An FMS Dynamic Production Scheduling Algorithm Considering Cutting Tool Failure and Cutting Tool Life

A Setiawan¹, R Wangsaputra¹, Y Y Martawirya² and A H Halim¹
¹ Department of Industrial Engineering and Management, Institut Teknologi Bandung, Bandung 40132, Indonesia.
² Department of Mechanical Engineering, Institut Teknologi Bandung, Bandung 40132, Indonesia.

E-mail : ari_setiawan@ithb.ac.id

Abstract. This paper deals with Flexible Manufacturing System (FMS) production rescheduling due to unavailability of cutting tools caused either of cutting tool failure or life time limit. The FMS consists of parallel identical machines integrated with an automatic material handling system and it runs fully automatically. Each machine has a same cutting tool configuration that consists of different geometrical cutting tool types on each tool magazine. The job usually takes two stages. Each stage has sequential operations allocated to machines considering the cutting tool life. In the real situation, the cutting tool can fail before the cutting tool life is reached. The objective in this paper is to develop a dynamic scheduling algorithm when a cutting tool is broken during unmanned and a rescheduling needed. The algorithm consists of four steps. The first step is generating initial schedule, the second step is determination the cutting tool failure time, the third step is determination of system status at cutting tool failure time and the fourth step is the rescheduling for unfinished jobs. The approaches to solve the problem are complete-reactive scheduling and robust-proactive scheduling. The new schedules result differences starting time and completion time of each operations from the initial schedule.

1. Introduction.

A Flexible Manufacturing System (FMS) consists of a group of automatic machine tools that integrated with an automatic material handling systems and a central computer. FMS has characteristic to process mid-size variety of different workpiece features simultaneously and adjustable quantity to response the flexible demand [1]. FMS has many capabilities such as automation and route flexibility. Automation means that FMS can operate in several hours without operator attendance (unmanned operation). Route flexibility means that the FMS could find another machine if the current or next machine tools had a problem [2]. The automatic machine tools as CNC machines are equipped with Automatic Pallet Changer (APC) to change the workpiece from outside into machining room in CNC Machine. The CNC machines are also equipped with Automatic Tool Changer (ATC) to move the cutting tools from spindle to tool magazine where the cutting tools are stored in CNC machine. The cutting tools have limitation for use. During the machining process, the cutting tools will be deteriorated by three factors. First factor is the wearing on the cutting edge...
during machining process. Second factors are defects during grinding process. Third factor is the external stresses, which may originate from technical failure on tool holder, spindle or some environmental stresses [3]. The cutting tool deterioration causes cutting tool failures and disruption in unmanned operation in FMS. The objective of this research is to explore the dynamic production scheduling in FMS when cutting tool failure occurs.

The FMS problems can be categorized by the implementation problems of FMS in industry [4]. The implementation of FMS consists of two phases, which are design phase and operation phase. Every industry may have different FMS design and operation. It depends on the products that will be produced in FMS. The design phase is the selection and construction of CNC machines and layout, material handling system and cutting tooling system. The operation phase consists of three stages, which are production planning, production scheduling and production controlling. The FMS construction in this paper is based on the FMS in Indonesian aircraft industry, which consists of identical CNC machines with in-line layout. The material handling system uses a stacker crane and pallet stocker. Each CNC machine has a same cutting tool configuration. The type of workpiece (part) is already selected during the production planning stage. The production planning for FMS considering the cutting tools has been modeled. This initial production scheduling process is done simultaneously to allocate workpiece on CNC machine and cutting tool in the same time [5]. When the cutting tool is broken during unmanned operation, the FMS requires rescheduling to allocate workpiece to other CNC machine and cutting tools. This research deals with dynamic production scheduling algorithm considering cutting tool failure and cutting tool life.

The discussion in this paper is divided into five sections. In the first section, an introduction of the research is discussed. A description of FMS configuration and operation are discussed in the second section. In the third section, problem formulation and solution method is discussed. A hypothetical example and analysis are discussed in the fourth section, and then the last section consists of concluding remarks and the problems to be dealt in further research.

2. FMS Configuration and Operation

2.1. FMS Construction.
The FMS developed in this study is a work center in Indonesian aircraft industry. Based on the layout, the FMS consists of identical CNC machines in a progressive or line type. Each CNC machine has a same cutting tool configuration, stored in a tool magazine. In this configuration, the entire workpiece could be processed on any CNC machine which is dependent on the availability and limitation of cutting tool life. A cutting tool could be used for several operations until the cutting tool time consumption reaches its cutting tool life. The FMS is equipped with a pallet stocker, which is a shelf used to store a workpiece which is either waiting to be processed, or has been completed. Each workpiece is mounted on the fixture contained in the pallet. The pallet will be stored in the pallet stocker. To install a workpiece that has to be processed on the fixture, the FMS provides two loading / unloading station. The material handling system to deliver the workpiece on the pallet is serviced by a stacker crane.

2.2. FMS Operation.
The FMS is designed to operate with almost no operator for 24 hours. The operator is responsible only for setup or install the workpiece in a fixture and install the cutting tools in the tool magazine each morning. The next day, the operator takes the finished workpiece and installs a new raw material and replaces the cutting tools which have been used. The Indonesian aircraft industry uses Enterprise Resource Planning (ERP) system to plan the daily job for FMS to be finished in one day. The feature of the workpiece has been previously determined in the production planning stage. In general, the job which will be processed by the FMS consists of two stages. Each stage has sequential operations. An
operation requires one type of cutting tool. Thus to process a stage of a job, it requires a set of cutting tool type.

3. Model Formulation

The model developed in this paper is the continuation initial FMS production scheduling developed by Setiawan et al. [5] based on [6]. The previous model is a static FMS scheduling, considering only cutting tool life. In this paper, the model also accommodates the dynamic of production scheduling in FMS, considering not only cutting tool life but also cutting tool failure.

The algorithm developed in this paper consists of four steps. The first step is to prepare the initial production schedule considering the cutting tools to minimize makespan, based on model that has been developed by Setiawan et al. [5]. In this step, the cutting tools are prepared as new cutting tools.

The second step is to determine the cutting tool failure time, as the event of cutting tool failure [3]. After the cutting tool failure occurs, the third step is to check the system status. The FMS will divide the jobs into three sets of jobs. The first set is the jobs that finished, the second set is jobs that are being processed, and the third set is the jobs that are waiting to be processed. In the second set, there are two types of jobs, which are the job that stopped because of the cutting tool to process this job is broken. The other type is the jobs that are being processed by other cutting tools which are not affected to the broken cutting tool. In this step, the consumption time of cutting tools need to be calculated. The fourth step is to reschedule the waiting jobs and the job that stopped because of the broken cutting tool. The rescheduling process is the same as the first step, but the cutting tools have been used for finished jobs.

To solve the problem in first step, the initial production schedule is generated using Setiawan et al. model [5]. This model is a static FMS production scheduling model considering cutting tools to minimize makespan. The mathematical model is explained as follows:

Indices:
- $j, j'$ : index for job, where $1 \leq j \leq J$.
- $k$ : index for cutting tool type, where $1 \leq k \leq K$.
- $m$ : index for machine, where $1 \leq m \leq M$.
- $n$ : index for cutting tool number, where $1 \leq n \leq N$.
- $o, o'$ : index for operation, where $1 \leq o \leq O$.
- $s, s'$ : index for stage, where $s \in \{1, 2\}$.

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-$m$.
- $ST_{j,s,o,m}$ : starting time of job-$j$, stage-$s$, operation-$o$, on machine-$m$.
- $Y_{j,s,o,j',s',o',m}$ : 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:
- $G_{j,s,o,k}$ : a binary number, $= 1$ means that a job-$j$, stage-$s$, operation-$o$, requires type-$k$ of cutting tool.
- $J$ : number of jobs.
- $K$ : number of cutting tool types.
- $L$ : a big number.
- $LT_{n,k,m}$ : 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.

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

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.
- Raw materials are already prepared on fixture before $t = 0$.

Using this notation and based on the assumption, the production scheduling model considering the cutting tools is presented as follow:

**Objective function:**

$\text{Min } CT_{\text{max}}$, \hspace{1cm} (1).

**Constraints:**

$\sum_{m=1}^{M} X_{j,s,o,m} = 1$, \hspace{0.5cm} \forall j, s, o, \forall \text{ machine}$, \hspace{0.5cm} (2).

$ST_{j,s,o,m} + CT_{j,s,o,m} \leq (X_{j,s,o,m}) \cdot L$, \hspace{0.5cm} \forall j, s, o, \forall m$, \hspace{0.5cm} (3).

$CT_{j,s,o,m} \geq ST_{j,s,o,m} + t_{j,s,o,m} \cdot (1 - X_{j,s,o,m}) \cdot L$, \hspace{0.5cm} \forall j, s, o, \forall m$, \hspace{0.5cm} (4).

$ST_{j,s,o,m} \geq CT_{j',s',o',m} - (Y_{j,s,o,j',s',o',m} - 1) \cdot L$, \hspace{0.5cm} \forall j, s, o, \forall j', s', o', \forall m$, \hspace{0.5cm} (5).

$ST_{j',s',o',m} \geq CT_{j,s,o,m} - (1 - Y_{j,s,o,j',s',o',m}) \cdot L$, \hspace{0.5cm} \forall j, s, o, \forall j', s', o', \forall m$, \hspace{0.5cm} (6).

$\sum_{m=1}^{M} ST_{j,s,o,m} \geq \sum_{m=1}^{M} CT_{j,s,o,m} - 1$, \hspace{0.5cm} \forall j, s, o, \forall m$, \hspace{0.5cm} (7).

$\sum_{m=1}^{M} CT_{j,s=1,o=0,m} < \sum_{m=1}^{M} ST_{j,s=1,o=1,m}$, \hspace{0.5cm} \forall j$, \hspace{0.5cm} (8).

$CT_{j} \geq \sum_{m=1}^{M} CT_{j,s=0,o=0,m}$, \hspace{0.5cm} \forall j$, \hspace{0.5cm} (9).

$CT_{\text{max}} \geq CT_{j}$, \hspace{0.5cm} \forall j$, \hspace{0.5cm} (10).

$CT_{\text{max}} \leq 1440$. \hspace{0.5cm} (11).

$X_{j,s,o,m} \cdot \sum_{k=1}^{K} \sum_{n=1}^{N_{k,m}} Z_{j,s,o,n,k,m} = 1$, \hspace{0.5cm} \forall j, s, o, \forall m$, \hspace{0.5cm} (12).

$X_{j,s,o,m} = \sum_{k=1}^{K} \left( G_{j,s,o,k} \cdot \sum_{n=1}^{N_{k,m}} Z_{j,s,o,n,k,m} \right)$, \hspace{0.5cm} \forall j, s, o, \forall m$, \hspace{0.5cm} (13).

$CC_{n,k,m} = \sum_{j=1}^{J} \sum_{s=1}^{S} \sum_{o=1}^{O} \left( X_{j,s,o,m} \cdot G_{j,s,o,k} \cdot Z_{j,s,o,n,k,m} \right) \cdot t_{j,s,o,m}$, \hspace{0.5cm} \forall n, k, m$, \hspace{0.5cm} (14).

$CC_{n,k,m} \leq LT_{n,k,m}$, \hspace{0.5cm} \forall n, k, m$, \hspace{0.5cm} (15).

$X_{j,s,o,m} \in \{0,1\}$, \hspace{0.5cm} \forall j, s, o, \forall m$, \hspace{0.5cm} (16).

$Y_{j,s,o,j',s',o',m} \in \{0,1\}$, \hspace{0.5cm} \forall j, s, o, j', s', o', \forall m$, \hspace{0.5cm} (17).
The objective function (1) in model Setiawan et al. is to minimize makespan. To ensure that a job-\( j \), stage-\( s \), operation-\( o \) is allocated only on a machine it is used equation (2). Constraint (3) ensure that the, a job-\( j \), stage-\( s \), operation-\( o \) is allocated to a certain machine. The approach is to determine the starting time and the completion time of an operations-\( o \) and the allocation of decision variables \( X_{j,s,o,m} \). Constraint (4) 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-\( m \) \((ST_{j,s,o,m})\) plus the processing time of the operation-\( o \) of job-\( j \), stage-\( s \) on machine-\( m \) \((LT_{j,s,o,m})\). Constraints (5) and (6) 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 machine. The relation is stated on the starting and completion time of operation-\( o \) (of job-\( j \), stage-\( s \)) and operation-\( o' \) (of job-\( j' \), stage-\( s' \)) and the decision variable \( Y_{j,s,o,j',s',o',m} \). Constraint (7) ensures that the precedence sequence of operation is not violated. The operation-\( o \) is started after the completion of previous operation of job-\( j \), stage-\( s \). Constraint (8) is to ensure that the stage-2 is started after the last of the operation on stage-1 is finished. It means that the precedence sequence of stage is not violated. Constraint (9) determines the completion time (of the final operations) of the job is the completion time of latest job on stage-2. The constraint (10) determines the makespan. The constraint (11) ensures that the makespan must not exceed 1440 minutes during unmanned. Equation (12) is the constraint to ensure that an operation select only a cutting tool in a machine. The decision variable to select a cutting tool is \( Z_{j,s,o,n,k,m} \) which is a binary number. The constrain (13) is to ensure that an operation requires only a cutting tool type. The decision variable to select a type of cutting tool is \( G_{j,s,o,k} \). This decision variable is a binary number which is determined by machining process plan. The consequences of selecting a cutting tool on the equations (12) and (13), will consume the life of cutting tool. Constrain (14) is the equation to find the total time consumption of selected cutting tool. In this model, tool sharing policy is applied to saving the amount of cutting tools in the tool magazine. Each cutting tool has the cutting tool life. The constraint (15) is to make sure that the time consumption of cutting tool does not exceed its cutting tool life. Of all of these problems, it is proposed an algorithm to find the solution when the cutting tool failure (broken) occurs.

**Step 0 – Initialization Step.**

Initialize the parameter of FMS configuration, which are number of machine-\( M \), number of cutting tool type-\( K \), number of cutting tool unit \( N_k \), and cutting tool life time of unit-\( n \), type-\( k \) on machine-\( m \) \((LT_{n,k,m})\). Initialize the parameter of process plan of the jobs, which are processing time of a job-\( j \), stage-\( s \), operation-\( o \), on machine-\( m \) \((LT_{j,s,o,m})\) and required cutting tools type-\( k \) \((G_{j,s,o,k})\) to process an operation-\( o \) of job-\( j \) and stage-\( s \).

**Step 1 – Generation Initial Schedule.**

Create the initial production schedule considering the cutting tools, to minimize makespan. Model Setiawan et al. creates the initial production schedule [5]. The schedule informs the Starting Time of job-\( o \), stage-\( s \), operation-\( o \), on machine-\( m \) \((ST_{j,s,o,m})\), Completion Time of job-\( o \), stage-\( s \), operation-\( o \),
on machine-\(m\) (\(CT_{j,s,o,m}\)), makespan (\(CT_{\text{max}}\)) and time consumption of each cutting tool unit-\(n\), type-\(k\) on machine-\(m\) (\(CC_{n,k,m}\)).

**Step 2 – Determination of Cutting Tool Failure Time.**
In the second step, determination of the cutting tool failure time can be developed from the deterioration of cutting tool explained by Vagnorius et al. [3]. But in this paper, the cutting tool failure time (\(FT_{n,k,m}\)) is determined as parameter which is smaller than the cutting tool life. It means that the cutting tool unit-\(n\), type-\(k\) on machine-\(m\) is going to fail at a time before the cutting tool life is reached.

**Step 3 - Determination of system status at Failure Time.**
At the failure time, divide the jobs into three groups. The first group is the finished job. The second group is the waiting job. The third is the work in process job. The work in process job consists of the job that cause cutting tool failure, and the job which is not affected by cutting tool failure. Calculate the total time consumption of each cutting tool unit-\(n\), type-\(k\), machine-\(m\) (\(CC_{n,k,m}\)).

**Step 4 – Rescheduling Step.**
Set the latest completion time from job being processed, as the starting point to reschedule. Set the jobs to be rescheduled, which are the jobs caused cutting tool failure and the waiting job. Model Setiawan et al. [5] then creates the revised schedule, considering the cutting tools. Because of cutting tools are already used by the finished jobs, this cutting tools have remaining cutting tool life.

4. Numerical Exercise and Analysis
The model testing is carried out by finding solution using the hypothetical data. In this exercise, the FMS consists of two CNC machines. The cutting tool configuration has two cutting tool types. Each type has two units of cutting tools. Each machine has same cutting tool configuration installed in the tool magazine. Each cutting tool has same life time (\(LT_{n,k,m}\)), which is 150 minutes as stated in Table.1. There are four jobs for FMS in this exercise. Each job has two stages, and each stage has two operations. In the process plan, an operation-\(o\) requires a specific cutting tool type-\(k\). The cutting tool requirement is binary number in the variable (\(G_{j,s,o,k}\)) and the operation time of each job and stage (\(t_{j,s,o}\)) are explained in Table 2.

| Cutting Tool Life Time in initial condition. | Table 1. Cutting tool Life Time in initial condition. | Table 2. Process plan for jobs in FMS. |
|---------------------------------------------|-----------------------------------------------|-----------------------------------------------|
| \(LT_{n,k,m}\)                           | Operation Time \(t_{j,s,o}\) (minutes)          | Operation Time \(t_{j,s,o}\) (minutes)          |
| \(n,k,m\)                                 | Cutting Tool Type, \(G_{j,s,o,k}\)             | Cutting Tool Type, \(G_{j,s,o,k}\)             |
| \(LT_{1,1,1}\)                           | \(j,s,o\)                                      | \(j,s,o\)                                      |
| 150                                       | \(1,1,1\)                                      | 1.1,1                                          |
|                                          | 150                                           | 20                                             |
|                                          | \(1,1,2\)                                      | 1.1,2                                          |
|                                          | 150                                           | 25                                             |
|                                          | \(1,2,1\)                                      | 1.2,1                                          |
|                                          | 150                                           | 20                                             |
|                                          | \(1,2,2\)                                      | 1.2,2                                          |
|                                          | 150                                           | 10                                             |
|                                          | \(2,1,1\)                                      | 2.1,1                                          |
|                                          | 150                                           | 35                                             |
|                                          | \(2,1,2\)                                      | 2.1,2                                          |
|                                          | 150                                           | 30                                             |
|                                          | \(2,2,1\)                                      | 2.2,1                                          |
|                                          | 150                                           | 20                                             |
|                                          | \(2,2,2\)                                      | 2.2,2                                          |
|                                          | 150                                           | 15                                             |

The first step, using the model Setiawan et al. [5] in Lingo software results the initial production schedule of job-\(j\), stage-\(s\), operation-\(o\) to CNC machine, considering the cutting tool. The job allocation, starting time and completion time each job-\(j\), stage-\(s\), and operation-\(o\) on machine-\(m\) in initial condition is shown in Table 3. Table 4 explains the allocation of job-\(j\), stage-\(s\), and operation-\(o\) to cutting tool unit-\(n\), type-\(k\) on machine-\(m\) in initial condition. The total cutting tool time consumptions in initial condition are shown in Table 5. The production schedule in Gantt chart of
job-j, stage-s, and operation-o to machine-m and cutting tool unit-n, type-k on machine-m in initial condition is shown in Figure 1.

Table 3. The operation allocation to machine in initial production schedule.

| j | s | o | m | X | ST | CT | t |
|---|---|---|---|---|----|----|---|
| 2 | 1 | 1 | 1 | 1 | 0  | 35 | 35|
| 2 | 1 | 2 | 1 | 1 | 35 | 65 | 30|
| 3 | 1 | 1 | 1 | 1 | 65 | 85 | 20|
| 3 | 1 | 2 | 1 | 1 | 85 | 110| 25|
| 3 | 2 | 1 | 1 | 1 | 110| 130| 20|
| 3 | 2 | 2 | 1 | 1 | 130| 140| 10|
| 4 | 2 | 1 | 1 | 1 | 140| 160| 20|
| 4 | 2 | 1 | 1 | 1 | 160| 175| 15|
| 4 | 4 | 1 | 1 | 1 | 0  | 35 | 35|
| 4 | 1 | 2 | 1 | 1 | 35 | 65 | 30|
| 1 | 1 | 1 | 2 | 1 | 65 | 85 | 20|
| 1 | 1 | 2 | 2 | 1 | 85 | 110| 25|
| 2 | 1 | 1 | 2 | 1 | 110| 130| 20|
| 2 | 2 | 1 | 2 | 1 | 130| 145| 15|
| 1 | 2 | 1 | 2 | 1 | 145| 165| 20|
| 1 | 2 | 2 | 2 | 1 | 165| 175| 10|

Job allocation to machine and the Starting and Completion Time

Production schedule of job-j, stage-s, operation-o (j,s,o) to each cutting tool unit-n, type-k on machines-m (C_{n,k,m}).

| C_{n,k,m} | C_{1,1,1} | C_{2,1,1} | C_{1,2,1} | C_{2,2,1} |
|---|---|---|---|---|
| 2,1,1 | 2,1,2 | 3,1,2 | 4,2,2 |

Cutting tool Consumption (CC_{n,k,m}): CC_{1,1,1} = 30 minutes
CC_{2,1,1} = 60 minutes
CC_{1,2,1} = 85 minutes
CC_{2,2,1} = 0 minute

CC_{1,1,2} = 10 minutes
CC_{2,1,2} = 80 minutes
CC_{1,2,2} = 85 minutes
CC_{2,2,2} = 0 minute

Production schedule of job-j, stage-s, operation-o (j,s,o) to machines-m.

| M1 | M2 |
|---|---|
| 2,1,1 | 4,1,1 |
| 2,1,2 | 4,1,2 |
| 3,1,1 | 1,1,2 |
| 3,1,2 | 2,2,1 |
| 3,2,1 | 2,2,2 |
| 4,2,1 | 1,2,1 |
| 4,2,2 |

Makespan = 175 minutes

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.

In second and third step, when the cutting tool C_{1,2,2} failed at the time 75 minute, then the production schedule will be divided into three groups which are the group of finished jobs, the group of work in process and the group of waiting job. These three groups are shown in Table 6. The waiting job and the job that stopped because of the broken cutting tool (job-1,stage1,operation-1) will be rescheduled and constrained with used cutting tools. The revised schedule will be started after job-3,stage1,operation-1 is finished at the time 85 minute. The jobs to be rescheduled constrained with used cutting tools as shown in Table 7 and Table 8.
The groups of jobs after the cutting tool $C_{l,2}$ failed in 75 minutes

| Job | Starting Time | Completion Time | Allocation |
|-----|---------------|----------------|------------|
| 1   | 120           | 140            | 2,1,1      |
| 2   | 35            | 40             | 1,2,1      |
| 3   | 50            | 60             | 1,2,2      |
| 4   | 70            | 80             | 1,1,2      |

The remaining life of cutting tools for rescheduling.

| Job | Remaining Life | Life Time |
|-----|----------------|-----------|
| 1   | 20             | 40        |
| 2   | 10             | 30        |
| 3   | 15             | 25        |
| 4   | 20             | 20        |

The waiting jobs.

| Job | Starting Time | Completion Time | Allocation |
|-----|---------------|----------------|------------|
| 1   | 120           | 140            | 2,1,1      |
| 2   | 35            | 40             | 1,2,1      |
| 3   | 50            | 60             | 1,2,2      |
| 4   | 70            | 80             | 1,1,2      |

The operation allocation to machine and the starting and completion time for the rescheduling.

| Job | Machine | Starting Time | Completion Time |
|-----|---------|---------------|-----------------|
| 1   | 1       | 120           | 140             |
| 2   | 2       | 35            | 40              |
| 3   | 3       | 50            | 60              |
| 4   | 4       | 70            | 80              |

The operation allocation to cutting tool of the rescheduling.

| Job | Cutting Tool Type | Operation Time |
|-----|-------------------|----------------|
| 1   | B                | 120            |
| 2   | C                | 140            |
| 3   | D                | 160            |
| 4   | E                | 180            |

The waiting job time consumption.

| Job | Cutting Tool Type | Operation Time |
|-----|-------------------|----------------|
| 1   | F                | 120            |
| 2   | G                | 140            |
| 3   | H                | 160            |
| 4   | I                | 180            |

The rescheduling process uses Setiawan et al. model in Lingo software [5]. This results the initial production schedule of job-$j$, stage-$s$, operation-$o$ to CNC machine, considering the cutting tool. The job allocation, starting time and completion time each job-$j$, stage-$s$, and operation-$o$ on machine-$m$ of rescheduling results are shown in Table 9. Table 10 explains the allocation of job-$j$, stage-$s$, and operation-$o$ to cutting tool unit-$n$, type-$k$ on machine-$m$ after the rescheduling. The total cutting tool time consumptions of the rescheduling result are shown in Table 11. The production schedule in Gantt chart of job-$j$, stage-$s$, and operation-$o$ to machine-$m$ and cutting tool unit-$n$, type-$k$ on machine-$m$ of rescheduling is depicted in Figure 2.

The algorithm steps in this exercise can give a solution regarding the cutting tool failure. The rescheduling considers the availability and remaining life time of cutting tools. The rescheduling process is conducted for all the waiting jobs and the job stopped because of the cutting tool failure (job-$1$, stage-$1$, operation-$1$). The job allocation including the starting and completion time in new...
production schedule is totally different with the initial production schedule. The new production schedule gives makespan in 10 minutes longer than initial production schedule, while the job waits until the job-3, stage-1, operation-1 is finished.

Figure 2. The Gantt chart of production reschedule, after the failure on cutting tool \(C_{1,2,2}\) at the time 75 minute.

Production rescheduling can be categorized into three categories, which are complete-reactive-scheduling, predictive-reactive-scheduling and robust-proactive-scheduling [7]. The proposed algorithm in the exercise is categorized into complete-reactive-scheduling. On the complete-reactive scheduling, no production schedule is confirmed and will be change when presence of real time events. The decision is made locally in real time. The complete-reactive scheduling is effective, when the scheduling is complicated. In the example, the jobs are complicated while the jobs consist of stages and each stage consists of many operations. The operation that faces the cutting tool failure will change the whole next operations and other un-finished operations. Predictive-reactive-scheduling is the production rescheduling which includes the estimation of the time of events is going to occur. The reliability model of cutting tool failure in Vagnorius model [3] will be integrated in the production scheduling. Robust-proactive scheduling is production rescheduling process that creates minimum differences between initial production schedule and new production schedule. This includes the differences between starting, completion time of the jobs and makespan. This approach is based on the practical approach while the planned operations, which are not disturbed of cutting tool failure, will be not rescheduled. Only the operations that are affected by the cutting tool failure will be rescheduled. In the example, all operations in \(machine-1\) is not affected by the cutting tool failure \(C_{1,2,2}\). But \(job-2, stage-2, operation-2\) and \(job-1, stage-2, operation-1\) are affected by the cutting tool \(C_{1,2,2}\). Meanwhile, the cutting tool \(C_{2,2,2}\) which is the same type with cutting tool \(C_{1,2,2}\), is not allocated to any operations. Therefore the cutting tool \(C_{2,2,2}\) can be used to process \(job-2, stage-2, operation-2\) and \(job-1, stage-2, operation-1\).

In the robust-proactive-scheduling, the operations which are not affected by cutting tool failure in \(machines-1\) are not changed. Except in \(machine-2\), the rescheduling proses waits until the \(job-3, stage-1, operation-1\) is finished. This makes the operations in \(machine-1\) is shifted for 10 minutes. There is no generic algorithm that built in this study relates to robust-proactive-scheduling approach. The example in robust-proactive-scheduling is coincidently a simple example. The solution

![Production Re-schedule of job-j,stage-s,operation-o (j,s,o) to each cutting tool unit-n, type-k on machines-m (C_n,k,m).](attachment:image.png)

![Cutting tool Consumption (CC_n,k,m):](attachment:image.png)

![Machines-m.](attachment:image.png)

![Makespan = 185 minutes](attachment:image.png)
can be found by trial and error. But if the jobs consist of many stages and many operations, the complete-reactive-scheduling is proposed.

Figure 3. The Gantt chart of robust-proactive production rescheduling approach.

5. Conclusion

The mechanism of FMS dynamic production scheduling algorithm considering cutting tool failure and cutting tool life has been established in this paper. To continue the production while a cutting tool failed during operation, the initial production schedule should be corrected. The next operations of the unfinished job must be rescheduled, and it is considered to the remaining cutting tool life. The complete-reactive scheduling algorithm is proposed to find the solution. Meanwhile this research will be further developed for predictive-reactive scheduling and robust-proactive scheduling by considering the remaining cutting tool life.

References

[1] N Singh, 1996 System Approach To Computer-Integrated Design and Manufacturing, (John Willey & Sons Inc.) 259-260.
[2] J Browne, D Dubois, K Rathmill, P Sethi and K E Stecke, Types Of Flexibilities And Classification of FMS, Division of Research, Graduate School of Business Administration, The University Michigan (367) (1984) 1-8.
[3] Z Vagnorius, M Rausand and K Sorby, Determining Optimal Replacement Time for Metal Cutting Tools, European Journal of Operational Research, Elsevier (206) (2010) 407-416.
[4] K E Stecke, Design, Planning, Scheduling and Control Problem of FMS, Annuals of Operations Research, J.C.Baltzer A.G., Scientific Publisher (3) (1985) 3-12.
[5] A Setiawan, R Wangsaputra, Y Y Martawirya and A H Halim, A Production Scheduling Model Considering Cutting Tools for an FMS to Minimize Makespan, Proceedings of the 16th Asia Pacific Industrial Engineering & Management Systems Conference, APIEMS-2015, Ho-Chi-Minh City Vietnam (Submitted) 2015.
[6] C Özgüven, L Ozbakir, and Y Yavuz, Mathematical Models for Job-shop Scheduling Problem with Routing and Process Plan Flexibility, Applied Mathematical Modelling, Elsevier, (34) (2010)1539-1548.
[7] Dj Ouelhadj and S Petrovic, A Survey of Dynamic Scheduling in Manufacturing Systems, Journal of Scheduling, Springer (12) (2009) 417-431.