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Energy driven process planning and machine tool dynamic behavior assessment

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Abstract

The current work outlines an approach to close the loop between process planning and machine tool dynamic modeling by addressing the problem of energy efficiency across the process design and realization chains, from the process settings and pallet configuration to the machine tool design and usage phases. The proposed closed loop approach consists of an off-line and on-line component enabling the process and equipment dynamic and energy assessment over time. The benefits of the approach have been evaluated against an industrial case study related to the automotive industry.

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Keywords: Process Planning, Machine Energy Modeling, STEP-NC.

1. Introduction

Design of a production machine is a very complex activity to be addressed by considering cost, ergonomics, occupied space, operational flexibility, power consumption, etc. Some key machine performance depends on the machine dynamic behavior, especially the ability to remove in a short time a large volume of work piece material (i.e. the “material removal capability”) [1]. In order to reach the optimal tradeoff in dynamic and kinematic performance, the designer acts on numerous design parameters, some of them linked to commercial components, like ball-screws and bearings, others to custom made structures (typically welded steel plates or cast iron). The relationship between those elements and the global machine performance is often very complex. The conception and optimization of the mechanical structure result often to be supported by Finite Element Analysis that allows forecasting the static and dynamic machine compliance with a reasonable accuracy. The gap between this analysis and the real machine capability is usually filled with the designer experience, who must be able, for example, to translate a required machining capability into an equivalent specification on the dynamic compliance. Besides the designer skills, the machining quality often depends upon the decision process developed by the process planner, who has to be tuned the process parameters on to machine characteristics.

Only very recently, the machine design and the process planning is starting addressing the energy efficiency profiling, as a result of the increasing interest towards the development of energy conscious manufacturing [2]. The study of a machine’s energy consumption requires analyses at component level and at system level, as the overall efficiency does not only depend on the performance of individual components (component level), but also on their interaction and the load cycle of the machine (process level and system level). This demands for a holistic approach towards modeling and optimization of energy flows [3]. Once proper models are available, the energy assessment of machine tools is believed to enable a more accurate machine selection process to exploit a certain set of operations.

The current work proposes a machine tool and process planning joint design approach - referred as CLAMP (Closed Loop Approach for energy efficient Machine tool and Process planning) - by explicitly addressing the energy efficiency problem in a way the design of the process, the equipment and the production strategies will target the trade-off between productivity and efficiency.

2. Literature review

The energy profiling of machine tools - MT and machining processes has generated a large number of academic and industrial contributions which could be clustered by increasing interaction levels between the MT and the workpiece - WP to be processed. The first set of works deal with the energy consumption associated to the realization of single working features, thus specifically referring the MT behavior while cutting the metal [4-7]. These works deal with only a partial evaluation of the MT energy profile as they only refer to the mechanical energy required to remove the material, without considering machine peripherals and the efficiency of components and subsystems.

A second branch of literature focuses on the energy modeling of MTs by means of the characterization of its operational states (for the basic energy consumption), while the process efficiency is evaluated computing an overall cutting specific energy considering the machine absorption for different combinations of process parameters. Avram and Xirouchakis [8] propose a methodology for estimating the mechanical energy requirements of the spindle and feed axes with respect to 2.5D machining strategies by taking into account steady-state cutting and positioning transients. Balogun and Mativenga [9] propose an extended MT electrical energy states for modeling the direct energy requirements in mechanical machining processes where the energy consumption of MTs is considered with respect to the basic, the ready state and the cutting states. This enables to associate to the realization of a working feature and energy profile that accounts all the MT subcomponents, including kinematic chains (guideways, motors, transmissions, etc.). However, all the above-mentioned models consider the cutting process in an approximated way: for instance, the effect of cutting force/torque dynamics on energy consumption and vibrations occurrence is not taken into account.

The last group of works refers to the machine modeling as a whole by including the static and dynamic features. The manufacturing of a WP can be enriched by energy efficiency information that embraces a realistic cutting force behavior, together with other performance indicators related to vibration occurrence (also due to regenerative chatter); energy consumption and performance indicators can be computed in time while executing a part program in a proper virtual environment, including positioning transients. Leonesio et al. [4] propose an integrated approach between MT and process planning where the MT architecture and performance are tuned on the basis of a set of performance indicators considering energy consumption, associated to static and dynamic components of cutting force. The research advances are concurrently pushed by a strong industrial commitment in the field of energy conscious manufacturing. A large number of MT builder are enriching their solutions with new sensors, controllers and HMI (Human Machine Interfaces) supporting the energy monitoring of the equipment over time [10-11]. New high-efficiency components have started to be adopted, together with more intelligent PLC strategies aimed at deactivating some peripherals when unused. Even if the available portfolio solutions are mainly related to the monitoring phase, this constitutes an interesting proof of the industrial sensitivity to this topic.

Within the MT energy profiling there is still a number of open issues. The current available energy models of MTs mostly consider the MT as a discrete set of operational states. In addition, the available machine energy models are frequently associated to the execution of very simple tasks rather than complex operation chains like a complete pallet execution where also the auxiliary devices and systems are instrumental contributors to the energy assessment. A further poorly addressed topic is that the evaluation of the MT under the energy efficient drivers is not currently linked to the MT design process so that the machine energy performance is not coupled to any design actions for the machine improvement.

The energy optimization drivers can be further exploited under the process planning perspectives by addressing several key questions. The energy efficient process planning is currently exploited by focusing on the execution of single WPs and considering a limited family of machining operations [12-13]. Only in few works the energy drivers are incorporated in the pallet set-up planning and configuration problems [4]. In addition, the energy efficient process planning is still considered as coupled to single MTs. The possibility to conceive the process plan as a distributed network coherently to the network part program (Net-PP) principles [14] constitutes an additional degree of freedom in the energy optimization process, where sub-portion of the pallet can be assigned and processed by different machines operating in the shop-floor coherently to their energy consumption. A further element of improvement for process planning should regard the MT natural degradation process and the related changes in the energy consumption which would require the process settings to be adapted over time and, possibly, the adjustment of the pallet assignment to the machines.

The current work will address a number of the outlined open issues. The rest of the paper is organized as follows: Section 3 describes in more detail the CLAMP framework; Section 4 outlines the MT dynamic and energy efficient modeling and assessment for the MWS characterization; Section 5 refers to the generation and the analysis of alternative pallet configurations; in Section 6, the proposed approach is tested on an industrial test case.

3. CLAMP framework

The CLAMP framework is conceived to enable a joint design of MTs and process planning where the energy efficiency represents the optimization driver. The energy efficient design strategy can be considered both during the green field design and also while the machine is running in the shop-floor. As a result of this perspective, CLAMP is structured in two components (Fig. 1). The off-line component referring to the green field design addresses the following topics: MT energy efficient modeling; process design and pallet configuration; MT design improvements based on the energy assessment while exploiting the process. The on-line component deals with the brown field design where all the equipment is dynamically managed while running in the shop-floor. It particularly refers to: pallet assignment to the most energy efficient MTs; process parameters adjustment based on anomalous MT behavior along with the MT natural degradation process; management of machine faults by adapting the pallet assignment and routing in the shop-floor.

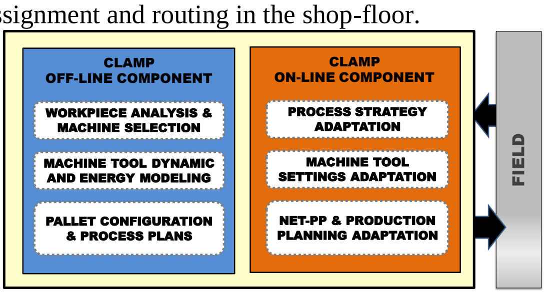


Fig. 1. CLAMP off-line component.

For seek of clarity, the current paper will pose the attention only on the CLAMP off-line component and will leave the description of the on-line component to future works. This off-line component is structured in three communicating modules dealing with process design, the MT evaluation and the pallet configuration and process planning.

The first step consists in the *analysis of the WP* CAD model and in the identification of a family of MTs whose architecture and performance match the WP technological minimum requirements. The WP is analysed according to the STEP standard [4,15] in terms of machining workingsteps MWS [4] and precedence and tolerance constraints among the MWSs [16].

Together with the data about the production demand and the forecasts about possible product evolutions, the geometric and technological information related to the family of products formalized through the WP analysis into the MWSs lead to the identification of a *family of MTs whose architecture and performance* match the technological minimum requirements. The identified MTs are modelled under the dynamic and energy perspectives so assess their behaviour over different operation modes, i.e. while realizing the cutting operations, the rapids and in stand-by operations. Information provided by this MT assessment is used to characterize the WP MWSs against a number of KPIs concerning MWS feasibility and performance such as the MWS energy efficiency.

The last step of the off-line CLAMP concerns the selection of one or more fixtures for each considered MT and the generation of *alternative pallet configuration* and process plans [17]. The alternative pallet configurations generated for a specific MT minimizing production costs, e.g. energy consumption cost, are evaluated under the machinability constraints by referring to the MTs available in the shop floor. The outcome of this analysis is clusters of MWSs that result to be feasible for each MT/pallet pair and the associated KPIs. The reader will find more details about the first module of the CLAMP off-line component in [5] where a comprehensive description of the WP analysis is provided. The other two modules have been described in the following sections.

4. MT dynamic and energy modeling for MWS characterization

The dynamic behaviour of MTs while performing the identified set of MWS is evaluated against a number of Key Performance Indicators (KPIs) dealing with tool wear, surface roughness, spindle bearings stress, 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 the selection of the most suited MT. Since the KPIs are strongly influenced by tool vibrations onset, they are computed exploiting the so-called *dynamic cutting* simulation, able to couple the forces originating from the material removal with the relative dynamic and static response between tool tip and WP (see [4] for further details).

From the energy point of view, in order to allow a consistent consumption evaluation, the usual CAE tools for machinery sector have to be enhanced with new functionalities to simulate the energy flows in a system: power and energy along with functional variables as force and displacement have to be computed for each model element. This leads to the development of a comprehensive MT energy simulator for estimating the energy consumption associated to each MWS: it allows the simulation of a work cycle, providing the estimation of the energy consumption for all the relevant machine elements (e.g. drives, spindle and axes, cooling systems, hydraulic units, etc.). In addition, the simulator performs post-processing analyses aimed at pointing out the internal energy flows and, consequently, identifying which is the machine "weak point" in terms of efficiency for a given MWS. Fig. 2 shows the internal architecture of the machine simulator and its four modules: the NC emulation module, the kinematic and geometric emulator, the cutting process modelling module, and the energy evaluator. Based on various information (like maximum axis speed and acceleration), the NC emulation module analyses the MWS part program (in ISO format) extracting the instantaneous speed and acceleration of each axis at a given time. Given tool geometry, raw material, and tool trajectory, the kinematic and geometric engine provides tool-WP engagement and material removal rate information over time. Then, the cutting process module, based on a mechanistic approach, determines the average cutting torques and forces due to milling parameters set, the instantaneous material removal rate, tool-WP engagement and the instantaneous feedrate. For heavy machining, when the simple average force component could not suffice for realistic cutting power estimation, the energy simulator retains the output of dynamic cutting simulation, where the forces and torques are typically affected by vibrations onset.

Once the machine load and the kinematic information are determined, the energy evaluator launches the energy simulation of the whole machine, including the peripherals. The model behind the simulation follows a modular approach consisting of an aggregation of several "virtual components" that correspond to the various MT subsystems [18]. Due to the complexity of the "MT as a system", the overall energy model is characterized by a multi-domain nature, ranging over pure mechanical phenomena (e.g., material removal), electromechanical devices (e.g., motors), thermodynamics (e.g., fluid transformations inside chillers and pumps, heat exchange) and electronics (e.g., motor drives, CNC). Given the part program and the real control strategies (both in terms of drives regulator and PLC), the behaviour of each MT subsystem is fully determined and the simulator is able to provide the energy consumption due to the execution of the work cycle and the basal losses associated to the various unproductive states (idle, stand-by, warm-up, etc..).

5. Generation and machinability of alternative pallet configurations

The MT modeling phase described in the previous section indicates if the identified MWSs can be processed by a set of MTs in specific set-ups and what is the associated energy effort and machine dynamic behavior. This analysis represents the basis for configuring the pallet where multiple parts will be loaded in specific set-ups in order to be processed by the machines.

The goal of this phase is to determine all the viable options of alternative configuration of the pallet, alternative machines that can perform the operations as well as several process plans which can be realized. This is realized by formulating a mathematical model that is comprehensively described in [5]. The idea is to identify clusters of MWS and to define new KPIs at cluster level for each pallet configuration/MT pair so that the best MT can be selected for each cluster. During this analysis, both the pallet feasibility and the MWS feasibility are analyzed: the MT working cube is checked against the pallet dimensions; the MWs accessibility is evaluated on the basis of the MT kinematics; MWS machining parameters are compared with the MT performance. New KPIs related to the MWS cluster such as the cluster energy consumption will be defined taking into account the characteristics of the MWS. The generated options will be consequently assessed during the on-line stage, i.e. when the best association of MWS, pallet configuration and MTs that accomplish the energy efficiency targets in the most effective way will be performed.

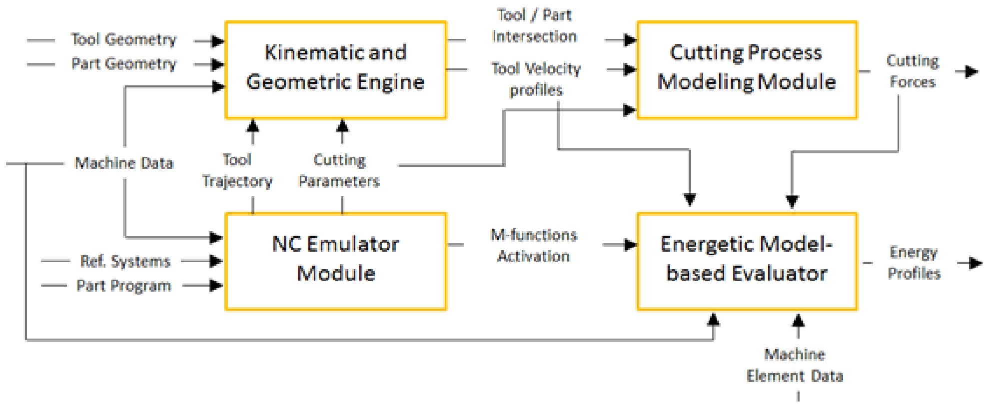


Fig. 2. Energy simulator architecture

6. Case study

The presented approach is tested on a family of six mechanical and medium-size engine carter for motorcycle industry requiring metal cutting processes on CNC MTs. For seek of clarity, the analysis presented in the current section will only refer to one part type – WP 311 - that will be considered the driving example (Fig. 3).

The WP analysis leads to the identification of 23 MWSs (drilling and milling operations) associated to three working directions. The accomplishment of geometric and technological characteristics requires MTs with minimum 4 axes. Two types of MTs selected from a MT builder standard catalogue have resulted viable. They will be referred as Machine A and Machine B. Machine A is a 4 axis machine tool with linear motors that require a specific refrigerating system. Machine B is characterized by the same architecture, but it is actuated by traditional rotational motors that do not require to be cooled. Besides the aforementioned actuating systems, the machines have been analyzed by going through all the other components: the electrospindle with its cooling system; the service cabinet (comprising the panel for distributing the air to the pneumatic actuators, hydraulic unit for powering the hydraulic actuators, air treatment unit); the electrical cabinet containing elements as power drive, numerical control, relays, etc.

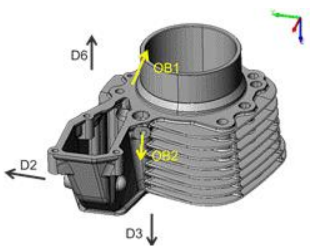


Fig. 3: WP 311

For both the MTs, the energy efficiency (among other performance indicators) has been assessed by relying upon the identified KPIs using the MT energy simulator. The results of the energy based MT analysis led to the following considerations:

- The consumptions in Machine A are always greater than the corresponding ones in Machine B as a result of the great impact of machine auxiliary devices as shown in Fig. 4 for a MWS taken as example (70% of the total consumption in Machine A and about 61% in Machine B, which is not equipped with axes cooling system).
- The milling and drilling operations of the workcycle do not require significant torques and forces: so drives (axes and spindle) do not represent the main energy consumers. Therefore, the optimization of MWSs specifically oriented to energy reduction does not provide a major contribution to the overall efficiency of the process.
- The absence of axes cooling system in Machine B (due to the very low heat dissipation of the rotational motors) determines the main energy saving respect to the Machine A.
- Boring and drilling operations require less energy in both machines compared to milling operations as the shorter processing times reduce the basal consumption (mainly due to the machine auxiliary systems) and the lower removal rate determines a less impact of drives on the total required energy.

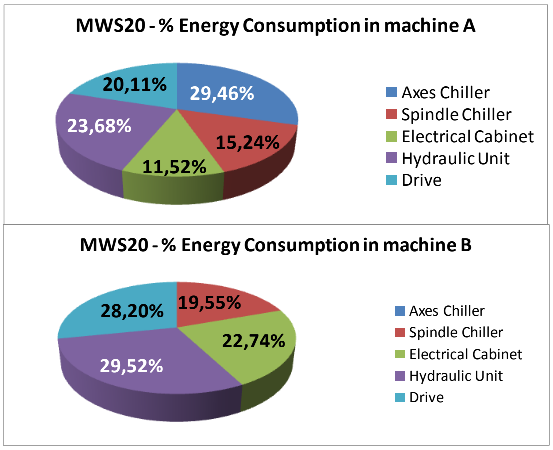
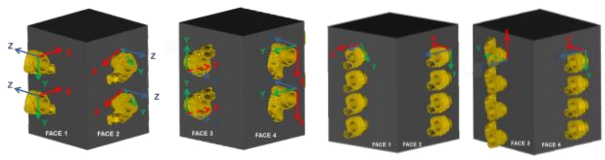


Fig. 4 Energy consumption for MWS 20

These energy related analysis along with the technological ones referring to the capability to process the identified MWSs lead to several alternative solutions of pallet configurations. As an example, two pallet configurations - identified as Pallet configuration 1 and 2 - are hereafter analyzed. These pallet configurations are respectively optimized in terms of energy consumption on the Machine A and B (Fig. 5). Pallet configuration 1, based on a cube fixture 0.8x0.8x0.8 m^3, presents 8 WPs in 4 different setups (2 WPs per setup in order to have a balanced pallet). The production costs related to energy consumptions (0.20 €/KWh) are 0.18 €/part. Pallet configuration 2 is generated considering a fixture whose dimensions are 1x1.1x1 m^3. It presents 4 WPs in the same setup for each face of the pallet. The production costs related to energy consumptions (0.20 €/KWh) are 0.10 €/part. The machinability of the Pallet configurations 1 and 2 are analyzed respectively in relation to the MT A and B. Pallet configuration 2 cannot be machined by the MT A since the machine working cube dimensions (1.2x2.19x1.05 m^3) do not fit the dimensions of the pallet. On the contrary, Pallet configuration 1 can be loaded on the Machine B and every MWS results to be feasible in terms of accessibility, required power and torque.



(a) (b)

Fig. 5: Pallet configurations 1 (a) and 2 (b)

The total energy consumption related to the MWSs execution on the machines A and B for Pallet configuration 1 is respectively 4.11 KWh and 2.13 KWh. The energy consumption for the machining of the Pallet configuration 2 on the Machine B is 1.065 KWh. During the on-line pallet assignment to the machines, it will be consequently necessary to choose between the flexibility coming from the possibility to dispatch the pallet across several resources or saving energy but having a very rigid process plan involving only one machine.

Summarizing, the results collected during the application of CLAMP to the case study outlined the major considerations:

- The complete energy modeling of MTs helped identifying that, in this specific case, the MT efficiency is dominated by auxiliaries. This aspect could not be addressed with traditional MT models accounting only the energy associated to material removal process.
- The energy based pallet configuration provides the decision maker with new additional pallet alternatives where surprisingly MTs with very large working cube can be adopted even though they are traditionally considered less effective (they have rotary motors that do not require the axis chiller).
- Drilling operations are quite different from milling operations in terms of rate of energy usage. This might enable a distributed process plan assigning different cluster of operations to different MTs.

7. Conclusions and future works

The proposed work outlines a new approach – entitled CLAMP – for concurrently managing the process and MT design by adopting the energy efficiency policies. As addressed with regard to the driving example, the energy driver revealed to strongly influence the MT design by considering the efficiency of every sub-component such as the auxiliary and, concurrently, leveraging the pallet configuration policies traditionally based on throughput maximization.

Future works will refer to the development of the CLAMPS on-online component as well as an extensive testing campaign on a case study.

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