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# An integrated approach to support the joint design of machine tools and process planning

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ABSTRACT

The configuration of machine tools and process planning problem are traditionally managed as independent stages, where the process plan is designed by considering a number of machine tool solutions available from catalogue. This strategy presents a number of disadvantages in terms of process results and machine capabilities fully exploitation. The current paper proposes an integrated approach for jointly configuring machine tools and process planning. The approach is structured in 4 major recursive steps that eventually ensure the accomplishment of the best trade-off between the machine tool static and dynamic behaviour, the process quality and the resulting economic efficiency. The benefits of the approach have been evaluated for a test case application in the railway and automotive sectors.

## 1. Introduction

The design and configuration of machine tools is instrumental for European manufacturing competitiveness [1]. Coherently with the mass customization principles and the traditional European know how in the field of instrumental goods production, machine tools should result from a configuration process tightly related to the analysis of the families of products and process quality requirements rather than being a standard and rigid catalogue equipment. This makes the machine configuration and the process planning as two steps of the same problem where the machine tool geometric and kinematics features influence the accessibility to the workpiece operations along with the fixturing system configuration and the machine dynamic impacts on the final quality and costs of the workpiece.

The relationships between machine tool configuration and process planning have been widely investigated by the scientific literature with reference to the following topics: the evaluation of machine capabilities to statically realize a process plan [2], the execution of a process plan across several resources [3], the energy efficient process planning [4–7] and, finally, evaluation of the impact of machine tool dynamic behaviour on the process planning definition [8]. However, the interest of these works is mostly focused on the impact of a specific machine tool architecture and performance on the process planning problem.

The current paper presents an integrated approach to support the joint design of machine tools and process planning. The proposed approach is structured in four major steps as illustrated in Fig. 1.

The first step consists in the analysis of the workpiece CAD model. The workpiece is analysed according to the STEP standard [9] through the identification of machining feature (geometrical description of the region of the workpiece to be machined), machining operations (selection of cutting tools, machining parameters and strategies) and machining workingsteps (MWS – association between a machining feature and a machining operation). On the basis of a number of alternative MWSs, Step 1 identifies the MWSs that globally better match the production requirements and machine behaviour.

The geometric and technological information related to the family of products together with the data about the production demand and the forecasts about possible product evolutions are utilized in Step 2 related to the machine tool design. The outcome of this step is a domain of general-purpose machine tools that fit the production requirements from both the dynamic and static point of view Steps 1 and 2 are traditionally handled as independent phases as general-purpose machine tools are normally configured with no knowledge of the actual products to machine and the process planning is usually developed starting from an existing machine catalogue.

Step 3 regards the dynamic simulation of the machine tool solutions resulting from Step 2 while executing the MWSs identified in Step 1. The dynamic behaviour of machine tools is evaluated against a number of Key Performance Indicators (KPIs) dealing with the energy consumption, tool wear, surface

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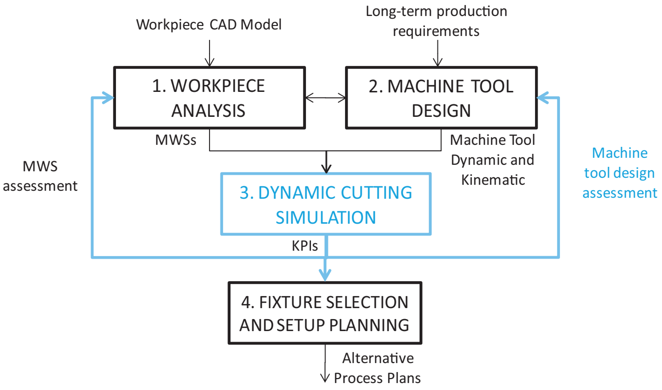


**Fig. 1.** The integrated approach.

roughness, maximal required spindle power and torque. The KPIs are concurrently relevant to the MWS assessment as they could drive the adjustment of process parameters and to the machine tool design by leading to the tuning of the kinematic and dynamic characteristics.

The last step of the approach concerns the selection of one or more fixtures and the definition of workpiece orientations as well as the association of the operations to a given orientation (workpiece setup) [10,11]. The outcome of this phase is the generation of alternative process plans feasible from the workpiece quality requirements [12]. Production time and costs are investigated and optimized on the basis of the MWS KPIs.

The following section of this work will provide the reader with a more comprehensive description of each step of the proposed approach (from Sections 2 to 6). Section 7 will present an industrial test case considered to evaluate the approach benefits. Section 8 will outline the conclusions and future work.

## 2. Workpiece analysis

The workpiece analysis is the first activity in feature-based process planning [13] and aims at defining the operations that are necessary for the complete machining of the workpiece. As stated in Section 1, the workpiece analysis is based on the STEP-NC standard, leading to the definition of the machining feature (geometric description of the region to be machined), machining operations (strategy of machining) and machining workingstep (association between a feature and an operation). As a region can be machined on the basis of alternative strategies in terms of cutting tools, machining parameters or tool path, the same feature can be realized by alternative operations and, consequently, alternative MWSs. The complete realization of a workpiece implies the identification of the technological constraints among the MWSs to be executed. The proposed approach considers two different kinds of technological constraints: precedence and tolerance constraints [14]. Precedence constraints impose an order of execution between two MWSs whereas tolerance constraints require the execution of two MWSs in the same setup to ensure the accomplishment of quality requirements. On the basis of these technological constraints, a network of operations can be built by taking into account the precedence constraints and the alternative strategies to process a specific feature. This network will be employed during the last step of the approach dealing with the fixture selection and setup planning.

## 3. Machine tool design

The configuration of the machine tool is an extremely articulated process that, coherently with the proposed approach, starts from the collection of data about the family of products to be processed. These data include the geometrical and technological characteristics of products synthesized in the workpiece analysis step along with the production volumes.

The configuration process involves the identification of the minimum set of machine tool requirements that accomplish the process constraints (such as the minimum working cube, the number of axes, the spindle orientation and power). On the basis of this minimum set, other types of constraints can be taken into account such as the productivity, the reliability, the available budget, the energy efficiency as well as the machine global size (in the case it should be integrated in a predefined shop-floor). In the case the demand is expected to be variable over time, additional evaluations can be done with regard to the customization of the machine flexibility degree to match the forecasted changes.

All this information leads to the identification of a domain of alternative machine solutions characterized by different architectures, performance and costs. At this stage, the machine design process requires the evaluation of machine performance while executing the process. The analysis of machine–process dynamic interactions enables the evaluation of the machine criticalities and possible improvements.

The next section outlines the dynamic cutting simulation as a means to assess the machine tool design and the workpiece analysis as part of the process plan.

## 4. Dynamic cutting simulation

In the metal cutting strategy, the objective of decreasing manufacturing time and costs is strictly connected to the need for ensuring the requested level of quality. The quality can concern directly the workpiece geometrical properties, or it may refer to the process, for instance, its efficiency in terms of energy consumption.

The workpiece quality is affected by all the phenomena that determine an undesired displacement of the tool with respect to the nominal path. A comprehensive assessment of workpiece quality entails an analysis of four major categories of phenomena: thermal deformations of machines and parts; volumetric positioning errors of the tool tip; dynamic interaction among machine, process and workpiece; trajectories errors due to CNC and/or feed drives performance. Due to the high demanding performance in terms of material removal rate (MRR), the modelling and minimization of vibrations, either forced or caused by chatter instability, represents a major limitation for improving productivity and part quality in metal removal processes. Vibrations occurrence has several negative effects: poor surface quality, out of tolerances, excessive noise, disproportionate tool wear, spindle damage, reduced MRR to preserve surface quality, waste of materials, waste of energy and, consequently, environmental impact in terms of materials and energy [15]. Besides the surface quality and the violation of tolerances, the other effects deal with process quality and have a direct impact of the overall production efficiency. The key for evaluating the level and the effects of vibrations onset is the so-called dynamic cutting process simulation, able to couple the forces originating from the material removal with the relative dynamic and static response between tool tip and workpiece [16]. While the simulation of single processes or machine characteristics is state of the art, the integration of process and the machine tool modelling in the simulations is particularly innovative. The interactions between machine tool, the workpiece and the process surely represent a great challenge as their modelling must be evaluated to address the forced vibrations onset and regenerative chatter instability. The discontinuous cutting forces produced by the machining process excite the tool tip causing a chip section modulation influencing the cutting force itself. In order to incorporate the described effects, the architecture of the dynamic cutting simulation approach should integrate the following functional modules:

- A part program interpreter able to provide the tool path with the related velocity law, together with the cutting parameters defining the operation (for instance, spindle speed and feed rate);
- A "geometric engine" for computing the workpiece-tool engagement and the chip geometry computation;
- A force model relating the chip geometry with the cutting forces expressed by each engaged cutter and their summation;
- A representation of the tool tip and workpiece relative dynamics;
- A time-domain integrator for the overall dynamic simulation.

In most of existing commercial applications, the dynamic loop between machine and process is not closed, as cutting forces disturbances are supposed to not affect tool position and consequently chip section. Actually, the complexity of the model severely reduces the existing commercial applications: the unique commercial application realizing a proper "Virtual Machining" taking into account dynamic cutting is MachPro$^{TM}$ by MALINC.

The dynamic simulation results contribute in evaluating the quality of the machining process. This means to identify a number of KPIs to be measured and tracked over time.

### 4.1. Key Performance Indicators (KPI)

The KPIs considered in the proposed approach are interpreted as a measure of the machine tool dynamics with respect to the required machining operations. On the basis of the value of these indicators some instrumental choices can be realized with reference to the machine structure and control system. In the following part of the current section, the most important considered KPIs are briefly introduced.

#### 4.1.1. Energy consumption

The mechanical energy necessary to perform the machining operation can be obtained by computing the integral of the mechanical power over machining time, namely:

$$\begin{aligned} E_{tot} &= E_{spindle} + E_{axes} \\ &= \int_0^{T_{MWS}} \Omega_{spindle} T_{spindle}(t)dt + \int_0^{T_{MWS}} \vec{v}_{feed}(t) \times \vec{F}_c(t)dt \end{aligned} \quad (1)$$

where $\Omega_{spindle}$ is the spindle velocity, $T_{spindle}$ is the spindle torque, $\vec{v}_{feed}$ is the instantaneous feed velocity, $\vec{F}_c$ is the cutting force and $T_{MWS}$ is the MWS duration.

The computation of electrical energy consumption can be more precisely computed by keeping separated axes and spindle mechanical power since the efficiency of the corresponding drives (whose estimation is out of scope) is usually different. Moreover, in order to compare the copper losses in spindle winding for different MWSs, the Root Mean Squared value (RMS) of spindle torque can be computed as well, starting from torque time history.

In literature, cutting energy consumption is commonly estimated by a constant volumetric specific energy associated to the material type: this approximated approach conflicts with the experimental data, whereas the specific energy changes with tool, process parameters and machines [17]. The specific spindle power consumption (SSPC) is inversely related to cutting speed, feed per tooth, depth of cut and width of cut. The situation can be different if the process becomes unstable (chatter occurrence): as the spindle copper losses are proportional to the RMS of the torque, the presence of a dynamic component in cutting force may cause an increase of SSPC.

All the above-mentioned considerations are automatically taken into account by the developed SW module.

#### 4.1.2. Spindle bearings load

Spindle bearings usually face a progressive wear during machining and most of the spindle maintenance time is devoted to bearings substitution. The bearing catalogues report a standardized formula to compute bearing life by referring to the "dynamic equivalent load", able to synthesize in a single number the effort requested to a bearing during a complex load history. Assuming that spindle bearings load is proportional to the spindle shaft bending moment, the "dynamic equivalent load" can be computed for each MWS, and used to compare the induced bearing stress. In formula:

$$BL = L_{tool} \cdot \int_0^{T_{MWS}} \sqrt[3]{\frac{F_{xy}^3(t)}{T_{MWS}}} dt \quad (2)$$

where $L_{tool}$ is the tool length and $F_{xy}$ is the cutting force resultant in the milling plane ($xy$).

#### 4.1.3. Roughness

Surface roughness depends on several factors related to cutting kinematic and vibration onset. In the proposed approach, the tool vibrations and deflection are directly addressed as a surface roughness indicator. They are crucial in determining an acceptable level of surface roughness and comparing the influence of different dynamic responses on this parameter. Thus, the indicator becomes:

$$R = \max_{T_{MWS}}(\|\vec{x}_{tool}(t)\|) \quad (3)$$

where $\vec{x}_{tool}(t)$ is the tool tip displacement over time.

#### 4.1.4. Tool cutter load

Tool chipping occurs when the shear pressure on the cutting edge overcomes the mechanical resistance of the material. The shear stress is proportional to the cutting force expressed by the single cutter $F_{cutter}$ normalized with respect to the cutting edge engagement ($b$). Therefore, the corresponding indicator is:

$$Cl = \frac{1}{b} \max_{T_{MWS}}(F_{cutter}(t)) \quad (4)$$

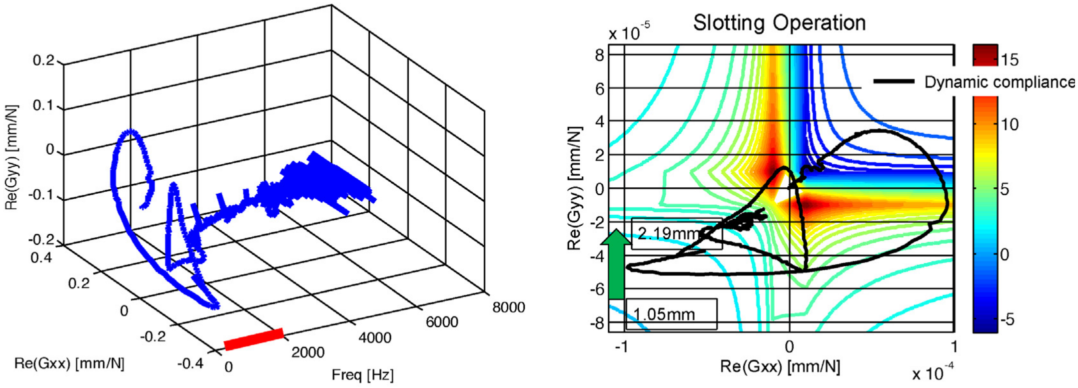
The other KPIs consist in an estimation of the tool wear exploiting by Taylor formula, the maximum spindle power and maximum spindle torque requested to cut the material, as well as the maximum load requested by machine tool axes to provide feed movement. They are directly available from simulation and represent constraints that the machine tool must respect to be able to perform a given operation.

## 5. Machine tool design and MWS assessment

Coherently with the proposed approach, the interpretation of KPIs can drive the improvement choices both for the process planning and the machine tools.

Based upon the KPIs values, a number of MWSs can be updated to obtain a more performing and feasible process. For example, in case the KPI expressing the *surface roughness* indicates that the process is not compliant to the workpiece quality constraints, some MWS such as feed rate or spindle speed can be adjusted; similarly, according to *maximum spindle power*, feed rate, spindle speed or cut of depth can be modified in order to reduce the cost associated to the manufacturing process.

The impact of KPIs on the machine tool choices is more complex to be addressed. The KPIs expressing the required



(a) dynamic compliance

(b) dynamic boundaries

**Fig. 2.** Machine tool dynamic compliance and boundaries. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

*maximum spindle power* and *maximum spindle torque* can be directly exploited to size the proper motor, while the *spindle bearings load* can be used to choose the proper bearings guaranteeing the desired component life. On the other hand, the KPIs associated to *energy consumption*, *tool life*, *tool cutter load*, may be wrongly related to the sole process parameters, whereas, together with *surface roughness* indicator, they strictly depend on machine tool dynamic performance, being severely degraded by vibration onset. Therefore, the enhancement of these latter KPIs can be traced back to the assessment of the best MT dynamic performance able to prevent chatter occurrence. A method to carry out this task is outlined in the following.

The relationship between chatter occurrence and the KPIs can be analysed by exploiting a reduced set of variables; for example, adopting the 0th-order approach described in [16]. Under the following hypothesis:

- Milling operation in $X$ and $Y$ plane, characterized by a straight line trajectory,
- No regeneration in $Z$ direction,
- No low immersion angles,

the relationship between chatter instability occurrence and machine tool is analytically expressed by the characteristic equation of the dynamical system “machine tool + milling process”:

$$\det(1 + \Lambda[A_0]G_{\text{tool-WP}}(\omega)) = 0 \tag{5}$$

where $\Lambda$ is an eigenvalue whose real part must be positive to assure the stability; $[A_0]$ is a matrix that takes into account the orientation of the average cutting force with respect to the axis feed; $[G_{\text{tool-WP}}]$ is the relative dynamic behaviour “observed” between tool tip and workpiece. As the eigenvalue $\Lambda$ also depends on stable depth of cut ($b$), radial and tangential cutting pressures ($K_t$ and $K_r$) and the number of teeth ($N$), it can be used to map the stability limit, knowing the process parameters.

Based on Eq. (5), a first consideration is that the critical depth of cut (i.e., the maximum depth of cut ensuring process stability for all spindle speeds) is strictly related to the minimum of the real part of the relative dynamic compliance between tool tip and workpiece in a frequency range that depends on Tooth Passing Frequency (TPF), while matrix $[A_0]$ indicates which compliance direction is more critical. Hence, the machine tool dynamic assessment can be reduced to the computation of boundaries in a space defined by: *frequency*, $Re(Gxx(\omega))$ and $Re(Gyy(\omega))$, where the variables represent the real part of the tool tip dynamic compliance along the directions defining the milling plane (feed direction $x$ and normal direction $y$). The respect of these boundaries represents a sufficient condition for cutting stability given an operation. From a practical point of view, it means that the compliances in $x$ and $y$ direction estimated by the machine tool designer must be compatible with these specification boundaries: thus, these boundaries may be used to orient the design choices for enhancing the KPIs affected by chatter onset.

For sake of clarity, let considered as an example the realization of a slot milling operation on unalloyed carbon steel performed with a 6 flutes solid end mill. The corresponding cutting pressures is Kt = 1800 N/mm$^2$ and Kr = 700 N/mm$^2$; the cutting velocity suggested by the tool manufacturer, together with the tool diameter, yields a spindle speed of 2000 rpm. These data enable the tracing of the boundaries depicted in Fig. 2: each curve corresponds to a value of desired depth of cut and traces a boundary in dynamic compliance space (negative values of depth of cut do not have any physical meaning, simply indicating that instability is impossible). The portion of dynamic compliance that must be considered ranges between the TPF (that in our case is 150 Hz) and the upper limit associated to process damping, that can be conservatively assumed to be 2 kHz. Thus, the designer is completely aware about the effects that machine tool resonances have in this frequency band on chatter vibration occurrence. For instance, to the dynamic compliance depicted in Fig. 2(a) it is associated the behaviour in the interesting frequency range outlined in Fig. 2(b): assuming the workpiece to be rigid, it results clearly that the most effective strategy to cross the curve corresponding to a higher depth of cut consist in stiffening the machine in Y direction (green arrow).

## 6. Fixture selection and setup planning

The fixture selection and setup planning represent the last step of the proposed approach. This step has been mathematically formulated in [18].

Fixture and workpiece setups are defined coherently with the kinematic structure of the machine tools, thus it can be addressed only after the final characterization of the machine tool that is realized on the basis of the KPIs. Once the setups are defined, a number of alternative process plans can be generated by considering the different machine tool solutions identified in Step 2. The final process plan can be determined by selecting the solution that minimizes the production costs. These costs are evaluated on the basis of MWS energy consumption and tool wear KPIs.

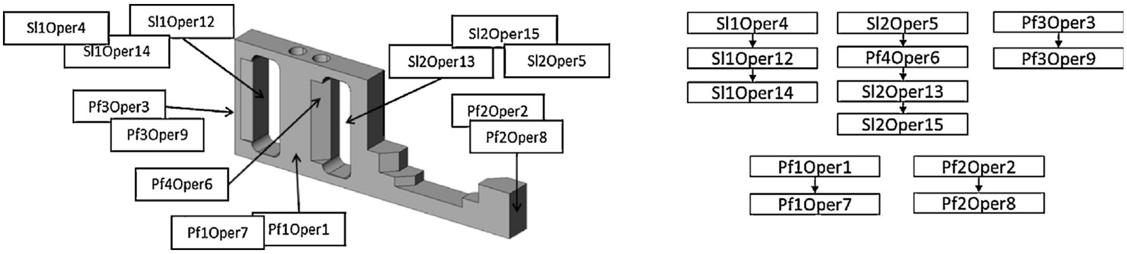


**Fig. 3.** Subset of workpiece MWSs and precedence constraints.

## 7. Application to a case study

The proposed approach has been tested on family of medium-size products realized for the railway and automotive sectors [9,12]. The first step of the approach (workpiece analysis) identified mostly 2.5D machining features mostly including planar faces and round holes and 53 MWSs. An example of the identified MWSs and precedence constraints is shown in Fig. 3.

On the basis of the workpiece analysis as well as the long term product requirements, a minimum set of machine tool requirements have been identified: working cube – 600 mm × 600 mm × 600 mm, required spindle power – 50 kW and minimum axis number 3.

Also, as a result of the productivity, quality and energy constraints, the domain of machine tool types has been reduced to mainly 20 possible alternatives. These machine tool types have been further evaluated in coherence with Step 3 of the approach that is the dynamic cutting simulation. As the workpiece material is not suited to be machined at high speed, a particular attention has to be paid to machine tool structure, which is usually responsible for the low frequency resonances that are excited in the case of low cutting speed; for this reason, machine tool with stud structures and high stiffness have been selected, while spindle stiffness and feed drives performance have not been taken into account. As an example, the process has been investigated one 4 axis machine tool (called “4Axis_MT_beta”) realizing two face milling operations Pf1Oper1 (roughing operation) and Pf2Oper8 (finishing operation). The dynamic analysis outlines that Pf1Oper1 is infeasible (poor surface roughness) because of chatter occurrence. A possible improvement would consist in increasing spindle speed from 300 rpm to 400 rpm in order to get a TPF greater than the limiting resonances, but the cutting speed would exceed the limits suggested by the tool manufacturer related to tool lifecycles and, thus, overall machine investment costs. As a result, the 4Axis_MT_beta version can be optimized with reference to the spindle speed (“4Axis_MT_optimized”) and, consequently, also the process plan requires an adjustment. Table 1 illustrates an example of KPIs indicators computed for the above-mentioned operations with respect to a “virtual” MT yielded by the “4Axis_MT_beta” design: the computation is based on the dynamic compliance at spindle nose provided by a FEM of the conceived machine structure (Fig. 4).

**Table 1**
KPIs of two MWSs.

| KPIs | 4Axis_MT_beta | | 4Axis_MT_optimized | |
|---|---|---|---|---|
| | Pf1Oper1 | Pf2Oper8 | Pf1Oper1 | Pf2Oper8 |
| En. Cons [kJ] | 473 | 5.3 | 318 | 5.2 |
| Tool load [N/mm] | 815 | 444 | 250 | 472 |
| Tool wear [%Max] | 0.03 | 0.015 | 0.02 | 0.015 |
| Spind. bear. [N m] | 371 | 50 | 263 | 53 |
| Surf. qual. [mm] | 0.15 | 0.009 | 0.005 | 0.001 |
| Max Sp power [kW] | 5.7 | 0.61 | 3.5 | 0.60 |
| Max Sp Torq. [N m] | 123 | 12.9 | 71 | 12.7 |

Focusing on Pf1Oper1, the KPI related to *surface quality* – namely, the oscillations of the tool tip – appears to be particularly critical: the peak-to-peak oscillation reaches the value of 0.15 mm, comparable with the feed per tooth that, in the case of Pf1Oper1, is equal to 0.125 mm. Obviously, oscillations are influenced by the maximum value of torque and power requested to the spindle; moreover, the increased RMS value torque negatively affects the energy consumption. Unlike Pf1Oper1, Pf2Oper8 exhibits a quite regular KPIs behaviour.

The great vibration level associated to Pf1Oper1 processing is caused by regenerative chatter occurrence. As Pf1Oper1 is a peripheral milling characterized by an entrance and exit engagement angles equal to 0° and 20°, respectively, the diagram expressing the dynamic compliance boundaries associated to levels of critical depth of cut (Section 5) can be utilized for improving the machine tool design choices (Fig. 5). Considering that Pf1Oper1 requires a spindle speed of 300 rpm with a 4 cutters, a TPF of 20 Hz and the range of frequencies significant for chatter varies from 20 Hz to 400 Hz, the dynamic compliance of the 4Axis_MT_beta design (red line) crosses the boundary associated to a critical depth of cut of 66 mm, while the depth of cut required by Pf1Oper1 is about 69 mm. This circumstance is at the basis of the poor performance stated by KPIs.

Observing Fig. 5, the designer can realize that the most penalizing stability limit is concentrated in the fourth quadrant of the diagram where *Re*(*Gxx*) is positive and *Re*(*Gyy*) is negative. Based on this fact, the designer may rearrange the property of the MT structure in order to keep closer the negative and the positive peaks of *Re*(*Gxx*) and *Re*(*Gyy*), moving these peaks away from the most critical zone. This choice has been implemented in the structure whose dynamic compliance is depicted in Fig. 5 (only the real part) and in Fig. 6 (real and imaginary part), showing that the limit associated to 66 mm is no more crossed, thus, with respect to regenerative chatter instability, the machine dynamical performance has been increased. The corresponding KPIs, with particular

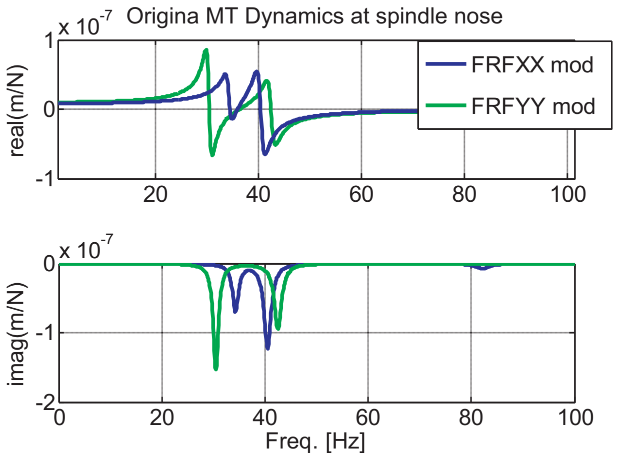


**Fig. 4.** Machine tool dynamics by a preliminary design.

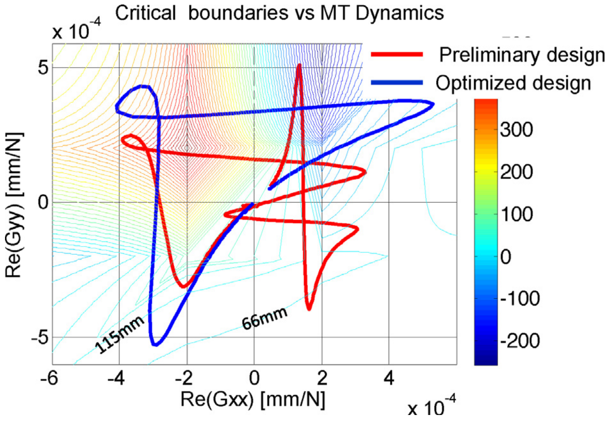


**Fig. 5.** Machine tool dynamics optimization with respect to MWS Pf1Op1. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

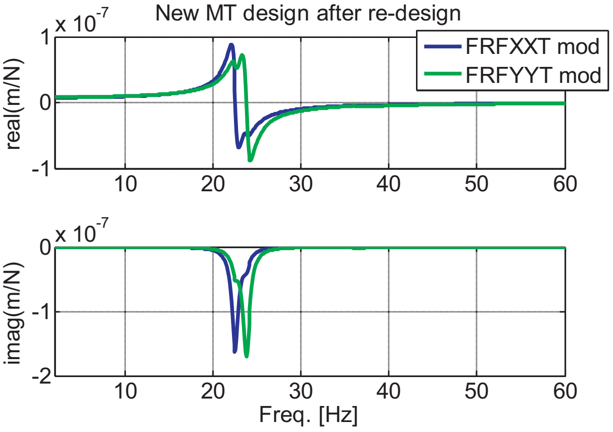
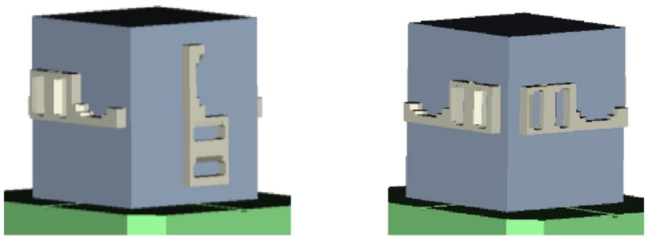


**Fig. 6.** Optimized machine tool dynamics.

reference to the surface roughness, are compliant with the performance enhancement (see the second column of Table 1). However, the final dynamic compliance is higher than the original dynamic compliance meaning that the performance enhancement might be achieved even reducing the dimension of the structural elements and, in turn, reducing mass.

The final set of machine tools is then utilized to generate the fixturing configuration and the setup planning. Specifically, the workpiece results to be completely machined in four setups on a tombstone fixture whose dimensions cope with the machine working cubes. From 6 alternatives of pallet configuration, the minimization of the operational costs leads to a pallet configured with one part per setup and, consequently, one finished workpiece produced per pallet (Fig. 7). Setup 1 and 4 are characterized by the same workpiece orientation but different MWSs. These MWSs could have not been executed in the same setup because of precedence and tolerance constraints.



(a) (b)

**Fig. 7.** Tombstone fixture – setup 1, 2 (a) and 3, 4 (b).

## 8. Conclusions and future work

The current work introduces an innovative approach for concurrent design of machine tools and process planning. The approach is structured as a sequence of steps leading to integrated machine and process solutions that globally optimize the production costs while considering a number of KPIs related to the machine tool static and dynamic behaviour as well as the quality of parts.

The benefits of the proposed approach have been evaluated with reference to a test case provided by a supplier of the automotive and railway sectors. The results outline the possibility to develop customized solutions of machine tools and pallets that – compared to traditional resources – lead to a 8% of production cost reduction (involving tool wear costs and the cost of energy) while accomplishing the products quality constraints.

Future work will mostly regard two aspects. The first one deals with the need to implement a software infrastructure embedding all the steps of the integrated approach so that the overall process can be automatically executed. The second aspect refers to the methodology enhancement by including a wider number of operation types, cutting tool types and machine tool types.

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