MANUFACTURING COMPLEXITY EVALUATION FOR ADDITIVE AND SUBTRACTIVE PROCESSES: APPLICATION TO HYBRID MODULAR TOOLING

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Reviewed, accepted September 10, 2008

Abstract

The aim of this work is to determine how to combine a subtractive process (HSM) and an additive process (SLS) to realize tools (dies or molds). In fact, the design and manufacturing of tools may be optimized with hybrid and modular points of view. Tools are not seen as single pieces but as 3-D puzzles with modules; each module is manufactured by the best process. So a new methodology is proposed: the most complex-to-manufacture areas of a tool are determined (based on a manufacturability analysis from tool CAD model) and a hybrid modular tool CAD model with a reduced manufacturing complexity is proposed.

1. Context of the study: hybrid modular tooling

In order to improve competitiveness in modern mass production industry, products have to be designed and manufactured with the following two goals that are often in opposition:

- Decreasing time and cost;
- Improving quality and flexibility.

These objectives imply two design and manufacturing constraints: a rapid manufacturing and a high level of reactivity when design evolutions are required. The current field of tooling (dies and molds) does not break these constraints and one answer to the problem is to design and manufacture hybrid modular tools, with modular and hybrid points of views.

Modular point of view: Instead of a single-piece tool, it is seen as a 3-D puzzle with modules realized separately and further assembled. The two advantages are: each module may be produced simultaneously and few modules may be changed without changing the whole tool. As it can be seen in the example in Figure 1, the two alternatives of the product may be advantageously manufactured with the same mold. Only one module of the mold is changed to provide new part functions.

Fig.1. Two alternatives of a product model (Logicom®).

Hybrid point of view: Each module of the tool is manufactured by the best process, in term of time, cost and/or quality. Presently, focus is put on comparison between a subtractive process (HSM: High-Speed Machining) and an additive process (SLS: Selective Laser Sintering). Another research topic investigates the combination of these two manufacturing processes. Figure 2 shows an example of a hybrid tool.

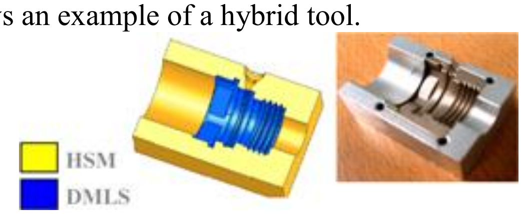


Fig.2. Industrial injection hybrid mold [1].

To illustrate the advantages of using hybrid modular tooling, Figure 3 presents an industrial example, developed at IRCCyN [2]. It is a part from automotive industry, manufactured by injection molding. In this part, the positions of the circular shapes have diversifying alternatives, there are a marking that changes with the model and an evolutionary feature for the seal positioning. The part with its evolutionary areas may be produced with just one mold creating modules for each changing area of the piece. So modules are designed and realized with the best process, and changed when the product model is modified.

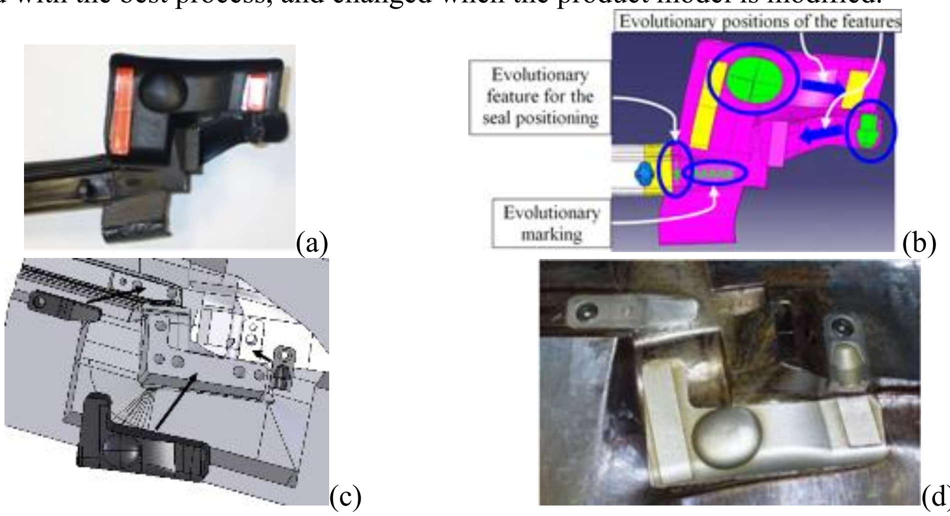


Fig.3. Industrial example of hybrid modular tool [2].
(a) Seal rear door of a vehicle (b) Seal rear door CAD model with evolutionary areas
(c) Seal rear door hybrid modular tool CAD model (d) Seal rear door hybrid modular tool.

2. One important issue in hybrid modular tooling

Hybrid modular tools allow diversifying alternatives of a product and are manufactured at lower cost in the shortest lead-time. In order to help tooling designers to choose between a hybrid modular tool and a traditional single-piece tool, the advantages of the hybrid modular design have to be quantified. In case of flexibility, it is quite evident that creating modules will help multiple geometric evolutions of the future part to produce.

To evaluate the impact of a hybrid modular design on the time, cost and quality of the tool is not easy before doing the complete preparation of manufacturing. For example, the machining time depends on the tool path strategy. And the choice of a strategy is based on the ability of the manufacturer, with the help of a Computer-Aided Manufacturing software. It will be more interesting for the designer to be able to choose the best hybrid modular tool design before complete manufacturing preparation. So criteria have to be elaborated and utilized at the early stage.

A new methodology is developed to determine which areas of the tool will be the most difficult-to-manufacture, directly from tool CAD model. The most difficult-to-manufacture areas are:

- The areas which will impose an increasing manufacturing time;
- The areas which will increase overall tool cost;
- The areas for which it will be difficult to achieve a high quality level.

Examples of complex-to-manufacture areas: the areas with a fine roughness; the back drafted areas, which obligate particular milling tool orientations (in five axis machining) or building support (in layered manufacturing).

This paper presents this new methodology, based on the calculation of manufacturing complexity indexes, in order to determine which areas of the tool are the most difficult-to-manufacture.

3. Manufacturing complexity evaluation

The aim of this section is to determine several parameters which have a great influence on the time, cost and quality. These parameters provide information on the most difficult-to-manufacture pieces, or areas of a piece.

Many works on the definition of manufacturability indexes were achieved. In fact, the determination of a manufacturing process is often based on such indexes [3]. Most typically, manufacturability indexes include manufacturing cost, product quality and production time. Some other works use the concept of "effort to produce the final part" as a quantification of product complexity [4].

Three categories can be distinguished for classifying manufacturability indexes: geometric parameters, material information and specifications. The following list of parameters is limited to those which can be determined only with CAD model. So parameters that require a complete manufacturing preparation analysis (for example: tool path strategy) are not taken into account to be free from manufacturer skills.

3.1. Geometric parameters

First of all, the geometry and dimensions of the part to realize clearly affect the manufacturing time, cost and quality. The geometric parameters have not the same influence in case of a subtractive or an additive process.

If the tool is machined, the geometric parameters that lead a mechanical part difficult-to-machine are:

- Maximal dimensions: a given machine has its own limitations on each axis;
- Minimal dimensions: if some dimensions are too small, it will be impossible to machine with traditional milling tools;
- Slenderness: parts with a high slenderness ratio will be more difficult-to-machine than other ones;
- Geometrical accessibility for the milling tool: machining the bottom of a depth pocket implies using a long milling tool which can generate a bad quality surface;
- Curvature radius: a convex surface with small curvature radius implies using a milling tool with a corresponding radius;
- Back drafted areas: surface orientations sometimes obligate particular milling tool orientations and five-axis machining;
- Free form surface: lots of changes in the surface orientations have a large influence on the number of feed rate alteration;
- Blank volume: the blank dimensions have an impact on the chip quantity and so a consequence on the part cost;
- Etc.

In case of layered manufacturing, other geometric parameters are taken into account to evaluate manufacturing complexity:

- Volume and height: direct influence on manufacturing time;
- Surfaces orientations: the quantity of support has an impact on the material cost, manufacturing time and surface quality;
- Distance from the centre of the platform: the dimensional error strongly depends on the distance from the platform centre [5];
- Quantity of skin surface: manufacturing time is higher for skin surfaces than for inner surfaces;
- Maximal and minimal dimensions, slenderness: same impact than for a machining process;
- Etc.

3.2. Material information

Obviously, the mechanical characteristics of material directly affect manufacturing process parameters.

As an example, when the material to machine is very hard (50-60 HRC), a special range of cutting tool materials is required (ceramic metal composites, polycrystalline cubic boron nitride) with low feed rate [6].

So manufacturability indexes based on material will be defined according to the following characteristics:

- Hardness;
- Young modulus;
- Ductility;
- Microstructure;
- Thermal conductivity;
- Etc.

And in layered manufacturing, the material choice is limited by the different powders available in a machine, and melting point temperature is clearly significant.

3.3. Technical specification

The specification of high degree tolerances and surface finish always increase the number of operations required and more expensive machines.

Of course, the consequence is a rise in the difficulty of manufacturing. Four parameters are very sensitive with respect to the accuracy and dynamical capability of manufacturing equipment (in case of machining process or layered manufacturing process) [7]:

- Dimensional tolerance;
- Geometric tolerance;
- Location tolerance;
- Surface finish.

4. Global and local indexes

These three categories of manufacturability indexes are subdivided in two types: global indexes and local indexes.

Global indexes are defined for the whole tool. As an example, an index may be calculated from the parameter “Volume”. In fact, volume has a great impact on manufacturing time in an additive manufacturing process.

Local indexes are defined for each area of the tool. Tool CAD model has to be decomposed into several elementary elements, and local indexes are calculated for each element. Several methods exist to decompose a CAD model into basic components. A choice must be done to determine the most appropriate method in this case.

4.1. Feature decomposition

Many decomposition methods are based on volume segmentation approaches [8], considering that elementary volumes, named features, form a part. Features usually rely on one specific field and are used as specific data to automate CAD, CAM, process planning, etc. As an example, machining features are developed for mechanical product definition for process planning (ISO 10303-224), but there are still no manufacturing features for additive process. And for free-form surfaces, usually used in tooling design, machining features do not bring enough information on the shape. Furthermore, comparing different manufacturing processes would involve including different manufacturing features which would make the evaluation of manufacturing complexity difficult. And sometimes there are several ways of decomposing a part, because some shapes can be interpreted as either two features or one long one [9]. So feature decomposition will not be the best way to decompose a CAD model in order to obtain a precise view of the tool complexity. It must be obtained with a neutral decomposition (not rely on one specific manufacturing process), which gives automatically only one way to decompose the tool CAD model.

4.2. Examples of other CAD model decompositions

Each solid modeling method (CSG, B-rep, decomposition method) has its advantages and disadvantages relative to the others in term of accuracy, robustness, data structure and computing time.

Construction Solid Geometry (CSG) method is very popular because this method can complete Boolean operations of any 3D part model relatively easily and accurately. The problem in the CSG approach is that it is computationally expensive to represent the parts with irregular surfaces [10].

A common decomposition method used in layered manufacturing is STL format. A major problem with STL is on its representation of curved surface, which can only be approximated by triangular facets [11]. The manufacturing complexity analysis will not be based on this format, because even if this deviation can be controlled according to user's requirements on approximation accuracy, information is lost. In fact, there are often few details of the tool that can change the manufacturing process choice (a curve radius of a small complex shape, for example).

4.3. Octree decomposition

An octree is a tree data structure, which represents a three-dimensional object by the division of space into small cubic boxes, or small parallelepipeds. The size of each box depends on the local geometric complexity of the object represented [13]. Each box in space corresponds to a node in the tree and each node is referred to as an octant.

To construct an octree, the object is first enclosed by the smallest box (octant) that can completely contain the object in any direction. This octant (a cube or a parallelepiped) makes up the root level of the octree. It is then subdivided into 8 sub-octants (4 sub-octants in case of a two-dimensional object) which then represent the first level. The octants are classified into three categories: black (full), white (empty) and grey (partially filled). Black octants are those that are completely contained in the object of interest, whereas white ones are those that are completely outside the object. Grey octants are those that are partially inside and outside the object. The subdivision process is performed on grey octants until a desired resolution is reached. The specified accuracy is used to determine the final size of the smallest octants [14].

Octree decompositions have been used for several years, first in computer graphics [15]. In mechanical engineering, octree decomposition is used for the verification of numerical command tool paths [13], for interference detection in five axis machining [14] and in robotics [16]. In rapid prototyping, octree decompositions of 3D models have been used to realize approximate prototypes before final machining [17].

The advantages of using an octree decomposition model are:

- It do not rely on one specific manufacturing process;
- Decomposition model can acquire relatively high accuracy;
- The special location of an octant is determined by an index code; with these codes, the position of each octant could be easily found and the geometric information such as centre point and edge lengths could thus be calculated.

That is why an octree structure is used in the following methodology for the calculation of local manufacturability indexes.

5. Methodology to evaluate manufacturing complexity

5.1. Interface

A procedure has been developed to evaluate manufacturing complexity from a tool CAD model. The work has been carried out on a CAD software (SolidWorks 2007) with Visual Basic language. The interface is presented in Figure 4.

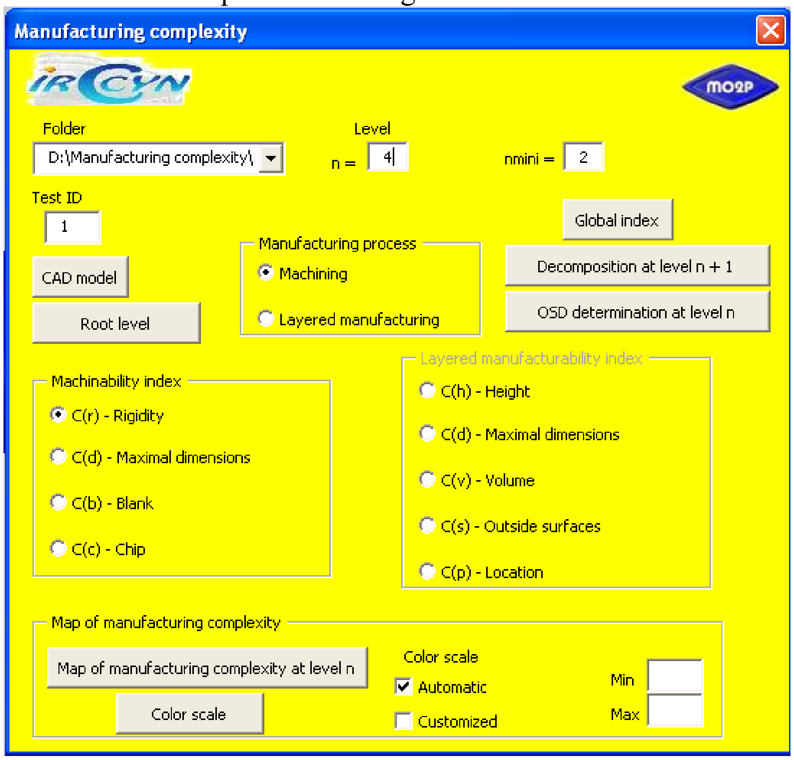


Fig. 4. Interface of the manufacturing complexity evaluation methodology.

5.2. Definition of the manufacturability indexes used in the methodology

Concentration is first put on geometric parameters. Manufacturability indexes have been developed, according to the previous analysis. Machinability indexes are defined and presented in Table 1, and layered manufacturability indexes in Table 2. The indexes based on an analysis of the surface orientations of the tool have not yet been developed. All these indexes must be calculated according to the help of the tool CAD model, and without a complete manufacturing preparation.

If the manufacturability index that has been chosen is a global index, the procedure directly post the index value. The higher the value of the index is, the more difficult-to-manufacture the tool is.

In case of local indexes, a step of decomposition is done, according to an octree decomposition algorithm. Then the index value is calculated for each grey or black octant and a color map of manufacturing complexity for this index is drawn (with automatic or customized color scale). For each octant, the higher the value of the index is, the more difficult-to-manufacture the fraction of the tool contained in the octant is. If the accuracy of the decomposition is not satisfying (the octants are too big compared to the dimensions of the tool), another level of decomposition is done, only for grey octants. When a sufficient accuracy is reached, the decomposition is stopped. The accuracy of the octree decomposition must be carefully determined, because if it is too high, it will dramatically increase computing time. Nevertheless, it must not be too small with respect to the smallest dimension of the tool. In this paper, four levels of decomposition have been chosen.

Index	Linked to	Type
$C(d_x)\ C(d_y)\ C(d_z)$	Maximal dimensions	Global
$C(r)$	Tool rigidity	Local
$C(b)$	Blank volume	Global
$C(c)$	Chip quantity	Global

Table 1. Manufacturability indexes for machining process.

Index	Linked to	Type
$C(d_x)\ C(d_y)\ C(d_z)$	Maximal dimensions	Global
$C(v)$	Volume	Global
$C(s)$	Outside surface	Global
$C(h)$	Height	Local
$C(\rho)$	Distance from the centre of the platform	Local

Table 2. Manufacturability indexes for layered manufacturing process.

5.3. Calculation of manufacturability indexes

The manufacturability indexes defined in Tables 1 and 2 are calculated with the help of the following equations (Equations 1-8):

(1) $$C(d_x) = \frac{LX_0}{LX_{max}}$$

where LX_0 is the maximal dimension of the tool in x-direction, and LX_{max} is the length of the X-axis of the machine. $C(d_y)$ and $C(d_z)$ are determined with similar equations. The machines and tool orientation in a machine have to be previously established. For further examples, Hermle C30U HSM and EOS 250 Xtend machine are used with z-direction as spindle axis and layer normal orientation.

(2) $$C(r) = \frac{L}{D}$$

where L is the minimal length of the milling tool that can machine the surface included in the octant and D is the maximal diameter of the milling tool that can machine the surface included in the octant.

This index is based on two reports. In most cases, when the milling tool diameter is reduced, machining time increases. Moreover, when the ratio length/diameter of the milling tool increases, the quality of the piece realized is reduced. It corresponds to a diminish of the milling tool stiffness. L is calculated by the difference of height between the top face of the highest octant and the bottom face of the octant for which $C(r)$ is being calculated. D takes into account both curvature radius of convex surface (a small curvature radius limits the diameter of the milling tool that can machine a convex surface) and space between two surfaces which may limit the milling tool diameter (Figure 5).

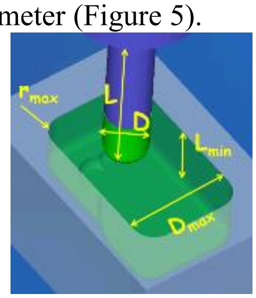


Fig. 5. Example of machining a pocket.

(3) $C(b) = LX_0 \times LY_0 \times LZ_0$

$C(b)$ represents the volume of the blank part. The higher $C(b)$ is, the more expensive the rough part is and consequently the more difficult-to-machine the tool is considered.

(4) $C(c) = \dfrac{LX_0 \times LY_0 \times LZ_0}{V}$

where V is the volume of the tool. Chips are considered as material lost, so if $C(c)$ has a low value, the tool will not require a large quantity of chips and the tool will be considered as easy-to-machine.

(5) $C(v) = V$

(6) $C(s) = S_{ext}$

where S_{ext} is the area of the whole outside surface of the tool.

(7) $C(h) = z - Z_0$

where z is the z-coordinate of the centre of gravity of the volume of the tool contained in the octant and Z_0 is the z-coordinate of the bottom face of the tool.

(8) $C(\rho) = \sqrt{(x - X_0)^2 + (y - Y_0)^2}$

where x and y are the coordinate in the X-Y plane of the centre of gravity of the volume of the tool contained in the octant and X_0 and Y_0 are the coordinate of the centre of the tool, considering that the tool will be manufactured with its centre exactly at the centre of the platform.

For each local index, a global one may be calculated (Equation 9) for an easier comparison between manufacturability indexes.

(9) $C(i_{global}) = \dfrac{\sum_j (C(i_{local})_j \times V_j)}{\sum_j V_j}$

where V_j is the volume of the fraction of the tool contained in the octant for which $C(i_{local})_j$ is calculated.

6. Examples of using the manufacturing complexity evaluation methodology

6.1. Comparison of CAD models for one manufacturing process: modular point of view

This methodology allows comparing different tool CAD models, regarding one manufacturing process. The most difficult-to-manufacture areas may be improved with a modular point of view, designing modules in order to decrease the value of manufacturability indexes in these areas.

As an example, a single-piece test-part CAD model is analyzed in term of local and global indexes for subtractive process. Figure 6a presents the test-part, which is representative of dies and molds traditionally made by High-Speed Machining, and Table 3 gives the values of machining indexes. For $C(r)$ - tool rigidity index, a map of machining complexity is obtained (Figure 6b) and most difficult-to-machine areas are thus known.

This map provides an accurate view of the manufacturing complexity of the test-part. With the example of machining process and $C(r)$ as manufacturability index, the easiest-to-manufacture areas are those where there are no limitations for the milling-tool diameter ($C(r) = 0$). The most difficult-to-manufacture areas of the test-part are at the bottom of the circular boss, with a small curvature radius and the surface between the two high bosses.

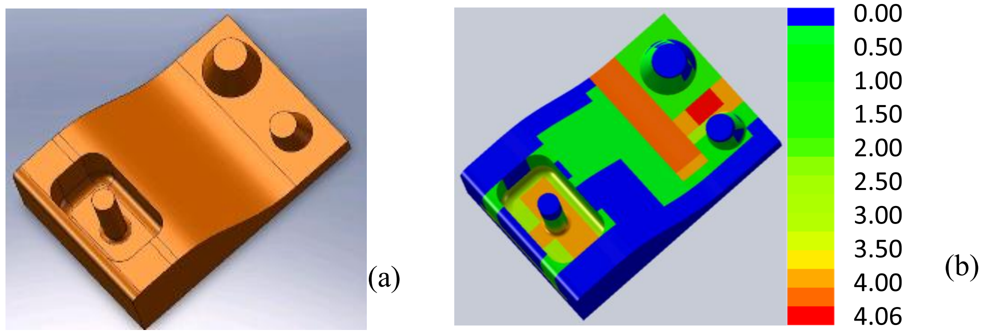


Fig. 6. Example of a test-part.
(a) CAD model.
(b) Map of machining complexity.

Then the aim is to concentrate on these areas to understand why there are complex-to-manufacture, according to this particular index. The difficulty can be due to a small space between two bosses that allows only small diameter milling tools. On the other hand, the difficulty can be due to a high wall that forces milling tools to be long. Alternatively, because there is a small radius on a convex surface that implies using a milling tool with a small radius. The further step of the methodology is to take into account modular point of view, creating modules, manufactured aside and further gathered, to reduce manufacturing complexity in the previous most difficult-to-machine areas, as it can be seen in Figure 7. In this example, assembly process is not treated.

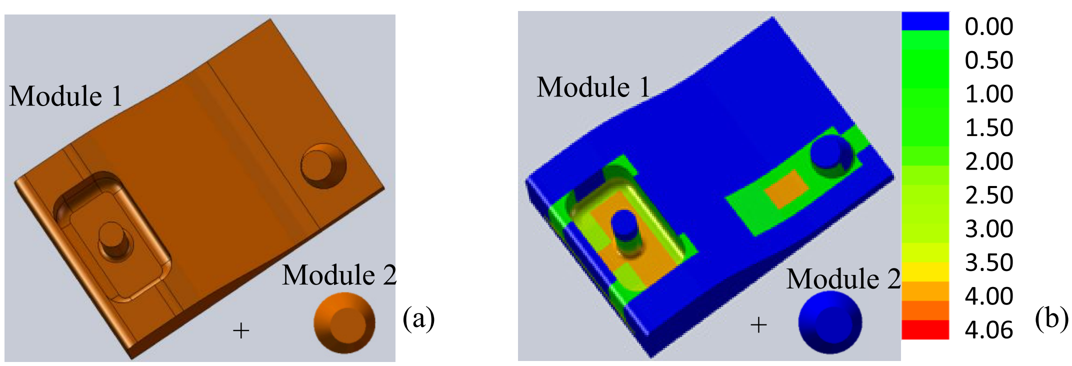


Fig. 7. Example of a modular test-part.
(a) CAD model.
(b) Map of manufacturing complexity.

For a global comparison of the two CAD models, manufacturability indexes are calculated for the single-piece test-part and the two modules of the modular one (Table 3). Concerning the modular test-part, total indexes are calculated with the following equation (Equation 10).

$$(10)\quad C(i_{total}) = \frac{C(i_{\mathrm{mod.1}}) \times V_{\mathrm{mod.1}} + C(i_{\mathrm{mod.2}}) \times V_{\mathrm{mod.2}}}{V_{\mathrm{mod.1}} + V_{\mathrm{mod.2}}}$$

In this methodology, it is still impossible to compare different indexes between themselves, so a comparison of the evolutions of the values of the machinability indexes is done between the two tools (Table 3).

So it can be concluded that the modular point of view provides a modular tool with less manufacturing complexity because the tool rigidity index $C(r)$ decreases by 40 % whereas the other indexes evolutions are not significant.

	Single-piece test part	Modular test-part			Comparison
		Module 1	Module 2	Total	
$C(d_x)$	0.185	0.185	0.043	0.178	- 4 %
$C(d_y)$	0.133	0.133	0.043	0.129	- 3 %
$C(d_z)$	0.100	0.100	0.06	0.098	- 2 %
$C(r_{global})$	1.700	0.998	0	0.998	**- 40 %**
$C(b)$	480 000	480 000	20 280	457273	- 5 %
$C(c)$	2.35	2.09	2.01	2.09	- 11 %

Table 3. Comparison of $C(r_{global})$ for the two CAD models.

6.2. Comparison of manufacturing processes: hybrid point of view

Another way of using this methodology is for comparison of two manufacturing processes (additive and subtractive) for one tool CAD model, in order to determine which parts of the tool may advantageously be machined or realized by a layered manufacturing process.

This second example is based on the comparison of the same test-part, but with changes in the pocket dimensions. The test-part presented in Figure 6a has the following pocket dimensions: 30x50x30 mm, whereas the second test-part shown in Figure 8 has a 20x30x30 mm pocket. Manufacturability indexes are calculated, first for machining process (Table 4).

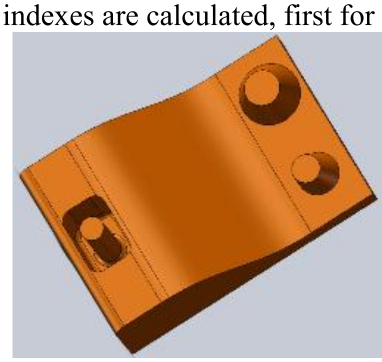


Fig. 8. Second test-part, with a smaller pocket.

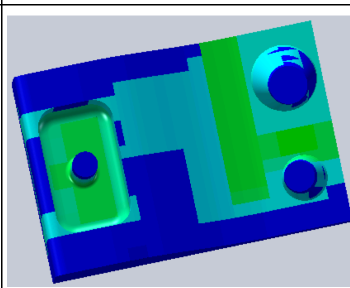
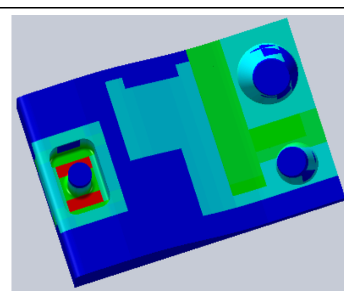
		Pocket dimensions: 30x50x30	Pocket dimensions: 20x30x30	Comparison
Machining	$C(d_x)$	0.185	0.185	=
	$C(d_y)$	0.133	0.133	=
	$C(d_z)$	0.100	0.100	=
	$C(r)$	  $C(r_{global}) = 1.700$	 $C(r_{global}) = 2.071$	**$C(r_{max})$ + 100 %** **$C(r_{global})$ + 22 %**
	$C(b)$	480 000	480 000	=
	$C(c)$	2.35	2.09	- 11 %

Table 4. Comparison of manufacturing indexes for machining process.

An analysis of the evolutions in machinability indexes between the two CAD models is done. In this example, it can be seen that changing the dimensions of the test-part provide new areas of the second test-part very complex-to-machine, according to the $C(r)$ index. The $C(r_{\max})$ value is doubled and the $C(r_{global})$ value increases by 22%, whereas the other values evolutions are not significant.

Then, manufacturability indexes are calculated for additive process (Table 5).

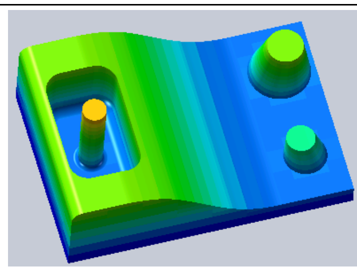
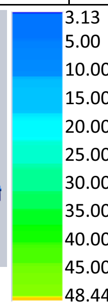
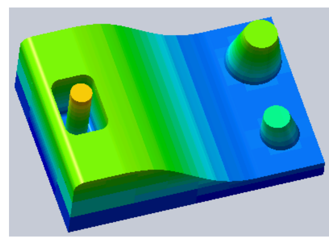
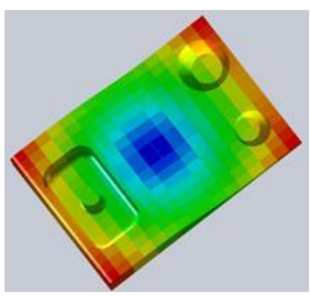
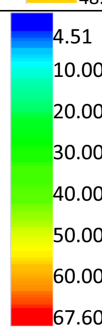
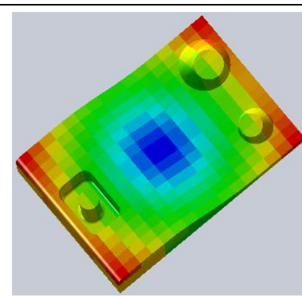
		Pocket dimensions: 30x50x30	Pocket dimensions: 20x30x30	Comparison
Layered manufacturing	$C(d_x)$	0.48	0.48	=
	$C(d_y)$	0.32	0.32	=
	$C(d_z)$	0.28	0.28	=
	$C(v)$	204 183	229 177	+ 12 %
	$C(s)$	36 866	35 557	- 4 %
	$C(h)$	 $C(h_{global}) = 14.250$ 	 $C(h_{global}) = 15.259$	+ 7 %
	$C(\rho)$	 $C(\rho_{global}) = 39.018$ 	 $C(\rho_{global}) = 39.042$	≈

Table 5. Comparison of manufacturability indexes for layered manufacturing.

Changing the dimensions of the test-part provide few evolutions in the values of the different indexes. So the two test-parts will have the same level of manufacturing complexity in case of an additive process.

Consequently, for this second test-part, the areas which are the most complex-to-machine would advantageously be manufactured with an additive process, creating a hybrid part. In this hybrid part, the areas which are easy-to-machine would be machined and the most difficult-to-machine would be manufactured by a layered manufacturing process.

7. Conclusion and future work

In this paper, a manufacturing complexity evaluation methodology is exposed. Manufacturability indexes have been developed, and an interface is created to calculate them directly from a tool CAD model. This new approach provides an accurate view of which parts of the tool have to be improved in order to reduce manufacturing difficulties. Then modular and hybrid points of view allow designing a hybrid modular tool which will be less difficult-to-machine than the first single-piece tool, and consequently be manufactured at lower cost, in the shortest lead-time and with high degrees of flexibility and quality. Two simple examples have been treated to illustrate the possibilities of this new methodology.

To have a more detailed view of manufacturing complexity, more accurate manufacturability indexes may be calculated, with other parameters involved and organized with fuzzy logic, so further researches will be conducted to develop new manufacturability indexes (based on material information and specifications). A study has to be done in order to be able to compare different indexes between themselves.

Assembly constraints generated by a hybrid modular design have also to be taken account, and the methodology will be applied an industrial die from automotive industry.

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