

## Bi-criteria Three Stage Fuzzy Flowshop Scheduling with Transportation Time and Job Block Criteria

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Received: 28 May 2012 ; Accepted: 17 September 2012

**Abstract** Scheduling is an enduring process where the existence of real time information frequently forces the review and modification of pre-established schedules. The real world is complex and complexity generally arises from uncertainty. From this prospective the concept of fuzziness is introduced in the field of scheduling. The present paper pertains to a bi-criterion in n-jobs, three machines flowshop scheduling to minimize the makespan and the rental cost of the machines taken on rent under a specified rental policy in which processing time, transportation time are in fuzzy environment and are represented by triangular fuzzy membership function. Further, the concept of job block to represent the relative importance of some jobs over other is also introduced. A heuristic algorithm to find optimal or near optimal sequence optimizing the bi-criteria is discussed. A numerical illustration is given to demonstrate the computational efficiency of proposed algorithm.

**Keywords** Flowshop Scheduling, Fuzzy Processing Time, Fuzzy Transportation Time, Equivalent Job, Rental Cost, Utilization Time.

### 1 Introduction

Multicriteria scheduling stems from the need to address real-world problems that often involve conflicting objective. A schedule that optimize one criteria may infact perform quite poorly for another. Decision makers must carefully evaluate the trade-offs involved in considering several criteria. Bicriteria scheduling problems are motivated by the fact that they are more meaningful from practical point of view. Over the last decades several theories such as fuzzy set theory, Probability theory, D – S theory and approaches based on certainty factors have been developed to account for uncertainty. Among them, fuzzy set theory is more and more frequently used in intelligent control because of its simplicity and similarity to human reasoning. Moreover, the fuzzy approach seems a natural extension of its crisp counterpart so that we need to know how the fuzziness of processing times and transportation times affects the job sequence itself. In most manufacturing systems, finished and semi-finished jobs are transferred from one machine to another for further processing. In most of the published literature explicitly or implicitly assumes that either there is an infinite number

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of jobs are transported instantaneously from one machine to another without transportation time involved. However, there are many situations where the transportation times are quite significant and cannot be simply neglected. Johnson (1954) whose work is one of the earliest, developed an algorithm to minimize the makespan in two stage flowshop scheduling problem. Dileepan and T.Sen [1988] extensively surveyed the bicriterion static scheduling research for a single machine. MacCahon and Lee [1990] discussed the job sequencing with fuzzy processing time. Ishibuchi and Lee [1996] addressed the formulation of fuzzy flow shop scheduling problem with fuzzy processing time. Some of the noteworthy approaches are due to Zadeh (1965), Gupta J.N.D (1975), Maggu and Das (1977), Yager (1981), Marin and Roberto (2001), Yao and Lin (2002), Singh and Gupta (2005), Singh, Sunita and Allawalia (2008).

Gupta D. and Sharma S. [2011] studied bicriteria in  $n \times 3$  flow shop scheduling under specified rental policy, processing time associated with probabilities including transportation time and job block criteria. As the fuzzy approach seems much more natural to us, we investigate its potential by solving the flowshop problem in real life situations. Here our study recommends the use of triangular fuzzy membership functions to represent the uncertain processing times and transportation times.

## 2 Practical Situation

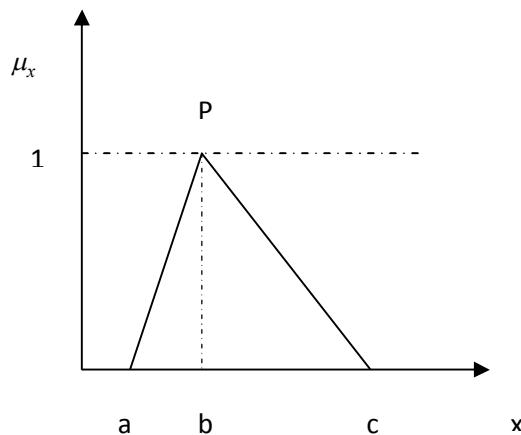
Fuzzy set theory has emerged as a profitable tool for controlling and steering of systems and complex industrial processes, as well as for household and entertainment electronics. Various practical situations occur in real life when one has got the assignments but does not have one's own machine or does not have enough money or does not want to take risk of investing huge amount of money to purchase machine. Under such circumstances, the machine has to be taken on rent in order to complete the assignments. Medical science can save the patient's life but proper care leads to a faster recovery. Care giving techniques often require hi-tech, expensive medical equipment. Many of these equipments can even help in saving the life of critical patients. Most of these equipments are expensive & they are often needed for a few days or weeks thus buying them do not make much sense even if one can afford them. Many patients even lose their lives just because they cannot afford to buy these products. In his starting career, we find a medical practitioner does not buy expensive machines say X-ray machine, the Ultra Sound Machine, Rotating Triple Head Single Positron Emission Computed Tomography Scanner, Patient Monitoring Equipment, and Laboratory Equipment etc., but instead takes on rent. Rental of medical equipment is an affordable and quick solution for hospitals, nursing homes, physicians, which are presently constrained by the availability of limited funds due to the recent global economic recession. Renting enables saving working capital, gives option for having the equipment, and allow up gradation to new technology. When the machines on which jobs are to be processed are planted at different places, the transportation time (which includes loading time, moving time and unloading time etc.) has a significant role in production concern.

## 3 Fuzzy Membership Function

All information contained in a fuzzy set is described by its membership function. The triangular membership functions are used to represent fuzzy processing times and fuzzy setup

times in our algorithm. The membership value of the  $x$  denoted by  $\mu_x, x \in R^+$ , can be calculated according to the formula

$$\mu_x = \begin{cases} 0; x \leq a \\ \frac{x-a}{b-a}; a \leq x \leq b \\ \frac{c-x}{c-b}; b < x < c \\ 0; x \geq c \end{cases}$$



**Fig. 1** Triangular membership function

Figure 1 shows the triangular membership function of a fuzzy set  $\tilde{P}$ ,  $\tilde{P} = (a, b, c)$ . The membership value reaches the highest point at 'b', while 'a' and 'c' denote the lower bound and upper bound of the set  $\tilde{P}$  respectively.

### 3.1 Average High Ranking (A.H.R.)

To find the optimal sequence, the expected processing time of the jobs are calculated by using Yager's(1981) average high ranking formula (AHR) =  $h(A) = \frac{3b + c - a}{3}$ .

### 3.2 Fuzzy Arithmetic Operations

The following are the four operations that can be performed on triangular fuzzy numbers:  
Let  $A = (a_1, a_2, a_3)$  and  $B = (b_1, b_2, b_3)$  then

1. Addition:  $A + B = (a_1 + b_1, a_2 + b_2, a_3 + b_3)$
2. Subtraction:  $A - B = (a_1 - b_3, a_2 - b_2, a_3 - b_1)$
3. Multiplication:  $A \times B = (\min(a_1 b_1, a_1 b_3, a_3 b_1, a_3 b_3), \max(a_1 b_1, a_1 b_3, a_3 b_1, a_3 b_3))$
4. Division:  $A / B = (\min(a_1 / b_1, a_1 / b_3, a_3 / b_1, a_3 / b_3), \max(a_1 / b_1, a_1 / b_3, a_3 / b_1, a_3 / b_3))$

A new operation for Subtraction on triangular fuzzy numbers

Let  $A = (a_1, a_2, a_3)$  and  $B = (b_1, b_2, b_3)$  then

$A - B = (a_1 - b_1, a_2 - b_2, a_3 - b_3)$ . This subtraction operation exist only if the following condition is satisfied  $DP(A) \geq DP(B)$ , where  $DP(A) = (a_3 - a_1) / 2$  and  $DP(B) = (b_3 - b_1) / 2$  where  $DP$  denotes difference point of a triangular fuzzy number.

#### 4 Notations & Various Definition's

$S$	: Sequence of jobs 1,2,3,...,n
$S_k$	: Sequence obtained by applying Johnson's procedure, $k = 1, 2, 3, \dots$
$M_j$	: Machine $j$ , $j = 1, 2, 3$
$M$	: Minimum makespan
$a_{ij}$	: Fuzzy processing time of $i^{th}$ job on machine $M_j$
$A_{ij}$	: AHR of processing time of $i^{th}$ job on machine $M_j$
$t_{i,j \rightarrow k}$	: Fuzzy transportation time of $i^{th}$ job from $j^{th}$ machine to $k^{th}$ machine
$T_{i,j \rightarrow k}$	: AHR of transportation time of $i^{th}$ job from $j^{th}$ machine to $k^{th}$ machine
$\beta$	: Equivalent job for job – block
$C_i$	: Rental cost of $i^{th}$ machine
$L_j(S_k)$	: The latest time when machine $M_j$ is taken on rent for sequence $S_k$
$t_{ij}(S_k)$	: Completion time of $i^{th}$ job of sequence $S_k$ on machine $M_j$
$t'_{ij}(S_k)$	: Completion time of $i^{th}$ job of sequence $S_k$ on machine $M_j$ when machine $M_j$ starts processing jobs at time $L_j(S_k)$
$I_{ij}(S_k)$	: Idle time of machine $M_j$ for job $i$ in the sequence $S_k$
$U_j(S_k)$	: Utilization time for which machine $M_j$ is required, when $M_j$ starts processing jobs at time $L_j(S_k)$
$R(S_k)$	: Total rental cost for the sequence $S_k$ of all machine
$CT(S_i)$	: Total completion time of the jobs for sequence $S_i$

##### 4.1 Definition

Completion time of  $i^{th}$  job on machine  $M_j$  is denoted by  $t_{ij}$  and is defined as:

$$t_{ij} = \max(t_{i-1,j}, t_{i,j-1}) + T_{i,(j-1) \rightarrow j} + a_{ij} \text{ for } j \geq 2.$$

where

$$a_{i,j} = \text{Fuzzy processing time of } i^{th} \text{ job on } j^{th} \text{ machine}$$

##### 4.2 Definition

Completion time of  $i^{th}$  job on machine  $M_j$  when  $M_j$  starts processing jobs at time  $L_j$  is denoted by  $t'_{ij}$  and is defined as

$$t'_{i,j} = L_j + \sum_{k=1}^i a_{k,j} = \sum_{k=1}^i I_{k,j} + \sum_{k=1}^i a_{k,j}$$

Also  $t'_{i,j} = \max(t_{i,j-1}, t'_{i-1,j}) + a_{i,j}$ .

### 4.3 Rental Policy (P)

The machines will be taken on rent as and when they are required and are returned as and when they are no longer required i.e. the first machine will be taken on rent in the starting of the processing the jobs, 2<sup>nd</sup> machine will be taken on rent at time when 1<sup>st</sup> job is completed on 1<sup>st</sup> machine and transported to 2<sup>nd</sup> machine, 3<sup>rd</sup> machine will be taken on rent at time when 1<sup>st</sup> job is completed on the 2<sup>nd</sup> machine and transported.

## 5 Problem Formulation & Assumptions

Let some job  $i$  ( $i = 1, 2, \dots, n$ ) are to be processed on three machines  $M_j$  ( $j = 1, 2, 3$ ) under the specified rental policy P. Let  $a_{ij}$  be the processing time of  $i^{\text{th}}$  job on  $j^{\text{th}}$  machine described by triangular fuzzy numbers. Let  $A_{ij}$  be the average high ranking (AHR) of processing time of  $i^{\text{th}}$  job on  $j^{\text{th}}$  machine. Let  $t_{i,j \rightarrow k}$  be the fuzzy transportation time of  $i^{\text{th}}$  job from  $j^{\text{th}}$  machine to  $k^{\text{th}}$  machine. Let  $T_{i,j \rightarrow k}$  be the AHR of transportation time of  $i^{\text{th}}$  job from  $j^{\text{th}}$  machine to  $k^{\text{th}}$  machine. Our aim is to find the sequence  $\{S_k\}$  of the jobs which minimize the rental cost of all the three machines while minimizing total elapsed time.

**Table 1** The mathematical model of the problem in matrix form

Jobs i	Machine M <sub>1</sub>		$T_{i,1 \rightarrow 2}$	Machine M <sub>2</sub>		$T_{i,2 \rightarrow 3}$	Machine M <sub>3</sub>	
	$a_{i1}$	$T_{i,1 \rightarrow 2}$		$a_{i2}$	$T_{i,2 \rightarrow 3}$		$a_{i3}$	
1	$a_{11}$	$T_{1,1 \rightarrow 2}$		$a_{12}$	$T_{1,2 \rightarrow 3}$		$a_{13}$	
2	$a_{21}$	$T_{2,1 \rightarrow 2}$		$a_{22}$	$T_{2,2 \rightarrow 3}$		$a_{23}$	
3	$a_{31}$	$T_{3,1 \rightarrow 2}$		$a_{32}$	$T_{3,2 \rightarrow 3}$		$a_{33}$	
4	$a_{41}$	$T_{4,1 \rightarrow 2}$		$a_{42}$	$T_{4,2 \rightarrow 3}$		$a_{43}$	
-		-		-	-		-	
n	$a_{n1}$	$T_{n,1 \rightarrow 2}$		$a_{n2}$	$T_{n,2 \rightarrow 3}$		$a_{n3}$	

Minimize  $U_j(S_k)$  and

$$\text{Minimize } R(S_k) = \sum_{i=1}^n A_{il}(S_k) \times C_1 + U_2(S_k) \times C_2 + U_3(S_k) \times C_3$$

Subject to constraint: Rental Policy (P)

Our objective is to minimize rental cost of machines while minimizing total elapsed time.

## 5.1 Assumptions

1.  $n$  jobs be processed through three machines  $M_1$ ,  $M_2$  &  $M_3$  in the order  $M_1M_2M_3$  i.e. no passing is allowed.
2. A sequence of  $k$  jobs  $i_1, i_2, \dots, i_k$  as a block or group-job in the *order*  $(i_1, i_2, \dots, i_k)$  shows priority of job  $i_1$  over  $i_2$ , etc.
3. Jobs may be held in inventory before going to a machine.
4. The storage space is available and the cost of holding inventory for each job is either same or negligible.
5. Time intervals for processing are independent of the order in which operations are performed.

## 6 Theorems

The various theorems have been given to find the latest time at which machines should be taken on rent so as to optimize the rental cost of the machines with minimum makespan.

### 6.1 Theorem

The processing of jobs on  $M_3$  at time  $L_3 = \sum_{i=1}^n I_{i,3}$  keeps  $t_{n,3}$  unaltered.

**Proof.** Let  $t'_{i,3}$  be the competition time of  $i^{th}$  job on machine  $M_3$  when  $M_3$  starts processing of jobs at time  $L_3$ . We shall prove the theorem with the help of Mathematical Induction.

Let  $P(n) : t'_{n,3} = t_{n,3}$

*Basic Step:* For  $n = 1$

$$\begin{aligned} t'_{1,3} &= L_3 + A_{1,3} = I_{1,3} + A_{1,3} \\ &= (A_{1,1} + (T_{1,1 \rightarrow 2} + A_{1,2}) + T_{1,2 \rightarrow 3}) + A_{1,3} = t_{1,3}. \end{aligned}$$

Therefore  $P(1)$  is true.

*Induction Step:* Let  $P(k)$  be true.

i.e.  $t'_{k,3} = t_{k,3}$ .

Now, we shall show that  $P(k+1)$  is also true.

i.e.  $t'_{k+1,3} = t_{k+1,3}$

But  $t'_{k+1,3} = \max(t_{k+1,2}, t'_{k,3}) + T_{k+1,2 \rightarrow 3} + A_{k+1,3}$  (As per Definition 2)

$$\therefore t'_{k+1,3} = \max(t_{k+1,2}, L_3 + \sum_{i=1}^k A_{i,3}) + T_{k+1,2 \rightarrow 3} + A_{k+1,3}$$

$$\begin{aligned}
&= \max(t_{k+1,2}, \sum_{i=1}^{k+1} I_{i,3} + \sum_{i=1}^k A_{i,3}) + T_{k+1,2 \rightarrow 3} + A_{k+1,3} \\
&= \max(t_{k+1,2}, \sum_{i=1}^k I_{i,3} + \sum_{i=1}^k A_{i,3} + I_{k+1,3}) + T_{k+1,2 \rightarrow 3} + A_{k+1,3} \\
&= \max(t_{k+1,2}, t_{k,3} + I_{k+1,3}) + T_{k+1,2 \rightarrow 3} + A_{k+1,3} \\
&= \max(t_{k+1,2}, t_{k,3} + I_{k+1,3}) + T_{k+1,2 \rightarrow 3} + A_{k+1,3} \quad (\text{by assumption}) \\
&= \max(t_{k+1,2}, t_{k,3} + \max((t_{k+1,2} - t_{k,3}), 0)) + T_{k+1,2 \rightarrow 3} + A_{k+1,3} \\
&= \max(t_{k+1,2}, t_{k,3}) + T_{k+1,2 \rightarrow 3} + A_{k+1,3} \\
&= t_{k+1,3}
\end{aligned}$$

$\Rightarrow P(k+1)$  is true .

Hence by principle of mathematical induction  $P(n)$  is true for all  $n$ , i.e.  $t_{n,3}^* = t_{n,3}$  .

### Remarks.

If  $M_3$  starts processing jobs for minimum  $L_3(S_r) = t_{n,3}(S_r) - \sum_{i=1}^n A_{i,3}$  then the total elapsed time  $L_3(S_r) = t_{n,3}(S_r) - \sum_{i=1}^n A_{i,3}$  is not altered and  $M_3$  is engaged for minimum time equal to sum of the processing times of all the jobs on  $M_3$ . Also, if  $M_3$  starts processing jobs at time  $L_3$ , then it can be easily shown that

$$t_{n,3} = L_3 + \sum_{i=1}^n A_{i,3}.$$

**Lemma.** If  $M_3$  starts processing jobs at  $L_3 = \sum_{i=1}^n I_{i,3}$  then

- (i).  $L_3 > t_{1,2}$
- (ii).  $t_{k+1,3}^* \geq t_{k,2}$ ,  $k > 1$ .

## 6.2 Theorem

The processing of jobs on  $M_2$  at time  $L_2 = \min_{i \leq k \leq n} \{Y_k\}$  keeps total elapsed time unaltered where  $Y_1 = L_3 - A_{1,2} - T_{1,2 \rightarrow 3}$  and  $Y_k = t_{k-1,3}^* - \sum_{i=1}^k A_{i,2} - \sum_{i=1}^k T_{i,2 \rightarrow 3}$ ;  $k > 1$ .

**Proof.** We have

$$L_2 = \min_{i \leq k \leq n} \{Y_k\} = Y_r \text{ (say)}$$

In particular for  $k = 1$

$$\begin{aligned}
&Y_r \leq Y_1 \\
&\Rightarrow Y_r + A_{1,2} + T_{1,2 \rightarrow 3} \leq Y_1 + A_{1,2} + T_{1,2 \rightarrow 3} \\
&\Rightarrow Y_r + A_{1,2} + T_{1,2 \rightarrow 3} \leq L_3 \\
&\left( \because Y_1 = L_3 - A_{1,2} - T_{1,2 \rightarrow 3} \right)
\end{aligned} \tag{1}$$

By Lemma 1; we have

$$t_{1,2} \leq L_3 \quad (2)$$

Also,  $t'_{1,2} = \max(Y_r + A_{1,2} + T_{1,2 \rightarrow 3}, t_{1,2})$

On combining, we get

$$t'_{1,2} \leq L_3$$

$$\begin{aligned} \text{For } k > 1, \quad & \text{As } Y_r = \min_{i \leq k \leq n} \{Y_k\} \\ & \Rightarrow Y_r \leq Y_k; \quad k = 2, 3, \dots, n \\ & \Rightarrow Y_r + \sum_{i=1}^k A_{i,2} + \sum_{i=1}^k T_{i,2 \rightarrow 3} \leq Y_k + \sum_{i=1}^k A_{i,2} + \sum_{i=1}^k T_{i,2 \rightarrow 3} \\ & \Rightarrow Y_r + \sum_{i=1}^k A_{i,2} + \sum_{i=1}^k T_{i,2 \rightarrow 3} \leq t'_{k-1,3} \end{aligned} \quad (3)$$

By Lemma 1; we have

$$t_{k,2} \leq t'_{k-1,3} \quad (4)$$

Also,  $t'_{k,2} = \max(Y_r + \sum_{i=1}^k A_{i,2} + \sum_{i=1}^k T_{i,2 \rightarrow 3}, t_{k,2})$

Using (3) and (4), we get

$$t'_{k,2} \leq t'_{k-1,3}$$

Taking  $k = n$ , we have

$$t'_{n,2} \leq t'_{n-1,3} \quad (5)$$

Total time elapsed =  $t_{n,3}$

$$\begin{aligned} &= \max(t'_{n,2}, t'_{n-1,3}) + A_{n,3} + T_{n,2 \rightarrow 3} \\ &= t'_{n-1,3} + A_{n,3} + T_{n,2 \rightarrow 3} \quad (\text{using 5}) \\ &= t'_{n,3}. \end{aligned}$$

Hence, the total time elapsed remains unaltered if  $M_2$  starts processing jobs at time  $L_2 = \min_{i \leq k \leq n} \{Y_k\}$ .

### 6.3 Theorem

The processing time of jobs on  $M_2$  at time  $L_2 > \min_{i \leq k \leq n} \{Y_k\}$  increase the total time elapsed, where

$$Y_1 = L_3 - A_{1,2} - T_{1,2 \rightarrow 3} \text{ and } Y_k = t'_{k-1,3} - \sum_{i=1}^k A_{i,2} - \sum_{i=1}^k T_{i,2 \rightarrow 3}; k > 1.$$

The proof of the theorem can be obtained on the same lines as of the previous Theorem 2.

By Theorem 1, if  $M_3$  starts processing jobs at time  $L_3 = t_{n,3} - \sum_{i=1}^n A_{i,3}$  then the total elapsed time  $t_{n,3}$  is not altered and  $M_3$  is engaged for minimum time equal to sum of processing times of all the jobs on  $M_3$ , i.e. reducing the idle time of  $M_3$  to zero. Moreover total elapsed time/rental cost of  $M_1$  is always least as idle time of  $M_1$  is always zero. Therefore the objective remains to minimize the elapsed time and hence the rental cost of  $M_2$ .

The following algorithm provides the procedure to determine the times at which machines should be taken on rent to minimize the total rental cost without altering the total elapsed time in three machine flow shop problem under rental policy (P).

## 7 Algorithm

**Step 1.** Find the average high ranking  $A_{ij}, T_{i,j \rightarrow k}$  of the processing times and transportation time respectively for all the jobs on three machines  $M_1, M_2$  and  $M_3$ .

**Step 2.** Check the condition

$$\begin{aligned} \text{Either } \min\{A_{i1} + T_{i,1 \rightarrow 2}\} &\geq \max\{A_{i2} + T_{i,1 \rightarrow 2}\} \\ \text{or } \min\{A_{i3} + T_{i,2 \rightarrow 3}\} &\geq \max\{A_{i2} + T_{i,2 \rightarrow 3}\} \text{ or both for all } i \end{aligned}$$

If the conditions are satisfied then go to step 3, else the data is not in the standard form.

**Step 3.** Introduce the two fictitious machines  $G$  and  $H$  with processing times  $G_i$  and  $H_i$  as

$$G_i = A_{i1} + T_{i,1 \rightarrow 2} + A_{i2} + T_{i,2 \rightarrow 3}, \quad H_i = A_{i2} + T_{i,1 \rightarrow 2} + A_{i3} + T_{i,2 \rightarrow 3}$$

**Step 4.** Find the expected processing time of job block  $\beta = (k, m)$  on fictitious machines  $G$  &  $H$  using equivalent job block criterion given by Maggu & Das [1977]. Find  $G_\beta$  and  $H_\beta$  using

$$G_\beta = G_k + G_m - \min(G_m, H_k), \quad H_\beta = H_k + H_m - \min(G_m, H_k)$$

**Step 5.** Define new reduced problem with processing time  $G_i$  &  $H_i$  as defined in step 3 and replace job block  $(k, m)$  by a single equivalent job  $\beta$  with processing times  $G_\beta$  &  $H_\beta$  as defined in step 4.

**Step 6.** Using Johnson's procedure, obtain all sequences  $S_k$  having minimum elapsed time. Let these be  $S_1, S_2, \dots, S_r$

**Step 7.** Prepare In – Out tables for  $S_k$  and compute total elapsed time  $t_{n3}(S_k)$

**Step 8.** Compute latest time  $L_3$  for machine  $M_3$  for sequence  $S_k$  as  $L_3(S_k) = t_{n3}(S_k) - \sum_{i=1}^n A_{i3}$

**Step 9.** For the sequence  $S_k$  ( $k = 1, 2, \dots, r$ ), compute

I.  $t_{n2}(S_k)$

II.  $Y_1(S_k) = L_3(S_k) - A_{1,2}(S_k) - T_{1,2 \rightarrow 3}$

III.  $Y_q(S_k) = L_3(S_k) - \sum_{i=1}^q A_{i2}(S_k) - \sum_{i=1}^q T_{i,2 \rightarrow 3} + \sum_{i=1}^{q-1} A_{i,3} + \sum_{i=1}^{q-1} T_{i,1 \rightarrow 2}; q = 2, 3, \dots, n$

$$\text{IV. } L_2(S_k) = \min_{1 \leq q \leq n} \{Y_q(S_k)\}$$

$$\text{V. } U_2(S_k) = t_{n2}(S_k) - L_2(S_k)$$

**Step 10.** Find  $\min \{U_2(S_k)\}; k = 1, 2, \dots, r$

Let it be for the sequence  $S_p$  and then sequence  $S_p$  will be the optimal sequence.

**Step 11.** Compute total rental cost of all the three machines for sequence  $S_p$  as:

$$R(S_p) = \sum_{i=1}^n a_{i1} \times C_1 + U_2(S_p) \times C_2 + U_3(S_p) \times C_3.$$

## 8 Numerical Illustration

Consider 5 jobs, 3 machine flow shop problem with processing time and transportation time described by triangular fuzzy numbers as given in table and jobs 2 and 4 are processed as group job (2,4). The rental cost per unit time for machines  $M_1$ ,  $M_2$  and  $M_3$  are 4 units, 2 units and 3 units respectively, under the rental policy P. Our objective is to obtain an optimal schedule to minimize the total rental cost of machines.

**Table 2** The machines with processing time and transportation time

Jobs i	Machine $M_1$	$T_{i,1 \rightarrow 2}$	Machine $M_2$	$T_{i,2 \rightarrow 3}$	Machine $M_3$
	$a_{i1}$		$a_{i2}$		$a_{i3}$
1	(7,8,9)	(2,3,4)	(6,7,8)	(1,2,3)	(3,4,5)
2	(12,13,14)	(4,5,6)	(5,6,7)	(2,3,4)	(4,5,6)
3	(8,10,12)	(5,6,7)	(4,5,6)	(3,4,5)	(6,7,8)
4	(10,11,12)	(2,3,4)	(5,6,7)	(1,2,3)	(11,12,13)
5	(9,10,11)	(5,6,7)	(6,7,8)	(3,4,5)	(8,9,10)

**Solution: As per step 1:** The A.H.R of processing time and transportation time of jobs is as follows:

**Table 3** Machines with AHR processing time and transportation time

Jobs i	Machine $M_1$	$T_{i,1 \rightarrow 2}$	Machine $M_2$	$T_{i,2 \rightarrow 3}$	Machine $M_3$
	$A_{i1}$		$A_{i2}$		$A_{i3}$
1	26/3	11/3	23/3	8/3	14/3
2	41/3	17/3	20/3	11/3	17/3
3	34/3	20/3	17/3	14/3	23/3
4	35/3	11/3	20/3	8/3	38/3
5	32/3	20/3	23/3	14/3	29/3

**As per step 3:** The expected processing time for two fictitious machine  $G$  &  $H$  is as shown in table 4.

**Table 4** Two fictitious machines  $G$  &  $H$ 

Jobs	$G_i$	$H_i$
1	68/3	56/3
2	89/3	65/3
3	85/3	74/3
4	74/3	77/3
5	89/3	86/3

**As per step 4:** Here  $\beta = (2,4)$

$$G_\beta = 89/3 + 74/3 - 65/3 = 98/3$$

$$H_\beta = 65/3 + 77/3 - 65/3 = 77/3$$

**As per step 5:** The reduced problem is

**Table 5** Reduced problem with fictitious machines  $G$  &  $H$ 

Jobs	$G_i$	$H_i$
1	68/3	56/3
$\beta$	98/3	77/3
3	85/3	74/3
5	89/3	86/3

**As per step 6:** Using Johnson's method optimal sequence is

$$S = 5 - \beta - 3 - 1 \text{ i.e. } 5 - 2 - 4 - 3 - 1$$

**As per step 7:** The In – Out table for the sequence S is

**Table 6** In-Out flow table

Jobs i	Machine $M_1$ In - Out	$T_{i,1 \rightarrow 2}$	Machine $M_2$		$T_{i,2 \rightarrow 3}$	Machine $M_3$ In - Out
			In - Out			
5	(0,0,0) – (9,10,11)	(5,6,7)	(14,16,18) – (20,23,26)		(3,4,5)	(23,27,31) – (31,36,41)
2	(9,10,11) – (21,23,25)	(4,5,6)	(25,28,31) – (30,34,38)		(2,3,4)	(32,37,42) – (36,42,48)
4	(21,23,25) – (31,34,37)	(2,3,4)	(33,37,41) – (38,43,48)		(1,2,3)	(39,45,51) – (50,57,64)
3	(31,34,37) – (39,44,49)	(5,6,7)	(44,50,56) – (48,55,62)		(3,4,5)	(51,59,67) – (57,66,75)
1	(39,44,49) – (46,52,58)	(2,3,4)	(48,55,62) – (54,62,70)		(1,2,3)	(57,66,75) – (60,70,80)

**(Tableau 6)**

Total elapsed time  $t_{n,3}(S) = (60, 70, 80)$

$$\begin{aligned}\text{As per Step 8: } L_3(S) &= t_{n,3}(S) - \sum_{i=1}^n a_{i,3} \\ &= (60, 70, 80) - (32, 37, 42) = (28, 33, 38)\end{aligned}$$

**As per Step 9:** For sequence  $S$ , we have

$$\begin{aligned}t_{n2}(S) &= (54, 62, 70) \\ Y_1(S) &= (19, 22, 25), Y'_1(S) = 24 \\ Y_2(S) &= (25, 28, 31), Y'_2(S) = 30 \\ Y_3(S) &= (27, 30, 33), Y'_3(S) = 32 \\ Y_4(S) &= (33, 36, 39), Y'_4(S) = 38 \\ Y_5(S) &= (37, 40, 43), Y'_5(S) = 42 \\ L'_2(S) &= \text{Min}\{Y'_k\} = 24 \\ \text{where } Y'_k &= \text{A.H.R of } Y_k, L'_2(S) = \text{A.H.R of } L_2(S) \\ U_2(S) &= t_{n2}(S) - L_2(S) \\ &= (35, 40, 45)\end{aligned}$$

The new reduced Bi – objective In – Out table is

**Table 7** The Bi-objective In-Out flow table

Jobs i	Machine M <sub>1</sub>		$T_{i,1 \rightarrow 2}$	Machine M <sub>2</sub>		$T_{i,2 \rightarrow 3}$	Machine M <sub>3</sub>	
	In - Out			In - Out			In - Out	
5	(0,0,0) – (9,10,11)		(5,6,7)	(19,22,25) – (25,29,33)		(3,4,5)	(28,33,38) – (36,42,48)	
2	(9,10,11) – (21,23,25)		(4,5,6)	(25,29,33) – (30,35,40)		(2,3,4)	(36,42,48) – (40,47,54)	
4	(21,23,25) – (31,34,37)		(2,3,4)	(33,37,41) – (38,43,48)		(1,2,3)	(40,47,54) – (51,59,67)	
3	(31,34,37) – (39,44,49)		(5,6,7)	(44,50,56) – (48,55,62)		(3,4,5)	(51,59,67) – (57,66,75)	
1	(39,44,49) – (46,52,58)		(2,3,4)	(48,55,62) – (54,62,70)		(1,2,3)	(57,66,75) – (60,70,80)	

The latest possible time at which machine M<sub>2</sub> should be taken on rent =  $L_2(S) = (19, 22, 25)$

Also, utilization time of machine M<sub>2</sub> =  $U_2(S) = (35, 40, 45)$

$$\begin{aligned}\text{Total minimum rental cost} &= R(S) = \sum_{i=1}^n a_{i1}(S) \times C_1 + U_2(S) \times C_2 + U_3(S) \times C_3 \\ &= (350,399,448)\end{aligned}$$

## 9 Conclusions

If machine  $M_3$  starts processing the jobs at latest time  $L_3 = t_{n3} - \sum_{i=1}^n a_{i3}$ , then the total elapsed time  $t_{n3}$  is not altered and  $M_3$  is engaged for minimum time equal to sum of processing of all the jobs on  $M_3$ , i.e. reducing the idle time of  $M_3$  to zero. If the machine  $M_2$  is taken on rent when it is required and is returned as soon as it completes the last job, the starting of processing of jobs at the latest time  $L_2(S_k) = \min_{1 \leq q \leq n} \{Y_q(S_k)\}$  on  $M_2$  will, reduce the idle time of all jobs on it. Therefore, the utilization time and hence total rental cost of machine  $M_2$  will be minimum. Also the rental cost of  $M_1$  will always be minimum as the idle time of machine  $M_1$  is always zero.

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