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An integer programming approach for process planning for mixed-model parts manufacturing on a CNC machining center

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ABSTRACT

The manufacturing system for mixed parts is prevalent in many industries due to the continuous demand of product variety. Thus, the mathematical model to design a process plan is developed by using the integer linear programming. The main aim is to minimize the total production time. The main time factors included in the model composed of the machining time, tool traveling time, tool changing time and tombstone face changing time. The significant design constraints are the precedence operations, fixture design, and available cutting tool constraints. Furthermore, a variation of part styles is also accounted for in this study as the different types of a part can be concurrently mounted and processed which makes this problem unique. Therefore, this problem is much more complex than the normal single model process planning. The model developed using integer programming will determine a sequence of required machining operations. It also decides the face of the machining part to be fastened on the tombstone face. In addition, a suitable cutting tool will be selected based on minimum total production time. The result of this paper, aids in solving process planning difficulty in the dedicated flexible manufacturing system in the era of Industry 4.0.

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1. Introduction

A process planning task is a part of product design and manufacturing system that considers the manufacturing resources and engineering techniques for decision making. The efficient process plan can be achieved by well-designed logical operation steps, technological machine capabilities, cutting tool selection, and machining conditions. Moreover, the process planner has to be concerned about the jigs and fixtures, route sheet generation, setup requirements and other important processes during the design process [1]. Thus, the process plan reveals the sequence of machining operations together with a selection of cutting tools as well as cutting conditions. A process planner must make a crucial decision whether to continue using the same cutting tool or to change to a new cutting tool for the next set of remaining operations. This decision dictates a resulted machining sequence and challenges researchers to innovate efficient algorithms for a generation of the process plan which is considered a classic problem for automated process planning. It is obvious that the process planning task is crucial and affects both of the economic and efficiency of the manufacturing system.

In decades, the CNC machine technology has been developed by equipment to make it more highly automated, flexible, and run at a faster speed. The ATC (Automated Tool Change) and APC

(Automated Pallet Change), as an example, augment the capability of the CNC machine and become the standard equipment equipped in the available CNC machine in the market. The ATC enables the quick tool change from the tool magazine at no time loss. In addition, a modular fixture for the CNC machine is developed to allow a quick change of fixture design to cope with the FMS (Flexible Manufacturing System) demand. The automated process plan plays a crucial role in FMS since it enables the system to work effectively and meet its design objective. The FMS is deemed an intelligent manufacturing system (IMS) which corporates computer networks, automation, and intelligent software.

It can be enhanced by wireless communication, sensor networks, Internet of thing (IoT) to become a high-resolution manufacturing system (HMS) [2, 3]. Therefore, the FMS is considered an indispensable physical platform for the fourth industrial revolution so-called Industry 4.0. The FMS enables mixed-model parts to be concurrently performed in the same environment. It requires an automated part identification and a quick change of both physical setup and part programming. To enable the quick physical setup change, a tower-type pallet or tombstone type, together with APC, are invented to fasten multi-part faces and to change a pallet in the CNC machine. The tower-type tombstone allows up to four different part faces to be machined in only one set up. The part fastened at each tombstone face is not necessarily from the same work-part. It can be from a totally different part which shares the same set of available tools. Logically, a process planner must make an additional effort to decide which part face has to be fastened at each tombstone face which certainly relates and affects a tool selection. Meaning that a planner can continue using the same tool for more operations at different locations by rotating the tombstone. The APC allows a quick pallet change in order to eliminate setup time due to part change. In other words, the machining operations can be performed at one tombstone whereas unloading/loading of the new parts can be concurrently operated at the other tombstone. As a result, the process planner's task is enlarged by the advent of the new mentioned technology. This will increase the complexity of a process planning task since more machining operations and more part-faces options needed to be considered. Therefore, a sound process plan must integrate the machining operation requirement and the work-part sequence and orientation in the consideration, in order to suit today's CNC machine. In other words, the intelligent process plan must be able to reveal a sequence of machining operations with the selected tool and also identify the tombstone rotation sequence with the selected work-part face. Obviously, this task cannot be accomplished without the intelligent mathematical program.

This research deals with the flexible job shop scheduling problem, which is the NP-hard problem [2]. This research also proposed the Computer-Aided Process Planning (CAPP) by using the integer linear programming.

2. Literature review

The research in an automated process planning area has been long conducted for a few decades. A myriad of algorithms and methods both in heuristic and optimization are presented in the previous literature [2]. However, one of the most classic methods used to generate a process plan is an optimization through a linear programming method and can be applied in all manufacturing systems. As referred to in [3], the mixed integer programming was a mathematical technique used for flow shop scheduling and job shop scheduling, including the fuzzy processing time under precedence constraints and machine capacity constraints. The mixed integer programming also was used in the work of [4] for integrated process planning and scheduling model (IPPS) in a job shop problem. The linear integer programming model was also used to select the machine-tool and allocate the operations for FMS, in which each part and tool can be dynamically changed during the production [5]. In addition, the mixed integer linear programming is used to minimize the maximum completion time of final products in a flexible assembly job shop with the sequential-dependent setup time [6]. The mathematical programming in the form of linear programming is always utilized in the flexible job shop scheduling problem (FJSP) [7-9], flow shop scheduling [3, 10, 11] and integrated process planning and scheduling (IPPS) systems [4, 6, 12]. Different conditions were found in the objective functions, for example, minimization of the make-span (the completion time of the last operation of all jobs), the lateness, the total processing cost and the weighted number of tardy jobs. In [8-9], the integrated constraint programming (CP) model was developed for the FMS, including the tool allocation, machine loading, part routing, and scheduling. The branch-and-bound algorithm was also used by the process planning and sequencing of CAPP and flexible manufacturing systems was studied [8]. Tool changing and tool sequencing problems were proposed where the branch-and-bound was used to minimize the total flow time [11, 12]. Various algorithms are proposed in the previous literature. For example, the game theory was proposed in [12] to investigate the interaction among decision alternatives, whereas the game theory was developed for multi-objective integrated process planning and scheduling (IPPS). The objective function is composed of the minimization of the maximal completion time of machines (makespan), the minimization of the maximal machine workload and the minimization of the total workload of machines. The integrated process planning was presented as a mathematical model to consider optimum machining conditions, operations sequences and tool magazine arrangement by CNC machine. The objective was to minimize the production costs [13]. As mentioned in [14], the process-planning model for machining cylinder heads in a typical engine manufacturing plant was designed in the form of mathematical programming models that include the part grouping, machine loading, tool allocation, and scheduling. The minimization of the non-productive tool movement and orientation time was proposed in this research. The problem of production scheduling, which consists of loading and sequencing, is tackled in this study [15]. The major findings of this study are generating an optimum sequencing order to complete all the jobs which have been assigned already on each machine. The solution for maximizing machine and labor utilization and reducing the idle time on each machine is presented. The two NP-hard optimization problems are composed of the flexible job-shop scheduling problems (FJSPs) and the FJSPs with process plan flexibility (FJSP-PPFs) [16]. The FJSPs is the routing and sequencing sub-problems, whereas the FJSP-PPFs, with process plan flexibility, is the process plan selection sub-problem. There are two steps for probe solving, which are 1) a mixed-integer linear programming model (MILP-1) is developed for FJSPs and 2) a modification of mixed-integer linear programming model is developed for FJSP-PPFs.

Table 1 Summary of mathematical modeling approach for process planning of machining processes

Author/ Year	Mathematical modeling approach				Process planning activities							
	Mathematical programming	Constraint programming	Branch and bound	Game theory	Sequencing of operation	Set-up planning	Selection of plan	Selection of part	Selection of machine	Selection of cutting tool	Cal. process times	Cal. cost
Li et al., 2010	*											*
Demir and Isleyen, 2013	*				*				*		*	
Milos Seda, 2007	*					*			*			
Li et al., 2010	*								*		*	*
Jahromi and Moghaddam, 2012	*							*	*	*		*
Nourali et al., 2012	*					*	*		*		*	
Deja et al., 2013			*		*				*			
Zeballos et al., 2010		*						*	*	*		
Zeballos, 2010		*						*	*	*	*	
Karakayal and Azizoglu, 2006			*			*					*	
Chandra et al., 2007			*			*					*	
Li et al., 2012				*			*				*	
Akturk and Avci, 1996	*				*					*		*
Das et al., 2009	*									*	*	
Ahmad et al., 2009	*					*			*		*	
Ozguven et al., 2010	*					*			*			*
Prombanpong et al.,1992	*					*						
Kongchuenjai and Prombanpong, 2015	*				*						*	

Computerized fixture design system and process plans generated by computer, aided the process planning. A mathematical model was developed to integrate process planning in fixture design considerations [17]. The objective of this research was to review the CAPP research works including the critical analysis of journals that publish CAPP research works and also the direction of future research work. The general information, past reviews, and discussions are summarized in various aspects [18]. In the work of [19], the mathematical programming to determine the optimal sequence of single part manufactured on a CNC machining center equipped with the single tombstone-type fixture was developed. The minimization of total production time required for machining, tool traveling and tool changing were then determined under relevant constraints. Table 1 concludes the relevant literature reviews of process planning of machining processes.

3. Materials and methods

3.1 Pallet configuration

As mentioned earlier the mixed-model parts in the FMS are to be machined by the CNC machining center with an automatic tool change and a pallet change function. With a pallet change function, it allows up to two pallets to be installed. Thus, the two tower-type pallets are equipped in the machine which allows up to eight-part faces to be ready for machining as shown in Fig. 1.

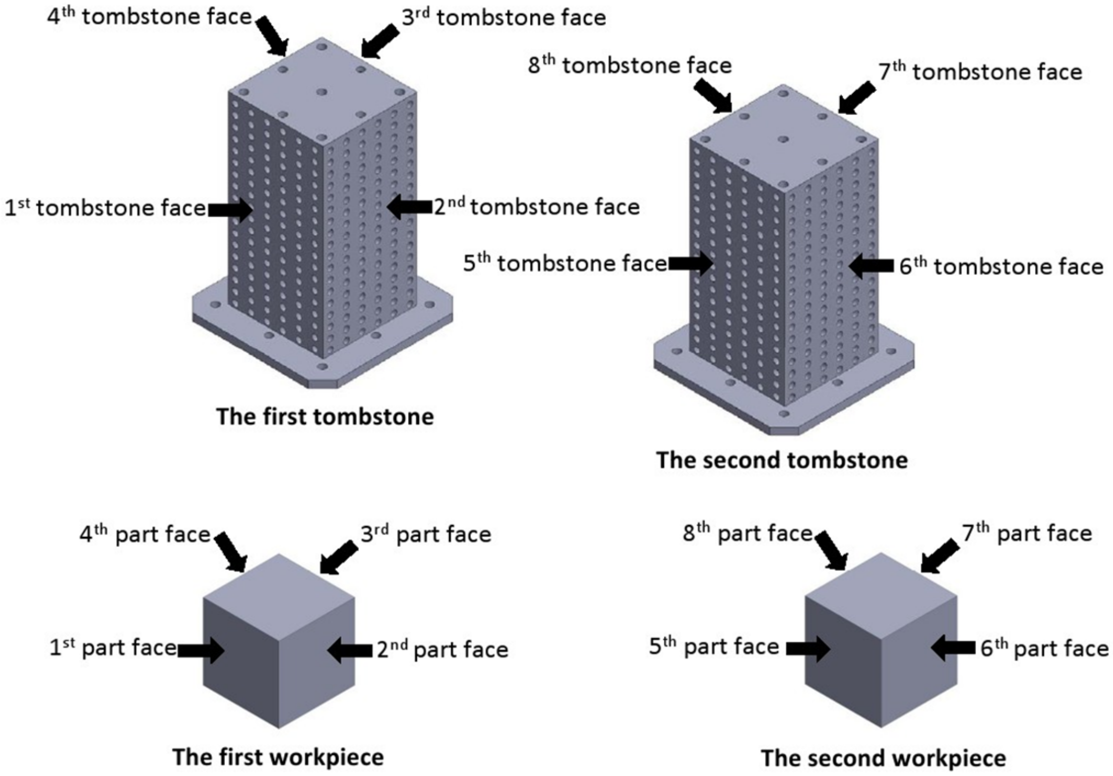

Fig. 1 Tower-type pallet

3.2 Mathematical model

Let assume two different parts are in the system and each four-part faces are required for machining operations. Thus, a process planner must integrate two planning tasks i.e. which part face to be fastened on each tombstone face and what is the sequence of machining operations and tools to complete all the required machining operations. It is obvious that the planning task is much more complicated; consequently, the mathematical model using 0-1 Integer programming is proposed and can be described as follows:

Indices:

i	Index of tombstone fixture faces ($i = 1, 2, \cdots, I$).
j	Index of part faces of the work-piece ($j = 1, 2, \cdots, J$).
k, k'	Index of machining operation number ($k, k' = 1, 2, \cdots, N$).
l	Index of tool number ($l = 1, 2, \cdots, L$).
m, m'	Index of consecutive number ($m, m' = 1, 2, \cdots, N$).

Parameters:

I	Maximum number of tombstone fixture faces
J	Maximum number of part faces
k_j	Set of operations to be performed in part face j
L	Number of all available cutting tools in the tool magazine
l_k	Set of tools that can perform for operation k; $l_k \subseteq L$
N	Maximum number of operations or sequences
MT_{kl}	Machining time for operation k by tool l
TC	Tool change time which is constant
$TT_{kk'}$	Tool travel time from operations k to operation k'
$TFC_{ii'}$	Tombstone face change time from the tombstone face i to i'

Decision variables:

E	Total production time.
X_{ijklm}	= 1 when operation k is performed on the tombstone face i on part face j with tool l in sequence m. = 0, otherwise
$Z_{kk'lm}$	= 1 when tool l is used for both operation k and k' in sequence m and $m + 1$, respectively. = 0, otherwise
$W_{ii'm}$	= 1 when sequence m is setup the tombstone face i and sequence $m + 1$ is setup the tombstone face i'. = 0, otherwise
Y_{ij}	= 1 when part face j occupies in tombstone face i. = 0, otherwise

The objective function is to minimize the total production time of the parts which is a summation of the four entities, namely, the machining times, the tool change time, the tool travel times and the pallet change time and can be formulated as (1).

$$\begin{aligned}\text{Minimize } E = &\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{N}\sum_{l\in l_k}\sum_{m=1}^{N}\left(MT_{kl}\times X_{ijklm}\right) + TC\times\sum_{m=1}^{N-1}\left(1-\sum_{k=1}^{N}\sum_{\substack{k'=1\\k'\neq k}}^{N}\sum_{l\in l_k} Z_{kk'lm}\right)\\ &+\sum_{m=1}^{N-1}\sum_{l\in l_k}\left[\sum_{k=1}^{N}\sum_{\substack{k'=1\\k'\neq k}}^{N}\left(TT_{kk'}\times Z_{kk'lm}\right)\right]+\sum_{m=1}^{N-1}\left[\sum_{i=1}^{I}\sum_{i'=1}^{I}\left(TFC_{ii'}\times W_{ii,m}\right)\right]\end{aligned} \tag{1}$$

The set of constrains in the mathematical model are as follows:

1. Operation completion constraint. All the required machining operations must be completed and must not be repeated. Each required machining operation must be completed at the only one tombstone pallet face and the only one cutting tool.

$$\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{l\in l_k}\sum_{m=1}^{N} X_{ijklm} = 1 \text{ for all } k \tag{2}$$

2. Singular sequence constraint. This constrain ensures that the operation k must be scheduled in only one sequence slot in the sequence plan.

$$\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k\in k_j}\sum_{l\in l_k} X_{ijklm} = 1 \text{ for all } m \tag{3}$$

3. Precedence constraint. An operation k' must follow the precedence constraint rule. That is if k must precede k' and k is sequenced in sequence m, k' must be able to perform only at sequence m' where $m' \geq m+1$. This constrain ensures a logical process sequence.

$$\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k\in k_j}\sum_{l\in l_k} X_{ijklm} - \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k'\in k'_j}\sum_{l\in l_k}\sum_{m'\geq m+1} X_{ijk'lm'} \geq 0 \tag{4}$$

4. Tool change time equation. Whenever there is any tool change, it will increase a production time in the objective function. Thus, this tool change time must be taken into account. In the mathematical expression, $Z_{kk'lm}$ is used as a flag to indicate the tool change action. That is, if the same tool *l* is used in operation *k* and *k*', then $Z_{kk'lm}$ is set to be 1; otherwise 0.

$$\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{\substack{k\in k_j\\ k\neq k'}} X_{ijklm} + \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{\substack{k\in k'_j\\ k\neq k'}} X_{ijk'lm'} - 2Z_{kk'lm} \geq 0 \tag{5}$$
$$\text{for all } k \neq k', m' = m+1,\dots,N-1, l \in l_k$$

$$\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{\substack{k\in k_j\\ k\neq k'}} X_{ijklm} + \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{\substack{k\in k'_j\\ k\neq k'}} X_{ijk'lm'} - 2Z_{kk'lm} \leq 1 \tag{6}$$
$$\text{for all } k \neq k', m' = m+1,\dots,N-1, l \in l_k$$

5. Tombstone face occupied constraint. This constrain ensures that there will be only one part face *j* occupied at each tombstone face *i*.

$$\sum_{j=1}^{J} Y_{ij} = 1 \text{ for all } i \tag{7}$$

$$\sum_{i=1}^{I} Y_{ij} = 1 \text{ for all } j \tag{8}$$

$$Y_{ij} - \sum_{k=1}^{N}\sum_{l\in l_k}\sum_{m=1}^{N} x_{ijklm} \geq 0 \text{ for all } i,j \tag{9}$$

6. Tombstone rotation or change time equation. Whenever there is any tombstone rotation by itself or completely alternate to the other one, the lost time of this action must be taken into account in the production time. The logic is that time required to rotate itself is less than that of changing to the other where $TFC_{ii'}$, tombstone face change time is varied depending upon face index relationship. In the mathematical expression, $W_{ii'm}$ is utilized as a flag to indicate the change action. If tombstone face *i* is scheduled in sequence m and the tombstone face *i'* is scheduled in sequence m + 1, then $W_{ii'm}$ is assigned to 1; otherwise 0.

$$\sum_{j=1}^{J}\sum_{\substack{k\in k_j\\ k\neq k'}} X_{ijklm} + \sum_{j=1}^{J}\sum_{\substack{k\in k_j\\ k\neq k'}} X_{i'jk'lm'} - 2W_{ii'm} \geq 0 \tag{10}$$

$$\text{for all } i, i' = 1,2,\ldots,I, k \neq k', m' = m+1,\ldots,N-1, l \in l_k$$

$$\sum_{j=1}^{J}\sum_{\substack{k\in k_j\\ k\neq k'}} X_{ijklm} + \sum_{j=1}^{J}\sum_{\substack{k\in k_j\\ k\neq k'}} X_{i'jk'lm'} - 2W_{ii'm} \leq 1 \tag{11}$$

$$\text{for all } i, i' = 1,2,\ldots,I, k \neq k', m' = m+1,\ldots,N-1, l \in l_k$$

7. Integrality constraints. All decision variables are 0-1 integer.

$$X_{ijklm} = 0,1 \text{ for all } i,j,k,l \text{ and } m \tag{12}$$

$$Z_{kk'lm} = 0,1 \text{ for all } k,k' \text{ and } m \tag{13}$$

$$W_{ii'm} = 0,1 \text{ for all } i,i' \text{ and } m \tag{14}$$

4. Case study: Automotive parts (manifold inlet and console)

4.1 Preparatory steps

The developed mathematical model is applied with actual two automotive parts. It is assumed that the manifold inlet and the console as shown in Fig. 2 and Fig. 3, respectively, are the mixed-model parts needed to be machined by the machining center in FMS.

A list of available cutting tools, equipped with the tool magazine, is shown in Table 2. It is assumed that there are nine cutting tools available that can be used to complete all the operations in the above-mentioned parts.

The manifold requires ten machining operations which are arbitrarily assigned as operation numbers 1 to 10. The console, on the other hand, also needs ten machining operations which will be assigned as operation numbers 11 to 20. Thus, there will be a total of twenty required machining operations to complete as shown in Table 3. Note that machining operation numbers 1 to 10 belong to the manifold and the remaining operations belong to the console. For each operation, there is a list of feasible tools as well as the calculated machining time associated with the tool. In addition, the required precedence operation is also provided. As an example, operation number 6 must precede operation number 7. Likewise, operation number 13 must precede operation number 14 and so on.

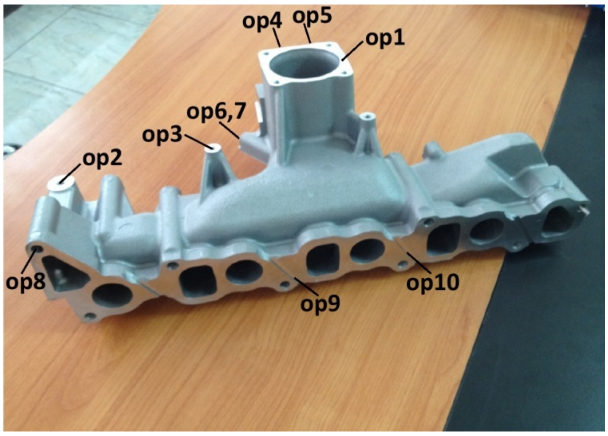

Fig. 2 Manifold

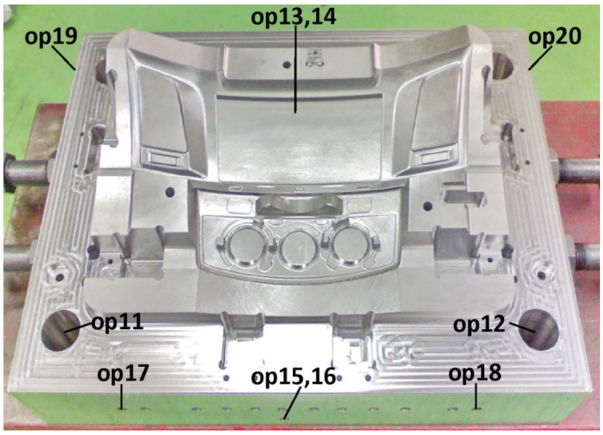

Fig. 3 Console

Table 2 A list of cutting tools in the tool magazine

Tool number	Tool specification
1	Face cutter 32 mm
2	Face cutter 80 mm
3	Spot face cutter 24 mm
4	Drill bit 6.8 mm
5	Drill bit 10 mm
6	Tap cutter M8
7	End mill 3 mm
8	End mill 6 mm
9	Ball mill 6 mm

Table 3 The necessary machining data

Work-piece	Part face	Operation no. and description		Tool no. and description		Machining time (min)	Precedence
Manifold	1	1	Face milling	1	Face cutter 32 mm	30	-
				2	Face cutter 80 mm	15	-
		2	Drilling	5	Drill bit 10 mm	1	-
		3	Drilling	5	Drill bit 10 mm	1	-
	2	4	Face milling	3	Spot Face cutter 24 mm	3	-
		5	Face milling	3	Spot Face cutter 24 mm	3	-
	3	6	Drilling	4	Drill bit 6.8 mm	1	-
		7	Tapping M8	6	Tap M8	2	Operation 6
	4	8	Boring	7	End mill 3 mm	8	-
				8	End mill 6 mm	5	
		9	Grooving	7	End mill 3 mm	7	-
		10	Grooving	7	End mill 3 mm	7	-
Console	5	11	Boring	7	End mill 3 mm	6	-
				8	End mill 6 mm	3	
		12	Boring	7	End mill 3 mm	6	-
				8	End mill 6 mm	3	
		13	Rough milling	7	End mill 3 mm	360	-
				8	End mill 6 mm	240	
		14	Finish milling	9	Ball mill 6 mm	480	Operation 13
	6	15	Drilling	4	Drill bit 6.8 mm	1	-
		16	Tapping M8	6	Tap M8	2	Operation 15
		17	Drilling	5	Drill bit 10 mm	1	-
		18	Drilling	5	Drill bit 10 mm	1	
	7	19	Grooving	7	End mill 3 mm	7	-
	8	20	Grooving	7	End mill 3 mm	7	-

Other essential data are tool travel time between the operations and tombstone rotation time and tombstone change time as shown in Table 4 and 5, respectively. The tool travel time is the time required to reach the next operation. It assumed that the travel speed used to calculate tool travel time is the maximum speed that the machine can provide. In this study case, the maximum travel speed (rapid traverse) is 1.969 in/min. In Table 5 the tombstone rotation time is around 0.6 min whereas the tombstone change time is around 2 min since this operation requires the other tombstone to swing into place.

All the necessary data in Tables 2 to 5 will be used to formulate the mathematical model and executed using Gurobi Optimizer. A total number of generated variables is 2.252 and the computer processing time is 31.18 min. The obtained result is summarized in Table 6 and 7.

Table 4 Tool travel time between the operations

From operation k	Tool travel time (min)																			
	To operation number k'																			
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	-	0.2	0.1	0.1	0.1	0.1	0.1	0.2	0.1	0.1	0.4	0.4	0.2	0.2	0.2	0.1	0.3	0.3	0.4	0.4
2	0.2	-	0.2	0.2	0.3	0.2	0.2	0.1	0.3	0.3	0.3	0.4	0.3	0.3	0.3	0.3	0.1	0.4	0.2	0.4
3	0.1	0.2	-	0.1	0.2	0.1	0.1	0.2	0.2	0.2	0.3	0.4	0.2	0.2	0.2	0.2	0.4	0.4	0.4	0.4
4	0.1	0.2	0.1	-	0.2	0.1	0.1	0.2	0.2	0.2	0.3	0.4	0.2	0.2	0.2	0.2	0.2	0.3	0.3	0.3
5	0.1	0.3	0.2	0.2	-	0.2	0.2	0.3	0.1	0.1	0.3	0.3	0.2	0.2	0.2	0.2	0.3	0.3	0.3	0.3
6	0.1	0.2	0.1	0.1	0.2	-	-	0.1	0.1	0.1	0.3	0.3	0.2	0.2	0.1	0.2	0.3	0.3	0.3	0.3
7	0.1	0.2	0.1	0.1	0.2	-	-	0.1	0.1	0.1	0.3	0.3	0.2	0.2	0.2	0.1	0.3	0.3	0.3	0.3
8	0.2	0.1	0.2	0.2	0.3	0.1	0.1	-	0.3	0.3	0.2	0.4	0.1	0.1	0.2	0.2	0.1	0.3	0.1	0.4
9	0.1	0.3	0.2	0.2	0.1	0.1	0.1	0.3	-	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.4
10	0.1	0.3	0.2	0.2	0.1	0.1	0.1	0.3	0.2	-	0.4	0.1	0.2	0.2	0.2	0.2	0.3	0.1	0.4	0.2
11	0.4	0.3	0.3	0.3	0.3	0.3	0.3	0.2	0.2	0.4	-	0.4	0.4	0.4	0.2	0.2	0.2	0.3	0.1	0.4
12	0.4	0.4	0.4	0.4	0.3	0.3	0.3	0.4	0.2	0.1	0.4	-	0.4	0.4	0.2	0.2	0.4	0.1	0.4	0.1
13	0.2	0.3	0.2	0.2	0.2	0.2	0.2	0.1	0.2	0.2	0.4	0.4	-	-	0.1	0.1	0.2	0.2	0.2	0.3
14	0.2	0.3	0.2	0.2	0.2	0.2	0.2	0.1	0.2	0.2	0.4	0.4	-	-	0.1	0.1	0.2	0.2	0.2	0.3
15	0.2	0.3	0.2	0.2	0.2	0.1	0.2	0.2	0.2	0.2	0.2	0.2	0.1	0.1	-	-	0.2	0.2	0.2	0.2
16	0.1	0.3	0.2	0.2	0.2	0.2	0.1	0.2	0.2	0.2	0.2	0.2	0.1	0.1	-	-	0.2	0.2	0.2	0.2
17	0.3	0.1	0.4	0.2	0.3	0.3	0.3	0.1	0.2	0.3	0.2	0.4	0.2	0.2	0.2	0.2	-	0.4	0.1	0.4
18	0.3	0.4	0.4	0.3	0.3	0.3	0.3	0.3	0.2	0.1	0.3	0.1	0.2	0.2	0.2	0.2	0.4	-	0.4	0.1
19	0.4	0.2	0.4	0.3	0.3	0.3	0.3	0.1	0.2	0.4	0.1	0.4	0.2	0.2	0.2	0.2	0.1	0.4	-	0.4
20	0.4	0.4	0.4	0.3	0.3	0.3	0.3	0.4	0.4	0.2	0.4	0.1	0.3	0.3	0.2	0.2	0.4	0.1	0.4	-

Table 5 Tombstone rotation and change time

From tombstone face i	Tombstone rotation and change time (min)							
	To tombstone face i'							
	1	2	3	4	5	6	7	8
1	-	0.6	0.6	0.6	2	2	2	2
2	0.6	-	0.6	0.6	2	2	2	2
3	0.6	0.6	-	0.6	2	2	2	2
4	0.6	0.6	0.6	-	2	2	2	2
5	2	2	2	2	-	0.6	0.6	0.6
6	2	2	2	2	0.6	-	0.6	0.6
7	2	2	2	2	0.6	0.6	-	0.6
8	2	2	2	2	0.6	0.6	0.6	-

4.2 Results and discussion

The obtained results in Tables 6 and 7 can be delineated as the following. In Table 6 the optimal solution indicates which part face of the part will be fastened on which face of the tombstone. It can be seen from Table 4 that both Manifold and Console are fastened at both tombstone towers and each part face is assigned to a particular tombstone face. Without the solution obtained from this paper, one will randomly fasten the part on a tombstone tower. In addition, it is common that one tombstone fixture for one type of work-part, not a mixed part. Therefore, the process planner will not be able to generate the most optimal process plan due to the work-part setup constraint. This paper therefore advances a further step in the process planning research field. According to Table 7, the resulted optimal operation sequence is 18-17-15-6-7-16-…..-5. In other words, the first operation sequence in the plan is operation number 18 which is a drilling operation with tool number 5. Note that the operation 18 is located at part face 6 which is fastened at tombstone face 2. The second sequence is operation number 17 using the same cutting tool as the first sequence. Next, the cutting tool will be changed to tool number 4 in order to perform another drilling operation number 15.

Table 6 Summary of part and fixture setup result

Tombstone face i	Part	Part face j	Operation k
1	Manifold	4	10,9,8
2	Console	6	18,17,15,16
3	Console	8	20
4	Manifold	3	6,7
5	Console	5	12,11,13,14
6	Manifold	1	3,2,1
7	Console	7	19
8	Manifold	2	4,5

Table 7 Summary of the result obtained from the optimization model

Sequence m	Operation no. k	Tool no. l	Machining time (min) MT_{kl}	Tool change time (min) TC	Tool travel time (min) $TT_{kk'}$	Tombstone face change time (min) $TFC_{ii'}$
1	18	5	1	-	0.4	-
2	17	5	1	0.5	-	-
3	15	4	1	-	0.1	0.6
4	6	4	1	0.5	-	-
5	7	6	2	-	0.1	0.6
6	16	6	2	0.5	-	0.6
7	20	7	7	-	0.2	0.6
8	10	7	7	-	0.2	-
9	9	7	7	0.5	-	-
10	8	8	5	-	0.4	2
11	12	8	3	-	0.4	-
12	11	8	3	-	0.4	-
13	13	8	240	0.5	-	-
14	14	9	480	0.5	-	0.6
15	19	7	7	0.5	-	0.6
16	3	5	1	-	0.2	-
17	2	5	1	0.5	-	-
18	1	2	15	0.5	-	0.6
19	4	3	3	-	0.2	-
20	5	3	3	-	-	-
			790	4.5	2.6	6.2
	Total production time(min)		803.3			

After that, the tombstone pallet rotates from face 2 to face 4 in order to perform the drilling operation number 6. Next, the cutting tool will be changed to tool number 6 in order to operate operation number 7 and then rotate the tombstone to face 2 in order to perform machining operation number 16 by the same cutting tool number 6.

In brief, all the twenty required machining operations are completed using a total of nine cutting tools. There is a total of nine tool changes with six times tombstone rotation and one tombstone change. The total machining time is 790 min, and tool change time, tool travel time, and tombstone face change time are 4.5 min, 2.6 min, and 6.2 min, respectively. Therefore, the total production time is 803.3 min.

5. Conclusion

This research proposed the integer linear programming approach to determine an optimal solution for a mixed-model part manufactured on a machining center. This model is a part of automated process planning, which has long been researched by using various mathematical techniques. The mathematical model has been verified by a number of examples in real cases and it is deemed practical. The uniqueness of this developed model is the ability to generate the optimal process plan with a simultaneous consideration of tombstone change for mixed-model parts. The mathematical model that was developed in this research deals with the complexity and decision making of Tombstone problems. In addition, based on the literature review, none of the research has addressed this type of problem. This research applied the real-world case study of automotive parts manufacturing. The two types of automotive parts under consideration compose of manifold inlet and console. The results provide the process planning that can simultaneously produce two different part types. This mixed-model part consumes the minimum total production time. For future research work, the heuristics methods and mathematical relaxation techniques should be applied to solve the problems that have more machining operations, whereas the large-scale problems cannot easily be solved by general linear programming.

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