts, when possible, to get them compatible with the need for support	Design	5		R2
A5	Scale the model to get it bigger	Design	5		
A6	Over-dimension thin parts resulting from critical dimensions ratios to get them compatible with the need for support	Design	5		R3
A7	Scale the model to get it bigger eliminating critical dimensions ratios	Design	5		
A8	Change the orientation of the product in the workspace to minimize the quantity of required support	Manufacturing	1		R4
A9	Over-dimension the part considering overall dimensions instead of overhangs to avoid the need for support	Design	5	A10	
A10	Post-process the product to make the overhangs from the bulk	Manufacturing	10	A9	
A11	Change the orientation of the product in the workspace to get the support removal easier	Manufacturing	1		R5
A12	Split the model to avoid the need for support	Design	8	A13	
A13	Post-process the model to merge the split parts	Manufacturing	5	A12	
A14	Scale the model to get it bigger eliminating critical dimensions of cavities	Design	5		
A15	Change the orientation of the product to avoid the need for support on surfaces needing best roughness	Manufacturing	1		R6
A16	Post process the surfaces needing best roughness	Manufacturing	10		
A17	Scale the model to get it bigger, thus compatible with the slicing	Design	5		R7
A18	Change the orientation of the product to avoid dimension ratios critical for the slicing	Manufacturing	1		R8
A19	Scale the model to get it bigger, thus avoiding dimension ratios critical for the slicing	Design	5		
A20	Post process the product to realize cavities after FDM building	Manufacturing	10		R9
A21	Change the orientation of the product to get the roughness resulting from slicing compatible with the requirements	Manufacturing	1		R10
A22	Post process the surfaces needing best roughness	Manufacturing	10		
…	…	…	…	…	…

Discovering the Relations among product features

In the present work, Actions and Rules are the tool facilitating the recognition of the relations between product features and process parameters and the key to discovering the relations among the different product features. From this perspective, to exploit the uniform format of the Actions ("verb-accusative-goal"), the first step consists in grouping the different Rules determining the same Actions, as shown in Table 6.

Table 6: Sets of Rules grouped by the same Actions

Label	Rule	Goal	Action
G1	R1	Make dimensions compatible with the workspace	Split the model
	R5	Avoid the need for support	
G2	R1	Make dimensions compatible with the workspace	Post- process gluing
	R5	Make cavities compatible with the need for support	
G3	R1	Make dimensions compatible with the workspace	Scale smaller
G4	R2	Make dimensions compatible with the need for support	Scale bigger
	R3	Make dimensions ratios compatible with the need for support	
	R5	Make cavities compatible with the need for support	
	R7	Make dimensions compatible with the slicing	
	R8	Make dimensions ratios compatible with the slicing	
G5	R2	Make dimensions compatible with the need for support	Over-dimension thin parts
	R3	Make dimensions ratios compatible with the need for support	
	R4	Make overhangs compatible with the need for support	
G6	R4	Make overhangs compatible with the need for support	Change the orientation
	R5	Make cavities compatible with the need for support	
	R6	Minimize roughness compatibly with the need for support	
	R8	Make dimensions ratios compatible with the slicing	
	R10	Minimize roughness compatibly with the slicing	
G7	R4	Make overhangs compatible with the need for support	Post process machine tooling
	R6	Minimize roughness compatibly with the need for support	
	R9	Make cavities compatible with the slicing	
	R10	Minimize roughness compatibly with the slicing	
…	…	…	…

Now, Rules depend on product features and manufacturing characteristics, so that if each group of Rules determining the same Action is analyzed, the links between features and characteristics, and, further, the relations among the product features themselves, are identified too. Thus, process parameters merit some consideration. Each group of Rules, highlighted in the previous step, permits the connection of a set of technological parameters. For example, G1 allows the collection of the set: xMmax, yMmax, zMmax xSmin, ySmin, αSmin, αSmax; in other words, it allows the collection of the parameters related to the manufacturing workspace dimensions, those to describe the minimum acceptable thickness on the XY plane, and, finally, those that characterize the need for support. Given the content of the previous tables and the process to generate Rules, Actions, etc, it is easy to connect this set of parameters with a second one, related to the product features: Xmax, Ymax, Zmax, xCmin, yCmin, dCmax, β, dxmin, dymin (product overall dimensions, and dimensions, orientation, and position of cavities). The result has been reached: these product parameters are related to one another, so as the product features they represent. Given a modification of one of these features, it is now possible to predict effects on other features.

Table 7 contains some relations among the product features that have been highlighted thanks to the DGLs usage. Considering, for example, the product feature "Bounding box" (F1), representing the maximum dimensions of the product; we observe that it is related to the cavities present in the product model (if any). This is a clear example of "unpredictable relation" determined by the manufacturing technology used. In other words, the additional information at the designer's disposal suggests that, if for some reason he desires to modify the overall dimensions of the product model (with a scaling action, for example), something unexpected could happen when manufacturing the cavities eventually present in the same model. Again, concerning the product feature “Minimum dimensions” (F2), while it is apparent that minimum dimensions are related to dimension ratios, it is also discovered that minimum dimensions are related to cavities, which was not so obvious. For example, changing the orientation in the workspace to avoid some problems related to the removal of support from thin parts (minimum dimensions) may imply an unwanted presence of support in the cavities. All of this confirms that DGLs are an effective tool to discover hidden relations between product features.

Table 7: Relations among product features

Label	Product feature	Related features	Technological characteristics
F1	Bounding box	Cavities	Workspace Support
F2	Minimum dimensions	Dimensions ratios Cavities	Support Slicing
F3	Dimensions ratios	Minimum dimensions Overhangs	Support Slicing
F4	Overhangs	Dimensions ratios Cavities Surface finishing	Support Slicing
F5	Cavities	Overhangs Surface finishing	Support Slicing
…	…	…	…

Until now, because of the short time that these results have been available, they have been taken into consideration only from a research point of view and validated on the basis of the authors’ experience, skill, and knowledge. In the near future, they will be coupled with the outcomes of the DGLs already tested and validated in the field, and further publications will summarize these experiences.

5. CONCLUSIONS

The aim of this work was to discover how the characteristics of the manufacturing process can affect the features defining a product, and, overall, the relations existing among the same features. A Knowledge Based System developed in previous work, the Design GuideLines (DGLs), provided proof of these relations, which in most cases are quite unpredictable. The inference procedure appeared not to straightforward; the DGLs knowledge structure and a clear roadmap for their application have made the research practicable and effective. The results are summarized in tables, informing the designer that the modifications of some features may have unexpected effects on others. The information could be given both in a qualitative manner (feature names) and in a quantitative one, recalling the values of the process parameters and the product features involved. The quality of the results is under evaluation from many points of view. Of course, knowledge content and significance are the main indicators. Additionally, the usability of the database and the comparison between the usage of this knowledge by different skilled users, are also under evaluation. Future papers will report the results of this evaluation phase, together with the description of some case studies where the feature relations table will be adopted and integrated.

REFERENCES

[1] Ullman, D., 2002, “Toward the ideal mechanical engineering design support system”, Research in Engineering Design, 13, (2), pp. 55-64

[2] Burr, H., Vielhaber, M., Deubel, T., Weber, C., Haasis, S.,, 2005, “CAx/engineering data management integration: enabler for methodical benefits in the design process”, Journal of Engineering Design, 16, (4), pp. 385-398

[3] Osteras, T., Murthy, D.N.P., Rausand, M., 2006, “Product performance and specification in new product development”, Journal of Engineering Design, 17, (2), pp. 177-192

[4] Holewnik, A., Lewis, K., 2006, “A decision support framework for flexible system design”, Journal of Engineering Design, 17, (1), pp. 75-97

[5] Hirschi, N.W., Frey, D.D., 2002, “Cognition and Complexity: an experiment on the effect of coupling in parameter design”, Research in Engineering Design, 13, pp. 123-131

[6] Hirtz, J., Stone, R. B., McAdams, D. A., Szykman, S., Wood, K. L., 2002, “A functional basis for engineering design: Reconciling and revolving previous efforts”, Research in Engineering Design, 13, (2), pp. 65-82

[7] Xue, D., 1997, “A multilevel Optimization Approach Considering Product Realization Process Alternatives

and Parameters for Improving Manufacturability", Journal of Manufacturing Systems, 16, (5), pp. 337-351
[8] Houssin, R., Bernard, A., Martin, P., Ris, G., Cherrier, F., 2006, "Information system based on a working situation model for a new design approach in concurrent engineering", Journal of Engineering Design, 17, (1), pp. 35-54
[9] Chiang, T. A., Trappey, A. J. C., Ku, C. C., 2005,"Using a knowledge-based intelligent system to support dynamic design reasoning for a collaborative design community", International Journal of Advanced Manufacturing Technology, DOI 10.1007/s00170-005-0231-6
[10] Koh, H., Ha, S., Kim, T., Lee, S., 2005, "A method of accumulation and adaptation of design knowledge", International Journal of Advanced Manufacturing Technology, 26, pp. 943-949
[11] Alisantoso, D., Khoo, L.P., Ivan Lee, B.H., Fok, S.C., 2005, "A rough set approach to design concept analysis in a design chain", International Journal of Advanced Manufacturing Technology, 26, pp. 427-435
[12] Shehab, E., Abdalla, H., 2002, "An Intelligent Knowledge-Based System for Product Cost Modelling", International Journal of Advanced Manufacturing Technology, 19, pp. 49-65
[13] Lee, K., Lee, K., 2004, "Evolutionary design and re-design using design parameters and goals", Journal of Engineering Design, 15, (2), pp. 155-176
[14] Kumaran, N., Chittaro, L. (eds.),1998, Reasoning About Function, Artificial Intelligence in Engineering, ELSEVIER, Vol. 12.
[15] EOS EOSINT250X user's manual.
[16] Bandera C., Cristofolini I., Filippi S., Toneatto G., 2004, "The definition of the geometrical characteristics of products in a knowledge based system for industrial design (DGL-Design GuideLines) - exploring the possibility of introducing ISO GPS (Geometrical Specification of Products) concepts", Proc. XIV ADM - XXXIII AIAS, ISBN: 88-900637-3-4, Italy.
[17] Bandera C., Cristofolini I., Filippi S., 2005, "Evolution of a Knowledge-Based System for industrial design, manufacturing and verification", Proc. Congreso internacional XVII Ingegraf – XV ADM, ISBN: 84-923253-3-X, Spain
[18] Bandera C., Cristofolini I., Filippi S., 2005, "Customizing a Knowledge-Based System for design optimization in Fused Deposition Modeling RP-technique", in AMST '05 Seventh International Conference on Advanced Manufacturing Systems and Technology, eds. Springer Wien-New York, ISBN 3 211 265376, pp. 607-616
[19] Filippi S., Bandera C., Toneatto G., 2001, "Generation and Testing of Guidelines for Effective Rapid Prototyping Activities", Proc. ADM International Conference on Design Tools and Methods in Industrial Engineering, Italy, pp. A2.18-A2.27
[20] Filippi, S., Cristofolini, I., 2006, "The Design Guidelines (DGLs), a Knowledge Based System for industrial design developed accordingly to ISO-GPS (Geometrical Product Specifications) concepts", submitted to Research in Engineering Design
[21] Gatto A., Iuliano L.,1998, Prototipazione rapida: la tecnologia per la competizione globale, eds. Tecniche Nuove, Italy.
[22] Cooper, K., 2001, Rapid prototyping Technology: Selection and Application, eds. Taylor and Francis Group Ltd
[23] Jacobs P. F., 1995, Stereolithography & Other Rp&m Technologies: From Rapid Prototyping to Rapid Tooling, eds. Society of Manufacturing Engineers.