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A graphical method for performance mapping of machines and milling tools

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Abstract

Optimal design of the machining setup in terms of installed machines, cutting tools and process parameters is of paramount importance for every manufacturing company. In most of the metal cutting companies, all choices related to machine eligibility and cutting parameters selection typically come from heuristic approaches and follow supplier indications or base on the skill of experienced machine operators. More advanced solutions, such as model-based and virtual approaches, are adopted less frequently mainly due to the lack of these techniques in grasping the underlying knowledge successfully. Aim of this work is to introduce a synthetic graphical representation of machining centers and cutting tools capabilities, to provide an accessible way to evaluate the feasibility and close-to-limit conditions of the cutting process. Taking inspiration from previous scientific works from the measurement engineering field, a set of 2D and 3D graphs are presented to map machine, tools and process capabilities, as well as their obtainable manufacturing performances and expectable tool life. This approach synthesizes the nominal data coming from different sources (catalogues, database, tool model geometries etc.) and the real cutting tools parameters used during the production phase. Some examples are provided to show the potential of this graphical evaluation in supporting process planning and decision-making and in formalizing the machining setup knowledge. Further developments are devoted to extend the method to other manufacturing processes, including hybrid processes. At the same time, an in-process data gathering software will be integrated for building a solid database that can be used by an autonomous multi-technological process selector, as well as by a pre-process condition advisor in an Industry 4.0 oriented way.

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Keywords: Machine capability; tool mapping; performance mapping; milling; optimization; production planning; predictive manufacturability

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1. Introduction

In the manufacturing field, although new technologies are constantly developed and improved, standard material removal processes are still the most common solution, for the production of components with complex geometry and good accuracy. All chip removal processes involved in most of the manufacturing industries (including strategic ones like aeronautics and oil&gas), need to be optimized to face the increasing competition of the global market in an economically-viable way. In fact, two different problems need to be solved: designing the manufacturing systems maximizing its reconfigurability – to face the rapid market change – and scheduling/planning the production on existing plants – to optimize the productivity and reduce costs [1,2]. Concerning the latter problem, one of main issues is that machines, tools and process parameters are selected using different and independent solutions in the majority of the cases, typically experience-based or "metaheuristic". The problem is faced by using multiple tools and design methods, which lack in grasping the complete problem as a whole, far from being optimally solved. This set of multiple solutions comes from the complexity of the problem, where the interrelation between each aspect of the problem is not properly formalized or is complex to represent in a comprehensible way.
A possible solution to this issue are computer-aided process planning (*CAPP*) systems, which incorporate manufacturing knowledge in a formalized way and exploit it to plan the various operations. However, their use is limited because they are only capable of generating a static planning, thus not able to establish direct connection with the existing manufacturing resources [3] and to relate the manufacturing knowledge with a dynamic and fast changing manufacturing environment. Virtual approaches like the ones presented in [4,5] are also able to provide deep understanding of the cutting related aspects, thus supporting machine and tools selection, but many times they do not suit the real production environments for their usage complexity.

To tackle the problem, this work presents a modelling technique for managing and comparing machining centers properties, chip removal tools geometries and cutting tool parameters through a graphical representation. This graphical representation can be used to model all the interrelations between machine and tools, granting the designers and programmers with a powerful technique to formalize the manufacturing knowledge.
This solution technique is inspired by similar approaches adopted in other fields. In fact, a classification using graphical tools into a 2D space was developed for surface measuring machines by Stedman [6,7] that found out that the capability of dimensional measurement instruments is a function of their vertical and horizontal resolution (i.e. maximum and minimum detectable dimensions). In addition to the resolution limits, also the limits due to the probe geometry and the quality of the reference can be represented onto this space as inclined lines. This way, a 2D performance mapping space was defined (Fig. 1top). Afterwards, in more recent days, a third "dynamic" axis was added to Stedman's space.

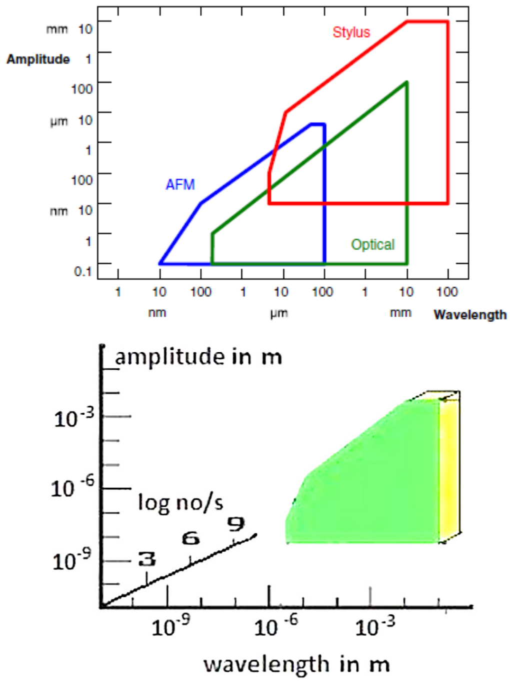

Fig. 1. (top) Stedman's mapping space from [6]; (bottom) augmented Stedman diagram for generic stylus instrument [9].

Leach [8] noticed that for a more complete mapping of the measurement instrument capability, the addiction of the in-plane scanning speed as third "dynamic" axis was necessary. By adding these limits to the previous ones, a polyhedron is represented on the new 3D space, giving a more complete overview on measurement instruments performances (Fig. 1bottom).

This approach is intended to formalize and simplify the comparison of different machine features, easily displaying the relationships between sets of complex data.

This paper is organized as follows: first, the approach is described by focusing on the base concepts, then the different mapping graphs are presented in a coherent way. Applications and test cases are showed, followed by discussion and conclusions.

Nomenclature and symbols

a_e	Radial depth of cut (mm)
a_p	Axial depth of cut (mm)
APMX	Maximum tool cutting length (mm)
C_m	Machining cost (€/piece)
$c_{machine}$	Machine usage cost (€/hour)
C_t	Tool cost (€/piece)
c_{tool}	Cost of a single milling tool (€)
DC	Tool diameter (mm)
η	Machine efficiency
f_z	Feed per tooth (mm/tooth)
κ_{re}	Primary lead angle
κ'_{re}	Secondary lead angle
k_c	Specific cutting pressure (MPa)
MRR	Material removal rate (mm^3/min)
P	Spindle power (kW)
T	Tool life (min)
t_m	Machining time (hour)
v_c	Cutting speed (mm/min)
v_f	Feed rate (mm/min)
ΔV	Total Material Volume Removed [mm^3]
ZEFP	Number of cutting edges

2. Method and base concepts

The overall idea of this modeling technique is to gather some of the knowledge and data related to the machine and tool selection and make a clear and rational graphical representation that can be exploited along the work cycle design and planning. According to the authors, the meaningful set of diagrams is composed by four different representations:

1. *Machine stereo kinetic diagram* (A)
2. *Tool-Machine stereo kinetic diagram* (A')
3. *Tools stereo kinetic diagram* (B)
4. *Operative cutting parameters diagram* (C)

Each one of these graphical representations, along with their defining dimensions, has three types of data contained: ranges, points and functions. Ranges can be used to map catalogue data and theoretical behaviors (e.g. possible axial engagement of a family of end mill cutters). Points are used to map specific machines or cutting tool features (e.g. feed and speed values used by a specific tool during a specific machining operation). Functions are needed to map quantities that are calculated starting from the values of the defining dimensions (e.g. cutting force estimation function given the radial and axial tool engagements). Volumes of interest are represented on these diagrams based on the identified ranges on the three axes (e.g. working volume of a certain tool family).

These data need to populate these diagrams as multiple possible sources. The first source of data are the catalogues provided by machines and tools suppliers. The second source of data are the cutting tool parameters actually used in the manufacturing processes, embedded within the part-program or formalized in a Computer Aided Manufacturing software database. A third source of data, currently not explored in the context of this paper, is the stream of signals coming from the machine, that can be used to represent realistic function data. In order to reduce data flaws or redundancies and uniform the information content, the ISO 13399 technical standard, *Cutting tool data representation and exchange* [10] has been used as reference.

Each specific graphical representation will be detailed and discussed in the following. It is worth mentioning that all the examples reported in the next sections will show information and data coming from the suppliers' catalogues.

2.1 Machine and work area representation

A first diagram maps the maximum dimensions of the workpieces that can be machined on a specific milling machine. This 3D mapping space is the *Machine stereo kinetic diagram* (A). Two of the three axes are machine physical axes' strokes (*x* or *y* and *z*) and the remaining axis is the spindle speed that is the kinetic element. As an example, two commercial high-speed machining centers are analyzed (Fig. 2). This diagram could also have four axes, including both the *x* and *y* machine axes.

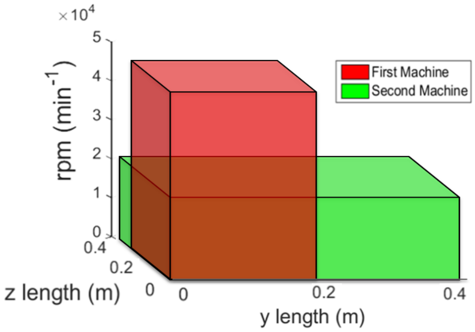

Fig. 2. *Machine stereo kinetic diagram* (A).

The use of this diagram is self-explanatory, as it can be used to support an upstream selection of the machines depending on their machining dimensional and kinetic capabilities. In the example of Fig. 2, the two machines show different kinetic capacity due to the different maximum achievable spindle speed, at the price of a reduced work area for the first machine.

To improve the effectiveness of this approach, the A diagram can be used in conjunction with another diagram. The idea is to synthetize the dimension of the geometrical features that can be manufactured on the considered machine. This map, called *Tool-Machine stereo kinetic diagram* (A'), gives information about the geometry of the clampable tools – constrained by the installed tool holders – and their maximum allowable cutting speed. The tool diameters *DC*, the tool maximum cutting length *APMX* and the cutting speed v_c allowed by the machine spindle populate the diagram (Fig. 3) in *x*, *y*, and *z* directions respectively.

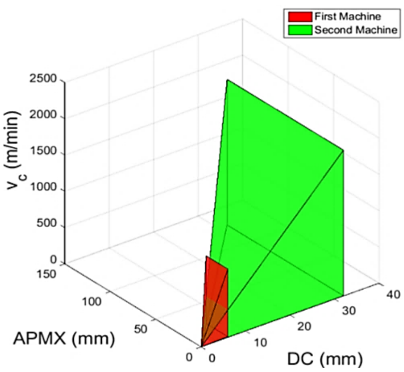

Fig. 3. *Tool-Machine stereo kinetic diagram* (A').

This graph contains coupled information between the machine and the installable tools. As in the case of the A diagram, A' involves two geometrical and one dynamic axis. These two diagrams can facilitate the selection of the most suitable machine for the considered milling operation.

This example considers the same machines presented in Fig. 2 and figures out the clear difference between the two machines' capabilities with respect to the clampable tools.

2.2 Cutting tool geometry representation

The third diagram consist in the *Tools stereo kinetic diagram* (B) and defines the information about the "tool families" geometry and dimensions and their maximum allowable cutting speed. It is useful to select the tools depending on the range of technological features to machine. This diagram has the tool diameter *DC*, the tool maximum cutting length *APMX* and the allowed cutting speed v_c on the x, y and z axes respectively (Fig. 4).

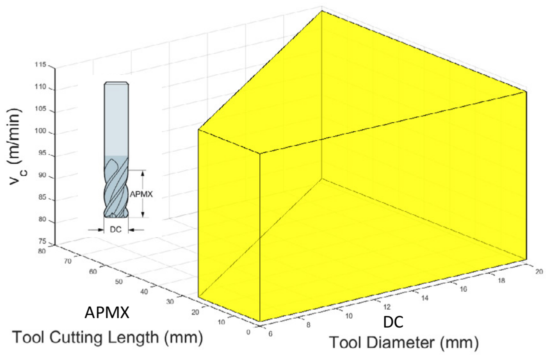

Fig. 4. *Tools stereo kinetic diagram* (B).

This graph contains an example of volume information that maps an entire tool family, collecting and evaluating a group of tools with varying dimensions. This diagram should be replicated as many times as the different possible milling strategies (e.g. face milling, side milling, high feed milling, etc.) and as the possible different materials of interest.

2.3 Cutting tool parameters representation

The fourth graph is the *Operative cutting parameters diagram* (C) and its purpose is to map the cutting parameters of a tool family.

The needed information regarding the milling tools can be extracted from tool suppliers' catalogues. A tool family is typically characterized by tools with different diameters but equal shape and characteristics, e.g. capable of machining the same materials with the same cutting strategies. It is also possible to compare equivalent milling tools from different producers, in order to understand which has the best performance for the specific selected operation. It is a 3D space having the axial depth of cut a_p, the feed per tooth f_z and the cutting speed v_c as axes (Fig. 5). The tool supplier suggests different ranges of cutting parameters for different end mills of the same family. This way, the interest volume represented in Fig. 5 is composed by the sum of the working volumes of each tool of the same family. When proper ranges of cutting parameters are not available from the tool supplier, even punctual data can be represented on the same diagram.

All the tools of a family can be considered in B (Fig. 4) and C (Fig. 5) diagrams or, alternatively, only the two extreme tool diameters (i.e. the maximum and the minimum in the family). The range for the axial depth of cut, instead, is built in a different way: the maximum depth of cut for each tool is represented by the suggested value obtained from the catalogue, while the minimum value corresponds to the minimum depth allowed to form the chip due to the "minimum chip thickness" effect. On the other side, no modifications on the radial depth of cut a_e are foreseen since this parameter is usually not eligible for operator adjustments.

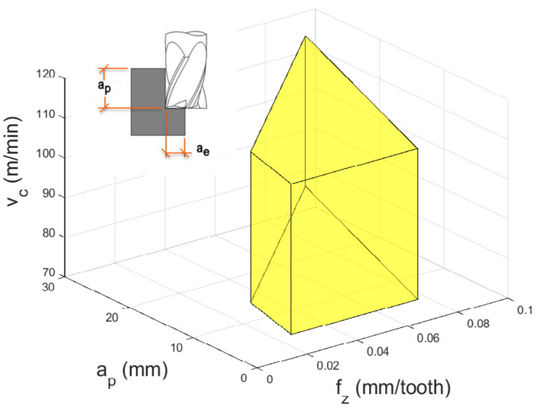

Fig. 5. *Operative cutting parameters diagram* (side milling operation) (C).

C-type diagrams as well clearly vary according to the different operations carried out by the tools, e.g. side milling and full slot milling have different C-type diagrams even when carried out by the same tool.

3. Cutting Performance Mapping

One of the most important cutting information is the achievable *material removal rate (MRR)*, which can be calculated as follows (Eq. 1):

$$MRR = a_p * a_e * f_z * n * ZEFP \qquad (1)$$

The Eq. 1 is rigorous for flat end milling tools but can be easily adjusted for different tool geometries like round-end or ball-end ones.

MRR can be expressed as a function of two of the variables on the axes of Fig. 5 (Eq. 2):

$$MRR(f_z, v_c) = (a_p * a_e * ZEFP * \frac{1000}{\pi * DC}) * f_z * v_c \qquad (2)$$

MRR can be visualized on the working plane $f_z - v_c$. Considering the border diameters of the tool family, i.e. the smallest and the biggest tool diameters for the same tool type, iso-*MRR* curves can be plotted thus generating the range of the obtainable *MRRs*, Fig. 6.

Once the mapping of the tool families is completed, it is possible to merge all the information coming from the mapping spaces, checking if the milling tools respect the limits imposed by the selected machine, according to the flow chart described in the following.

By defining k_c as the cutting pressure, provided by the tool manufacturer or obtained from experimental tests, the cutting power can be calculated from (Eq. 3):

$$P = \frac{a_p * a_e * v_f * k_c}{60 * \eta * 10^6} \qquad (3)$$

If we consider the expression of v_f (Eq. 4):

$$v_f = f_z * n * ZEFP = f_z * \frac{1000 * v_c}{\pi * DC} * ZEFP \qquad (4)$$

we can obtain the power in function of the tool main parameters (Eq. 5):

$$P(f_z, v_c) = \frac{a_p * a_e * k_c * f_z * ZEFP}{60 * \eta * 10^6} * \frac{v_c * 1000}{DC * \pi} \qquad (5)$$

By extracting v_c (Eq. 6):

$$v_c = \frac{P * 60 * \eta * 10^3 * DC * \pi}{a_p * a_e * k_c * ZEFP} * \frac{1}{f_z} \qquad (6)$$

it is possible to obtain the hyperbolic iso-power curves on the $f_z - v_c$ plane. The maximum iso-power curve corresponds to the machine spindle maximum power (Fig. 7).

In addition to the star (*), which represents the recommended working conditions, a bold circle in the graph of Fig. 6-10 represents an example of the working conditions selected by the operator, which must rely on the allowed tool area.

If a region of the nominal tool working area exceeds the machine power limit, for example, the tools cannot be exploited for all their *MRR* capability. In this case, the user must adjust the cutting parameters (v_c, f_z and/or engagement conditions a_p and a_e).

The analysis can be expanded also to the obtainable surface finishing and tool life. This can be done by adopting simplified models, often adopted in industry [12,13], that estimate the surface roughness starting from the tool characteristics and feed rate.

Due to their assumptions, these models are reliable only in some real conditions, i.e. absence of vibrations and static/dynamic tool runout, accurate motion of the machine etc. The calculation mainly depends on three parameters: the feed per tooth f_z and the two lead angles of the milling tool κ_{re} and κ'_{re}[11-13] (Eq. 7).

$$R_{a,face} = \frac{1000 * f_z * tan(\kappa_{re}) * tan(\kappa'_{re})}{4(tan(\kappa_{re}) + tan(\kappa'_{re}))} \quad (7)$$

A constraint on the roughness R_a directly represents a limit for f_z (vertical red line in Fig. 7).

In the proposed method, tool life is estimated by following a modified Taylor approach [14] where the feed per tooth term is added (Eq. 8):

$$v_c T^k f_z^m = C^* \quad (8)$$

When all the Taylor constants are known from experiments or catalogues, it is possible to plot the iso-tool life lines. Fig. 8 represents the tool life in function of v_c.

Finally, an indicative information about the costs of the operation carried out by the selected tool on the selected machine can be calculated [15,16]. This feature bases on some basic assumptions:

- only the contact time between tool and workpiece is considered
- the volume of material to remove must be known.

Two graphs can then be created, the former being composed by three graphs related to the time and cost of the single cutting operations (Fig. 9), and the latter reporting a total cost of the process based on the previous ones (Fig. 10).

Firstly, cutting time is calculated follows (Eq. 9):

$$t_m = \Delta V / MRR \quad (9)$$

where *MRR* depends on the cutting parameters (Eq. 2). Then the cost of the machine usage is computed (Eq. 10):

$$C_m = t_m * c_{machine} \quad (10)$$

The tooling cost is calculated as (Eq. 11):

$$C_t = \frac{t_m}{T} * c_{tool} \quad (11)$$

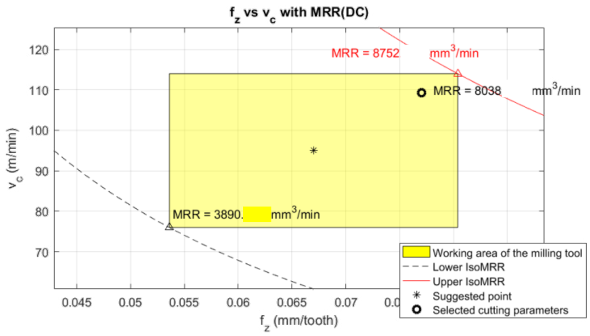

Fig. 6. Iso-*MRR* curves.

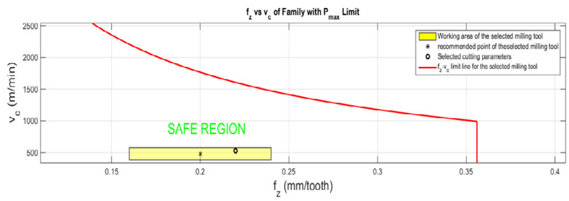

Fig. 7. Performances of the selected tools against power and roughness constraints (red curve).

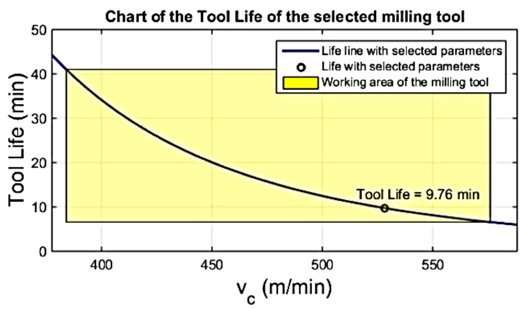

Fig. 4. Tool Life performance.

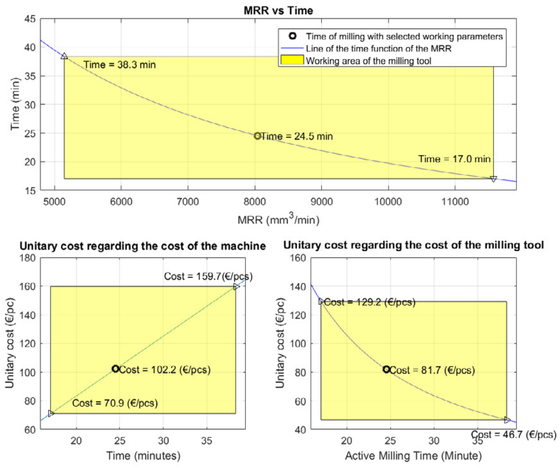

Fig. 5. Machining time, machine cost, tooling cost diagrams.

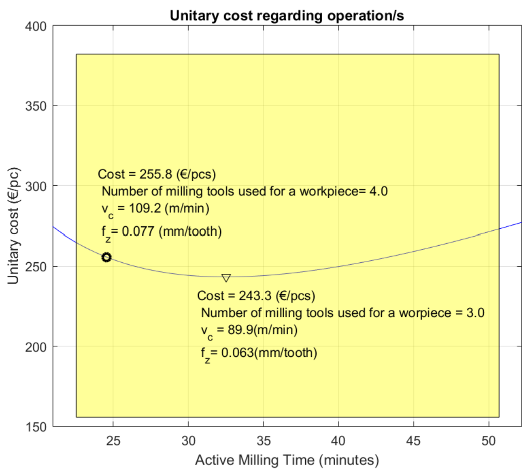

Fig. 6. Workpiece unitary total cost diagram.

4. Application scenarios and test-cases

The presented graphical method is a useful tool to support the selection of machine, tool and cutting parameters in milling applications.

There are various possibilities of exploiting this graphical method for decision making purposes. The *Machine stereo kinetic diagram* (A) is useful when information about the macro dimensions of the workpieces to machine are known: the machine selection can be done to allow the placement of the workpiece on the table. The *Tool-Machine stereo kinetic diagram* (A') is obtained once the tool holder limitations on the tool diameters are known. A' usually works together with A, so it will not be considered as a stand-alone diagram in the following. On the other hand, the knowledge about the geometrical features to machine (e.g. pockets, walls, pillars, etc.) allows for the selection of the most eligible tools for those operations by using the *Tools stereo kinetic diagram* (B). Finally, with the *Operative cutting parameters diagrams* (C), the analysis terminates to be strictly geometrical and becomes technological. This diagram can be used to easily find the optimal cutting conditions based on the manufacturing objectives as quality, productivity and costs.

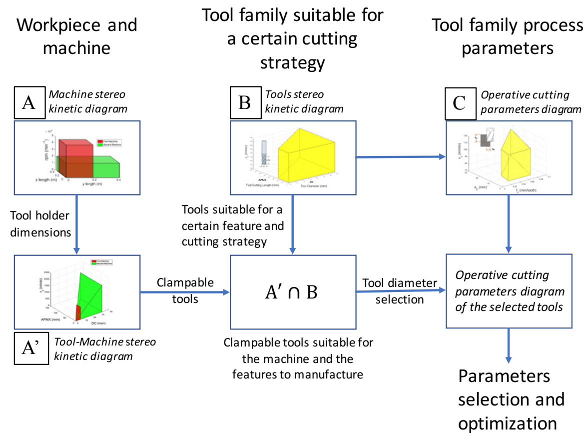

Fig. 11. Flow chart describing the typical use of the presented approach.

Fig. 11 describes a typical use of these diagrams, even if they can be used either singularly or together depending on the cases. For instance:

- A+B+C: machine, tool and cutting parameters must be selected together when a new company/manufacturing line is created. The products that must be obtained are already known.
- B+C: the machine is already defined and the task is to decide which is the most suitable tool for manufacturing certain features on a workpiece. In this case, the selection involves the milling tool and its cutting parameters.
- C: in agreement with the tool producer suggestions, the user already decided to manufacture a certain workpiece feature (or a group of features) on a defined machine and tool cutting parameters must be selected. An A+B verification is recommended in any case.

- A+C: The workpiece features that must be manufactured are known (i.e. *DC* is known), but the machines and the cutting parameters are not.
- A: The workpiece features that must be manufactured are known and the milling tools and cutting parameters have been already selected. The task is to select the machine that could host the machining operations.

The presented graphic approach can be also used to directly map two equivalent tool families from suppliers competing for the same application.

In this case, five tools per family were considered, having diameters of 6, 8, 10, 12 and 16 mm and only the productivity of the two families was analyzed. Three diagrams were produced for this purpose. Competitor α tool family is represented in yellow while competitor β tool family in blue.

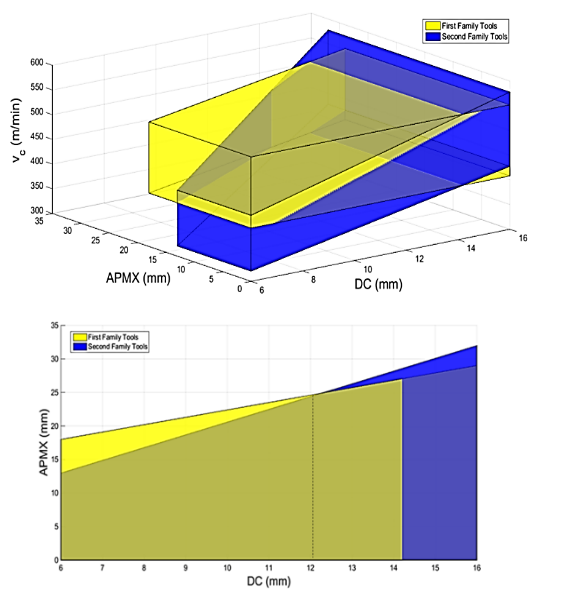

Fig. 12. Geometrical mapping of the milling tools and 2D detail of the APMX and DC plane.

The *Tools stereo kinetic diagram* (B) (Fig. 12) maps the two families' geometrical characteristics. It is easy to see that competitor α tools are designed to work at the same cutting speed, while the β ones cover different cutting speed values, increasing from the smallest diameter to the biggest one. This fact could guide the choice of the correct tool family.

Other analyses are allowed by this diagram (Fig. 12). Although it is not possible to notice any differences on the *DC* axis, since we are mapping the same diameters from the two families, the attention can be shifted on the remaining parameters: the maximum tool cutting length *APMX* and cutting speed v_c. For small and deep features, that imply small tool diameters, competitor A tools are the most suitable, since they have greater cutting lengths. Vice versa, if we look at the bigger diameters of the two families, it is easy to understand that competitor β guarantees deeper features.

The last graph addresses the productivity of the two tool families and is based on the $f_z - v_c$ plane. Competitor α tools are preferable from the *MRR* point of view, Fig. 13. With bigger diameters, the *MRR* difference between the two suppliers is quite small. Competitor α shows a higher *MRR* with respect to Competitor β (+3,5%). With smaller diameters Competitor α assures *MRR* values that are almost twice than Competitor β (+82%).

As previously reported, the use of such graphs can be useful to better guide possible users for selecting different tools depending on the process requirements.

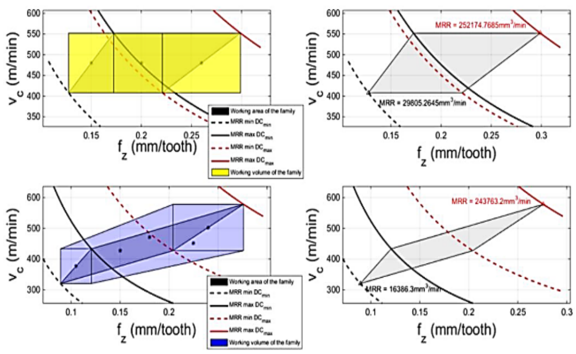

Fig. 13. *MRR* of the two tool families.

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5. Conclusions

The presented method is an effective solution to easily represent the main characteristics of milling machines and tools. Its purpose is to graphically represent the various working volumes of machines and tools, starting from their nominal main features.

The most common and simple formulas for power and roughness calculations are considered in the present release, but this method shows high flexibility since it can easily incorporate different and more complex analytical models.

Only simple milling tool geometries were implemented so far, but future developments will be devoted to study more complex tool geometries. Cost modelling can be improved taking into account inactive production times. An additional further step is to extend this method to other subtractive processes, e.g. turning, but also additive and manufacturing hybrid processes.

Synthetic indicators coming from the real field as well could be incorporated in the presented diagrams with the purpose of tracking tool and machine condition trends and achieving monitoring functionalities.

At the current state of the development, this framework could be considered as a decisional supporting tool that need the human intervention. However, this approach can be potentially integrated in future software architectures capable of providing automatic decision-making solutions to find optimal conditions of machines, tools and operating parameters in an Industry 4.0 environment.

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