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An Integrated Setup Planning and Pallet Configuration Approach for Highly Automated Production Systems with Energy Modelling of Manufacturing Operations

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Abstract

In production environment characterized by frequent changes of the part families demand together with the need of reducing the environmental impact of manufacturing, new solutions of machine tool and production system architectures could result extremely strategic together with process planning activities as a mean to exploit all the resources capabilities. The current work proposes an integrated methodology and a software infrastructure to support the process planning and pallet configuration solutions whose major goal is to minimizing production costs – including costs for energy consumption and cutting tool wear - while maximizing the number of finished workpieces per pallet.

Keywords: Setup planning; Pallet configuration; Energy efficient manufacturing operation

Glossary

Machining feature, *Machining operation, Machining workingstep* (MWS): [1]; *Workpiece Orientation*: orientation of the workpiece when mounted on the fixture; *Workpiece Setup*: orientation of the workpiece on the fixture and description of the MWSs to be executed, *Pallet*: fixture mounting more workpieces; *Pallet face*: geometrical zone of the pallet that can mount identical workpieces in the same setup; *Pattern*: workpiece rows and columns number for each pallet face.

1. Introduction

The European Manufacturing sector represents the 20.1% of the global European value added production corresponding to 8.1 Billion Euros [2]. A significant amount of this production consists in the process of medium size, complex shape metal components manufactured by means of metal cutting processes. With specific focus to families of products manufactured in high variety and mid-high volumes together with a heterogeneous product portfolio, the production demand is frequently affected by the evolution of product geometric and technologic features as well as by volume fluctuations.

As a result, both machine tools and systems are generally conceived with a number of reconfigurability options and/or flexibility degrees which can be exploited coherently with production requirements, thus enabling the ability to robustly matching evolving production demands [3].

However, despite the specific machine and system architecture, the scientific community and the industrial practise jointly recognize in the process planning and pallet/fixture configuration very strategic keys to improve system throughput and concurrently an efficient

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mean to control the energy consumption of the system over time [4].

Traditional process planning activities are rarely structured in an integrated methodology which can comprehensively support the process planner across the entire task. In addition, existent commercial software tools for computer aided process planning (CAPP) do not cope with the automatic definition of pallet configurations, the optimization of the operation sequence for the part machining [5] or the energy modelling of the cutting process [6].

The proposed work outlines an integrated approach for holistic process planning for flexible and reconfigurable production solutions whose goal is to maximize the throughput of parts while reducing production time and cost taking into account the energy consumption.

The current paper is structured as it follows: Section 2 outlines the main features of the process planning and introduces the new proposed approach by highlighting the major novelties compared to the state of the art; Section 3 describes the mathematical modelling of the pallet configuration task; Section 4 deals with the application of the proposed approach to an industrial case while Section 5 addresses the work conclusions and future works.

2. Holistic process planning

This section introduces a semi-automatic process planning approach and a software platform. The process planning methodology refers to components requiring the adoption of pallets to be machined. The proposed methodology has two major innovative aspects. The first one deals with the capability to generate several solutions of process plan over time by accomplishing the product evolutions. The second aspect focuses on the energy modelling of the machining process where the execution of each workingstep by a specific machine tool is dynamically simulated. Indeed, the proposed approach aims at generating alternative process plans minimizing production time or costs. Production costs consist of costs that are strictly related and directly associable to the MWS execution, such as the energy consumption cost and the tool wear cost. The MWS energy consumption is calculated by the machine-tool dynamic simulation that estimates the energy absorbed by the cutting and required for moving the machine tool axes. The cost related to MWS energy consumption is inferred from the manufacturer's energy cost, e.g. Euro/KJ. The cost related to the tool wear consumption is evaluated considering the tool cost and the tool life reduction due to the MWS execution.

The proposed approach is structured in 5 main steps, as illustrated in Figure 1. The w*orkpiece analysis* (Activity A1) deals with the identification of the MWSs necessary for the complete machining of the workpiece and the holding surfaces (HSs) for the fixturing of the workpiece on the pallet. A number of alternative operations (e.g. alternative MWSs) can be identified for the same feature, depending on alternative cutting tools, process parameters or tool access directions (TADs). MWSs pertaining to the HS lose their accessibility and are considered as not-machinable in that related setup.

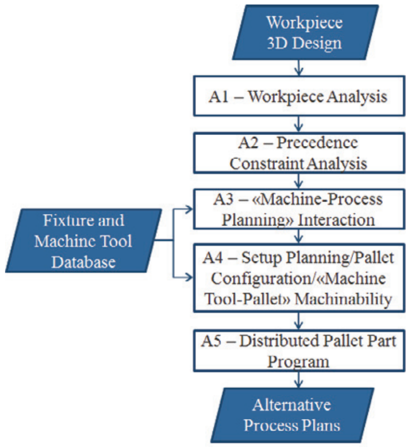


Fig. 1. Activity Schema of the proposed approach

The *precedence constraint analysis* (Activity A2) deals with the generation of a MWS network that guarantees the satisfaction of manufacturing quality specifications [3]. Two kinds of constraints are considered: precedence constraints and tolerance constraints. The former represent the necessity to perform a MWS before another; the latter impose the machining of two MWSs in the same setup.

Consequently, MWSs of the network are evaluated with regards to a set of Key Performance Indicators (KPIs) describing the *machine-process planning interaction dynamics* (Activity A3). KPIs are determined by performing a dynamic cutting simulation of the MWS execution and evaluating the machine tool dynamic compliance [7]. KPIs mainly refer to *product quality* (i.e. surface finish quality), *machine tool kinematics and dynamics* (i.e. spindle bearings load and tool cutter load) and *cutting energy consumption* of machine tools while executing the machining process (i.e. energy consumption). Unlike green and energy consumption process planning approaches [8-9], the presented paper does not evaluate the energy absorbed by the machine tool during the operation execution but the cutting energy and axes moving consumption.

On the basis of the workpiece analysis and the generated network, the production cycle for the complete workpiece machining requires the resolution of the *setup planning and pallet configuration* problems (Activity

A4). The setup planning problem determines the number of orientations of the workpiece in the 3D space to be completely machined. Each change in the orientation of the workpiece requires an un-mounting and re-mounting of the workpieces on the fixture, and consequently a certain time utilization and the risk of compromising the machining precision and manufacturing quality. The pallet configuration problem determines the number, disposition (pattern) and mix of pieces to be clamped on the fixturing device of the pallet as well as part positions and orientations.

The pallet assignment to a specific shop-floor machine implies that the resource has the capability to execute the requested operations (*machine tool-pallet machinability*). This means to ensure the appropriate number of axes and working cube for processing the pallet as well as the achievement of specific MWS KPIs.

Based on the final set of pallet solutions, the last step is to implement the *distributed pallet part program* (distributed across resources of the shop-floor) (Activity A5) involving the development of the program for each MWS, the MWS execution order and, finally, the generation of the rapid movement of axes [10].

The proposed process planning approach has been implemented in a software tool composed of two different modules: the first module handles the A1 and A2 activities, while the second module handles the A3, A4 and A5 activities.

3. Developed methodologies

The current section outlines the methodologies employed for the activity A4.

The proposed approach aims at contemporary solving the setup planning and pallet configuration problems while accomplishing two alternative optimization strategies:

- the minimization of the machining time and maximization of the saturation of the pallet, under the constraint of a maximum cost-per-part,
- the minimization of the production cost-per-part and maximization of the saturation of the pallet under the constraint of a maximum production time.

The process generates a number of alternative pallet configurations ranked for different costs and time. In both cases, the production costs take into account the energy consumption and cutting tool wear for each operation. The cost related to the energy consumption is evaluated considering the energy consumption of each MWS provided by Activity A3 and, as an input, the energy cost per KJ. The cost related to the cutting tool wear is estimated on the basis of the cutting tool life percentage reduction for each performed MWS and the cost of the cutting tool.

The proposed approach considers as input the number of the machine tool axes, the pallet geometrical description and the workpiece analysis (holding surfaces, alternative machining operations and MWs precedence and tolerance constraints) [11]. The number of machine tool axes influences the MWS feasibility given the workpiece orientation, thus leading to different pallet configurations. The algorithms are currently developed for deciding on the MWS visibility only cope with 3 and 4 axis machine tools.

3.1. Pallet configuration mathematical model

Pallet configuration and setup planning problems are based on a linear mathematical model and it assumes that each pallet mounts one part type in different setups.

Indexes

$m \in Mws = 1..NMws$ - MWS identifier (alternative MWSs are included); $w \in FMws = 1..NFMws$ - Identifier of selected MWSs; $s \in Setup = 1..NSetup$ - Setup identifier; $k \in RepSetup = 1..NRepSetup$ - Identifier of the number of times for which the replication of each setup is allowed; $r \in Orient = 1..NOrient$ - Workpiece orientation identifier; $v \in VFace = 1..NVFace$ - Pallet face identifier; $q \in Pattern = 1..NPattern$ - Identifier of possible different pattern; $d \in Dir = 1..NDir$ - Identifier of MWS tool access directions; $c \in Tool = 1..NTool$ - Cutting tool identifier; $u \in Run = 0..NRun$ - Identifier of desired solutions.

Decision Variables

$Z_{s,m,r}$ - 1 if MWs m is associated to the workpiece characterized by orientation r is machined in the setup s,; otherwise 0; $X_{v,q,r}$ - 1 if pattern q is selected for the machining of the workpieces mounted on the face v with orientation r,otherwise 0; $Y_{d,q,r}$ - 1 if direction d is associated to the pattern q and orientation r, otherwise 0; $O_{v,q,s}$ - 1 if face v mounts workpieces characterized by setup s and pattern q; otherwise 0; $N_{v,s,r}$ - 1 if setup s is characterized by orientation r and mounted on the face v, otherwise 0; $J_{s,r}$ - 1 if setup s is defined by orientation r, otherwise 0; $L_{s,q}$ - 1 if setup s is characterized by pattern q; otherwise 0; $B_{s,k}$ - 1 if setup s is replicated k times.

Parameters

NbPart - Number of the part to be produced in a defined period (batch size); *AvailableTime* - Available time for the production of a batch [s]; *MaxPartCost* - Maximum cost per produced part [€]; *coeffa* - High value constant; *coeffb* - 1 if energy consumption is taken into account during cost minimization, otherwise 0; *coeffc* - 1 if cost associated to tool wear is taken into account during cost minimization, otherwise 0; $V_{d,q,r}$ - Visibility matrix – 1 if direction d is visible given orientation r and pattern q, otherwise 0; $AC_{v,q,r}$ - 1 if pattern q can be selected for the machining of the workpieces mounted on the face v

with orientation r, otherwise 0; $A_{m,d}$ - 1 if MWS m has direction d, otherwise 0; $AM_{i,j}$ - 1 if MWS i and j are alternatives, otherwise 0; $WR_{v,r}$ - Maximum number of workpiece rows that are mountable with orientation r in the face v; $WC_{v,r}$ - Maximum number of workpiece columns that are mountable with orientation r in the face v; $Pr_{Fmws1,FMws2}$ - 1 if MWS p_1 or its alternative MWSs has a precedence relationship with MWS p_2 or its alternative MWS; otherwise 0; $Tl_{FMws1,FMws2}$ - 1 if MWS p_1 or its alternative MWSs has to be machined in the same setup of MWS p_2 or its alternative MWS; otherwise 0; Qt_q - Vector of patterns [<row_1, $column_1$> ,…, <row_n, $column_n$>]; EC_m - Cost related to the energy consumption of MWS m [€]; MT_m - Machining time of MWS m [s]; $W_{c,m}$ - Cost related to the wear of the cutting tool c required for the machining of MWS m [€]; H - High value constant; $Xrep_{u,v,q,r}$ - 1 if the pattern q is selected for the machining of the workpiece with orientation r on the face v in the run; *AltOrient* - High constant value if the constraint containing it has to be activated, otherwise 0; *AltPattern* - High constant value if the constraint containing it has to be activated, otherwise 0.

Objective function

The objectives functions deal with the minimization of either production-cost (1) or production-time (2). Production costs include the cost related to the energy consumption and the tool wear for each MWS modelled by the use of *coeffb* and *coeffc*.

$$min\ -PP + coeffb\sum_{r,m,s}\left(EC_m \cdot Z_{s,m,r}\right) + coeffc\sum_{r,m,s,c}\left(W_{c,m}\cdot Z_{s,m,r}\right) \quad (1)$$

$$min\ -PP + \sum_{s,m,r}\left(Z_{s,m,r}\cdot MT_m\right) \quad (2)$$

where $$PP = \frac{\sum_{s,v,q}\left(O_{v,q,s}\cdot Qt_q.row\cdot Qt_q.column\right) / NSetup}{coeffa}$$

Production times are the sum of cutting times for all the MWSs. Both in case of production-cost and production-time minimization, the objective function concurrently maximize the number of parts per pallet (*PP*). In order to make irrelevant the impact of the number of the finished part per pallet on the value of the objective function, the coefficient *coeffa* is employed as divisor of the number of finished parts. As a consequence, the value of the objective function could be approximated to the real production costs or time.

Constraints

The model is based on 41 constraints that can be clustered into 5 classes: (a) constraints for the solution coherence; (b) economic constraints; (c) time constraints; (d) constraints for alternative configurations and (e) precedence and tolerance constraints.

For sake of brevity, only a subset of these constraints is presented in the followings.

Constraint (3) defines the range of values the variables can assume in order to correctly describe the problem solution (cluster (a)); constraint (4) describes the relationship among variables and input data in order to obtain a coherent solution (cluster (b)); constraints (5-6) are employed during cost and time minimization in order to cope respectively with time and cost constraint (cluster (c)); constraint (7) provides pallet configurations alternative to the previous solution based on workpiece different orientations and/or different patterns (cluster (d)); constraint (8) ensures tolerance and precedence constraints (cluster (e)).

$$\sum_{r,s} N_{v,s,r} \le 1 \quad \forall v \in VFace \quad (3)$$

$$H\cdot\sum_{m,s}\left(Z_{s,m,r}\cdot A_{m,d}\right) \ge \sum_{q}\left(Y_{d,q,r}\cdot V_{d,q,r}\right) \quad \begin{matrix}\forall r\in Orient,\\ \forall d \in Dir\end{matrix} \quad (4)$$

$$\sum_{s,m,r} Z_{s,m,r}\cdot MT_m \le AvailableTime / NbPart \quad (5)$$

$$\sum_{r,m,s} EC_m\cdot Z_{s,m,r} + \sum_{r,m,s,c} W_{c,m}\cdot Z_{s,m,r} \le MaxPartCost \quad (6)$$

$$\sum_{q,r} r\cdot X_{v,q,r} - \sum_{q,r} r\cdot Xrep_{u,v,q,r} + AltOrient\cdot H \ne 0 \quad (7)$$
$$\forall u\in Run, \forall v \in VFace$$

$$\sum_{m\in\left[AM_{w1,1}:AM_{w1,2}\right]} Z_{s,m,r} - \sum_{m\in\left[AM_{w2,1}:AM_{w2,2}\right]} Z_{s,m,r} = 0 \quad (8)$$
$$\forall r\in Orient, \forall s\in Setup, \forall w1,w2 \in FMws : T_{w1,w2} = 1$$

3.2. Machine tool-pallet machinability

The machine tool-pallet machinability aims at defining the machinability of each MWS and each pallet on the considered machine tools. The machine tool pallet machinability problem is addressed by means of two incidence matrices automatically generated by the pallet configuration model (Section 3.1). The first matrix shows the machinability of a pallet in a certain configuration by a specific machine tool type taking into account constraints related to the pallet size; the second matrix shows the relationship between pallet configurations, machine tools and MWSs. The information considered for the definition of the MWS feasibility is based on the following parameters: feed rate, spindle speed, spindle power, spindle torque and accessibility to the MWS. The MWS is feasible if these parameters are compliant to the machine tool corresponding characteristics.

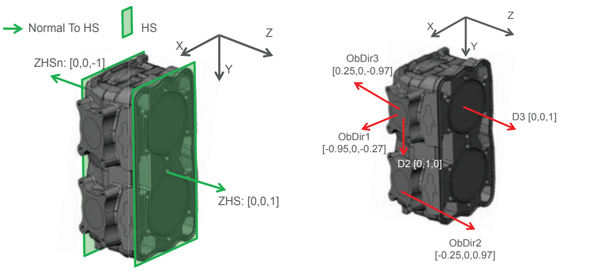
On the basis of the incidence matrices, a number of machine tools can alternatively be selected for processing the pallets, thus constituting a fundamental input for the production system configuration problem in which the best set of machine tools is selected. Together with the pallet machinability, the selection of the machine tool refers to the pallet machining time and, in turn, to the machine throughput.

The developed mathematical model has been implemented in ILOG OPL 6.3 and can provide a solution for problem up to 300 MWSs on a 4GB RAM workstation in 5 minutes. Model performances could be improved running on higher processing power workstations.

4. Industrial application

The proposed process planning approach has been tested with reference to a family of products provided by a SME. These parts undergo frequent technical modifications and a variable demand. The analysed family of products is composed by five part types belonging to an engine cylinder family. The products are machined on a FMS composed by 4 MCM Clock 600 CIM, one MCM Clock 700, two transporters and one shared tool magazine. In this paper, the analysis of the code “492”, produced for the recreational market will be proposed.

The code presents 23 features, 63 operations, 63 MWSs, 2 holding surfaces (Figure 2) and 40 precedence constraints. The active TADs are D3[0;0;1] and ObDir1[-0.97;0;-0.25]. A number of 6 alternative MWSs (D2[0;1;0], ObDir2[-0.25;0;0.97] and ObDir3[-0.25;0;-0.97]) has been considered for the analysis. As an example, the energetic consumption of the MWS #25 (face milling) and the alternative MWS #25-1 (side milling) are respectively equal to 31.6 KJ and 20.8 KJ [12]. The considered MWSs present besides different TADs and tools also different cutting parameters. In details, #25-1 requires lower cutting depth, feed rate and spindle speed.



(a) Holding surfaces (b) TADs

Fig. 2. “492”

Company solution

The pallet configuration currently adopted by the company has a square geometry (430mmx 590mmx100mm) with two holding faces. Two workpieces are mounted on each face (1 column, 2 rows) (Figure 3). A back draft angle of 15° is considered. The workpiece is machined in one setup (matrix: [-1,0,0; 0,-1,0; 0,0,1]; directions: D3, ObDir1). The pallet is processed by the four axis MCM Clock 600 CIM.

Proposed solutions

The proposed methodology generate for part code 492 a number of 8 alternative pallet configurations to be processed on the same machine type (MCM Clock 600 CIM). The generation of each alternative process plan required from few seconds up to 5 minutes. Two alternative fixture geometries have been considered, i.e. the original fixture (A) and a cube 400mmx590mm x400mm (B). Fixture B represents the biggest fixture in accordance to the machine tool working cube. The pallet configuration model has been run both for the case of a complete processing of the parts in one single and two setups. Cost and time minimization criteria have been considered. Results based on the two configuration criteria are respectively shown in Table 1 (orientations: O1[-1,0,0;0,-1,0;0,0,1], O2[1,0,0;0,1,0; 0,0,1], O3 [1,0,0;0, -1,0;0,0,-1], O4[0,-1,0;1,0,0;0,0,1], O5[-1,0,0;0,1,0;0,0,-1]).

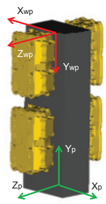


Fig. 3. “492” – Industrial pallet configuration

Table 1. Pallet configurations – Cost minimization [€] (ID 1-4) and time minimization [s] (ID 4-8)

Id	# Setup	Pallet	Alt MWS	OF	Faces
1	1	A		7.9	Face 1,2: 2x1\O1\ D3,ObDir1
2	2	B		7.9	Face 1,3: 2x1\O2\ D3 Face 2,4: 2x1\O3\ ObDir1
3	1	A	X	7.9	Face 1,2: 2x1\O1\ D3,ObDir1
4	2	B	X	7.4	Face 1,3: 2x1\O1\ObDir1 Face 2,4: 2x1\O4\ D2,D3,D5
5	1	A		282	Face 1,2: 2x1\O1\D3, ObDir1
6	2	B		282	Face 1,4: 2x1\O3\ObDir1 Face 2,3: 2x1\O2\ D3
7	1	A	X	279	Face 1,2 : 2x1\O1\D3,ObDir1, ObDir2
8	2	B	X	279	Face 1,2: 2x1\O5\ObDir1,ObDir3 Face 3,4: 2x1\O1\D3

The pallet configurations 1 and 5 generated by the method result identical to the industrial solution. However, compared to the industrial solution, the method generates some configuration solutions which present some improvements in terms of machining times and cost per parts simply by selecting alternative MWSs (solution 4, 7 and 8). Other generated solutions permit the machining of 4 parts per pallet (solutions 2, 4, 6 and 8) instead of two parts (solutions 1, 3, 5 and 7).

In particular, the solution 4 grants a reduction in the energetic consumption of 21.6 KJ (25%). Although only two alternative MWSs are selected, this massive energy reduction is related to the fact that the MWSs deal with roughing milling operations which compared to drilling ones have a much higher energy impact (e.g. 31.6 KJ versus an average global energy consumption of 1.35 KJ).

All the generated configurations have been mapped on 11 machine tools. The incident-matrices generation needed less than 10 minutes. Since the alternative pallet configurations (Figure 4) are generated according to the characteristics of the MCM Clock 600 CIM machine tool and the MCM Clock 600 CIM has the smallest working cube and the lowest performances, results showed that each pallet and each MWS can be machined by every considered machine tool.

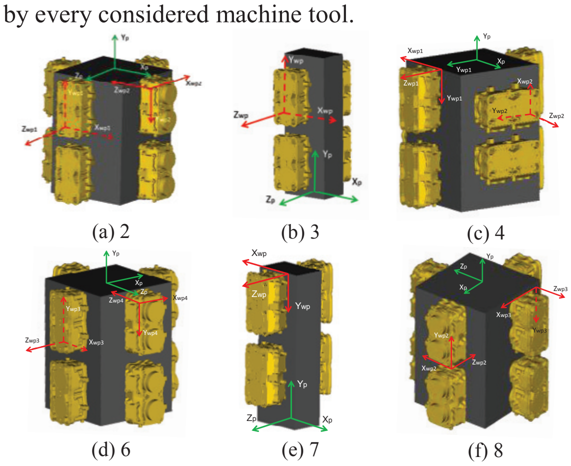


Fig. 4. Pallet Configurations

Together with time criterion, also investment costs and machine tools energy consumption should be considered for the selection of the best machine tool and a more comprehensive analysis.

5. Summary and future works

As highlighted by the industrial practise and academic studies, the development of structured process planning methodologies could result strategic for the production of components to be pushed in very dynamic markets characterized by frequent evolution of products and fluctuations of the demand. The holistic process planning approach proposed in this paper is based on five different activities integrated in a common software infrastructure. The benefits of the holistic process planning modules have been evaluated with regards to an industrial case showing the possibility to severely reduce the cost per part together and maximizing the throughput. Results proof a 25% reduction of cutting energy consumption. Future works will concern the extension of the approach with reference to two aspects. A first extension would enable the MWS visibility modelling for 5 axis machine tools while the second improvement would deal with the modelling of multi-pallet solutions.

Acknowledgements

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