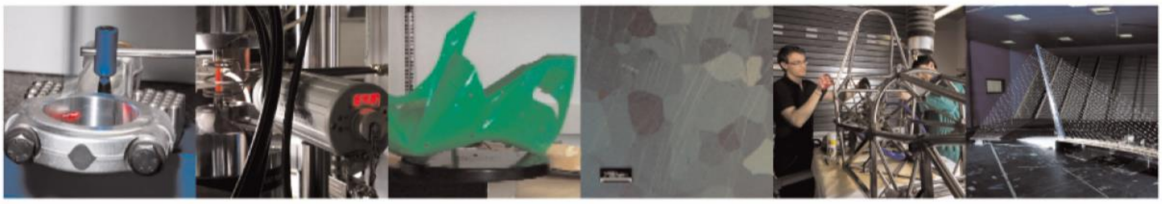

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An integrated framework for combined designing dematerialized machine tools and production systems enabling flexibility-oriented business models

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Abstract

The current work outlines an innovative production system design and management approach based on the concept of dematerialization whose major purpose is to reduce the amount of material, energy and degrees of flexibilities of machine tools and systems to the minimum requirements based on the user needs. The successful introduction of this new generation of Demat Machines and Systems relies on a structured design framework. It starts from an accurate identification of the business models driving the company strategy and the identification of specific markets where the dematerialization principle is a winning leverage to compete. Based on the analysis of production demand and the reference market context, the framework presents a set of methodologies related to the pallet configuration and process planning, the machine tool configuration and the system configuration, all nested together.

The benefits of the Dematerialization framework will be investigated with regards to a set of benchmarks coming from the industrial practice.

Keywords:

Demat machine tools and process design, Demat Manufacturing Systems Energy conscious design

1 INTRODUCTION

The principle of dematerialization is conceived to embrace the instrumental importance of reaching production system and machine tool architectures whose capabilities and level of flexibility are design to match the production requirements of the user. From the production system perspective, this means to indentify a mix of machine tools enabling the addressing of the production demand over a specific reference time horizon. The concept of dematerialization for machine tools refers mainly to the machine tool structure and its dynamic behavior that is designed only with regards to well defined range of performance. As a result of these new design principles, also the process planning design requires a number of new challenges to be addressed.

The complexity of the dematerialization approach is justified with regards to particular production problems where it presents major advantages compared to traditional systems' and machines' solutions. Compared to Flexible Manufacturing Systems (FMS) (Koren and Shpitalni, 2010; Mehrabi et al., 2000), for example, the technological and volumes capabilities along with the flexibility and reconfigurability levels for Demat Manufacturing Systems (DMS) are carefully designed as a result of a configuration process starting from the product analysis and the evaluation of potential evolutions of the reference part family. This makes this system category more cost-effective if compared to FMSs but less robust to unforeseen events which have not been planned. Conceived as an evolution of Focused Flexibility Manufacturing Systems (FFMS) (Terkaj et al., 2009), DMSs are additionally benefited by the adoption of new solutions of machine tools (Demat Machine Tools - DMTs) able to enhance the set of alternatives which can be selected. Thus, users - such as subcontractors - who are asked to manage production demands which can change over time but still have a good visibility over the future orders that can be forecasted would find in the dematerialization strategy a fruitful path. At the machine tool level, the dematerialization design process would produce extremely light structures of machine tools, very fast and energy conscious, whose dynamic performance is satisfying only in specific operating ranges (Van Brussel et al., 2001, Cau et al., 2009, Brecher et al., 2009, Leonesio et al., 2006, Zulaika et al., 2011,).

A first key for successful Demat solutions is the capability to comprehensively match customer needs. In addition, as a result of an increased global awareness about environmental and energy savings in manufacturing, a second key aspect to capture the interest of machine tool builders and system integrators is the production of solutions that are more efficient and sustainable over time. The last strategic factor deals with the development of machine and system solutions capable of dynamically adapting over time the changes of production requirements resulting from products and technologies frequent evolutions.

The aforementioned three key factors can contribute in boosting machine tool builders and system integrators competitiveness. However, the ability to concurrently consider all these aspects while generating cost effective machine and systems asks for renewed and structured design practices. The current work presents a framework for designing DMTs and DMSs. The present paper is an evolution of (Copani et al., 2012) since a detailed description of the methodology and its application on a real case are given.

The rest of the paper will be structured as follows: Section 2 outlines the combined DMT and DMS design framework; Section 3 introduces new flexibility-oriented business models requiring the dematerialization strategy; Section 4 introduces the combined machine tool and process planning design; Section 5 describes the DMS configuration problem; Section 6 introduces an industrial case study and some preliminary results; Section 7 describes conclusions and future works.

2 FRAMING THE DEMATERIALIZED CONFIGURATION PROCESS

The Dematerialization Framework consists in four major tasks nested in a structured approach. It is illustrated in Figure 1 in the form of an IDEF0 diagram. In comparison to (Copani et al., 2012), Figure 1 better underlines the relations between the machine tool design and the process planning, thus giving more relevance to the machine-process co-design methodology stressed in this paper.

The identification of new Dematerialization-oriented business models to be potentially adopted is a preliminary strategic task that will affect the configuration process. Different business models, in fact, will imply different type of supply chain relationships determining a different distribution of responsibilities, costs and risks between manufacturer and system supplier. Thus, they will dictate different type of requirements to be faced by DMT and DMS (such as the volumes to be manufactured, the priorities in terms of costs, throughput times, flexibility, etc.). The production information - structured in a scenario tree representing evolving production demand over time – is passed to the DMT configuration step and the Dematerialize Process Planning. The DMT configuration identifies the Dematerialized machines’ architecture and capabilities. A number of preliminary machine solutions are generated and shared with the Dematerialized Process Planning where a set of alternative process plans are generated and mapped upon the alternative machine architectures and a number of machining KPIs are evaluated. Alternative process plans associated to DMT solutions become the input of DMS configuration. The system configuration problem aims at selecting a number of alternative DMS configurations suiting the production requirements over time. These configurations are passed back to the business model evaluation stage, which selects the most competitive configuration after simulating financial performance under a coordinated customer-supplier business perspective.

3 BUSINESS MODELS AND PRODUCTION ASSESSMENT

In production contexts where market demand can vary unpredictably in terms of volumes, mix and type of products, innovative value propositions of machinery suppliers and system integrators might have the potential to increase manufacturers’ competitiveness and, consequently, to generate added value that can be shared with suppliers. These value propositions (ensemble of products and services) should go in the direction of supplying the most appropriate system solution according to the short-medium term horizon, and of managing efficiently the evolution of production system by adapting it to the change of the demand. On the basis of the analyzed context, two innovative business models are proposed (Copani and Urgo 2012). The first business model -

labeled as “Reconfiguration Guarantee business model” – requires that system suppliers tailors the system on the actual type of customer’s demand without adding additional flexibility whose future utilization is uncertain, and guarantees potential future reconfiguration options at fixed price when eventual change in the demand will happen. In this case, system suppliers would sell reconfigurable machines with limited flexibility, thus decreasing their initial income and postponing further earnings to future reconfigurations that may be needed by customers to address eventual demand changes. For suppliers, the advantage will stay in the possibility to enlarge their market by exploiting this innovative value proposition and in the establishment of long-term relationships with customers. The advantage for customers will lay in limiting the initial investment for extra flexibility and postponing it if and when it will be necessary.

The second business model – labeled as “Capacity Guarantee business model” – implies that the system supplier retains the ownership of machines and guarantees the customer with the right production capacity to manufacture what the market requires during the contractual period, by taking care himself of system adaptations over time. This requires that the customer is able to forecast and continuously communicate changes in market requirements, so that the supplier can design and manage efficiently system flexibility and reconfigurability. Advantages for customers would be the guarantee to have always available -within a pre-fixed range- the appropriate resources, by paying a contractually fixed fee preventing new investments required to support system evolution and management. This strategy is supposed to increase suppliers’ market and profits that can compensate the additional risks they undertake, due to the significant added value of this offer for customers.

To estimate the performance of these two new flexibility-oriented business models, it is necessary to model the customer manufacturing problem through the analysis and forecast of production requirements (e.g. demand and product mix) over time. The manufacturing problem is synthesized in a production scenario tree where each node (scenario) represents a production condition. The root node embraces the present production condition while future nodes represent possible demand evolutions together with the related probability of occurrence. The manufacturing problem formulated in a scenario tree is a necessary input for the generation of alternative solutions of DMT and DMS and for the selection of the optimal solution, as described in the following paragraphs. The optimal technical solution of DMT and DMS is than evaluated under the assumptions of the two business models above described adopting the probabilistic approach of the event-decision tree (Damodoran 2008), which allows the selection of the optimal DMT-DMS-business model combination.

4 COMBINED MACHINE TOOL DESIGN AND PROCESS PLANNING

End users require the design of machine tools increasingly performing in given ranges of cutting parameters (Newman et al. 2012, Wang et al. 2003). This requires the identification of a number of indicators to evaluate the execution of a machining process on a machine tool and adjusting the resulting process plan so to fully exploit the characteristics of the machine tool. In this context, a new methodology for the combined design of the Demat machine tool and the process planning has been proposed. The methodology is based on three steps: (i) analysis of the workpiece machining process coming in the form of scenario tree, (ii) machine tool design and evaluation of the key performance indicators (KPIs) for the assessment of the machining process on the designed machine tool, (iii) process planning.

Coherently with the STEP-NC standard (ISO14649 2003), the analysis of the workpiece machining process (Pellegrinelli and Tolio 2013) leads to the definition of a set of alternative machining workingsteps (MWSs) differing in tool access direction or machining strategy. This analysis is exploited both in the machine tool design and in the process planning hereafter described.

4.1 MACHINE TOOL DESIGN AND KPI

Next generation of machine tools targeting high productivity levels, and consequently high Material Removal Rate (MRR), require the implementation of stiff and heavy mechanical structures, which result in long-delivery-time and high-energy-consuming solutions. The basic idea addressed by DMT concept is to exploit knowledge-based technologies and tools to conceive new solutions of ultra-light machines, capable of achieving cutting edge performance and lower of energy consumption by tailoring the machine behavior to the effective productive mission.

The successful application of DMT paradigm implies the adoption of new design processes that overcome the common practice. As a matter of fact, machine tool designers usually prevent the risk of vibrations during heavy operations by properly selecting the machine structure and component size: in order to avoid the costs, extra energy consumption and the environmental impact caused by over-sizing, the machine tool dematerialization design principle focuses on specific cutting operations that are required across machine lifecycle based on the production demand scenario tree, thus facing two distinct sub tasks:

- Identification of a significant set of cutting operations - provided by process planner after workpiece analysis - relevant for machine tool design;
- Synthesis of the static and dynamic behavior matching the required operations.

Dealing with the second point, a fundamental limitation for achieving high MRR is given by vibrations onset mainly related to regenerative chatter instability and can be interpreted by the analysis of Stability Lobes Diagram (SLD) (Altintas and Budak 1995).

While a great amount of literature exists dealing with chatter modeling and process parameters optimization (Quintana and Ciurana 2011), few works tackle machine tool design criteria aimed at MRR maximization. One of the most recent contribution on this topic is represented by (Zulaika, J.J. et al. 2011): it proposes an integrated approach for designing large milling machines taking into account both mass reduction of mobile structural components and the maximum MRR (assuming it is limited by regenerative chatter). Anyway, the approach shows a couple of relevant limitations: machine tool dynamic behavior is described by a single DoF model and the tooth passing frequency of the target milling operation is not considered. Aiming at overcoming these limitations, in (Leonesio et al. 2013) a new approach has been proposed that can be effectively adopted in Demat design framework.

Indeed, 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”:

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

where Λ 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; $G_{tool\text{-}WP}$ is the relative dynamic compliance “observed” between tool tip and workpiece (denoted with *‘WP’*), that is a function of the excitation frequency ω. As the eigenvalue Λ also depends on stable depth of cut (*b*), radial and tangential cutting pressures

(Kr and Kt, respectively) and the number of teeth (N), it can be used to map the stability limit, knowing the process parameters.

Based on Eq.(1), 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, $\mathrm{Re}(G_{xx}(\omega))$ and $\mathrm{Re}(G_{yy}(\omega))$, where these two latter quantities 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 drive the design choices for enhancing the performance concerned with 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=1800N/mm^2 and Kr=700N/mm^2; the cutting velocity suggested by the tool manufacturer, together with the tool diameter, yields a spindle speed of 2000rpm. These data enable the tracing of the boundaries depicted in Figure 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 150Hz) and the upper limit associated to process damping (Tunc and Budak 2012), that can be conservatively assumed to be 2kHz. Thus, the designer is completely aware about the effects that machine tool resonances have in this frequency band on chatter vibration occurrence. For instance, the dynamic compliance depicted in Figure 2 referred to a traditional MT design (red line), can be optimized according to DMT paradigm in the compliance represented by the blue line.

The new compliance profile assures a higher depth of cut, even if its amplitude is largely greater. Indeed, while traditional machine shows a good dynamic performance in all directions, DMT behavior is very good only along the direction which is more sensitive to chatter onset. The lighter tailoring of DMT material and related energy usage, together with the accomplishment of the stability requirements, severely reduce DMT investment and operating costs.

Once the dynamic compliance is available, a set of proper Key Performance Indicators (KPIs) can be computed for evaluating the suitability of this compliance with respect to the various operation alternatives: these KPIs are strictly linked to vibration onset and deal with the energy consumption, tool wear, surface roughness, maximal required spindle power and torque. The key for evaluating the KPIs 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 (Merdol 2008). The KPIs are exploited in process planning phase to rank different machining alternatives in terms of part quality and energy consumption, thus enriching the optimization objective that is traditionally limited to cycle time minimization.

The algorithm has been implemented and solved by Matlab and Simulink 2010b.

4.2 PROCESS PLANNING

Based on the analysis of the workpiece machining process and the machine design, the goal of the process planning is the definition of an optimized setup plan (Kafashi, 2011, Attila et al, 2013) and pallet configuration (Yao et al., 2007) according to which several parts are mounted in different setups on the same fixture and concurrently machined (Contini and Tolio, 2004; Pellegrinelli and Tolio, 2013). In comparison to existing methodologies (Rameshbabu and Shunmugam, 2009; Mohapatra et al., 2013; Abedini et al., 2013), the here described mixed integer mathematical model (Pellegrinelli et al., 2012) minimizes the number of setups and the pallet energy consumption while saturating and balancing the pallet. Given the number of desired setups (*NSetup*), the model selects for each face v of the pallet, one setup s (i.e. boolean matrix $O_{v,q,s}$) and one pattern q (number of workpiece rows $Qt_{q.row}$ and columns $Qt_{q.column}$). In addition, the model enables the association of the MWSs m to a setup s, characterized by the workpiece orientation r, (i.e. boolean matrix Zs,m,r). The model stands on two different objective functions: productive cost (Eq-2) or productive time (Eq-3). Productive costs include the energy consumption (EC_m), while production times are determined by calculating the time necessary for the MWS execution (MT_m). Both in case of production-cost and production-time minimization, the objective functions maximize the number of parts per pallet, while balancing the number of parts in each setup.

$$\min \sum_{r,m,s} EC_m \cdot Z_{s,m,r} - \frac{\left\{\left[\sum_{s,v,q}\left(O_{v,q,s} \cdot Qt_q.row \cdot Qt_q.column\right)\right] / NSetup\right\}}{a} \tag{2}$$

$$\min \quad \sum_{s,m,r} Z_{s,m,r} \cdot MT_m - \frac{\left\{\left[\sum_{s,v,q}\left(O_{v,q,s} \cdot Qt_q.row \cdot Qt_q.column\right)\right] / NSetup\right\}}{a} \tag{3}$$

Since each pallet could be machine on a single general purpose machine tool as well as on several focused-flexibility machine tools, the generated pallet configurations are evaluated on a set of pre-defined machine tools in terms of feasibility, energy consumption and production time.

The pallet configuration model has been implemented and solved using the IBM ILOG CPLEX Optimization Studio Version 12.3.

5 DMS CONFIGURATION

The DMS configuration activity consists in identifying the set of resources (such as machines, load/unload stations, carriers) that exactly match production requirements while minimizing investment and operational costs over time. This choice is addressed by equipping the system with a degree of flexibility and reconfigurability that is specifically necessary for the considered demand. While the resulting solution is extremely profitable from the economic perspective, the capability of DMS to be focused on a specific production domain also represents a considerable risk whether an unforeseen change occurs and the system is not able to face the changes. This becomes extremely critical in production environment characterized by frequent and unforeseen changes of the family of products in terms of volumes and technological features. In other words, providing an optimized DMS configuration aims at cutting those system capabilities that are not specifically needed, thus reducing the potential of the system to work in modified conditions. Such DMS solutions result to be largely efficient and profitable in production cases where the system user can embrace the demand volatility and, in the case unforeseen events occur, he can rely upon strategic partnerships and agreements with the system builder (coherently to Demat Business Models).

The use of deterministic approaches when dealing with uncertain environments usually leads to poor performance compared to the capability provided by stochastic approaches able to exploit the stochastic information. Other techniques and indicators have been provided to manage the robustness and stability of a given configuration for aproduction system (Gurevsky et. Al. 2013a, Gurevsky et. Al. 2013b). However, stochastic programming has been addressed as one of the techniques to use the available information on uncertainty, even when it is provided in an incomplete form (Birge and Loveaux 2007, Terkaj et al. 2009, Tolio and Urgo 2013).

In two-stage stochastic programming approaches the set of decisions can be divided in:

- a set of decisions that have to be taken before the observation of any of the uncertain elements in the problem. These decisions are called *first-stage* decisions and the period when these decisions are taken is called *first stage*;
- a set of decisions that can be taken after the occurrence of uncertain events. They are called *second-stage* decisions. The corresponding period is called *second stage*.

The definition of first and second stage, together with the corresponding variables, plays an important role in the stochastic programming models. In fact, besides being a simple classification, first and second stage variables define when decisions can be taken and their mutual influence. In the application of stochastic programming to the design of a manufacturing system, first-stage variables define the initial system configuration to be acquired. Second-stage variables are instead used to represent reconfigurations of the initial system to be implemented as a response to changes affecting the production problem to be addressed.

The definition of first and second stage periods grounds on modeling the production problem and its evolution over time. A common approach is encapsulating the possible occurring events in a set of scenarios and organizing them together to define a scenario tree.

An example of scenario tree together with the associated sets of decisions is represented in Figure 3.

The blue nodes represent the production demand over time. The root node represents the initial production problem to be addressed. From this node, two branches depart towards two leaves of the tree (in this case with only two levels). The leaves in the tree model the different characteristics of the production problem in the second stage. The path from the root node to a leaf represents a scenario. It models a possible evolution of the production problem starting from the current characteristics to the one in the associated leaf. Each scenario is associated an occurrence probability, the sum of the occurrence probability for all the scenarios must be equal to 1.

On the basis of demand evolution, a different production system configuration is provided for the considered scenario (Figure 3, red leaf bullets). Two-stage stochastic programming approaches implement this solution definition mechanisms aiming at optimizing an objective function taking into consideration the performance of the solution over all the considered scenarios, usually the expected value.

Grounding on the definition of the scenario tree, the DMS configuration approach considers the following objective function:

$$\min C_{INV} + C_{OP_1} + E_{\xi}\left[\min C_{REC}(\psi) + C_{OP_2}(\psi)\right] \tag{4}$$

where C_{INV} is the investment cost at the beginning of Stage 1; C_{OP_1} is the operational cost in during Stage 1; $C_{REC}(\psi)$ is the reconfiguration cost at the beginning of Stage 2 given the scenario ψ; $C_{OP_2}(\omega)$ is the operational cost during Stage 2 given the scenario ψ and $E_{\xi}\left[\cdot\right]$ is the expected value calculated over all the possible scenarios ψ in ξ (Tolio and Urgo 2007, Terkaj et al. 2009, Alfieri et al. 2012, Tolio and Urgo 2013).

The decision variables are associated to the two stages defined in the scenario tree.

The first-stage variables are:

- the number and type of machine tools in the system configuration in the time period associated with root scenario node;
- the number and type of load/unload stations in the system configuration in the time period associated with the root scenario node;
- the number and type of carriers in the system configuration in the time period associated with the root scenario node;
- the number and type of pallets in the system configuration in the time period associated with the root scenario node;
- the process plans to be used to process the different workpieces in the time period associated with the root scenario node;
- the assignment of the execution of each machining working step to the machine type in the time period associated with the root scenario node.

Second stage variables model the reconfiguration of the initial system at the occurrence of each of the considered scenarios in the tree. Hence second-stage variables model:

- the number and type of machine tools acquired and dismissed before the time period associated with the second-stage for a given scenario node;
- the number and type of load/unload stations acquired and before the time period associated with the second-stage for a given scenario node;
- the number and type of carriers acquired and before the time period associated with the second-stage for a given scenario node;
- the number and type of pallets acquired and dismissed the time period associated with the second-stage for a given scenario node;
- the process plans to be used to process the different workpieces in the time period associated with the second-stage for a given scenario node;
- the assignment of the execution of each machining working step to the machine type in the time period associated with the second-stage for a given scenario node.

The stochastic programming configuration approach has been implemented and solved using the IBM ILOG CPLEX Optimization Studio Version 12.3 providing as result a set of near-optimal solutions together with their reconfiguration options to match the occurrence of uncertain events modeled through the scenario tree.

The resulting set of configuration solutions represent optimized technological alternatives of systems and machines meeting customer's production problem and uncertainty, each one described in terms of resources, costs and other key-performance indicators.

6 INDUSTRIAL APPLICATION

The proposed approach has been tested on an industrial case study provided by an industrial player operating in the motorbike sector as a subcontractor, thus managing a production demand undergoing changes over time. The studied family of parts is composed by three part types: the first workpiece (WPA) is a medium-size engine carter for motorcycle industry characterized by 23 MWSs (21 drilling operations and 2 milling operation); the second workpiece (WPB) is a 4-stroke cylinder characterized by 41 MWSs (37 drilling operations and 4 milling operation); the third workpiece (WPC) is a medium-size engine carter for motorcycle industry characterized by 24 MWSs (22 drilling operations and 2 milling operation). This family of products is expected by the subcontractor to evolve over time as a result of an increasing market request for the analyzed part types. First, the annual demand is 19950, 79000 and 18000 respectively for codes WPA, WPB and WPC; subsequently, the demand of codes WPA and WPC increases to 25950 and 23000 parts/year; finally, the demand of codes WPA and WPC decreases to the initial values, while the demand of code WPB reaches 89000 parts/year.

The family of part types is machined on a flexible manufacturing system composed by 4 four-axis machine tools (MCM Clock 600), 1 load/unload station and 1 pallet transporter. The characteristics of the part types as well as the description of the system are presented in detail in the paper “Energy efficient distributed part program for highly automated production systems” of this issue. The analysis of the part family in terms of (A) machine tool and process planning design, (B) system configuration and (C) business model are described in the following.

A - Combined design of machine tool and process planning

The family parts are analyzed in order to assess the combined design of the machine tool and the process planning. For each part type, some alternative MWSs are identified and the precedence constraint network is defined. The MWSs are evaluated through the KPIs described in Section 4.2 in relation to their machining on a Clock 600 MCM machine tool. The energy consumption related to some MWSs is described in “Energy efficient distributed part program for highly automated production systems” of this issue. For instance, the MWS20_1 and MWS20_2 of WPA are considered. In Table 1, the KPIs concerned with energy consumption and surface integrity have been computed for the nominal parameters (MWS20_1) and one distinct alternative (MWS20_2). It is worth to be remarked that, as claimed in the premises, the energy consumption is referred to the sole material removal (Leonesio et al., 2013): it does not represent an estimation of the overall electrical power adsorbed by the machine, but it is to be interpreted as a mean to drive the choice of MWS alternatives.As the workpiece under consideration is constituted by easy-to-cut material and it can be obtained by several but rather light machining operations, both the energy consumptions are very low. However, MWS20_2 is characterized by a higher feed rate and spindle speed (300 mm/min and 1200 rpm versus 150 mm/min and 700 rpm), as suggested by the greater power consumption. On the other side, the cutting duration is lower and the resulting energy consumption is favourable to MWS20_2, whereas the power loss due to the edge component of the cutting force, depending on the cutting time, is slightly lower. As MWS20_2 is rather heavier than the nominal operation, the better performance in terms of energy efficiency is paid with a higher level of roughness that however remains extremely limited. The KPI referred to roughness is defined as the magnitude of the tool tip displacement estimated by the time-domain dynamic cutting simulation introduced in section 4.

On the basis of this analysis, the model presented in Section 4.2 provides several alternative pallet configurations, 6 of which are detailed in “Energy efficient distributed part program for highly automated production systems” of this issue. This pallet configurations (or pallet type), called 1 and 2 for WPA, 3 and 4 for WPB and 5 and 6 for WPC, result to be improved in comparison to a benchmark case in terms of energy consumption.

B – DMS Configuration

According to what described in Section 5, a scenario tree is fitted on test case data to model the evolution of the production problem over the considered time horizon. In particular, a horizon of eight years has been considered, divided in two stages covering the first and the second block of four years. The scenario tree consists of a root node to model the production problem in the first four years, while two further nodes are defined to match the possible changes affecting the production problem in the second block of years.

The nodes in the scenario tree representing the two considered scenarios are shown in Table 2.

The results of the application of the DMS configuration approach to the test case are reported in Table 3 in terms of the best found solution. Moreover, further information related to this solution, i.e. the saturation of the machines and the machining of the pallets, is reported in Table 4. The results show a proposed initial configuration of four 4-axes machines in the first stage and an additional 4-axes machine to be added in both the scenario nodes in the second stage.

The two-stage stochastic programming approach for the configuration acts in a proactive way, thus taking into consideration the production problem to be currently addressed and the possible evolution over time. In particular, the proposed pallet configuration for code WPB is not the most convenient for the first node but, since future reconfiguration are taken into consideration, the chosen configuration (Type 6) has a smaller number of parts mounted and, hence, provides a higher granularity at the reconfiguration phase. As a consequence, it results to be the most profitable solution considering both current and future system configurations. To provide a comparison with the real case, the company decided to acquire an additional 5-axis machine and to deal with a possible increase in the volume of part WPC (as in scenario A), using a different pallet configuration to reduce the number of setups and machining it on the 5-axis machine. Using the proposed approach, it was clear that an additional 4-axis machine would have been enough to match this increase, although with some risk, since the saturation of the pallet of type 6 would have been close to 100%. Besides this, the choice of an additional 4-axis machine would have been a robust solution since it can also match the needs in scenario B. Clearly, the company decided on the investment in a 5-axis machine also considering other factors. However, if we simply rely on the defined scenarios, an additional 4-axis machine would have been the best solution. Further analysis related to the system configuration solutions can be done considering additional inherent factors like the energy consumption associated to the system (reported in the last line of Table 4) or considering the viable business models as described in the next subsection.

C – Business model

The optimal DMT-DMS optimal solution was finally tested under the hypotheses of the two flexibility-oriented business models proposed in section 3. To this purpose, an event-scenario tree was built, in which the two initial roots represent the two business models. The solution of the tree under different business hypotheses (in terms of price of the production system, reconfiguration service, service fee and residual value of machines) outlined the existence of a negotiation area in which the DMT-DMS solution is sustainable both for system supplier and manufacturer. Thus, there is no optimal overall solution, but a set of sustainable solutions among which it is possible to choose considering the business priorities of customer and suppliers. Priorities can be determined for example by the non-availability of capital for the initial investment in case of the first business model, or by the risk aversion of the parties (in the second business model, the volatility of returns is maximum for the supplier and minimum for the customer). For a detailed discussion, refer to the paper "Sustainability Assessment of New Flexibility-oriented Business Models in the Machine Tools Industry" of this issue.

7 CONCLUSIONS AND FUTURE WORK

The current work presents an innovative methodology for the design and management of a production system with dematerialized machine tool. The approach is bases on three different modules related to the dematerialized machine tool and process planning design, dematerialized system design and business models. During the machine tool and process planning design, the part family is analyzed through several KPIs that take into account the dynamics of the machine tools. According to this KPIs a set of alternative pallet configuration is generated. The pallet configurations are selected during the configuration of the dematerialized system that aims at reducing the investment and reconfiguration costs. Both the pallet configuration and the system configuration model are based on a mathematical programming. The generated system configurations are evaluated according to two flexibility-oriented business models called Reconfiguration Guarantee business model and Capacity Guarantee business model. The benefits of the presented methodology have been investigated with regards to a benchmark coming from the motorbike sector.

Further developments will concern more detail investigations of the energy consumption criteria in pallet configuration and system design problems both with traditional and dematerialized machine tools. The machine tool and process planning design will be better investigated trying to exploit the information deriving from the product analysis for an improvement of the machine tool characteristics and behavior. Finally, the pallet configuration model will be extended to simultaneously mount different part types.

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