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A mixed-integer linear programming model for part mix, tool allocation, and process plan selection in CNC machining centres

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Abstract

A mixed-integer linear programming model is developed for the simultaneous determination of part mix, tool allocation and process plan selection in CNC machining centres. Illustration of the use of the model in a hypothetical example and its application to a real problem arising in deep seabed operations demonstrate the utility of the model as one more step towards the integration of computer-aided process planning (CAPP) tasks in CNC machining enviroments.

Keywords: Process planning; CNC machining

1. Introduction

In automated manufacturing systems, such as CNC machining centres, a number of process plans are generated for each part type. In each process plan, requirements are specified for operations, tools, fixtures, etc. The selection of the best process plan depends on cost factors as well as characteristics of the manufacturing environment under consideration. Kusiak and Finke [1] developed a mixed-integer linear programming (MILP) model in which the sum of process plan dissimilarity and cost functions is minimised. Bhaskaran [2] proposed a multi-stage procedure in which initial process plans are gradually consolidated with a view to cost minimisation. Chang [3] included sequencing of part type machining in the process plan selection problem, employing the same objective function as Kusiak and Finke [1].

None of the aforementioned works take into account operational aspects such as part selection and tool allocation when selecting process plans. On the other hand, Iakocou et al. [4] developed an MILP model for determining the optimal part–tool combination with a view to maximizing total revenue; however, it was assumed that each part can be machined by one and only one out of several tools. This is a severe restricting assumption in practice, as a part is machined by one out of several process plans, each of which requires one or more tools. It is the objective of this paper to address this gap in developing an MILP model for the integration of determining optimal part mix, tool allocation, and process plan selection.

The structure of the rest of the paper is as follows. A concise problem statement is first presented. This is followed by the development of the MILP model. Next, the procedure employed in generating machining process plans is presented. The use of the model is then illustrated via the machining of three hypothetical parts. The model is then applied to a real case involving the machining of a 3-part assembly employed in deep seabed oil drilling operations.

2. Problem statement

The manufacturing system under consideration consists of a CNC machining centre, which is capable of processing several part types. The following assumptions are made:

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Nomenclature

p	index denoting part type; $p = 1, P$
q	index denoting machining process plan; $q = 1, Q$
t	index denoting tool; $t = 1, T$
M_p	set of plans to machine part p
N_q	set of tools employed in plan q
R_p	revenue for part p
C_{pq}	machining cost of part p employing plan q
S_t	setup cost of tool t
A	tool magazine capacity
W_t	number of magazine slots occupied by tool t
X_{pq}	binary decision variable, 1 if part p is produced using plan q, 0 otherwise
Y_t	binary decision variable, 1 if tool t is loaded, 0 otherwise
Z_{pqt}	binary decision variable, 1 if tool t is used in plan q to machine part p, 0 otherwise

1. A part type may be produced by one or more machining process plans, each of which consists of several operations obeying precedence logical constraints.
2. Each operation is associated with one or more cutting tools, each of which can process one or more part types.
3. Each tool can occupy one or more slots in the machine magazine which has finite capacity.
4. For each part–plan pair, there is an associated machining cost.
5. For each tool, there is an associated setup cost accounting for tool loading and calibration times.
6. For each part type, there is an associated sale revenue.

The problem under consideration may be stated as follows: Given the configuration of each process plan, the set of tools used in each process plan, the number of slots occupied by each tool, the magazine capacity, the machining cost for each part–plan pair, the setup cost for each tool, and the revenue for each part, determine the subset of part types to be machined, the subset of tools to be loaded, and the subset of process plans to be computer-programmed so as to maximise net profit.

3. Model formulation

The model may be stated as:

$$\text{Maximise} \sum_{p=1}^{P}\sum_{q=1}^{Q} R_p.X_{pt} - \sum_{p=1}^{P}\sum_{q=1}^{Q} C_{pq}.X_{pq} - \sum_{p=1}^{P}\sum_{q=1}^{M_p}\sum_{t=1}^{N_q} S_t.Z_{pqt} \qquad (1)$$

subject to

$$\sum_{q=1}^{Q} X_{pq} \leq 1, \quad p = 1, P, \qquad (2)$$

$$Z_{pqt} = Y_t, \quad p = 1, \; P, q = 1, \; Q, t = 1, \; T, \qquad (3)$$

$$Y_t - X_{pq} \geq 0, \quad p = 1, P; \, q = 1, Q, t = 1, T, \qquad (4)$$

$$\sum_{t=1}^{N_j} W_t.Y_t \leq A \qquad (5)$$

$$X_{pq} \geq 0, \quad p = 1, P, q = 1, \; Q, \qquad (6)$$

$$Y_t \geq 0, \quad t = 1, \; T, \qquad (7)$$

$$Z_{pqt} \in \{0,1\}, \quad p = 1, \; P, q = 1, \; Q, t = 1, \; T. \qquad (8)$$

The objective function (1) represents net profit. The constraints (2) ensure that a part is machined by one process plan or not at all. The constraints (3) ensure that if a tool is used in more than one plan, this is reflected in its setup cost. The constraints (4) ensure that if a part is machined, all tools necessary for the selected plan are loaded. The constraint (5) guarantees that tool magazine capacity is not exceeded. The constraints (6)–(8) ensure the necessary nonnegativity and binarity of the decision variables. The model formulated as (1)–(8) constitutes a mixed-integer linear programming (MILP) model.

4. Process plan generation

In order to use the MILP model developed in the last section, a set of process plans must first be generated for each part type. This is performed according to the following procedure:

1. The part geometry is analysed with a view to identifying the necessary machining operations, such as drilling and turning.