Network Part Program approach based on the STEP-NC data structure for the machining of multiple fixture pallets

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Abstract

The adoption of alternative process plans, i.e. process plans that include alternative ways of machining a workpiece, can improve system performance, through a better management of resource availability. Unfortunately even if this opportunity is deeply analysed in literature, it is not frequently adopted in real manufacturing practice. In order to fill up this gap, this paper presents the Network Part Program (NPP) approach for the machining of multiple fixture pallets. The NPP approach is based on the STEP-NC data structure which supports non-linear sequences of operations and process flexibility. In the NPP approach, a machining system supervisor defines the machining sequences and generates the related part programs just before the execution of the pallet. The paper provides an approach with high scientific value and industrial applicability based on the integration of new and existing process planning methods. A real industrial case study is considered in order to show that in real applications the final quality is unaffected by the change of the sequence of the operations due to the employment of non-linear process plans. Since the results appear very encouraging, the proposed approach is a possible solution to accelerate the adoption of non-linear process planning in real manufacturing practice.

Keywords

STEP, CAPP, Network Part Program, Pallet Configuration

1 INTRODUCTION

Current market dynamics have considerably modified the context in which companies operate, imposing manufacturing firms to react with different strategies. In particular, some companies have tried to focus on their working activities, making the rationalization of operations a key factor of their success (Borgia and Tolio, 2008). In the field of the production of mechanical components, companies currently invest in production capacity characterized by a high level of flexibility (e.g. Machining centres and Flexible Manufacturing Systems) in order to respond to market changes (Koren and Shpitalni, 2010). However, actually firms may not take all the advantages given by their

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manufacturing systems, because they are unable to properly exploit all the available flexibility (Molina *et al.*, 2005, Tolio, 2009).

A possible way of facing the market dynamics is to act on the definition and execution of the manufacturing processes. Indeed, at present part program generation and execution are critical factors (Fogliazza, 2004). Currently, work cycles are implemented on machines with linear part programs, i.e. classical NC-codes which sequentially define the operations to obtain the final product from the blank. This approach presents two main limitations: part program sequentiality and part program execution mode.

Typical part programs are collections of instructions related to tools, tool paths, and operation sequencing. They are interpreted in a sequential way by the Numerical Control (NC) of the machine for which they have been developed. The sequence is fixed during the creation of the part program in the process planning phase (Pellegrinelli and Tolio, 2013). Therefore, the resulting operation sequence is only one of the many feasible sequences. The sequence choice: (i) introduces unnecessary constraints which are not related to technological considerations, but are due to the current limitations of NC programming languages and NC execution capabilities (Kruth, 1992); (ii) leads to the lack of reactivity to the events that occur at shop floor level during part program executions. Indeed, the possibility to react to unexpected events and to resume the production after work cycle interruptions is very limited.

According to the STEP-NC standard ISO 14649 (ISO 14649), the sequence of operations may be given in a non-linear way, thus increasing flexibility in task execution. Thanks to non-linear process planning (Kruth *et al.*, 1996, Colosimo *et al.*, 2000) the final process can be fixed once the machine tool loads and availability are known, obtaining an increase of the mean throughput and a decrease of the throughput variance. Even if the network part program approach uses the STEP-NC data structure that is based on machining workingsteps (MWSs) composed in turn of machining features and machining operations, regarding the coding of the machining operation it adopts the ISO 6983 standard (ISO 6983). This feature guarantees backward compatibility in the STEP-NC standard and allows the description of operation which cannot be thoroughly described by the STEP-NC standard.

The execution of non-linear process plans based on the STEP-NC standard on machines without a STEP-NC compliant numerical control is granted by the Network Part Program (NPP) approach, thus leading to the applicability in real industrial contests. Regarding technological constraints, the NPP approach considers one-to-one, one-to-many and many-to-many constraints. One-to-one constraints can be used, for instance, to model the relationship between centring and drilling while one-to-many constraint may refer, for instance, to the milling of a surface on which different holes have to be executed later on. Therefore, a part program can be seen as a network in which the nodes represent the operations and the arcs represent the technological precedence constraints among the operations (Matta and Tolio, 2001) (Figure 1).

The main advantage of using the NPP in NC machines is the possibility of breaking the process cycle into a set of operations connected by technological constraints only, thus bringing all the advantages of non-linear process planning to the part program level. In comparison with a standard sequential part program, the removal of non-technological constraints increases the flexibility by enlarging the number of operation sequences that can be used to machine the product . During the execution of the work cycle, a supervisor of the numerical control selects the sequence based on the previously-built network taking into account both the technological precedencies among the operations and the information on the current state of the system (Fogliazza, 2004) such as tool availability, spindle saturation, state of the machines, etc. The introduction of the NPP approach in automated manufacturing systems allows to better react to the various disruptive events that frequently affect manufacturing systems such as lack of cutting tools, machine breakdown and to optimize the process execution according to the current state of the system (Fogliazza, 2004). For instance, in case of cutting tool breaking during the machining of a pallet, NPP identifies all the remaining MWSs that can be executed according to the precedence constraint network, re-generates the part program and executes the MWSs. Similarly, in case of problems leading to an interruption of the machining process, the operation at which the machining process was interrupted is known. Once the problems are solved, the machining process can be automatically restarted. The flexibility of the process plan at shop-floor and the system throughput are increased. However, the NPP applicability in real industrial contests is not guaranteed a priori: the respect of the quality constraints on the final product has to be verified. Indeed, flexibility allows the possibility to select different operation sequences for the machining of a given product, but does not assure that changes in sequence do not affect the quality of the final product.

This paper presents the complete structure of the approach, including the validation phase. It is organized as follows: the next section presents a literature review on STEP-NC and non-linear process planning; Section 3 presents the objective of the paper; Section 4 introduces the problem statement, specifying hypothesis, assumptions and application context; Section 5 is related to the description of the employed data structure; Section 6 describes in details the various steps of the approach for the creation of a Network Part Program; Section 7 presents the validation phase, demonstrating the applicability of the approach on a real industrial case. Finally the last section gives the conclusions, and indicates some directions for further research.

2 OVERWIEV

2.1 STEP-NC

In the last decade, significant improvements, such as higher productivity, reduced design time, more accurate designs and less time required for modifications, have been made with the rapid development of CAD/CAM software based on sophisticated programming capabilities for highly configurable NC code generation (Newman *et al.,* 2003, Zhao *et al.,* 2009). Although these developments have revolutionized CNC processes and programming capabilities, the G&M programming language (ISO 6983) has remained basically unchanged. G&M code is a family of programming languages in which CNC is only a passive executor of tool movements in terms of position and feed rate (Liu *et al.,* 2006). The aim for the next STEP-NC based CNC generation is interoperability and adaptability, so that CNCs can respond quickly to market demand changes and manufacturing needs (Yusof, 2009, Yusof *et al.,* 2009). As extension of the ISO 10303 (STEP) (ISO 10303), STEP-NC is being developed as data interface between computer aided design/manufacturing (CAD-CAM) software and this new generation of intelligent CNC machine tools. Since the new data model enables the CNC systems to have a comprehensive understanding of the part to manufacture together with the information about process planning and manufacturing operations

(Suh *et al.*, 2006), this new generation of STEP-compliant CNCs is required to choose autonomously the cutter tool path and other details regarding the process (i.e. feed rate, spindle speed, collision detection, space error, compensation, etc.) (Xun *et al.,* 2006). So, STEP-NC abstracts away from the very low-level language of traditional controllers to a new high-level information communication within the manufacturing process chain (Nassehi *et al.,* 2007). Low-level manufacturing instructions are therefore not required as part of STEP-NC data models.

STEP-NC is being developed by two different subcommittees of ISO Technical Committee 184, and is coded in a couple of standards (Feeney *et al.* 2003, ISO 10303-238): ISO 14649 "Data model for computerized numerical controllers" ISO TC 184/SC1 (ISO 14649, Feeney *et al*. 2003) and ISO 10303-238 "Application interpreted model for computer numeric controllers" ISO TC 184/SC4 (ISO10303-238).

Application Reference Model (ARM) based on ISO 14649-10, 11, 12, 111 and 121 describes the manufacturing processes in terms of a structured, feature-based process plan. It provides an object-oriented data model for CNCs with a detailed and structured data interface that incorporates feature-based programming on the basis of a range of information such as the features to be machined (machining feature), tool type (machining tool), strategy for the machining of the features (machining operation) and process plan (workplan) (Xu *et al.,* 2005, Xu *et al.,* 2006, Lee *et al.,* 2006, Laguionie *et al.,* 2011). STEP-NC grounds on four different data groups: task data, technology data, tool data and geometric data (Suh *et al.,* 2006). Task data describe the logical sequence of executable tasks called machining workingsteps - MWSs (i.e. association between a machining feature and a machining operation). Technology data that are resumed in the machining operation contain the description of the strategy chosen to machine a feature and include machining parameters, path and cutting tool. Tool data present a detailed and formalized description of the cutting tools that could be selected to machine the feature. Finally, geometric data describe the machining features. The structure is coded in a data modelling language called EXPRESS.

The ISO 10303-238 Application Interpreted Models (AIM) refers to the EXPRESS models in ISO 14649 but it is based on more generic and fundamental data elements. This offers the ability to directly exchange single data elements with other STEP protocols. Although ISO 10303-238 presents much longer, more complex and less human-readable files than the ISO 14649, it enables long-term extensibility and integration of files with other STEP applications. Moreover AIM grants a better integration between CAD and CNC, especially when data flow from CNC to CAD (Suh *et al.,* 2006).

Different research activities have been carried out on the employment of STEP-NC in milling operations. The Shop-floor Programming System (SFPS) introduced by Suh is the first system fully compliant with ISO 14649 (Allen *et al*., 2005). SFPS is a computer-assisted part programming system based on STEP interface, feature recognition, process planning, ISO 14649 part program generations and CNC interface. It is able to interface with a STEP-compliant CNC controller called STEP-CNC. In (Liu *et al.* 2006), (Xu *et al.,* 2005) and (Allen *et al.,* 2005) the authors developed a STEP-NC compliant process planning system (AB-CAM) based on multi-agent technology, while a Multi-Agent System for CAPP (MASCAPP) was presented by (Nassehi *et al.,* 2006). (Nassehi *et al.,* 2006) developed the Integrated Platform for Process Planning and Control (IP^{3}AC), which adopts a two-stages methodology for STEP-NC part program generation. Firstly, a general workplan (GP), which is a generic part program based on basic manufacturing knowledge and feature information, is generated. Secondly, a specific workplan (SP) is developed taking the generic workplan and determining the details required for a specific machine.

However, all the presented approaches consider manufacturing processes characterised by the machining of a workpiece at a time, thus not coping with multiple fixture pallet and the machining of more workpiece mounted on the same pallet. Moreover, these approaches do not consider the system status since the controller knowledge is limited to the machine tool status. Finally, the main current limitation of these approaches is that STEP-NC compliant NC controllers are not spread and the offer of such types of controllers by NC manufacturers is not growing.

2.2 Non-linear and alternative process planning

Non-linear and alternative process plan, by definition, includes a set of different ways of machining a workpiece. It is basically composed of parallel operations, that can be executed in any sequence (i.e. are not tied by precedence constraints), and alternative operations. Many studies (Colosimo *et al.* 1999, 2000, Kumar *et al*., 2010) have analysed the performance improvement that non-linear process plan adoption can determine, due to an improved balancing of workloads and a highly adaptive reaction to unplanned situations. (Matta *et al*., 2004) proposed a study on the flexibility related to non-linear part program exploitation in numerically controlled machines, assessing the impact of introducing this process flexibility in real FMSs with a simulation campaign. FMSs with non-linear part program have been compared with FMSs with traditional sequential part program on the same part types taking into account two real cases of the automotive and aeronautic sectors, respectively. This study has also allowed the definition of a new tool management rule to be used in flexible manufacturing systems. It must be noted that this paper aims only at evaluating the system performance and does not provide any methods for process planning or network part program generation. Indeed, testing activity has been performed only using discrete event simulation techniques. So, the real industrial feasibility of the network part program is not proved.

Authors have pointed out the great opportunity that non-linear process plans can offer in filling the existing gap between planning and control. Although the potential achievable advantages, there is still a gap between academic research and manufacturing practice. To overcome this distance, a lot of efforts have been made in the past in order to develop non-linear Computer Aided Process Planning systems (CAPP): (Kruth and Detand, 1992, Kruth *et al*., 1996) proposed the first CAPP system coping with non-linear process planning; (Wang *et al.,* 2003) proposed a two stage system architecture for dynamic and distributed process planning in order to be responsive and adaptive to the rapid changes of production capacity and functionality; (Li and McMahon 2007, Haddadzade *et al.,* 2009), highlighting the importance of integration between process planning and scheduling in flexible manufacturing systems (FMS) and job-shop systems, managed three different types of flexibility in non-linear process planning: process flexibility, sequence flexibility, and routing flexibility; (Matta and Tolio, 2001) performed an evaluation of the impact of different structures of network part programs on FMS performances showing that the introduction of network part programs in FMS can increase system performance.

Despite research effort in developing systems desirable for real industrial practice, all the described CAPP systems had a limited diffusion. Reasons for this limited diffusion may be mainly related to the common difficulties these systems have in generating feasible solutions for a wide range of part types and manufacturing operations as well the inability to manage multiple fixture pallets. Due to the inherent complexity of generative CAPP systems, this kind of approach often shows problems in generating feasible process plan solutions, especially when complex part programs have to be considered. Moreover, the presented approaches focus on non-linear process planning without addressing the problem of the generation of part programs in such a contest. They do not completely exploit process non-linearity since the part program is generated at planning level instead of at shop-floor level, when the real conditions of the manufacturing system are known. For instance, the absence of a tool on a machine tool could be verified only before the loading of the pallet: unlike the here proposed approach, existing work is not able to optimally manage this unavailability. Another critical aspect is that presented papers mainly consist of research scientific contributions and do not prove the effective applicability of the proposed approaches in manufacturing context.

3 CONTRIBUTION AND NOVELTY

Existing research contributions evaluate the positive impact of the process flexibility granted by the use of network part program logics on the system performance (Matta *et al.,* 2004). Therefore, improvements due to NPP approach will not be discussed here. Differently, this paper proposes the implementation of an approach, which trying to get over the previously described limitations, integrates existing and new process planning methods with high scientific value and industrial applicability. Indeed, (i) the approach takes into account non-linear process planning objectives, the STEP-NC standard, the machining of multiple fixture pallets and the need of an increased knowledge about production resource state at shop floor level; (ii) the Network Part Program approach has been tested on a real manufacturing system, proving that its application grants process flexibility without altering the quality of the final products.

The approach is based on STEP-NC data structure that supports the sequencing of executable objects (MWSs) in a non-linear way. However, since the presented approach involves the machining of multiple workpieces mounted on the same pallet, the STEP-NC data structure is adapted in order to manage data needed for the generation of multiple fixture pallet part programs. Moreover, differently from what envisioned in the STEP-NC standard, a machine tool supervisor is added to the CAM-NC chain. This supervisor aims at overseeing the execution of a pallet according to the network part program of the workpieces mounted on that pallet. As already mentioned STEP-NC controllers are not currently employed in real industrial fields. Even if a number of public demonstrations have taken place, developing a STEP-compliant numerical controller has been proved to be a difficult task, as reported in Section 2.1. Furthermore, STEP-NC approaches have been tested on ad-hoc cases which do not reflect the real complexity and the whole spectrum of chip removal machining. To overcome these limitations, in the proposed approach the functionalities of the traditional CNC as well as its characteristics remain unchanged thanks to a supervisor. Three advantages are connected to the use of the supervisor: first, the supervisor is able to support and interact with different controllers (e.g. FANUC, Siemens, and Z32); second, the supervisor grants a bi-directional manufacturing data flow, thanks to its link to both the CNC and the network part program generation system; third, the supervisor knows the current status of the manufacturing system and can really exploit the flexibility granted by non-linear process planning.

4 PROBLEM STATEMENT

The addressed problem considers the realization of prismatic workpieces on multiple fixture pallets in integrated manufacturing systems. The definition of a specific pallet work cycle in terms of part program is a process planning problem regarding all the three main areas of product, process, and production systems. Non-linear process planning is considered in order to take advantage of process flexibility and fully exploit system flexibility. The main potentialities of the network part program approach reside in the following points:

- Increased real-time reaction possibility to shop floor accidents and unpredictable events;
- Easiness in recovering an interrupted machining sequence;
- Possibility to change the operations execution order within a process plan;
- Possibility to split a specific part program on different machines;
- Possibility to optimize the operation sequence;
- Shift of decisional aspects to a level higher than the one of the CNC;
- Possibility of splitting technological aspects from production ones during the process plan definition;
- Possibility of choosing and designing systems with focused flexibility, i.e. the minimum level of flexibility needed to satisfy the requirements arising from the manufacturing problem.

The problem deals with the machining of prismatic parts on 4-axis CNC machining centres with rotary table in flexible manufacturing systems. Specifically, the problem is related to the machining of prismatic features (the so-called "2½D features" (ISO 14649) on prismatic parts. Each geometric feature is associated with one or more machining operations. According to STEP-NC, each operation on a feature brings to the creation of a unique machining workingstep that represents the match of the feature and the operation. Both preferred and alternative workingsteps have to be considered and managed during the process plan definition. Moreover, the generation of the process plan is strictly influenced by constraints related to precedence relationships among workingsteps, tolerance analysis, the presence of clamping fixtures and the number of machine tool axes. On the basis of these constraints, the process plan is optimized for one single product while considering different setups on the same pallet. An experimental validation has to be carried out to verify the potential impact of the proposed approach on the part quality of changes in the machining sequences.

5 STEP-NC-COMPLIANT DATA STRUCTURE

The proposed approach is based on the STEP-NC concept of separate management of the geometric and the technological information of the workpiece in order to fill the gap between the product design information and the CNC manufacturing data. Moreover, the employment of the STEP-NC standard allows the generation of the part program at shop-floor level though the exploitation of non-linear process planning and MWS concept. Specifically, the goal is to employ the STEP-NC data formalization to generate a network part program based on ISO 6938 programming language for prismatic part machining on machine tools with conventional control. The developed data structure looks at the ARM as a reference and exploits its simplicity to define some of the crucial elements on which the described approach is built (Figure 2). Even if information about the pallet ("*Pallet"* class) is introduced by the present work, the paper does not aim at extending the STEP-NC standard.

6 NETWORK PART PROGRAM APPROACH

The proposed approach aims at defining:

- a non-linear process plan for a single workpiece
- the part program to machine all the workpieces mounted on the pallet (based on the non-linear process plan of each workpiece).

The approach is based on 6 different steps (Figure 3). Within STEP 1, the planner analyses the 3D design of the workpiece. According to the STEP-NC standard, the goal of the analysis is to extract the workpiece geometrical information, i.e. the *machining features*, and the bounding box. Each feature is associated to one or more technological operations (*machining operations*) which together with the machining feature define the *machining workingsteps* (MWSs) and the production process. In other words, the association between one machining feature and one machining operation leads to the definition of one MWS. A tool access direction (TAD), i.e. the tool working direction for machining a feature, is univocally associated to each workingsteps. A CAM software tool is used for setting these data, which are then translated from the proprietary format of the CAM to the developed STEP-NC object-oriented data structure.

Within STEP 2 precedence constraints among the workingsteps are defined. Two kinds of precedence constraints are considered: tolerance constraints and technological constraints. Tolerance constraints depend on the geometrical specifications imposed on the workpiece (e.g. concentricity, parallelism). Technological constraints are related to the logical operation sequencing and to good manufacturing practice.

On the basis of these constraints and of the possible orientations of the workpiece on the pallet, STEP 3 checks the visibility of the tool access direction of the MWSs and defines the setup plan of the workpiece.

Considering the product demand and the machining requirements, in STEP 4 the planner defines the pallet configuration. The problem concerns the mounting of more workpieces in different setups on pallets. As said before, the approach addressed in this paper consists in the optimization of the pallet configuration for a single product type with the constraint that each face of the pallet holds parts in the same setup. In this paper, STEP 3 and 4 only cope with the analysis of one type of workpiece per time; however, the general approach allows the generation of pallet mounting different workpiece types.

Within STEP 5 the machining sequence is chosen considering the knowledge about the availability of shop-floor resources and in STEP 6 the part program to machine all the workpieces on the pallet is created.

The selection of the fixture and the machine tool, the generation of the pallet machining sequence and part program at shop-floor level, i.e. in real time, increase the flexibility and the robustness of the process planning approach. Indeed, only at shop-floor level the actual availability of the resources is known. In the following subsections, the steps of the approach are described in details.

6.1 Workpiece analysis

The goal of the workpiece analysis (STEP 1 in Figure 3) is to fill the proposed data structure with information about workpiece machining features, machining operations and machining workingsteps. The proposed data structure is based on (Borgia *et al.,* 2010).

During this analysis the planner is supported by a specifically developed software module interacting with a commercial CAM software tool (Figure 4). All CAM databases and functionalities, like the feature-recognition module, can be employed. The obtained information is saved in the STEP-NC compliant data structure. The first phase consists of the workpiece characteristics analysis (STEP 1A of Figure 4), and the filling of the "*Workpiece"* class instance.

The STEP 1B of Figure 4 is the feature recognition, carried out on the workpiece 3D file by the feature-based module of the CAM software tool. For each feature the planner has to identify the reference system, the feature type (e.g. slot, planar face, round hole) and the geometric characteristics (e.g depth, contour, radius, course of travel, end conditions). For each recognized feature, an instance of the "*Machining_Feature*" class is generated and compiled in the data structure based on the feature identified by the planner in the CAM software tool.

Afterwards, for each feature the planner can identify one or more machining operations defining machining strategy and necessary cutting parameters, e.g. spindle speed and feed rate (STEP 1C of Figure 4). The planner can access the CAM database of the machining resources like the cutting tool database. For each operation defined in the CAM environment, a "*Machining_Operation*" is automatically generated and compiled in the data structure. Moreover, the employment of the CAM software allows the generation of the part program for each operation and the simulation of the tool path before saving the GCode (Liu *et al.,* 2006) under the Machining operation object of the data structure. As an alternative, the database can be populated with existing part programs already converted into MWSs (Cobianchi *et al.,* 2009). In both cases, auxiliary information such as reference system of the part program, initial spindle speed and initial feed rate is stored in the developed data structure. Some required information depends on the numerical controller. However, this approach only copes with some predefined controllers and still do not face the NC-interoperability problem.

The creation and the compilation of an instance of the "*Machining_Tool*" class are guaranteed for each selected tool. Finally a machining workingstep is generated for each feature-operation association.

6.2 Precedence constraints

A machining sequence for a part should maximize productivity or minimize product cost under technological constraints, including geometry-based precedence relations, tolerance specifications and machining expertise (Ma *et al*. 2000). Interrelations among the features provide critical information to determine these constraints. Obtaining precedence relations from feature information has been previously considered as an application connected to feature recognition. However, the automatic recognition of precedence constraints is described elsewhere (Miao *et al.,* 2002, Yao et al., 2007, Donaldson and Corney, 2007) and lies outside the goal of this paper. Therefore, after the compilation of the data structure, the planner is required to manually identify all the constraints among the generated MWSs (STEP 2 of Figure 3). Both technological constraints and geometrical tolerance constraints are taken into account.

Single feature constraints depend on the geometry of the machined feature and the machining strategy. These constraints are related to the specifications imposed on the feature, the feature accessibility, the logical operations sequencing and the good manufacturing practice.

Multiple feature constraints impose some limitations connected with more than one feature in order to ensure the dimensional and geometric requirements defined on the drawing of the workpiece (e.g. concentricity, parallelism).

Two examples of the types of constraints described above are depicted in Figure 5. In Figure 5(a) (a multi-diameter hole), the hole with smaller diameter should be machined first (all the MWs involved are related to the same machining feature). In Figure 5(b) to position a drilling tool correctly, the drilling hole should follow the milling of the face on which the hole is positioned (the MWs involved are related to two machining features).

The planner is supported during the identification of precedence constraints by a specifically developed module of the proposed software tool (STEP 2 in Figure 3). The planner can set precedence constraints by means of a graphical interface and easily build the MWS network (Figure 6). Every possible sequence is already included in this network, thanks to its structure, and there is no need to enumerate them explicitly. This information is stored in the data structure and will be available in the following steps.

6.3 Setup planning and pallet configuration

The setup planning problem consists in determining the various positioning of the workpiece in the 3D space needed to perform the machining of all its features (STEP 3 in Figure 3). The aim is the minimization of the number of changes in the orientation (setup) of the workpiece: each of them implies to un-mount and re-mount the workpieces on the fixture, with an increment of non-cutting time (time not related to material removal, e.g. pallet loading time) and a reduction of machining accuracy. Indeed, re-mounting the workpiece can cause a shift of the machining reference points in terms of distances or rotations, affecting the machining accuracy, especially considering error propagation. After the setup planning phase, the pallet configuration problem has to be tackled (STEP 4 in Figure 3): the number of pieces clamped onto the fixturing device of the pallet, their disposition and setup have to be defined, in order to minimize the air time (time related to tool changes, table rotations and rapid movements and part of the non-cutting time) when processing the pallet. For this planning phase, the method presented in (Borgia *et al.,* 2010) is employed (Figure 7).

An elaboration of the geometrical data concerning the workpiece and its features is executed in order to explore in a combinatorial analysis all the possible orientations of the workpiece in the space for clamping matters. It has been assumed the workpieces are clamped on the face of the pallet and aligned in rows and columns, in a rectangular pattern as in most of real production pallets. For each possible setup-pattern combination, the visibility of the MWS tool access direction (TAD) is checked.

The solution of the problem is performed through an optimization model that can be easily and quickly solved using traditional optimization algorithms implemented in commercial software (Borgia *et al*., 2010). The model takes as input: machining features and machining workingsteps of the part to be manufactured, feasible part orientations and patterns on a pallet face, visible MWSs according to all the possible clamping conditions of the piece, precedence and tolerance constraints among MWSs. The setup planning problem is then translated into a mixed integer programming problem (Borgia *et al*., 2010). The optimality of the solution is guaranteed by the adoption of a commercial mixed integer problem solver (IBM ILOG CPLEX, 2013). A recursive procedure has been implemented, which allows to run the model more than once to obtain several different feasible solutions with the same level of optimality. This has been recognized to be an important issue for the approach; probably it is neither possible nor particularly useful to endow the method with all the skills that a human operators may have: therefore, the final selection among the feasible and equally optimal solutions automatically found is performed by a human operator.

The obtained information about pallet configuration is finally saved in the STEP-NC compliant data structure. According to the formalized structure, data regarding optimal setups and optimal workpiece orientation for each setup are respectively stored in instances of "*Setup*" class and "*Workpiece_Setup*" class. Information concerning the pallet is formalized through an instance of "*Pallet*" class.

6.4 Sequancing of pallet MWSs

The essence of operation sequencing includes the determination of the order of selected MWSs minimizing the machining times of the part mounted on the pallet (STEP 5 of Figure 3). The resulting order fulfils different constraints including the MWS precedence constraints. The operation sequence generation problem is usually modelled as a large-scale combinatorial optimization problem. Mathematical programming (Qiao *et al*., 2000, Moon *et al*., 2002), neural network (Chang and Angkasith, 2001, Hua and Fan, 2010), genetic algorithms (Hua *et al*., 2007, Shabaka and ElMaraghy, 2008, Kumar and Deb, 2012), search heuristics (Hua et al. 2007), branch-and-bound algorithms (Lee et al. 2001) as well as Taguchi particle swarm (Guo *et al.,* 2006, Kumar *et al*., 2010, Zhang and Zhu, 2011), simulated annealing (Pandev *et al.,* 2006) and ant colonies (Krishna and Rao, 2006, Bhardwaj and Tiwari, 2011) approaches have been applied to the operation sequencing problem.

In the last decades, different strategies for determining the optimal operation sequence for machining a workpiece have been proposed. (Das et al. 2009), (Chang and Angkasith, 2001), (Gologlu, 2004), (Kumar et al. 2010) and (Pandev et al., 2006) aim to reduce air time during the machining of a single workpiece on a CNC machine tool considering precedence constraints. In (Ohashi, 1999), the sequencing problem for various workpieces simultaneously mounted on a pallet is analysed. The operation sequence is defined by first of all optimizing the machining sequence for each workpiece, and subsequently the machining order of the workpieces. Thanks to the small number of operations in analysis, the problem is reduced to the Traveller Salesman Problem (TSP) and solved through a branch-and-bound algorithm.

In this paper the approach presented in (Pellegrinelli and Tolio, 2013) is applied. The aim of the approach is the selection of the sequence allowing the machining of all the workpieces mounted on a pallet minimizing the air time and obeying to geometrical and technological constraints among operations on a workpiece in a given orientation (STEP 5 in Figure 3). The approach is based on two different steps (Figure 8). First, the portions of part program connecting the various cutting operation, i.e. part programs not related to material chip removal (the so-called "air time PP"), are generated for each possible couple of MWSs. The relative times of execution are calculated. Second, the pallet MWSs sequence is optimized according to an air-time minimization criterion. The optimization of the sequence that takes into account the precedence constraints among the MWSs is based on a mathematical model and several algorithms described in (Pellegrinelli and Tolio, 2013).

In the first step (STEP 5A of Figure 8), part programs representing rapid movements, tool change and table rotation are generated automatically by the developed application according to the ISO language and the industrial practice. Safety planes are evaluated according to the tool movements and to the pallet configuration in order to avoid collisions of the tool with fixtures or workpieces. For the generation of these part programs, requested information are: initial and final position of the tool, cutting tool and tool access direction (TAD) for each MWS, position and orientation of each workpiece on the pallet, pallet dimension, and kinematics of the selected machine tool. The generated part programs are simulated by the commercial software Vericut® (CGTech) in order to evaluate the air time: air time has to be estimated through CNC machining simulation, since it greatly influences the final result. The employed simulation software perfectly simulates acceleration and deceleration phase as well as the motion from and to the tool change position. Information required to simulate the machining processes is easily gathered by the planner. In particular, the planner defines the simulation environment in terms of machine tools, numerical controller, pallet and workpieces. All the remaining information, such as part programs, tool changing time, table rotation time are automatically loaded by the developed application into the simulation environment. Similarly, the simulation results are automatically acquired.

In the second step (STEP 5B of Figure 8), mathematical programming and specifically developed heuristic algorithms are employed to obtain a correct and near-optimal solution in short time. Depending on the characteristics of the real problem, the proposed method decomposes the problem into sub-problems which are solvable through mixed integer programming. The final solution is obtained combining the solutions of the sub-problems by heuristic algorithms which allow to obtain a global near-optimal solution. Three post-processors strategies (heuristic algorithms) are then introduced to improve the final solution. Post-processors aim at reducing the optimality gap according to specific rules.

6.5 Definition of network part program for pallet

The last phase of the proposed approach (STEP 6 in Figure 3) is the definition of the part program for the machining of the pallet on the selected machine tool. Pallet part program definition as well as pallet MWS sequencing is carried out at shop-floor level by the supervisor of the machine tools. This is a relevant advantage of the presented approach, since it allows unpredictable event such as the lack of a fixture or the presence on the pallet of a reduced number of workpieces to be rapidly tackled. Data related to pallet configuration are sent to the supervisor from the planning level. These data are eventually confirmed or modified by an operator at the load-unload station where the pallet is configured. For the generation of the pallet part program, different inputs are required. These data are described in Figure 4 and detailed in Figure 9 where the process for the pallet part program is described. The part program of each MWS ("MWS PP" - MPP) and its auxiliary information ("MWS auxiliary info"), generated during the STEP 1 through the employment of a CAM software (Section 6.1), are required. The "MWS PP" contains the G-code instructions that are responsible for the chip removal path. The "MWS auxiliary info" presents all the instruction that qualify the machining such as the origins used in the part program, initial feed rate and spindle speed. These data are elaborated at shop-floor by the machine-tool supervisor in order to define both the optimized sequence for the MWS execution (“MWS Sequence”) and the G-Code instructions. These G-Code instructions set the machine tool for the execution of the selected MWS after the execution of previous MWS (“Air PP” - APP). Since MWSs belonging to workpieces in the same setup employ the same part program with different origins, the origin of each MWS part program has to be set according to the various workpieces during the generation of the pallet part program. The supervisor is able to identify the MWS that have been already executed and the MWSs that still have to be executed. Indeed, the supervisor knows exactly which MWSs are executed on which machine tools every time. The process that leads to the generation of the part program is depicted in Figure 10 where the MWS PPs generated during the Step 1 of the approach are merged to the “Air PPs” directly generated by the supervisor on the basis of the MWS sequence.

7 NETWORK PART PROGRAM VALIDATION

The advantages of adopting a NPP philosophy for process planning should be apparent from the discussion above, in terms of flexibility, time savings, etc. The impact of the process flexibility provided by the use of network part program logics on manufacturing system performance have been already verified in previous research studies (Matta *et al.,* 2004). The actual applicability of the Network Part Program approach in industrial filed is now taken into account. In particular, its feasibility is subject to quality constraints, that is, it has to be demonstrated that manufacturing a product with the NPP logic does not reduce its quality, or at least that final products are suitable for the intended usage. This corresponds to verifying the process performance and capability (ISO 22514-1,4, ISO/TR 22514-4) do not drop due to the application of the new logic. The (ISO 22514-3) International standard defines the following performance indices:

$$\hat{P}_m = \frac{U-L}{\hat{X}_{99.865\%}-\hat{X}_{0.135\%}} \qquad \hat{P}_m = \frac{U-L}{6S}$$

$$\hat{P}_{mk} = \min\left\{\frac{U-\bar{X}}{\hat{X}_{99.865\%}-\hat{X}_{0.5\%}}, \frac{\bar{X}-L}{\hat{X}_{0.5\%}-\hat{X}_{0.135\%}}\right\} \qquad \hat{P}_{mk} = \min\left\{\frac{U-\bar{X}}{3S}, \frac{\bar{X}-L}{3S}\right\} \qquad (6.1)$$

Where *U* e *L* are, respectively, upper and lower specification limits (and therefore *U*-*L* is the amplitude of the tolerance interval), $\bar{X}$ and *S* are, respectively, the sample mean and standard deviation of the considered quality characteristic (estimated by the present sample), and $\hat{X}_{\alpha\%}$ is the *α* left quantile of the empirical distribution of the quality characteristic. Formulas on the right are valid only if the characteristic is distributed according to a Gaussian statistical distribution (in which case they reduce to those on the right of 6.1). Similar indexes may be defined for capability (ISO/TR 22514-4). In general, the values of the specification limits are defined to guarantee the part functionality and the ability of the manufacturing process to produce parts with the specified tolerances (the latter is guaranteed by the adoption of suitable design for and tolerancing techniques). In the case of NPP validation part functionality is the same regardless of the adoption of the NPP itself, and the aim of this validation is to prove that the capability of the process is not affected by the adoption of the NPP, so under this assumption specification limits do not depend on the adoption of the NPP. Therefore process performance verification when NPP is applied reduces to verifying that its application does not alter significantly the expected value and standard deviation of the process output. This can be checked by a correct design and analysis of experiments (ISO 3534-3, Montgomery, 2004).

An experimental campaign has then been setup in collaboration with FERRAIOLI S.p.A. The campaign focuses on a real industrial case study regarding the machining of a railroad part named "Catenaccio" on multiple fixture pallets. Tolerance constraints on the quality of the final product are present. A series of 22 geometric and dimensional characteristics have been chosen among those describing the part, and labelled with letters in Figure 11[1].

The "Catenaccio" was originally manufactured with a traditional linear part program and required three setups. Each setup is associated to a different pallet (Figure 12). The parts have been manufactured on a "MCM Clock 800 multipallet" machining centre. The MWSs required by each setup are reported in Table 1. Even if the NPP approach and the STEP-NC standard allow the definition of alternative operations, in the following test case the authors do not concentrate on the possibility of completely changing the technological operation to machine a given feature.

The STEP-NC compliant data structure has been compiled according to the presented information defining in details data on MWSs, workpiece setups and pallet configurations. Then, the Network Part Program for each pallet has been generated using the proposed approach. The networks are presented in Figure 13 according to the representation rules presented in (Kruth and Detand, 1992).

Thirty-five parts have been manufactured on the real manufacturing system. The experimental design is the following:

- Two factors have been considered. The first factor is the operation sequence. Five possible sequences have been considered. The first sequence is the original sequence. Then considering that three setups are required, the next three sequences have been defined by considering the original sequence in two setups, and a modified sequence (coherent with the NPP constrains) in the remaining setup (respectively the first, the second, and the third). Finally, the last sequence sees modifications of the original sequence in each setup. The second factor is the repositioning of the part (load/unload). In practice, if the load/unload of the part is "on", at a randomly selected step of the manufacturing process, the process itself is interrupted, the part is unloaded and then loaded again on the machine, and the process restarted. This sequence is introduced to simulate the possibility of breaking the manufacturing cycle of all the parts of a lot when a tool is missing and completing the remaining operations on the parts of the lot once the tool becomes available again.
- Of the 35 manufactured parts, 15 have been manufactured with the original sequence, without load/unload. Of the remaining 20 parts, for each sequence defined before 4 parts have been manufactured, and of each group of 4 parts, 2 where subject to load/unload. This experimental design which manufactures many parts with the standard process has been chosen due to the need of an

[1] Geometric and dimensional tolerances where defined for these 22 characteristics. Tolerance values are confidential and cannot be reported in this paper. However, as mentioned before, if tolerance values are considered fixed the independence of product quality from NPP can be proved by analysing only the expected value and the variance of the quality characteristics.

adequate estimate of the process standard deviation when the original non-NPP process is adopted.

After the machining phase the 22 quality characteristics have been measured for each part on a "DEA 10.07.05" Coordinate Measuring Machine (CMM). Measurement results provided the required data for the subsequent statistical analysis.

To verify that the process average is not influenced by the adoption of the NPP an Analysis of Variance (ANOVA) (Montgomery, 2004) has been conducted on the data for each quality characteristic. The influence of the sequence, of the load/unload, and of the interaction of the two factors have been tested. The obtained results for each characteristic can be summarized in a table (see Table 2 for an example referring to characteristic D).

In general, large values of the p-values (last column of Table 2) lead to the conclusion that there is no statistical evidence the null hypothesis should be refused, that is, the considered factor is not influencing the average. In the Catenaccio experiment, 66 p-values have been obtained, and none of them resulted lower than 0.01. ANOVA results are subject to the verification of a series of hypotheses on the residuals: normality, homoscedasticity, and absence of correlation. These hypotheses have been verified, respectively, by the Anderson-Darling, Levene, and Ljung-Box tests (Montgomery 2004). The first two tests have been passed for every considered characteristic. Conversely, the Ljung-box test was not passed by characteristics A1, B1, D1, F, H, M, Z. A closer look at how the surfaces which define these characteristics were machined, reveals that in the case of A1, B1, D1 and Z tool T5 is involved, and in the other characteristics of the list tool T12 is involved. The characteristics machined with other tools do not show any autocorrelation in the residuals. A time series plot of the residuals, i.e. a plot of the residuals against the order in which the related part has been manufactured, shows a trend in the residuals (see e.g. Figure 14). Therefore, one can reasonably suppose the correlation is due to tool wear, and tool wear cannot be ascribed to NPP logic.

On the basis of the analysis carried out it is possible to conclude that in this case sequence and load/unload do not affect the average output.

Similarly, a Levene test has been applied to verify whether the NPP logic influences the output dispersion or not. In this case, only two groups have been considered, i.e. parts manufactured with the original sequence, without load/unload, and any other part. Again, the resulting p-values of the test are never lower than 0.01 (Table 3). The same discussion on hypothesis testing proposed for ANOVA applies here. Therefore, the final conclusion is that in this case the application of the NPP logic does not influence nor the expected value nor the dispersion of the production output.

8 CONLUSIONS AND FUTURE WORK

The present research focuses on a CAPP approach aiming at part program generation for the machining of parts mounted on multiple fixture pallets. Even if the approach is theoretically applicable to 5 axis machine tools, it is currently available only for 3 and 4 axis machine tools. The developed process planning scheme is based on two different levels (planning level and production level) that are in communication thanks to a STEP-NC compliant data structure. This data structure was specifically modified with respect to the one described by the STEP-NC standard in order to allow the management and the exchange of pallet and fixture information between the planning level and the production level. Moreover, based on the network part programs logic, the proposed NPP approach grants an increase in flexibility at shop-floor level through the employment of a supervisor. The supervisor can access the data structure, interpret the operations network, select an operation sequence and generate a pallet part program on the basis of technological precedence constraints and the current resource availability. However, issues related to CNC interoperability require deeper studies. Afterwards, the supervisor lets the controller execute the generated part program. The feasibility of the CAPP proposed method is stressed by one test case conducted on a real application. The independence of the process average and dispersion from the adoption of the NPP is statistically assessed.

Future development of the presented work include the definition of an extended framework able to support the feedback on the process condition from the shop-floor level to the planning level, thus granting process improvement over time. The interoperability issue will be faced. Moreover, quality operations will be considered during workpiece setup analysis as well as throughout the different phases of the approach, and a module for the automatic recognition of precedence constraints will be investigated. Finally, the extension to 5 axis machine tools for the modules related to setup planning and pallet configuration as well as MWS sequencing will be addressed.

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10 REFERENCES

Allen, R.D., J.A. Harding, and Newman, S.T. 2005. "The application of STEP-NC using agent-based process planning." *International Journal of Computer Integrated Manufacturing* 43(4): 655-670. Bhardwaj, B. and Tiwar, M.K. 2011. "Process Planning through Ant Colony Optimization." Chap. In *Evolutionary Computing in Advanced*.

Borgia, S. and Tolio, T. , 2008. "Design of flexible transfer lines in dynamic environments: a configuration approach", *Proceedings of 5th International Conference on Digital Enterprise Technology*, Nantes, France, 509-526.

Borgia, S., A. Matta, and Tolio, T. 2010. "STEP-NC compliant approach for setup planning problem on multiple fixture pallet" APMS International Conference, Cernobbio, Como, Italy.

Chang, C.A. and Angkasith, V. 2001. "Using Hopfield neural networks for operational sequencing for prismatic parts on NC machines." *Engineering Applications of Artificial Intelligence* 14: 357-368.

Cobianchi, P., Moriggi, P., and Tullio, T. 2009. Method For Automatically Partitioning A Part Program Into Fundamental Operations. *EP2417498*.

Colosimo, B.M., Pellizzaro, M., Semeraro, Q., and Tolio, T. 1999. "APPG1: A new approach for alternative process plans generation." The *32nd CIRP International Seminar on Manufacturing Systems* – New supporting tools for Designing Products and Production Systems, Leuven, Belgium, May 24-26 1999.

Colosimo, B.M., Semeraro, Q., and Tolio, T. 2000. "Rule based System for non-linear process plan generation." *Studies in Informatics and Control*, (9):2: 133-143.

Das, K., Baki, M.F. and Li, X. 2009. "Optimization of operation and changeover time for production planning and scheduling in a flexible manufacturing system." *Computers & Industrial Engineering* 56(1): 283-293.

Donaldson, I.A. and Corney, J.R. 2007. "Rule-based feature recognition for 2·5D machined components." *International Journal of Computer Integrated Manufacturing* 6(1-2): 51-54

Feeney, A.B., Kramer, T., and Proctor, F. 2003. "STEP-NC Implementation – ARM or AIM?" White Paper. *ISO T24 STEP-manufacturing Meeting*, San Diego, California.

Fogliazza, G. 2004. "How information technology enables the potential flexibility and reconfigurabilty of highly automated manufacturing plants." IFAC Information Control Problem in Manufacturing, San Salvador, Brazil

Gologlu, C. 2004. "A constraint-based operation sequencing for a knowledge-based process planning." J Intell Manuf 15: 463-470.

Guo, Y. W., Mileham, A. R., Owen, G. W. and Li, W. D. 2006. "Operation sequencing optimization using a particle swarm optimization approach." Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture 220 (12): 1945-1958.

Haddadzade, M., Razfar, M. R. and Farahnakian, M. 2009. "Integrating Process Planning and Scheduling for Prismatic Parts Regard to Due Date." World Academy of Science, Engineering and Technology (27): 64-67.

Hua, G. and Fan, X. 2010. "An Intelligent Approach of Obtaining Feasible Machining Processes and Their Selection Priorities for Features Based on Neural Network." International Conference on Computational Intelligence and Software Engineering (CiSE), p. 1-4

Hua, G., Zhou, X. and Ruan, x. 2007. "GA-based synthesis approach for machining scheme selection and operation sequencing optimization for prismatic parts." *Int J Adv Manuf Tech* 33: 594-603.

IBM ILOG CPLEX. 2009. http://www-01.ibm.com/software/integrationoptimization/ cplex-optimizer/

ISO 10303. 1994. Industrial automation systems and integration — Product data representation and exchange.

ISO 10303-238. 2004. Industrial automation systems and integration — Product data representation and exchange — Part 238: Application protocol: Application interpreted model for computerized numerical controllers.

ISO 14649. 2003. Data Model for Computerized Numerical Controllers - Parts 1, 10, 11, 12, 111, 121.

ISO 22514-1. 2009. Statistical methods in process management - Capability and performance - Part 1: General principles and concepts.

ISO 22514-3. 2008. Statistical methods in process management - Capability and performance - Part 3: Machine performance studies for measured data on discrete parts.

ISO 3534-3. 1999. Statistics - Vocabulary and symbols - Part 3: Design of experiments, .

ISO 6983. 1982. Numerical control of machines - Program format and definition of address words.

ISO/TR 22514-4. 2007. Statistical methods in process management - Capability and performance - Part 4: Process capability estimates and performance measures.

Krishna, A.G. and Rao, K.M. 2006. "Optimisation of operations sequence in CAPP using an ant colony algorithm." *The International Journal of Advanced Manufacturing Technology* 29: 159-164.

Kruth, J.D. 1992. "A CAPP System for Nonlinear Process Plans." *Annals of the CIRP* 41(1): 489-492.

Kruth, J.P., Van Zeir. G., Kempenaers, J., Pinte, J. 1996. "Methods to improve the response time of a CAPP system that generates non-linear process plans." *Advances in Engineering Software* 25(1): 9-17.

Koren, Y., Shpitalni, M. 2010. "Design of reconfigurable manufacturing systems" *Journal of Manufacturing Systems* 29(4): 130-141.

Kumar, V.,; Pandey, M., Tiwari, M., Ben-Arieh, D. 2010. "Simultaneous optimization of parts and operations sequences in SSMS: a chaos embedded Taguchi particle swarm optimization approach." *Journal of Intelligent Manufacturing*21(4): 225-353.

Kumar, C. and Deb, S. 2012. "Generation of optimal sequence of machining operations in setup planning by genetic algorithms." *Journal of Advanced Manufacturing Systems* 11: 67

Laguionie, R., Rauch, M., Hascoët, J.-Y. and Suhm S.-H. 2011. "An eXtended Manufacturing Integrated System for feature-based manufacturing with STEP-NC." *International Journal of Computer Integrated Manufacturing* 24(9): 785-799.

Lee, D.-H., Kiritsis, D., and Xirouchakis, P. 2001. "Search heuristics for operation sequencing in process planning." *International Journal of Production Research* 39(16): 3771-3788.

Lee, W., Bang, Y.- B., Ryou, M. S., Kwon, W. H., and Jee, H. S. 2006. "Development of a PC-based milling machine operated by STEP-NC in XML format." *Journal of Computer Integrated Manufacturing* 19(6): 593-602.

Li, W.D. and McMahon, C.A. 2007 "A simulated annealing-based optimization approach for integrated, process planning and scheduling." *International Journal of Computer Integrated Manufacturing* 20(1): 80-95.

Lin, C.-J. and Wang, H.-P.1993. "Optimal operation planning and sequencing: minimization of tool changeovers." *Int. J. Prod. Res.* 31(2): 331-324.

Liu, R., Zhang, C. and Newman, S.T. 2006. "A framework and data processing for interfacing CNC with AP238." *International Journal of Computer Integrated Manufacturing* 19(6): 516-522.

Ma, G.H., Zhang, Y.F. and Nee, A.Y.C. 200. "A simulated annealing-based optimization algorithm for process planning." *Internation Journal of Production Research* 38(12): 2671-2687.

Matta, A. and Tolio, T. 2001. "A simulation study of tool management policy in FMS with network part program" Proceedings of the *CIRP International Conference on Agile, Reconfigurable Manufacturing,* Ann Arbor, Michigan, USA.

Matta, A., Tontini, F. and Tolio, T. 2004. "Tool management in flexible manufacturing systems with network part program." *International Journal of Production Research* 42(17): 3707-3730.

Miao, H.K., Sridharan, N. and Shan, J.J. 2002. "CAD-CAM integration using machining features." *International Journal of Computer Integrated Manufacturing* 15(4): 296-318.

Molina, A. Rodriguez, C. A., Ahuett, H., Cortés, J. A., Ramírez, M., Jiménez, G., Martinez, S. 2005. "Next-generation manufacturing systems: key research issues in developing and integrating reconfigurable and intelligent machines." *International Journal of Computer Integrated Manufacturing* 18(7): 525-536.

Montgomery, D.C. 2004. Design and Analysis of Experiments. Wiley.

Moon, C., Seo, Y., Lee, Y.H. 2002. "Integrated machine tool selection and operation sequencing with capacity and precedence constraints using genetic algorithm." *Computers and Industrial Engineering* 43(3): 605-621.

Nassehi, A., Liu, R. and Newman, S.T. 2007. "A new software platform to support feature-based process planning for interoperable STEP-NC manufacture." *International Journal of Computer Integrated Manufacturing*20(7): 669-783.

Nassehi, A., Newman, S.T. and Allen, R.D. 2006. "The application of multi-agent system for STEP-NC computer aided process planning of prismatic components." *International Journal of Machine Tools & Manufacture* 46(5): 559-574.

Newman, S.T., Allen, R.D. and Russo Jr, R.S.U. 2003. "CAD/CAM solutions for STEP-compliant CNC manufacture." *International Journal of Computer Integrated Manufacturing* 16(7-8): 590-597.

Ohashi, K. 1999. "Dynamic Process Planning System for a Machining Center in an FMS Environment." *Int J Prod Econ* 60-61: 475-464.

Pandev, V., Tiwari, M.K. and Kumar, S. 2006. "An interactive approach to solve the operation sequencing problem using simulated annealing." *International Journal of Advanced Manufacturing Technologies* 29: 1212-1231.

Pellegrinelli, S. and Tolio, T. 2013. "Pallet operation sequencing based on network part program logic", Robotics and Computer-IntegratedManufacturing, On-line.

Qiao, L., Wang, X.Y. and Wang, S.C. 2000. "A GA-based approach to machining operation sequencing for prismatic parts." *Int. j. Prod. Res*. 38(14): 3283-3303.

Shabaka, A. I. and ElMaraghy, H. A. 2008. "A model for generating optimal process plans in RMS." *International Journal of Computer Integrated Manufacturing* 21(2): 180-194.

Suh, S.-H., Chung, D.-H., Lee, B.-E., Shin, S., Choi, I., and Kim, K.-M. 2006. "Step-compliant cnc system for turning: data model, architecture, and implementation." *Computer-Aided Design* 38(6): 677–688.

Tolio, T. 2009. Design of Flexible Production Systems: Methodologies and Tools. Springer.

Wang, L.H., Feng, H.Y. and Cai, N.X. 2003. "Architecture design for distributed process planning." *Journal of Manufacturing Systems* 22(2): 99-115.

Xu, X., Wang, H., Mao, J., Newman, S. T., Kramer, T. R., Proctor, F. M., and Michaloskid, J. L. 2005. "STEP-compliant NC research: the search for intelligent CAD/CAPP/CAM/CNC integration." *International Journal of Production Research* 43(17): 3703-3743.

Xu, X., Klemm, P., Proctor, F., and Suh, S. H. 2006. "STEP-compliant process planning and manufacturing." *International Journal of Computer Integrated Manufacturing* 19(6): 491-494.

Xun, X., Xu, W., Wang, L. and Rong, Y. 2006. "STEP-NC and Function Blocks for Interoperable Manufacturing." IEEE transactions on automation science and engineering (3)3: 297-308.

Yao, S., Han, X., Yang, Y., Rong, Y., Huang, S.H., Yen, D.W. Zhang, G. 2007. "Computer aided manufacturing planning for mass customization: part2, automated setup planning." *International Journal of Advanced Manufacturing Technologies* 32: 205-217.

Yusof, Y., Tan, N.Z.Z. and Kasim, N. 2009."Exploring the ISO14649 (STEP-NC) for intelligent manufacturing system." *European Journal of Scientific Research* 36(3): 445-457.

Yusof, Y. 2009. "STEP-NC-compliant system for the manufacturing environment." World Academy of Science, *Engineering and Technology* 922-927.

Zhao, Y.F., Habeeb, S. and Xu, X. 2009. "Research into integrated design and manufacturing based on STEP." *International Journal of Computer Integrated Manufacturin*g 44(5-6): 606-624.

Zhang, W.B. and Zhu G.Y. 2011. "Comparison and application of four versions of particle swarm optimization algorithms in the sequence optimization." *Expert Systems with Applications* 38(7): 8858–8864.

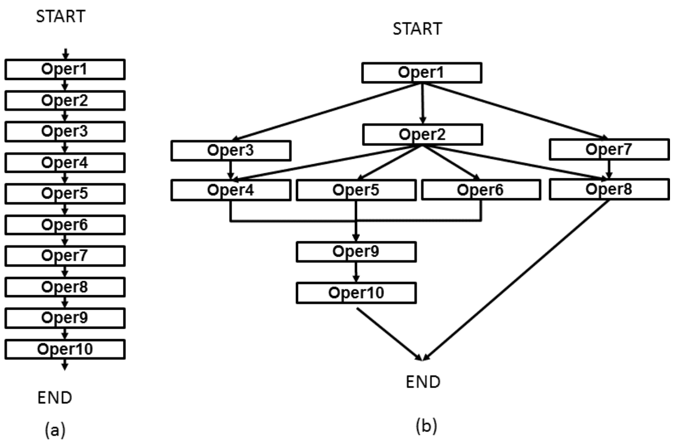


Fig. 1. (a) Sequential part program and (b) network part program.

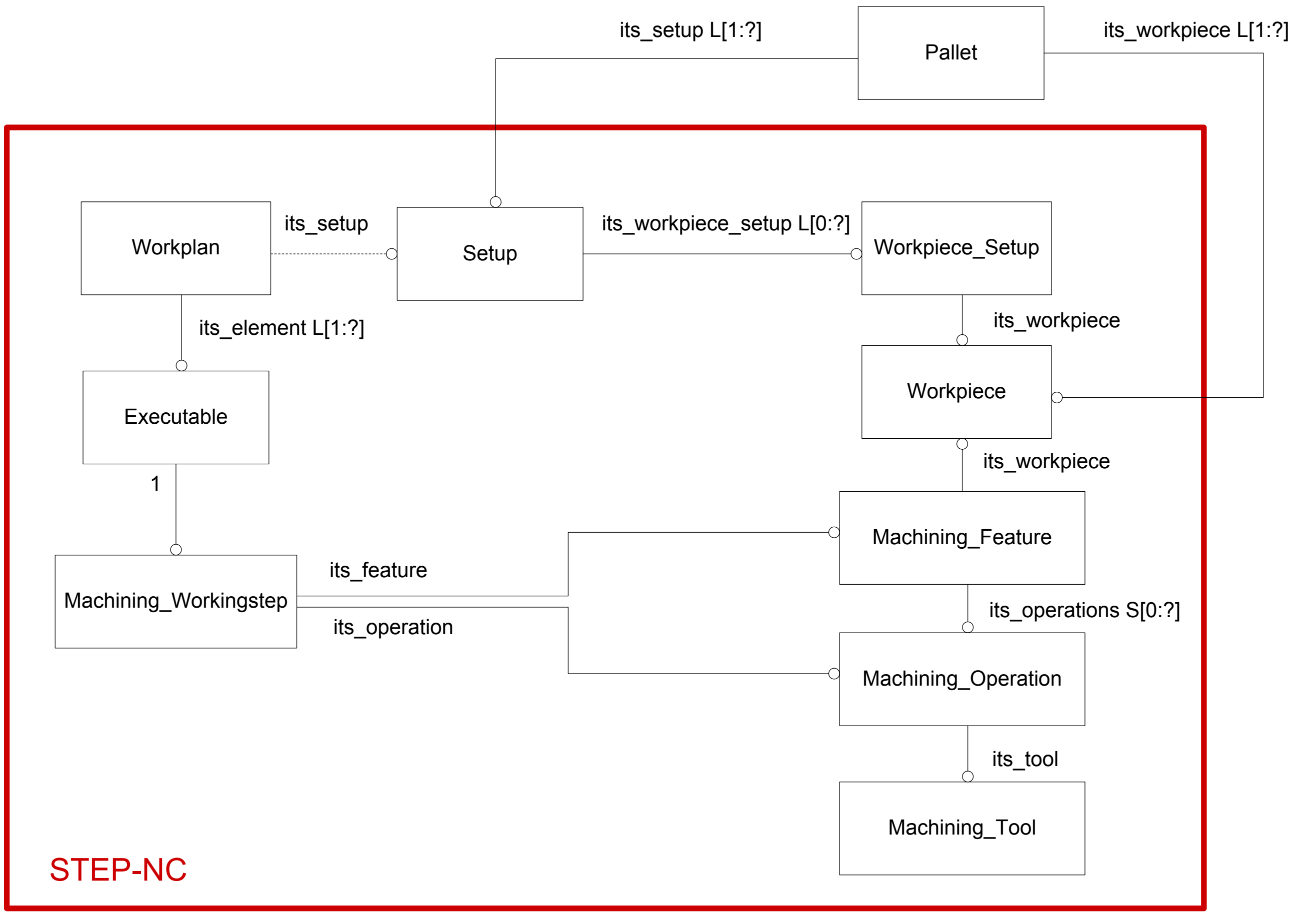


Fig. 2. EXPRESS-G diagram of the developed data structure.

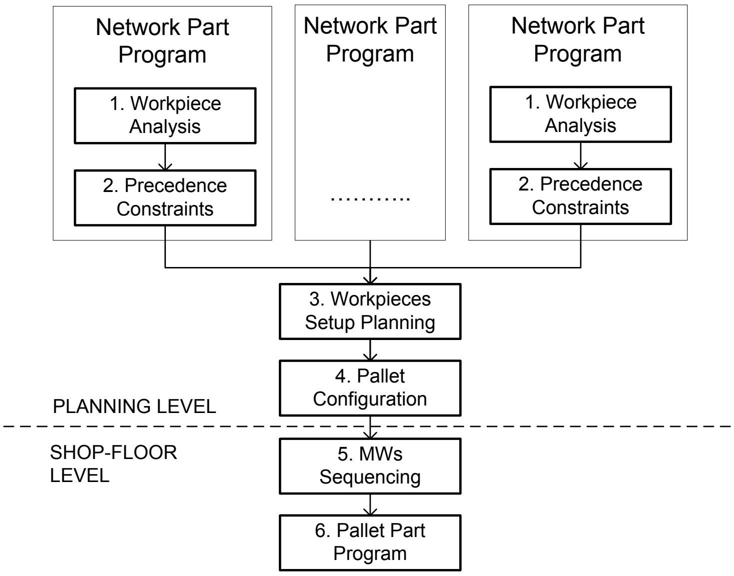


Fig. 3. Process for the definition of a pallet part program according to the NPP logic.

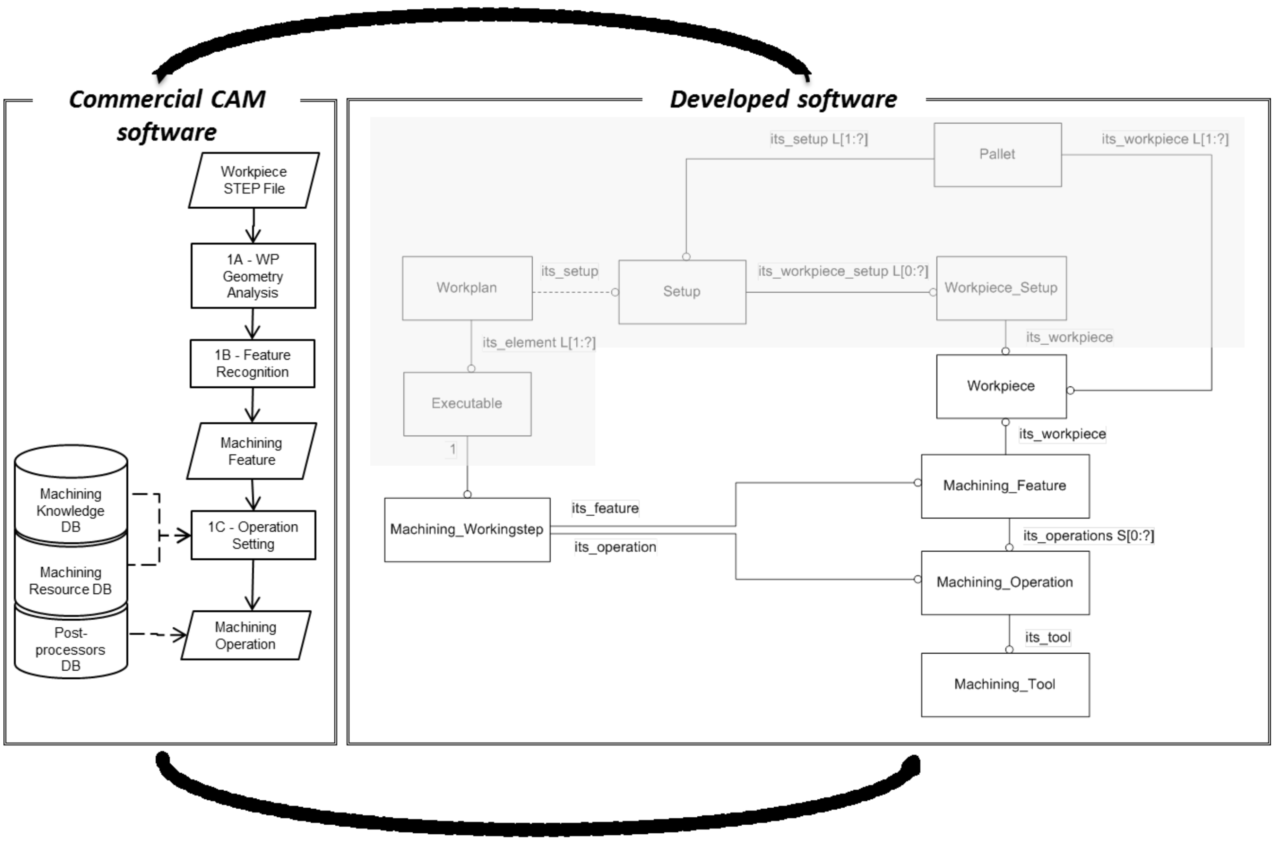
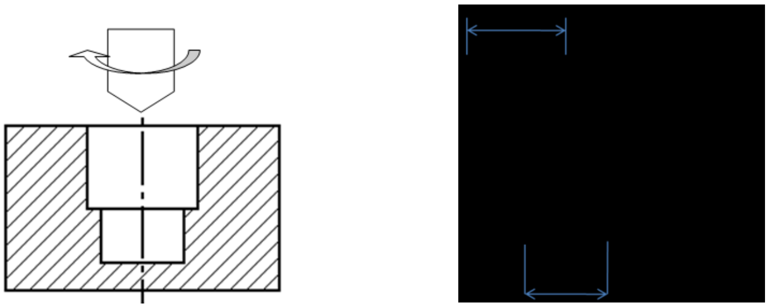


Fig. 4. Workpiece analysis – integration between the developed and the employed commercial CAM software.



(a) *Technological precedence constraint* (b) *Tolerance precedence constraint*

Fig. 5. Examples of technological and tolerance precedence constraint.

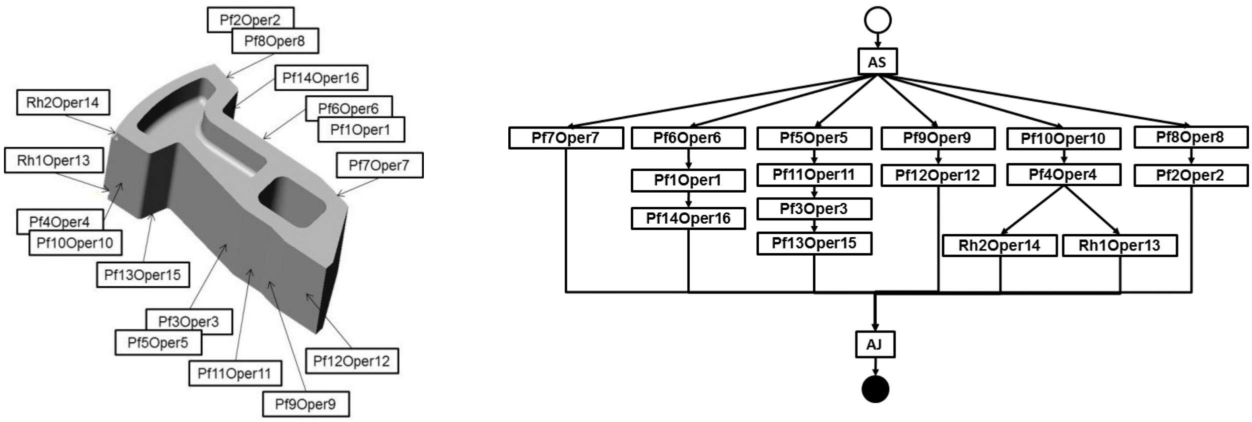


Fig.6. Workpiece MWSs and network of workpiece MWSs according to the representation rules presented in (Kruth and Detand 1992).

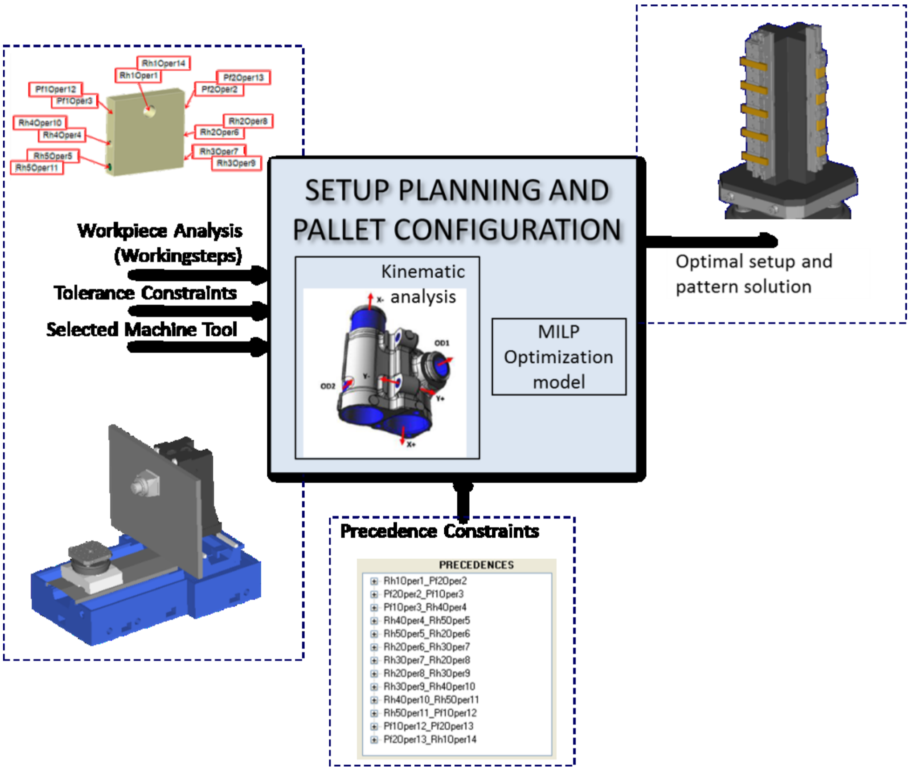


Fig. 7. CAPP approach for Setup Planning and Pallet Configuration.

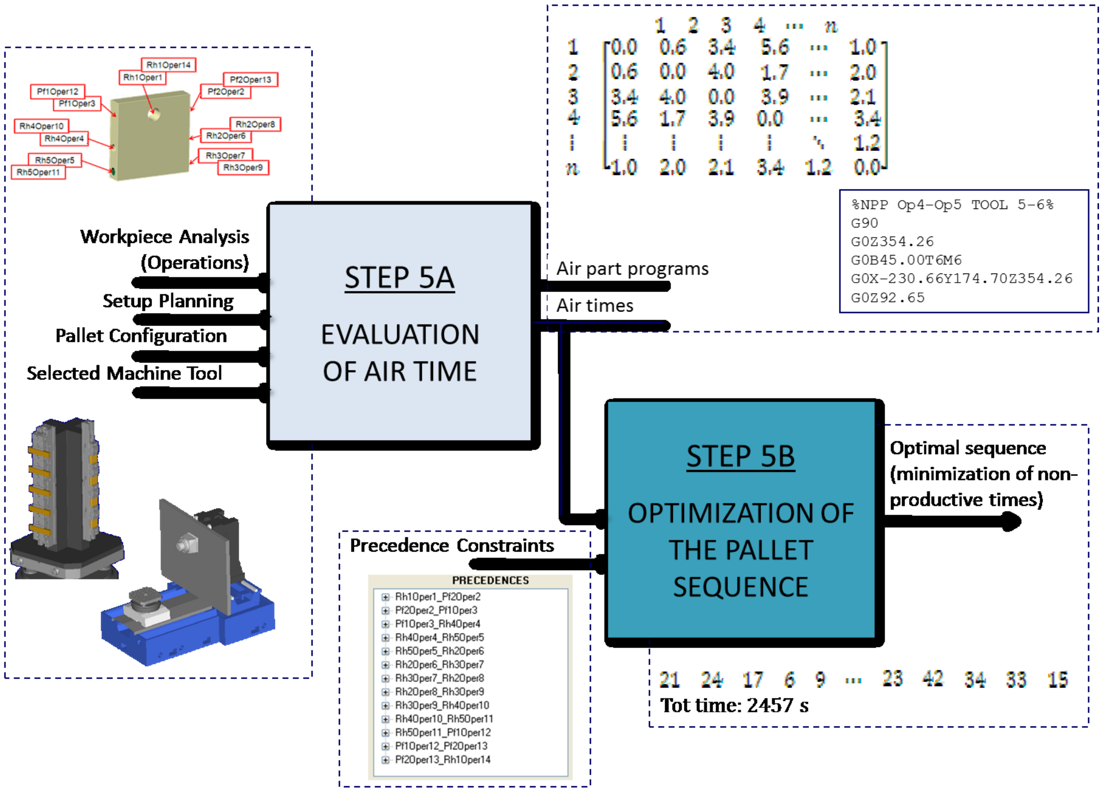


Fig. 8. Approach for the sequencing of the pallet MWSs.

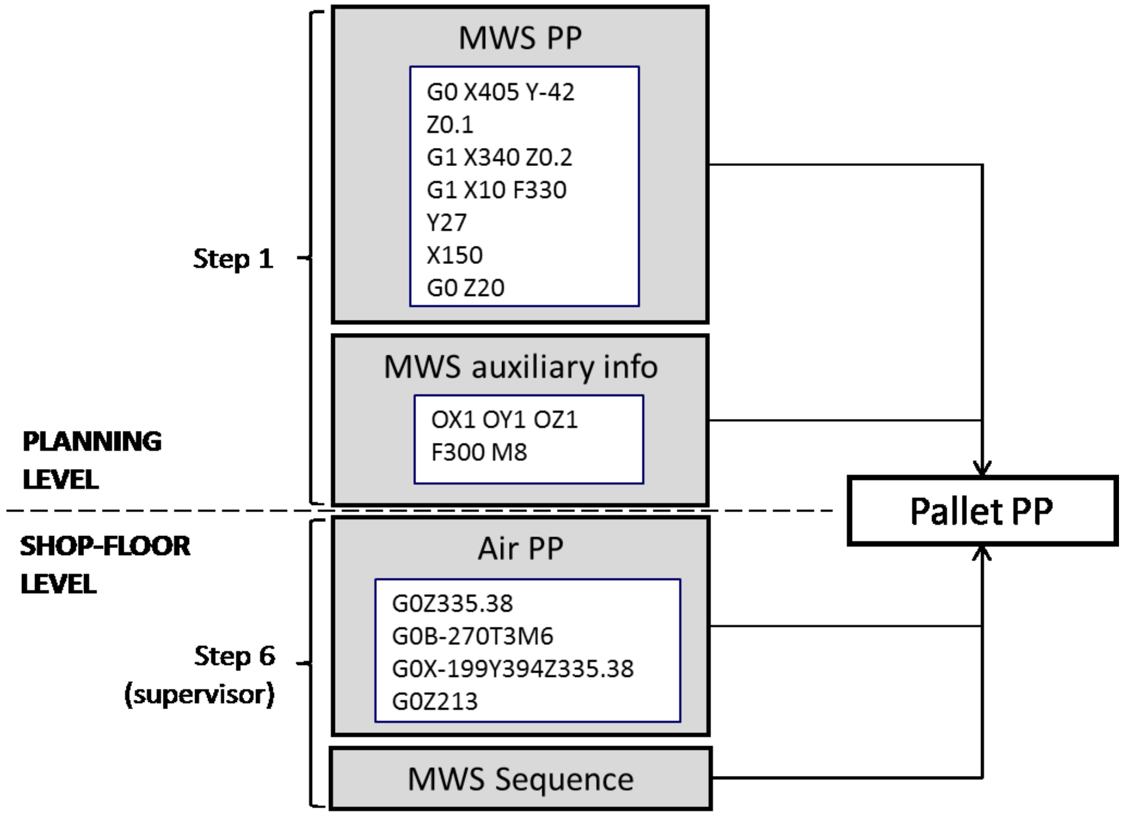


Fig. 9. Input data for the generation of the part program for the machining of a pallet.

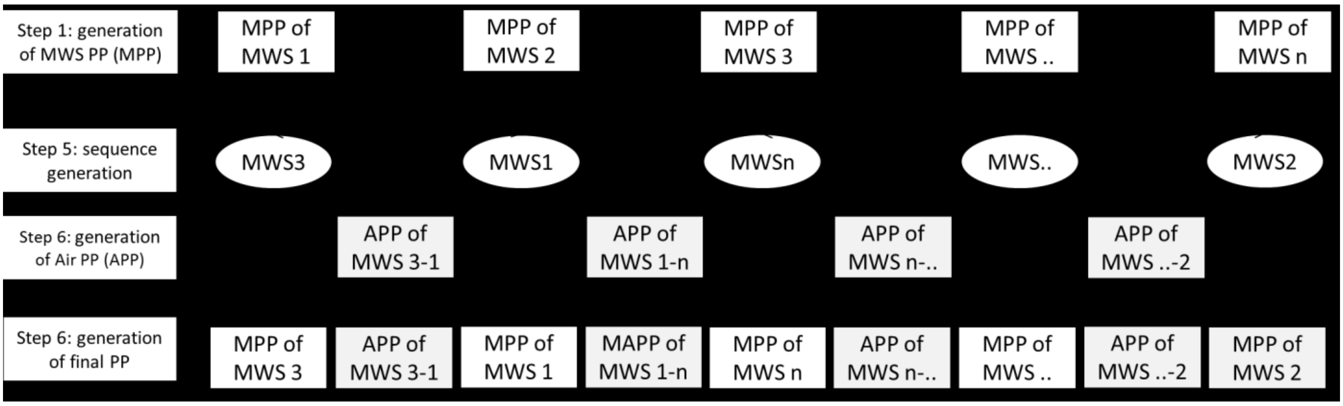


Fig. 10. Process related to the **g**eneration of the part program for the machining of a pallet.

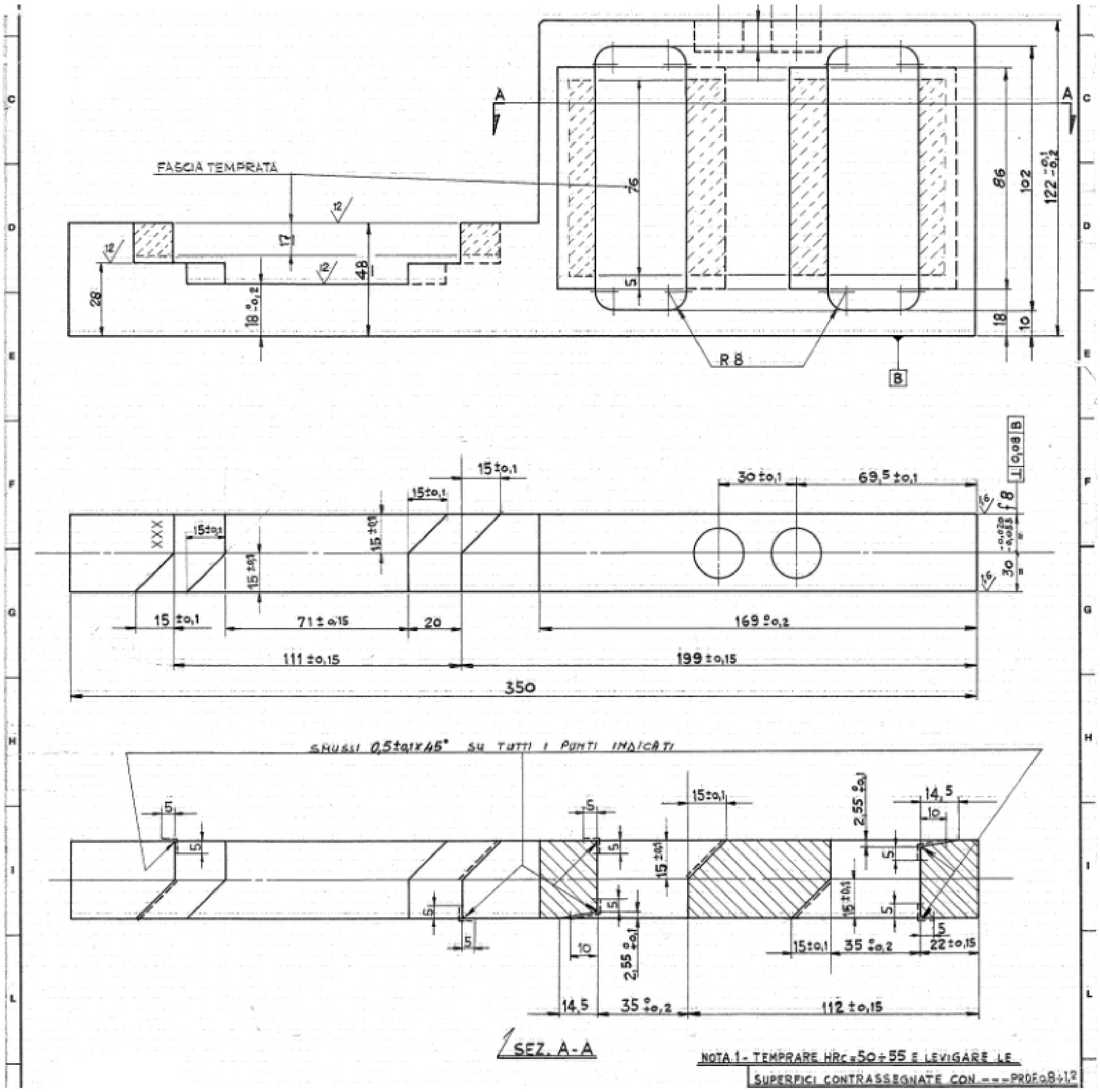
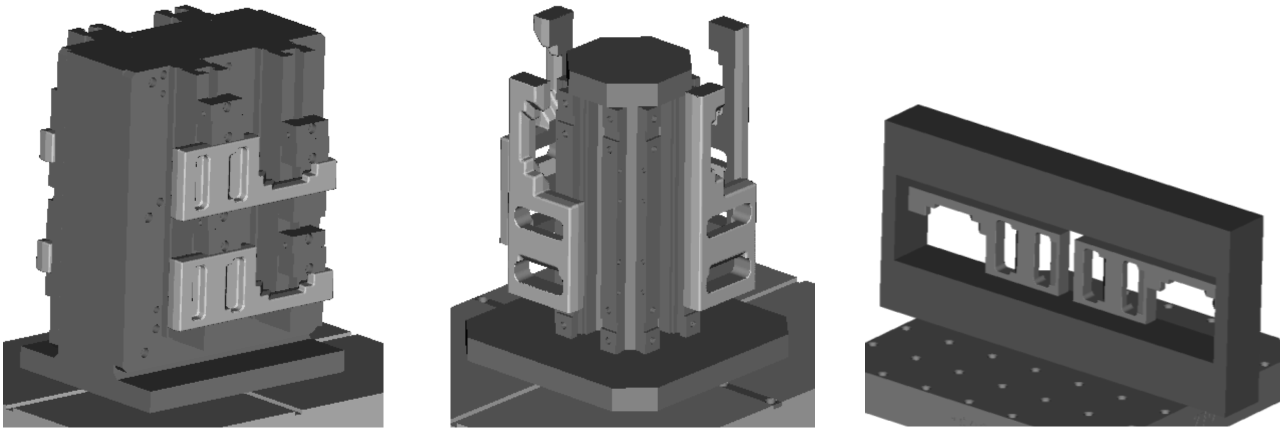
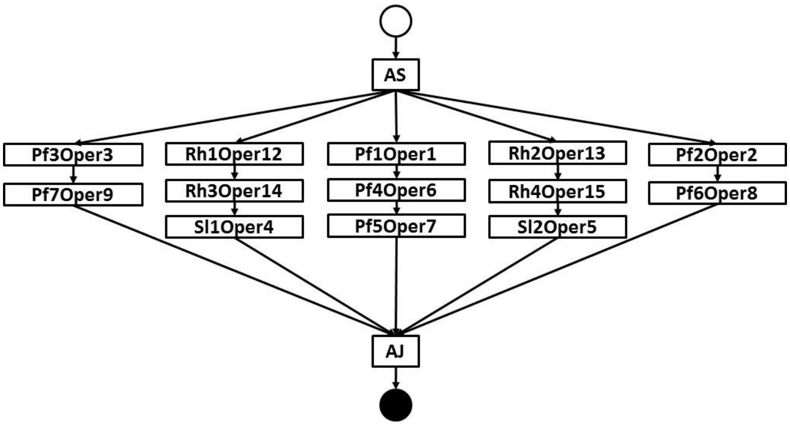


Fig. 11. Technical drawing of Catenaccio.

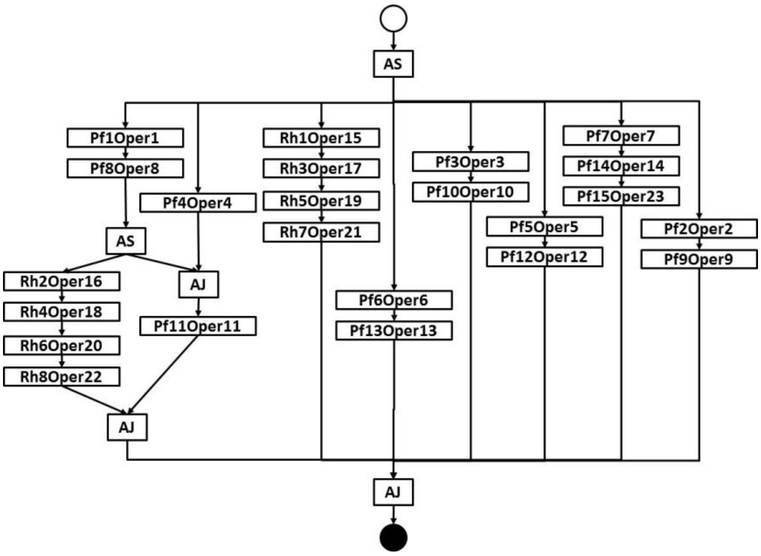


(**a**) *First Pallet* (**b**) *Second Pallet* (**c**) *Third Pallet*

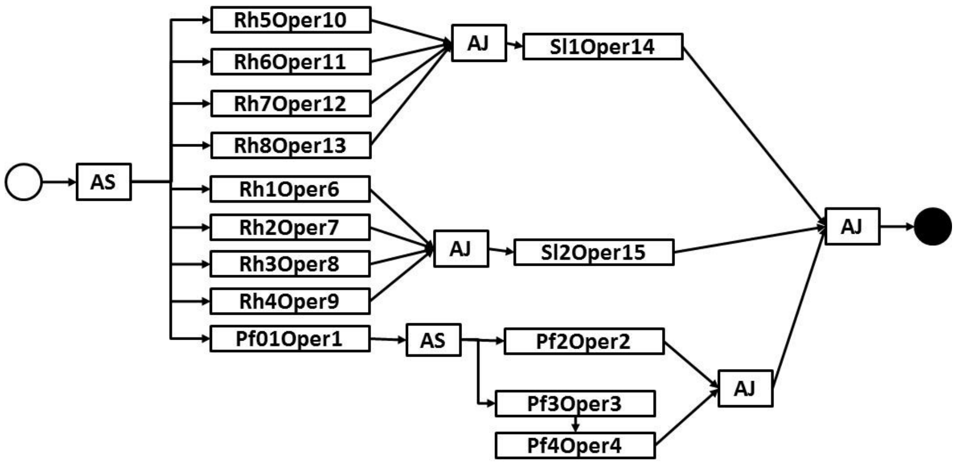
Fig. 12. Catenaccio pallet configuration.



(**a**) *First Setup*



(**b**) *Second Setup*



(**c**) *Third Setup*

Fig. 13. Catenaccio networks.

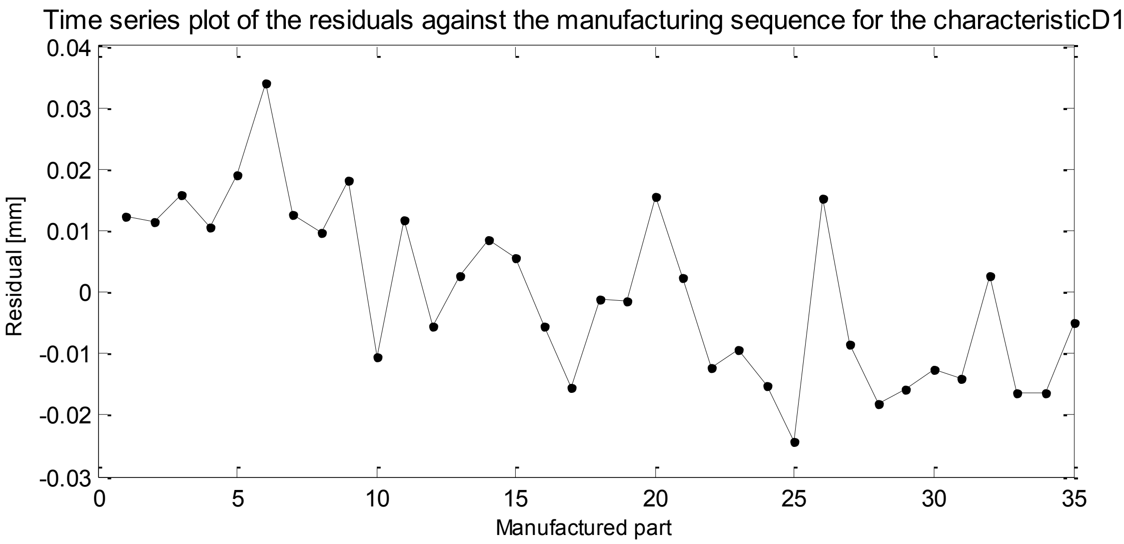


Fig. 14. Time series plot of the residuals against the manufacturing sequence for the characteristic D1.

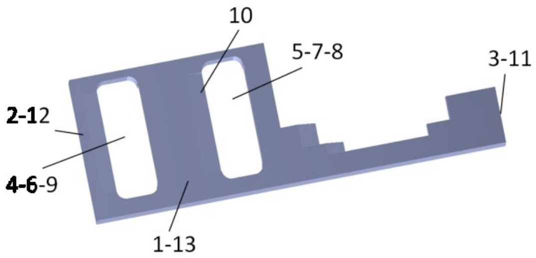
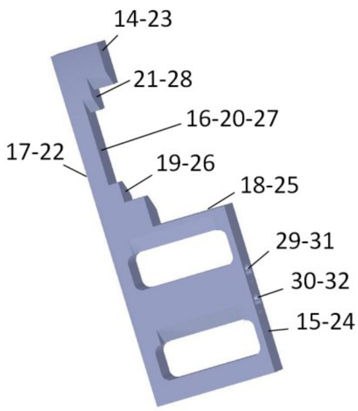
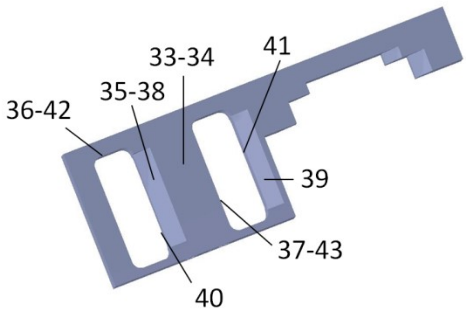
Setup	*MWSs*	*Description*	*Tool*
	(1)Pf1Oper1	Milling (rough.)	T2_1 $\phi 88$
	(2)Pf3Oper2	Milling (rough.)	T2_1 $\phi 88$
	(3)Pf2Oper3	Milling (rough.)	T2_1 $\phi 88$
	(4)Sl1Oper4	Drilling	T4_1 $\phi 12$
	(5)Sl2Oper5	Drilling	T4_1 $\phi 12$
	(6)Sl1Oper6	Drilling (widen.)	T7_1 $\phi 16$
	(7)Sl2Oper7	Drilling (widen.)	T7_1 $\phi 16$
	(8)Sl2Oper8	Milling	T5_1 $\phi 25$
	(9)Sl1Oper9	Milling	T5_1 $\phi 25$
	(10)Sl1Oper10	Milling	T3_1 $\phi 50$
	(11)Pf2Oper11	Milling (finish.)	T6_1 $\phi 80$
	(12)Pf3Oper12	Milling (finish.)	T6_1 $\phi 80$
	(13)Pf1Oper13	Milling (finish.)	T6_1 $\phi 80$
	(14)Pf2Oper1	Milling (rough.)	T2_2 $\phi 50$
	(15)Pf1Oper2	Milling (rough.)	T2_2 $\phi 50$
	(16)Pf6Oper3	Milling (rough.)	T2_2 $\phi 50$
	(17)Pf3Oper4	Milling (rough.)	T2_2 $\phi 50$
	(18)Pf4Oper5	Milling (rough.)	T3_2 $\phi 50$
	(19)Pf5Oper6	Milling (rough.)	T4_2 $\phi 32$
	(20)Pf6Oper7	Milling (rough.)	T4_2 $\phi 32$
	(21)Pf7Oper8	Milling (rough.)	T4_2 $\phi 32$
	(22)Pf3Oper9	Milling (finish.)	T5_2 $\phi 63$
	(23)Pf2Oper10	Milling (finish.)	T5_2 $\phi 63$
	(24)Pf1Oper11	Milling (finish.)	T5_2 $\phi 63$
	(25)Pf4Oper12	Milling (finish.)	T6_2 $\phi 37$
	(26)Pf5Oper13	Milling (finish.)	T12_2 $\phi 20$
	(27)Pf6Oper14	Milling (finish.)	T12_2 $\phi 20$
	(28)Pf7Oper15	Milling (finish.)	T12_2 $\phi 20$
	(29)Rh2Oper16	Drilling	T7_2 $\phi 19$
	(30)Rh1Oper17	Drilling	T7_2 $\phi 19$
	(31)Rh2Oper18	Drilling	T8_2 $\phi 14$
	(32)Rh1Oper19	Drilling	T8_2 $\phi 14$
	(33)Pf1Oper1	Milling (rough.)	T2_1 $\phi 88$
	(34)Pf1Oper2	Milling (rough.)	T3_3 $\phi 80$
	(35)Pf2Oper3	Milling (rough.)	T4_3 $\phi 50$
	(36)Sl1Oper4	Milling (rough.)	T5_3 $\phi 16$
	(37)Sl2Oper4	Milling (rough.)	T5_3 $\phi 16$
	(38)Pf2Oper6	Milling (finish.)	T7_3 $\phi 25$
	(39)Pf3Oper7	Milling (finish.)	T7_3 $\phi 25$
	(40)Pf4Oper8	Milling (finish.)	T7_3 $\phi 25$
	(41)Pf5Oper9	Milling (finish.)	T7_3 $\phi 25$
	(42)Sl1Oper10	Milling (finish.)	T6_3 $\phi 14$
	(43) Sl2Oper11	Milling (finish.)	T6_3 $\phi 14$

Table 1. Catenaccio Machining Workingsteps.

Source	*Sum Sq.*	*d.f.*	*Singular?*	*Mean Sq.*	*F*	*P-value*
Sequence	0.000954	4	0	0.000239	0.2020	0.9349
Load/Unload	0.000086	1	0	0.000086	0.0730	0.7893
Sequence * Load/Unload	0.000536	4	0	0.000134	0.1135	0.9766
Error	0.029521	25	0	0.001181		
Total	0.031106	34	0			

Table 2. ANOVA table for characteristic D.

Characteristic	P-value
A1	0.504427
B1	0.159893
C	0.646755
C1	0.257684
D	0.570546
D1	0.428909
E	0.07953
F	0.025111
H	0.285568
I	0.946554
J	0.311681
K	0.389332
M	0.80921
N	0.568846
O	0.035441
P	0.82487
Q	0.942701
R	0.525489
V	0.616454
W	0.098286
Y	0.135646
Z	0.264677

Table 3. Levene tests p-values.