A Job Rescheduling Model Considering Cutting Tool Failure and Cutting Tool Life for a Flexible Manufacturing System

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Abstract. This paper deals with a job-rescheduling problem for an FMS considering the unavailability of cutting tools, as they are broken, during unmanned operation. The FMS consists of several parallel identical CNC machines integrated to a material handling system. The CNC machines have the same number and types of cutting tools on each tool magazine. The jobs to be processed are parts having two surfaces. Finishing a setup, each of sequential operations requires a specific cutting tool type. In the initial job scheduling, the assignment of the operation to each machine is based on the life of the cutting tools. During operations, the cutting tool could be broken before the life time limit is reached. If the cutting tool is broken then the operation will stop. In this situation, the FMS checks the status of the operations and the cutting tools. To continue the FMS operation, the stopped and the waiting operations will be rescheduled to the machine or another machine, considering the remaining life of cutting tools. The objective of the rescheduling model is to minimize the difference of starting time of the initial and new schedules and to minimize makespan.

Keywords: FMS; Rescheduling; Cutting Tool Life Time; Cutting Tool Failure.

1. INTRODUCTION

Flexible Manufacturing System (FMS) has been developed to provide flexibilities to process medium-size variety and volume of production. The FMS is an integrated computer controlled of CNC machines and automated material handling system (Stecke 1985). There are many explanations of flexibility characteristics for FMS (Browne et al. 1985). This research considers only two characteristics, which are automation and routing flexibility. Automation means that the FMS facilities can operate in several hours in unmanned operations controlled by the central computer. Routing flexibility is the ability to find another machine if the current or next CNC machines has problem with cutting tools during unmanned operations. In this research, the FMS is defined as a machining process facility that consists of several identical CNC machines, each of which is equipped with an automatic pallet tool changer (APC), an automatic tool changer (ATC) and a tool magazine to store the cutting tools. The CNC machine has the same number and type of cutting tool on each tool magazine.

The FMS problems can be categorized into FMS design problem and FMS operation problem as found in the real situation in industries (Stecke, 1985). The FMS design problem is the selection and construction of FMS facilities, which depend on the product that will be processed in FMS. The FMS operation problems consist of three categories, i.e., planning problems, scheduling problems and controlling problems. The example of FMS operation planning problem is the strategy to configure the machines in the FMS, by grouping the similar operation into a particular machine. The FMS scheduling problem can be approached as job shop with parallel machines, which have alternative routes and limitation on the handling equipment, pallets, cutting tools, material storage (Souier et al. 2013). Ösguven et al. (2013) developed a mathematical model for job shop scheduling with two fixed routes options for processing a job. The FMS scheduling can be approached with single resource scheduling and simultaneous resource scheduling. Heuristic algorithm for FMS simultaneous resource scheduling approach has been developed by Raj et al. (2014) to allocate the job to a CNC machine and determine the required cutting tool in the FMS that has a Central Tool Magazine (CTM). Another approach was proposed by Setiawan et al. (2015), which developed a mathematical model for FMS initial scheduling considering cutting tools life for an FMS to minimize makespan. The global optimal solution was found through long computation time. Meanwhile, the object oriented modeling approach has been developed to provide initial scheduling under shortest processing time criteria without considering the cutting tool lifetime (Setiawan et al. 2016-b). During the machining process, the cutting tools will be deteriorated by three factors, i.e., the wearing at the cutting edge; defect during re-sharpening and external stresses that originated from tool holder and spindle system. This causes the cutting tool broken before the estimated life time limit is reached (Vagnorius et al. 2010). If the cutting tool is broken during unmanned operation then the operation will stop. To continue the operation, the FMS requires rescheduling to allocate the stopped and waiting jobs to other CNC machine and cutting tools. The objective of this research is to develop a rescheduling model considering cutting tool failures and the remaining cutting tool life for an FMS. The approach to rescheduling can be classified into three categories, which are completely-reactive scheduling, predictive-reactive scheduling and robust-proactive scheduling (Ouelhadj and Petrovic 2009). Completely-reactive scheduling approach for cutting tool failure has been developed by Setiawan et al. (2016-a). Now, in this paper, the robust-proactive scheduling is introduced as another approach to rescheduling, which considers efficiency and stability simultaneously. The efficiency is measured by makespan while the stability is measured by the difference of initial schedule with the new schedule.

This paper is organized into five sections. In the first section, the introduction of the research is explained. The FMS configuration and operation are discussed in the second section. In the third section, the problem formulation and solution method are discussed. A hypothetical example and the analysis are explained in the fourth section, and then the last section is concluding remarks and the problems to be dealt in future work.

2. FMS CONFIGURATION AND OPERATIONS

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2.1 FMS Configuration

In the proposed model, the FMS configuration and operations are based on the FMS in the Indonesian aircraft industry. The FMS consists of four identical CNC machines, which installed in parallel configuration. The machines are horizontal CNC machines, each of which equipped with Automatic Pallet Changer (APC) and Automatic Tool Changer (ATC). Each CNC machine has the capacity of 90 cutting tools and has a same cutting tool configuration (the same number and type of cutting tool) in the tool magazine. In this FMS configuration, entire job (workpiece) could be processed by any CNC machines, which are dependent on the availability and limitation of cutting tool life (Setiawan et al. 2015). In this paper, a specific process of a workpiece requires a certain type of cutting tool. A cutting tool can be used for several operations until the cutting tool time consumption reached its lifetime. These processes consumed cutting tool's lifetime, therefore the usefulness of the cutting tool is limited. Whenever an operation requires a certain type of cutting tool, the priority would fall to any cutting tool that were previously used, except if the required operation time exceeds the remaining cutting tool's lifetime. When this is the case, new cutting tool of the same type (which were installed in the same CNC machine), would be selected for the operation.

The CNC machines are integrated with an automatic material handling system that consists of a pallet stocker to store raw materials and finished parts. The FMS is equipped with a stacker crane to transfer the workpiece, to the CNC machines and pallet stocker. To setup the material on fixture, there are two loading/unloading stations in this FMS.

2.2 FMS Operations

The ERP system in this aircraft industry prepares the batch of the jobs that will be processed by FMS for one day period to fulfill the unmanned operation in 24 hours. Every morning, the operator is responsible for unloading the finished workpiece and setup the raw material on the fixture in the loading/unloading station. The raw materials and its fixture will be stored in the pallet stocker. The stacker crane takes automatically the raw materials from pallet stocker to the CNC machines. The operator is also responsible to replace the worn cutting tools and install the new cutting tools in the tool magazine.

The jobs for the FMS are independent jobs, which are the workpiece that will be machined by the CNC machines. The workpiece has two surfaces, and each surface has to be machined into several sequential operations in linear precedence relationship. Each operation requires a specific cutting tool type. After all of operations on a surface are finished, then the workpiece has to be inverted to continue the next operations on the another surface. In this paper, a set of operations to complete a surface is called a stage.

During operations, the cutting tools could be broken due to uncontrollable damage before the life time limit is reached. The particular CNC machine where the damage occurred will then stopped while the other CNC machines continue their machining process until the work in process were finished. The FMS will then compile the status of the operations and the cutting tools. There will be three sets of operations at this condition, i.e., the finished operations, the work in process operations, and the waiting operations. The previously stopped process will be considered as work in process operation and thus will be rescheduled along with the waiting operations. The operation time of the stopped process will be the same as it was at the beginning, because physically the cutting tool will start on the same point of reference and continue to cut until it touches the surface of the workpiece (dry cutting process).

3. MODEL FORMULATION

The model in this research is to accommodate the dynamic of the FMS operation, considering not only cutting tool life but also cutting tool failure during machining before the life time is reached. The complete-reactive FMS rescheduling approach has been developed by Setiawan et al. (2016-a). The algorithm in the dynamic scheduling in this research consists of four steps. The first step is the initial FMS schedule considering the estimated life time of the cutting tool to minimize makespan. In this situation, all cutting tools are assumed new or re-sharpened and the cutting tool consumption is zero minute. The initial FMS schedule is generated by the model Setiawan et al. (2015). The second step is the operation step, which a cutting tool is broken during machining process as the event of a cutting tool failure. The notation for the failure time of broken cutting tool unit n^*, type k^*, on machine m^* is FT_{n^*,k^*,m^*}. The third step is to check the system status, i.e., the status of the operations of the jobs, status of the cutting tools. After the cutting tool failure occurs, the operations will be divided into three sets of operations. The first set is the operations that have been finished. This set consists of operations that have the completion time less then and equal to the failure time of the cutting tool. The second set is operations that are being processed and the third set is the operations that are waiting to be processed. In the second set, there are two types of operations, which are the operations that stopped because of the cutting tool to process this operation is broken. The other type is the operations that are being processed by other cutting tools on other CNC machine, which are not affected by the broken cutting tool. Meanwhile, in third step, the cutting tool consumptions need to be calculated. The fourth step is the rescheduling for set of stopped and waiting operations, considering the remaining life of cutting tools.

The approaches to rescheduling could be classified into three categories, which are completely-reactive scheduling, predictive-proactive scheduling and robust-proactive scheduling (Ouelhadj and Petrovic, 2008). The approach to completely-reactive scheduling model for FMS has been proposed by Setiawan et al. (2016-a). The important point in this model is to optimize the efficiency measurement, which the objective is to minimize makespan considering to the remaining cutting tool life time. The result of the completely-reactive scheduling model is the new allocation for the waiting operations and stopped operation to CNC machines. The starting time of each operations in the new schedule are different with the starting time in the initial schedule.

The other approach is the rescheduling that considers the stability. The objective in this model is to minimize the difference of the starting time of the operation in the initial and the new schedules. However, to keep the model efficient, the model should have also the objective to minimize makespan. Therefore, the proposed FMS rescheduling model in this paper is the robust-proactive scheduling, which considers the stability and the efficiency simultaneously. The model is explained as follows:

Indices:

j, j', j^*	:	index for job, where $1 \leq j \leq J$, j^* is the job, which is stopped by the broken cutting tool.
k, k^*	:	index for cutting tool type, where $1 \leq k \leq K$, k^* is the type of cutting tool, which is broken.
m, m^*	:	index for machine, where $1 \leq m \leq M$, m^* is the machine where the cutting tool is broken.
n, n^*	:	index for cutting tool number, where $1 \leq n \leq N$, n^* is the unit number of cutting tool, which is broken.
o, o', o^*	:	index for operation, where $1 \leq o \leq O$. o^* is the operation, which is stopped by the broken cutting tool.
s, s', s^*	:	index for stage, where $s \in \{1, 2\}$, s^* is the stage, which is stopped by the broken cutting tool.

Decision variable:

$CC_{n,k,m}$	:	time consumption of cutting tool *unit-n*, *type-k* on *machine-m* (minutes)
$CT_{j,s,o,m}$	:	completion time of *job-j*, *stage-s*, *operation-o*, on *machine-m* on the new schedule.
$CT'_{j,s,o,m}$	:	completion time of *job-j*, *stage-s*, *operation-o*, on *machine-m* on the initial schedule.
$ST_{j,s,o,m}$	:	starting time of *job-j*, *stage-s*, *operation-o*, on *machine-m* on the new schedule.
$ST'_{j,s,o,m}$	:	starting time of *job-j*, *stage-s*, *operation-o*, on

machine-m on the initial schedule.

$X_{j,s,o,m}$: a binary number, = 1 means that *job-j*, *stage-s*, *operation-o*, is allocated on *machine-m* on the new schedule.

$X'_{j,s,o,m}$: a binary number, = 1 means that *job-j*, *stage-s*, *operation-o*, is allocated on *machine-m* on the initial schedule.

$Y_{j,s,o,j',s',o',m}$: a binary number, = 1, means that *job-j*, *stage-s*, *operation-o*, precedes *job-j'*, *stage-s'*, *operation-o'*, on *machine-m*.

$Z_{j,s,o,n,k,m}$: a binary number, = 1, means that cutting tool *unit-n*, of *type-k* on *machine-m*, is selected to process *job-j*, *stage-s*, *operation-o*.

Parameter:

FT_{n^*,k^*,m^*} : failure time of the broken tool unit *number-n*, *type-k* on *machine-m*.

$G_{j,s,o,k}$: a binary number, = 1 means that a *job-j*, *stage-s*, *operation-o*, requires *type-k* of cutting tool.

J : number of independent jobs.

K : number of cutting tool types.

L : a big number.

$LT_{n,k,m}$: remaining life time of cutting tool *unit-n*, *type-k* on *machine-m* (minutes).

M : number of machines.

$N_{k,m}$: number of unit cutting tool of *types-k* on *machine-m.*

O : number of operations.

UP : unmanned period, 1440 minutes.

$t_{j,s,o,m}$: operation time of an operation of *job-j*, *stage-s*, *operation-o*, on *machine-m*.

Sets :

FO : Finished operations, $FO = \{j,s,o \mid CT'_{j,s,o,m} \le FT_{n,k,m}\}$.

WO : Waiting operations, $WO = \{j,s,o \mid FT_{n,k,m} \le ST'_{j,s,o,m}\}$.

PO : Processing operation,

$PO = \{j,s,o \mid ST'_{j,s,o,m} \le FT_{n,k,m} \le CT'_{j,s,o,m}\}$. This set includes the stopped *job-j**, *stage-s**, *operation-o**, which is caused by the broken cutting tool *unit-n**, *type-k** on *machine-m**, C_{n^*,k^*,m^*}.

Assumptions adopted for the model are:

- CNC machines, fixtures, stacker crane are available.
- The travel time, speed and distance of stacker crane are ignored.
- Setup time at each stage is ignored since the setup the workpiece are handled by robot.
- Raw materials are already prepared on fixture before $t = 0$.

Using this notation and based on the assumption, the robust-proactive FMS rescheduling model considering the cutting tool failure and the remaining life of the cutting tool is presented as follow:

Objective function:

$$Min\ F = CT_{\max} + \Delta ST \quad (1).$$

Constraints:

$$\Delta ST = \sum_{j=1}^{J}\sum_{s=1}^{S}\sum_{o=1}^{O}\left|ST_{j,s,o,m} - ST'_{j,s,o,m}\right| , \quad (2).$$
$$\forall j \in WO \cup j^*, \forall s \in WO \cup s^*, \forall o \in WO \cup o^*$$

$$\sum_{m=1}^{M} X_{j,s,o,m} = 1 \quad , \quad \forall j, \forall s, \forall o \quad (3).$$
$$\forall j \in WO \cup j^*, \forall s \in WO \cup s^*, \forall o \in WO \cup o^* \quad ,$$

$$ST_{j,s,o,m} + CT_{j,s,o,m} \le \left(X_{j,s,o,m}\right)\cdot L \quad , \quad (4).$$
$$\forall j \in WO \cup j^*, \forall s \in WO \cup s^*, \forall o \in WO \cup o^* \quad ,$$

$$CT_{j,s,o,m} \ge ST_{j,s,o,m} + t_{j,s,o,m} - \left(1 - X_{j,s,o,m}\right)\cdot L \quad , \quad (5).$$
$$\forall j \in WO \cup j^*, \forall s \in WO \cup s^*, \forall o \in WO \cup o^* \quad ,$$

$$ST_{j,s,o,m} \ge CT_{j',s',o',m} - (Y_{j,s,o,j',s',o',m})\cdot L \quad ,$$
$$\forall j \in WO \cup j^*, \forall s \in WO \cup s^*, \forall o \in WO \cup o^*, \quad (6).$$
$$\forall j' \in WO \cup j^*, \forall s' \in WO \cup s^*, \forall o' \in WO \cup o^* \quad ,$$

$$ST_{j',s',o',m} \ge CT_{j,s,o,m} - (1 - Y_{j,s,o,j',s',o',m})\cdot L \quad ,$$
$$\forall j \in WO \cup j^*, \forall s \in WO \cup s^*, \forall o \in WO \cup o^*, \quad (7).$$
$$\forall j' \in WO \cup j^*, \forall s' \in WO \cup s^*, \forall o' \in WO \cup o^* \quad ,$$

$$\sum_{m=1}^{M} ST_{j,s,o,m} \ge \sum_{m=1}^{M} CT_{j,s,o-1,m} \quad , \quad (8).$$
$$\forall j \in WO \cup j^*, \forall s \in WO \cup s^*, \forall o \in WO \cup o^*,$$

$$\sum_{m=1}^{M} CT_{j,1,O,m} < \sum_{m=1}^{M} ST_{j,2,1,m} \quad , \quad \forall j \in WO \cup j^*, \quad (9).$$

$$CT_j \ge \sum_{m=1}^{M} CT_{j,2,O,m} \quad , \quad \forall j \in WO \cup j^*, \quad (10).$$

$$CT_{\max} \ge CT_j \quad , \forall j \in WO \cup j^*, \quad (11).$$

$$CT_{\max} \le UP \quad , \quad (12).$$

$$X_{j,s,o,m}\cdot \sum_{k=1}^{K_m}\sum_{n=1}^{N_{k,m}} Z_{j,s,o,n,k,m} = 1 \quad , \quad (13).$$
$$\forall j \in WO \cup j^*, \forall s \in WO \cup s^*, \forall o \in WO \cup o^* \quad ,$$

$$X_{j,s,o,m} = \sum_{k=1}^{K_m} \left(G_{j,s,o,k} \cdot \sum_{n=1}^{N_{k,m}} Z_{j,s,o,n,k,m} \right), \quad (14).$$
$$\forall j \in WO \cup j^*, \forall s \in WO \cup s^*, \forall o \in WO \cup o^* \quad ,$$

$$CC_{n,k,m} = \sum_{j=1}^{J} \sum_{s=1}^{S} \sum_{o=1}^{O} \left(X_{j,s,o,m} \cdot G_{j,s,o,k} \cdot Z_{j,s,o,n,k,m} \right) \cdot t_{j,s,o,m}, (15)$$
$$\forall j \in WO \cup j^*, \forall s \in WO \cup s^*, \forall o \in WO \cup o^*$$

$$CC_{n,k,m} \le LT_{n,k,m} \quad , \quad \forall n, \forall k, \forall m \quad , \quad (16).$$

$$ST_{j^*,s^*,o^*,m^*} \ge FT_{n^*,k^*,m^*} \quad , \quad (17).$$

$$X_{j,s,o,m} \in \{0,1\} \quad , \quad (18).$$

$$Y_{j,s,o,j',s',o',m} \in \{0,1\} \quad , \quad (19).$$

$$G_{j,s,o,k} \in \{0,1\} \quad , \quad (20).$$

$$Z_{j,s,o,n,k,m} \in \{0,1\} \quad , \quad (21).$$

$$CT_j \ge 0 \quad , \quad (22).$$

$$CT_{j,s,o,m} \ge 0 \quad , \quad (23).$$

$$ST_{j,s,o,m} \ge 0 \quad , \quad (24).$$

$$CC_{n,k,m} \ge 0 \quad , \quad (25).$$

The objective function (1) in the model is to consider the stability and efficiency simultaneously, where F represents the makespan and the difference of starting time of the operations in the initial and new schedules as formulated in equation (2). The equation (3) ensures that a *job-j*, *stage-s*, *operation-o* is allocated only on a CNC machine. Formula (4) ensure that a *job-j*, *stage-s*, *operation-o* is assigned to a certain CNC machine. The approach is to determine the allocation of decision variables $X_{j,s,o,m}$ and the starting time and the completion time of an *operations-o*. Formula (5) explains when an *operation-o* is allocated on the *machine-m*, then the completion time of an *operation-o* of *job-j*, *stage-s* on *machine-m* ($CT_{j,s,o,m}$) is the starting time of the *operation-o* of *job-j*, *stage-s* on *machine-m* ($ST_{j,s,o,m}$) and the processing time of the *operation-o* of *job-j*, *stage-s* on *machine-m* ($t_{j,s,o,m}$). Constraints (6) and (7) are to ensure that the *operation-o*, (of *job-j*, *stage-s*) and *operation-o'*, (of *job-j'*, *stage-s'*) on the same machine are processed in sequence and cannot be done in the same time. The relation of the operation sequence is formulated on the starting and completion time of *operation-o* and *operation-o'* and the parameter $Y_{j,s,o,j',s',o',m}$. Formula (8) is to ensure that the *operation-o* is started after the completion of previous operation,*o*-1. Constraint (9) ensures that the *stage*-2 is started after all operations on *stage*-1 are completed. Formula (10) determines the completion time of a job is the completion time of the latest operation of the stage-2. Meanwhile formula (11) determines the makespan, which must not exceed the unmanned period (*UP*) as is stated in the formula (12). Constraint (13) is to ensure that an operation selects only a cutting tool in a machine and the decision variable is $Z_{j,s,o,n,k,m}$. The variable $G_{j,s,o,k}$ in equation (14) is the machining plan and it determines that an operation requires only a certain cutting tool type. The equation (15) calculates the cutting tool consumption as the consequences of selecting a cutting tool on the equations (12). To saving the amount of cutting tools in the tool magazine, the cutting tool sharing policy is applied. The constraint (16) is to ensure that the time consumption of the cutting tool does not exceed the remaining life of the cutting tool. The formula (17) is to make sure that the starting time of the stopped *operation-o** of the *job-j**, *stage-s** (ST_{j^*,s^*,o^*}) is started at the failure time of the broken cutting tool *unit-n**, *type-k** on *machine-m** (FT_{n^*,k^*,m^*}).

4. NUMERICAL EXERCISE AND ANALYSIS

The numerical exercises are carried out by finding solution using hypothetical data for the proposed model. Due to the limited capability of the software and the computer to find the optimal solution, the exercises are conducted in small size FMS configurations and jobs. The FMS construction consists of two CNC machines, and each CNC machine has the same cutting tool configuration, which consists of two cutting tools types. Each cutting tool type has two cutting tool units, which has the same life time ($LT_{n,k,m}$) 150 minutes as explained in Table 1. The jobs are four independent jobs. Each job has two stages, and each stage has linear precedence operations. The processing time of each operations and the required cutting tool types are stated in the machining plan in Table.2.

Table 1. FMS Configuration Data.

CNC Machine number (*m*)	Cutting Tools Type (*k*)	Cutting Tools unit number (*n*)	Cutting Tool Life Time (*LT*)
m = 1	*k* = 1	*n* = 1	150
		n = 2	150
	k = 2	*n* = 1	150
		n = 2	150
m = 2	*k* = 1	*n* = 1	150
		n = 2	150
	k = 2	*n* = 1	150
		n = 2	150

Table 2. FMS Jobs and Process Plan.

Job (j)	Stage (s)	Operation (o)	Triplets (j,s,o)	Cutting Tool Type ($G_{j,s,o,k}$) in minute	
				k = 1	k = 2
1	1	1	1,1,1		20
		2	1,1,2	25	
	2	1	1,2,1	20	
		2	1,2,2		10
2	1	1	2,1,1	35	
		2	2,1,2		30
	2	1	2,2,1	20	
		2	2,2,2		15
3	1	1	3,1,1		20
		2	3,1,2	25	
	2	1	3,2,1	20	
		2	3,2,2		10
4	1	1	4,1,1	35	
		2	4,1,2		30
	2	1	4,2,1	20	
		2	4,2,2		15

The FMS initial schedule was already determined in Setiawan et al. (2015). The Gantt chart of the FMS initial schedule is shown in Figure 1. During processing the *job*-1, *stage*-1, *operation*-1 (1,1,1), the required cutting tool, *unit*-1, *type*-1 on *machine*-1 ($C_{1,2,2}$) is broken in 10 minutes. This event is happened at the time 75 minutes and it stops the *job*-1, *stage*-1, *operation*-1 (1,1,1). Meanwhile, the next operations in *machine*-1 are waiting to be machined by the same cutting tool or the other cutting tools. To continue the unmanned-operation, the stopped operation and waiting operations have to be rescheduled automatically.

The proposed method for rescheduling in this paper is the robust-proactive scheduling that considers the efficiency and stability simultaneously and the remaining life of the cutting tools. The objective function for efficiency is measured by makespan while the stability is measured by the difference from initial schedule with the new schedule. Therefore, the rescheduling model requires data of the starting time (ST') of the stopped operation and the waiting operations from the initial schedule. Other than that, the model requires the remaining cutting tool life $LT_{n,k,m}$. Table 3 shows the remaining cutting tool life and the starting time $ST'_{j,s,o,m}$ of the initial schedule.

The rescheduling model was run under Lingo and the result in the Gantt chart is shown in Figure 2. The Gantt chart shows that to consider the stability, only the operations, which are affected by the broken cutting tool, will be rescheduled. The broken cutting tool $C_{1,2,2}$ was also required to process *job*-2, *stage*-2, *operation*-2 (2,2,2) and *job*-1, *stage*-2, *operation*-1 (1,2,1). Meanwhile in *machine*-2, the cutting tool $C_{2,2,2}$ is the same type with cutting tool $C_{1,2,2}$. The cutting tool $C_{2,2,2}$ is not allocated yet to any operation. Therefore the cutting tool $C_{2,2,2}$ will be used to process *job*-1, *stage*-1, *operation*-1 (1,1,1), *job*-2, *stage*-2, *operation*-2 (2,2,2) and *job*-1, *stage*-2, *operation*-1 (1,2,1). The stopped operation *job*-1, *stage*-1, *operation*-1 (1,1,1) begins to process at the time 75 minute (in this situation is equal to the failure time, $FT_{1,2,2}$) as stated on the constraint (17). The duration of the processing time of the stopped operation $t_{1,2,2,2}$ is the same with the duration time in the initial schedule.

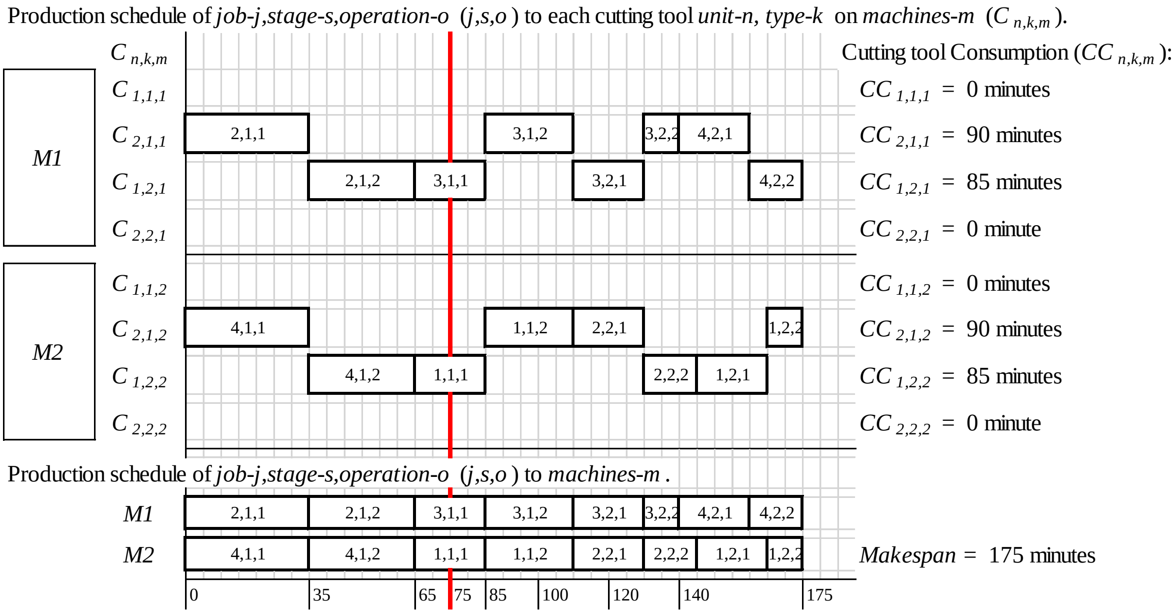

Figure 1. The Gantt chart of production schedule of *job-j*, *stage-s*, and *operation-o* to *machine-m* and cutting tool *unit-n*, *type-k* on *machine-m* in initial condition, and the cutting tool $C_{1,1,1}$ failed at the time 75 minutes.

Table 3. The data for rescheduling: remaining cutting tool life and the Starting Time of the operations of the initial schedule.

Remaining Cutting Tool Life Time (minutes),	
n,k,m	$LT_{n,k,m}$
1,1,1	150
2,1,1	60
1,2,1	65
2,2,1	150
1,1,2	150
2,1,2	60
1,2,2	0
2,2,2	150

Starting Time (*ST'*) of the initial schedule (minute)				
j	*s*	*o*	*m*	*ST'*
1	1	1	2	65
1	1	2	2	85
1	2	1	2	145
1	2	2	2	165
2	2	1	2	110
2	2	2	2	130
3	1	2	1	85
3	2	1	1	110
3	2	2	1	130
4	2	1	1	140
4	2	2	1	160

The jobs, which have to be rescheduled in *machine*-2: *job*-1, *stage*-1, *operation*-1 and 2, (1,1,1 and 1,1,2); *job*-1, *stage*-2, *operation*-1 and 2, (1,2,1 and 1,2,2); *job*-2, *stage*-2, *operation*-1 and 2, (2,2,1 and 2,2,2) are independent with the operations in *machine*-1: *job*-3, *stage*-1, *operation*-1 and 2, (3,1,1 and 3,1,2); *job*-3, *stage*-2, *operation*-1 and 2, (3,2,1 and 3,2,2); *job*-4, *stage*-2 *operation*-1 and 2, (4,2,1 and 4,2,2). Therefore only the operations in *machine*-2 need to be rescheduled. Meanwhile, all jobs in *machine*-1, which are not affected by the cutting tool failure, do not need to be rescheduled. The result shows that all operations in *machine*-2 are shifted by 10 minutes. Therefore, the makespan in the new FMS schedule is 180 minute.

5. CONCLUSION

To continue the production while a cutting tool is broken during unmanned operation, the initial FMS schedule has to be corrected. The stopped and the waiting operation of the unfinished operations have to be rescheduled considering to the remaining cutting tool life. The robust-proactive FMS scheduling model considering the stability and the utilization simultaneously has been proposed in this paper. The model also considers the cutting tool failure and remaining cutting tool life. The utilization is measured by the makespan, while the stability is measured by the difference of the starting time of the stopped and waiting operations from the initial and the new schedule. The heuristic approach will be further developed to solve more complex problem in FMS, such as increasing the number of job, machining plan and CNC Machine.

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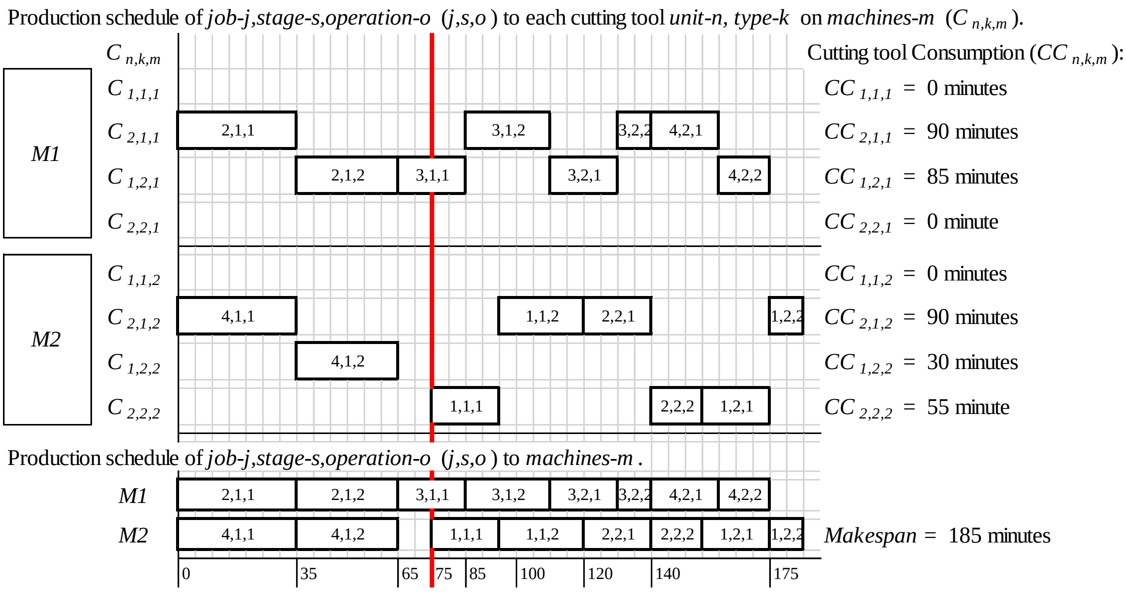

Figure 2. The Gantt chart of robust-proactive FMS rescheduling approach that considering the stability and makespan simultaneously.

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