PROCESS ANALYSIS AND FLEXIBLE TRANSFER LINE CONFIGURATION

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The offer of the best machine tool configuration for the specific customer's need is a decisive factor to compete in the machine tool sector. Actually the offer is organized by the manufacturer mostly on the basis of his own experience and requires a considerable amount of time and money. This effort does not always lead to tangible results, since few offers actually lead to purchases. So there is the need of tools that supports manufacturers in making the configuration choices. This paper is a step towards this direction, it illustrates a method for process analysis and transfer lines configuration.

1. INTRODUCTION

Currently manufacturing companies are under the intense pressure of global market competition.
To successfully compete in such a market environment companies have to continually release new products or modifying the existing ones in order to meet the evolving customers requests. This strategy leads to a considerable reduction of products life cycle. So related to product feature changes, production systems have to be properly configured or reconfigured to efficiently tackle the new production requirements.

At present system configuration is carried out manually by skilled operators that using their expertise are able to determine the most appropriate production resources to deal with the considered production problem. As systems configuration implies the selection of a huge set of decision parameters, it requires a considerable amount of time.

In addition, from a system manufacturer point of view, system configuration is cornerstone in the offer generation process to their customers. To be noted that only a small amount of offers, about 15%, are actually followed by an order, so the configuration phase is an expensive task for system manufacturers.

Thus there is the need of tools which support the configuration phase evaluating the performance of a wide range of configuration alternatives in a short time.

In particular this paper proposes an approach for automatic transfer line configuration. The method starts with a process analysis that evaluates the manufacturing requirements, then a set-up planning module and an equipment selection module define the line configuration.

2. OUTLINE OF THE PROPOSED METHOD

As transfer lines are dedicated manufacturing systems their configuration is strictly dependant on the part mix to be produced. The high degree of customization allows these systems to obtain high productivity because high production rate and working accuracy can be obtained with low investment costs. Conversely design cost, given the high degree of customization, tend to be pretty high. To face these problems modern transfer lines are designed according with modular design principle. So line configuration implies the selection of the number, characteristics and positioning of the modules the line is composed of. Consequently it is easy to notice that the combination of all the decision variables rapidly leads to an explosion of the number of feasible transfer line configurations.

In other terms system configuration is very complex so hierarchical approaches are often used to face this complexity[4], [7].

Therefore the proposed approach divides the configuration problem into two sub problems which are hierarchically related. At the higher hierarchical level transfer lines are described by few decision variables, especially by the ones which mostly affect line investment costs. At the lower level the lines are described in a more detailed way by several decision variables in addition to the ones previously considered.

In particular in the present approach at the first hierarchical level the decision variable considered is the number of set-ups necessary to process the production mix. The set-up number directly affects the number of transfer lines of the considered production system. In fact especially in contexts characterized by high production rate each set-up is processed on a dedicated transfer line, thus reducing idle time due to line set-up. Once the number of transfer lines needed to address a particular production problem is defined the decisions of the second hierarchical level are the number of working stations which compose the line and some technical characteristics of the machining units of each working station. In other words at the second level the production resources of the transfer line are selected.

3. PROCESS ANALYSIS

The production problem imposes some manufacturing requirements, which include features to be realized and operations required to machine them. Manufacturing requirements directly affect both the set-up planning and the equipment selection phase by some technological constraints that must be considered to correctly manufacture the product mix.

The analysis of these manufacturing requirements is managed in the proposed approach by the ISO (14649) STEP-NC standard. The features of the workpieces are defined by STEP-NC as *Manufacturing Features* and each of them needs a set of *Machining Operations* to be processed. Furthermore according to this standard each *Manufacturing Feature* is combined with a *Machining Operation*, to be performed on the feature, to obtain the entity *Machining Workingstep* (MW). A MW, therefore, represents a precise operation a machine can make on a particular feature of the workpiece. In this study each MW has been characterized with information about the machining direction, that is the direction of the axis of the tool body that realizes the MW.

The MWs of the workpiece are often linked by technological priorities or tolerance constraints. In this regard the paper examines shape and position tolerance, these relationships are considered as precedence relationships. In particular precedence relationships have been classified in three types according to [1]. Type 1 constraints refer to tight tolerance constraints which impose to process some MWs in the same set-up and in a defined sequence in order to ensure the maximum working precision thus avoiding repositioning errors. Type 2 constraints are technological constraints, which impose an order of execution of the MWs involved, but do not impose the sharing of the same set-up. For example drilling a workpiece imposes a previous milling of the surface involved. Finally Type 3 priorities affect manufacturing quality and efficiency, but are not essential for the correct production of the workpiece, so these relationships could be dropped if this allows to reduce the set-up number. An example of this type of constraints is the manufacturing of two nested pockets, the sequence of execution does not affect the machining feasibility but only the efficiency of the process itsef.

4. SET-UP PLANNING

Set-up planning plays a key role in system configuration since it influences both production costs and quality. The reduction of the number of set-ups implies a decrease of the number of transfer lines necessary to correctly process the part thus reducing the investment costs. Also manufacturing quality improves due to the reduction of positioning errors which inevitably occur passing from a set-up to the next one.

4.1 Graph Approach

This paper proposes a graph approach to determine transfer line set-up planning. Precedence constraints information, analyzed in the process analysis phase, are organized in an oriented graph usually indicated by the name of *Process Graph* [5], [6]. The nodes of this graph are MWs, while the edges represent precedence constraints. The edges of the graph could be of different types according to the type of precedence constraints.

Set up planning is carried out considering each set-up of the workpiece as a group of MWs and therefore as a group of machining directions. Anyway a group of machining directions represents a feasible set-up only if all its operations can be machined exploiting the degrees of freedom of the considered machine. Therefore initially the method creates groups of MWs which share the same machining direction and therefore are certainly accessible to the machine. To this purpose another oriented graph is created called *Direction Graph*. Each node of this graph represents a group of MWs, while each edge describes the precedence relations that exist among the MWs belonging to different groups, figure 1.

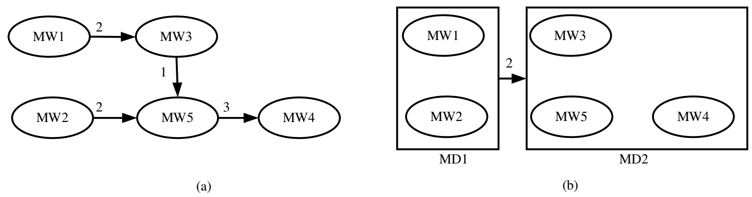

Figure 1 – *Process Graph* (a) and a corresponding *Direction Graph* (b)

This clustering allows to machine the created groups on a transfer line whose working stations are able to machine in only one direction. Nowadays however each working station of a line is usually equipped with more than one production unit so the number of machining directions which could be processed in the same set-up increases. Therefore each set-up could be composed by MW belonging to different machining directions. In these cases the previous considered groups of MWs could be enlarged adding more machining directions.

Therefore the method, starting from the *Direction Graph* computes all the combinations of groups, so each combination is an hyper group that includes more than one machining direction.

Moreover the workpiece orientation affects the number of machining directions which could be processed at each work station of the line. So the method looks for alternative workpiece orientations in order to maximize the number of machining directions that are within the reach of the production units, thus going in the direction of minimizing the total number of set-ups. Alternative orientations are generated for each combination of groups taking into account the feasible directions of the machining units of the considered type of transfer line.

An accessibility analysis is then used to determine if the machine, exploiting its degrees of freedom, is able to reach all the machining directions of the considered combination. If this condition is satisfied in regards with at least one alternative workpiece orientation the considered combination of groups could be treated as potential set-up. The set-up plan is thus generated with the aid of an oriented graph called *Set-up Graph*. The nodes of this graph are potential set-ups, while the edges represents the precedence relationships between the linked potential set-ups. The presence of a cycle in the *Set-up Graph,* implies that the generated set-up plan is unfeasible, since it is not possible to establish the sequence of the set-up execution. So the method selects among acyclical *Set-up Graph* the ones characterized by the minimum number of nodes, thus minimizing the number of set-ups.

Theses alternative set-up plans are then used as input data to the equipment selection module.

5. EQUIPMENT SELECTION

After a set of alternative set-up plans has been computed the configuration method proceeds with the equipment selection phase which selects the resources of the line

In particular the equipment selection establishes the number of workstations of the line and also the number and the technical characteristics of the machining units that equip each working station.

This approach in particular refers to flexible transfer lines which are able to process different workpieces through appropriate line reconfigurations.

One of the key characteristics of the transfer lines is the possibility of processing different operations in parallel thus increasing the production rate. In particular different machining units in a given station can be simultaneously activated. Moreover each machining unit, if properly equipped, can perform more than one MW simultaneously.

To capture the system behavior the MWs are clustered in blocks of operations, [2]. Blocks are formed by operations which could be simultaneously machined by the same spindle. So the operations which belong to the same block have to share the same working feed and the same machining direction, and to respect some technological constraints imposed by the adopted tool.

The model assumes that blocks could be manufactured by different types of machining units characterized by different technical parameters, capabilities and investment costs. Moreover blocks processing time are deterministic and do not rely on the characteristics of the machining units.

The equipment selection module minimizes the investment costs by balancing the work load of the line and selecting the production resources cost while satisfying the production rate imposed by the production problem and the technological constraints.

5.1 Problem formulation

This section presents the mixed integer programming model developed to face the equipment selection phase previously illustrated.

The problem is defined by the following parameters:

$BD_{b,d}$ = *1 if the block b must be processed by a machining unit belonging to the d direction, otherwise 0 (set-up planning output).*

$WUBC_b$ = *cost of the machining units equipped with the minimum technical characteristics required to correctly process the block b.*

TB_b = *block b working time.*

CT_p = *cycle time imposed by the production rate for the workpiece p.*

PREC = set of block couples related by precedence constraint.

ZN = set of block couples related by "negative zoning" constraint.

ZP = set of block couples related by "positive zoning" constraint.

The decisions that have to be made address to the following issues:

$WSB_{s,b}$ = *1 if the block b is assigned to the working station s, otherwise 0.*

$WUC_{s,d}$ = *cost of the machining unit that equips the direction d of the working station s.*

So the model developed to configure the transfer line is now illustrated:

$$\text{Min } C\left(\sum_{p\in P} LT_p + \sum_{p\in P}\sum_{s\in S} WST_{p,s}\right) + \sum_{s\in S}\sum_{d\in D} WUC_{s,d}$$

subject to:

1. $WUC_{s,d} \geq WUBC_b \cdot WSB_{s,b} \cdot DB_{b,d}$ $\forall s\in S, \forall d\in D, \forall d\in D$
2. $\sum_{s\in S}\left[s\cdot\left(WSB_{s,b2} - WSB_{s,b1}\right)\right] \geq 1$ $\forall (b1,b2)\in PREC$
3. $\sum_{s\in S} WSB_{s,b} = 1$ $\forall b\in B$
4. $WSB_{s,b2} + WSB_{s,b1} \leq 1$ $\forall s\in S, (b1,b2)\in ZN$
5. $WSB_{s,b2} = WSB_{s,b1}$ $\forall s\in S, (b1,b2)\in ZP$
6. $WUT_{p,s,d} = \sum_{b\in B}\left(TB_b \cdot WSB_{s,b} \cdot DB_{b,d}\right)$ $\forall p\in P, \forall s\in S, \forall d\in D$
7. $WST_{p,s} \geq WUT_{p,s,d}$ $\forall p\in P, \forall s\in S, \forall d\in D$
8. $LT_p \geq WST_{p,s}$ $\forall p\in P, \forall s\in S$
9. $LT_p \leq CT_p$ $\forall p\in P$

The objective function is composed by two parts. The minimization of the part in bracket is useful to determine the $WST_{p,s}$ and LT_p which represent respectively the working station time and the line time. $WST_{p,s}$ is the maximum of the machining unit times in respect to each line working station. The term LT_p is the line time which correspond to the maximum $WST_{p,s}$, and so to the slowest working station.

The objective function second part minimizes the investment cost of the line which is the sum of the investment costs of the machining units.

The constraint set (1) ensures that the characteristics of each machining unit are appropriate to process the assigned blocks of operation. To be note that the investment costs of the machining unit are related to the equipment technical characteristics. The second constraint set imposes the respect of the precedence relationships. The constraint set (3) specifies that all the blocks that compose the problem must be manufactured. The constraint set (4) represents exclusion constraints [3] and describes the impossibility of two operation to share the same working station. For example roughing and finishing operations are usually manufactured at different working station due to vibration and chip problems that could affect the quality of the machined surface.

Inclusion constraints [3] are modeled by constraint set (5). These constraints are usually imposed when there are tight tolerance relationships that involve some operations of the two considered blocks. The sharing of the same working station allows to avoid repositioning errors, thus ensuring the best precision that could be obtained. The constraint set (6) allows to compute $WUT_{p,s,d}$ as the sum of the block working time allocated to the same machining unit. The constraint sets (7) and (8) are necessary to determine the working station time and the line time. These time variables have to be considered in order to check if the line throughput satisfies the imposed production rate. To this purpose the constraint set (9) ensures that the line time, in respect to a workpiece *p*, does not excide the cycle time, thus assuring the respect of the production rate.

6. MODEL APPLICATION

The illustrated method for flexible transfer line configuration was applied to a real production case supplied by an Italian manufacturer of transfer line, Riello Sistemi S.p.A.. This case refers to a pick up steering gear holder, figure 2, that had to be produced with a production rate of 214 [piece/hour]. Do to some planned future changes to the pick up power train, some features of the steering gear holder had to be modified, so another version of the same subassembly had to be produced with the same production rate of the previous one.

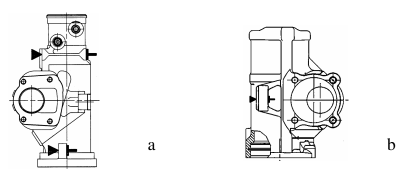

Figure 2 – First *a)* and second *b)* version of steering gear holder

To compare the configuration obtained by the proposed approach with the one of Riello Sistemi, the same resolution strategy of the system manufacturer was pursued.

The first step consists in the evaluation of rigid transfer line configurations, so these systems are equipped with the only production resources necessary to effort the manufacture of one version of the steering gear holder. Thus in respect to each product version the number of transfer lines that compose the system, the number of line working stations and the characteristics of the machining units that equip each working station are determined.

The configuration of the flexible transfer line is determined starting from the rigid ones. In particular the number of lines of the flexible system is imposed by the workpiece version that need the maximum number of set-ups to be processed. The same could be stated in regard with each working station of the line . The characteristics of the machining units are instead detected by the equipment selection module considering simultaneously the manufacturing requirements of the two product versions.

Table 1 – System configuration: *a)* proposed approach and *b)* Riello Sistemi S.p.A.

Presented approach	N° working stations	N° machining units	Investment cost [Euro]
Line 1	11	28	368000
Line 2	5	8	120000
System	16	36	488000

a)

Riello Sistemi	N° working stations	N° machining units	Investment cost [Euro]
Line 1	7	19	246000
Line 2	11	17	258000
System	18	36	504000

b)

Table 1 synthesizes some main characteristics of the configuration generated by the presented approach and the one proposed by Riello Sistemi. It could be noted that the configuration computed by the proposed approach allows to face the production problem with the same number of machining units and with two working stations less than the one of Riello Sistemi, thus reducing the investment costs of the system.
In particular the promising result obtained is due to the large number of alternative set-up plans generated by the set-up planning module.

7. CONCLUSION

The present work proposes a possible solution to the problem of automatic configuration of flexible transfer line. The method could support the system manufacturer in the evaluation of alternative system configuration.
The proposed methodology starts with an analysis of the customer's production requirements following the ISO 14649 (STEP-NC) standard and thus considering both the technological and geometrical issues. These issues are then considered as input to the set-up plan module. A graph approach to set-up planning has been developed that generates, through an accessibility analysis, a set of alternative set-up plans characterized by the minimum set-up number. This set is useful evaluate different line configurations through the equipment selection phase. In this regard the methodology proposes a mixed integer programming model that minimizes the transfer line investment cost, selecting the most appropriate production resources for each working station of the line. The configuration method was applied to a real case, showing good agreement with the real configuration adopted by the system manufacturer.

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