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RESEARCH ARTICLE

HEURISTIC FOR THREE MACHINES IN TANDEM.

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Abstract

This paper considered the problem of three machines in tandem including the loading times, transportation times and unloading times for jobs to be transported. It also considered breakdown time of machines and weights of jobs according to their importance in the sequence. A heuristic approach was made for finding optimal or near optimal schedule. The procedure was illustrated with the help of an example.

Introduction:-

The idea of two production stages was given by Jackson (1954) while studying a queuing system concerned with an industry in which the production of an item took place in two distinct but successive stages. Such stages were called by Jackson in tandem (or in series). Johnson(1954) and Bellman(1956) studied the problem of scheduling of n jobs on two machines arranged in tandem where time required to transport jobs from first machine to the second was assumed to be negligible. As the problem size increases, NP- completeness of flow shop problems necessitates the development of heuristics to get near optimal solutions. Campbell et al. (1970) proposed a heuristic algorithm to minimize the makespan. Maggu and Das (1980) introduced the concept of transportation time in going from one stage to the other. They studied a system in which an infinite number of transport agents were available and no transport agent was required to return to stage 1 from stage 2. It was assumed that Machine 1 starts processing the next item immediately after finishing the preceding one. (Mehrotra et al.,2012) solved the problem of two machines in tandem with a single transport agent and loading and unloading times of jobs for transport agent also included. In addition to loading and unloading times of all the jobs for the transport agent(as the loading and unloading times may not be negligible if the size of items is large) we have also considered break-down intervals for machines and weights of jobs according to their importance in the sequence.

Three Machine n-Job Flow-Shop Scheduling Problem involving Loading and Unloading Times along with Transportation Time of Jobs:-

Let us consider n items $(I_1, I_2, ..., I_n)$ being processed through three machines $(A, B \& C)$ in the order ABC with agents who transport an item processed at machine A to the machine B and then to machine C. Let t_i and g_i be the transportation times for item i to carry it from machine A to B and B to C respectively. Let an item i to be transported from machine A to machine B requires loading and unloading times denoted by l_{ab_i} and u_{ab_i} respectively and for transporting it machine B to machine C, it requires loading and unloading times denoted by

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l_{bc_i} and u_{bc_i} respectively. The problem is to find an optimal schedule of items to minimize the total production time for completing all the items.

Theorem 1 *An optimal sequence is obtained by sequencing the item* $i-1, i, i+1$ *such that:*

$$\min\left\{A_i + l_{ab_i} + t_i + u_{ab_i} + B_i + l_{bc_i} + g_i + u_{bc_i},\ l_{ab_{i+1}} + t_{i+1} + u_{ab_{i+1}} + B_{i+1} + l_{bc_{i+1}} + g_{i+1} + u_{bc_{i+1}} + C_{i+1}\right\}$$
$$< \min\left\{A_{i+1} + l_{ab_{i+1}} + t_{i+1} + u_{ab_{i+1}} + B_{i+1} + l_{bc_{i+1}} + g_{i+1} + u_{bc_{i+1}},\ l_{ab_i} + t_i + u_{ab_i} + B_i + l_{bc_i} + g_i + u_{bc_i} + C_i\right\}$$

Proof: To prove this theorem, we first prove the following lemma:

Lemma 1 If $\min\left\{A_i + l_{ab_i} + t_i + u_{ab_i}\right\} \geq \max\left\{B_i + l_{ab_i} + t_i + u_{ab_i}\right\}$, then $CA_p + l_{ab_p} + t_p + u_{ab_p} \geq CB_{p-1}$.

Proof: Consider the statement $P(q)$, for an arbitrary number q, defined as:

$$P(q): CA_{q+1} + l_{ab_{p+1}} + t_{p+1} + u_{ab_{p+1}} \geq CB_q \ \ (q = 1, 2, ...)$$

For any arbitrary natural number q

$$CA_1 = A_1$$
$$CB_1 = A_1 + l_{ab_1} + t_1 + u_{ab_1} + B_1$$
$$CA_2 + l_{ab_2} + t_2 + u_{ab_2} = A_1 + A_2 + l_{ab_2} + t_2 + u_{ab_2}$$

Since $\min\left\{A_i + l_{ab_i} + t_i + u_{ab_i}\right\} \geq \max\left\{B_i + l_{ab_i} + t_i + u_{ab_i}\right\}$

$$\Rightarrow \quad CA_2 + l_{ab_2} + t_2 + u_{ab_2} > CB_1.$$

Hence $P(q)$ be true for $q = 1$.

Let $P(q)$ be true for $q = m$, i.e.,

$$CA_{m+1} + l_{ab_{m+1}} + t_{m+1} + u_{ab_{m+1}} \geq CB_m.$$

Now

$$CB_{m+1} = \max\left\{CA_{m+1} + l_{ab_{m+1}} + t_{m+1} + u_{ab_{m+1}}, CB_m\right\} + B_{m+1}$$
$$= CA_{m+1} + \left(l_{ab_{m+1}} + t_{m+1} + u_{ab_{m+1}} + B_{m+1}\right).$$

But $CA_{m+2} + l_{ab_{m+2}} + t_{m+2} + u_{ab_{m+2}} = CA_{m+1} + A_{m+2} + l_{ab_{m+2}} + t_{m+2} + u_{ab_{m+2}}$

And $A_{m+2} + l_{ab_{m+2}} + t_{m+2} + u_{ab_{m+2}} \geq B_{m+1} + l_{ab_{m+1}} + t_{m+1} + u_{ab_{m+1}}$

Hence $CA_{m+2} + l_{ab_{m+2}} + t_{m+2} + u_{ab_{m+2}} \geq CB_{m+1}$.

Therefore, $P(q)$ is true for $q = m+1$.

We now proceed to the proof of the theorem.

Let S and S' denote the sequences of items given by :

$$S = \left(I_1, I_2, ..., I_{i-1}, I_i, I_{i+1}.I_{i+2}, ..., I_n\right)$$
$$S' = \left(I'_1, I'_2, ..., I'_{i-1}, I'_{i+1}, I'_i.I'_{i+2}, ..., I'_n\right)$$

Let $\left(X_p, X'_p\right)$ and $\left(CX_p, C'X_p\right)$ be respectively the processing time and completion time of any item p on machine $X\,(= A \text{ or } B)$ for the sequences $\left(S, S'\right)$. Let $\left(t_p, t'_p\right)$ and $\left(g_p, g'_p\right)$ denote the transportation times of item p to transport it from machine A to machine B and from machine B to machine C respectively for the sequences $\left(S, S'\right)$. Let $\left(l_{ab_p}, l'_{ab_p}\right)$ and $\left(u_{ab_p}, u'_{ab_p}\right)$ be respectively the loading times and unloading times of an item p in transporting it from machine A to machine B and $\left(l_{bc_i}, l'_{bc_i}\right)$ and $\left(u_{bc_i}, u'_{bc_i}\right)$ be the loading and unloading times for transporting it from machine B to machine C for the sequences (S, S') respectively.

The completion time of p^{th} item on machines B & C is given by

$$CB_p = \max\left(CA_p + l_{ab_p} + t_p + u_{ab_p}, CB_{p-1}\right) + B_p$$
$$= CA_p + l_{ab_p} + t_p + u_{ab_p} + B_p$$
$$CC_p = \max\left\{CB_p + l_{bc_p} + g_p + u_{bc_p}, CC_{p-1}\right\} + C_p$$
$$= \max\left\{CA_p + l_{ab_p} + t_p + u_{ab_p} + B_p + l_{bc_p} + g_p + u_{bc_p}, CC_{p-1}\right\} + C_p \quad (1)$$

Now, we will choose the sequence S if

$$CC_n < C'C_n \quad (2)$$

i.e., if

$$\max\left(CA_n + l_{ab_n} + t_n + u_{ab_n} + B_n + l_{bc_n} + g_n + u_{bc_n}, CC_{n-1}\right) + C_n$$
$$< \max\left(C'A_n + l'_{ab_n} + t'_n + u'_{ab_n} + B'_n + l'_{bc_n} + g'_n + u'_{bc_n}, C'C_{n-1}\right) + C'_n$$

Now $CA_n + l_{ab_n} + t_n + u_{ab_n} + B_n + l_{bc_n} + g_n + u_{bc_n} = C'A_n + l'_{ab_n} + t'_n + u'_{ab_n} + B'_n + l'_{bc_n} + g'_n + u'_{bc_n}$ and $C_n = C'_n$, so the result (2) will be true if:

$$CC_{n-1} < C'C_{n-1} \quad (3)$$

Proceeding in this way we get that inequality (2) is true if:

$$CC_p < C'C_p \quad \left(p = i+1, i+2, ..., n \text{ and } i = 1,2,....n-1\right) \quad (4)$$

We now calculate the values of CC_{i+1} and $C'C_{i+1}$

$$CC_{i+1} = \max\left\{CB_{i+1} + l_{bc_{i+1}} + g_{i+1} + u_{bc_{i+1}}, CC_i\right\} + C_{i+1}$$
$$= \max\{CA_{i+1} + l_{ab_{i+1}} + t_{i+1} + u_{ab_{i+1}} + B_{i+1} + l_{bc_{i+1}} + g_{i+1} + u_{bc_{i+1}}, CC_i\} + C_{i+1}$$
$$CC_{i+1} = \max\{CA_{i+1} + l_{ab_{i+1}} + t_{i+1} + u_{ab_{i+1}} + B_{i+1} + l_{bc_{i+1}} + g_{i+1} + u_{bc_{i+1}},$$
$$\max\left\{CB_i + l_{bc_i} + g_i + u_{bc_i}, CC_{i-1}\right\} + C_i\} + C_{i+1}$$
$$= \max\{CA_{i+1} + l_{ab_{i+1}} + t_{i+1} + u_{ab_{i+1}} + B_{i+1} + l_{bc_{i+1}} + g_{i+1} + u_{ab_{i+1}},$$
$$CB_i + l_{bc_i} + g_i + u_{bc_i} + C_i, CC_{i-1} + C_i\} + C_{i+1}$$
$$= \max\{CA_{i+1} + l_{ab_{i+1}} + t_{i+1} + u_{ab_{i+1}} + B_{i+1} + l_{bc_{i+1}} + g_{i+1} + u_{ab_{i+1}},$$
$$\max\left\{CA_i + l_{ab_i} + t_i + u_{ab_i}, CB_{i-1}\right\} + B_i + l_{bc_i} + g_i + u_{bc_i} + C_i, CC_{i-1} + C_i\} + C_{i+1}$$
$$= \max\{CA_{i+1} + l_{ab_{i+1}} + t_{i+1} + u_{ab_{i+1}} + B_{i+1} + l_{bc_{i+1}} + g_{i+1} + u_{bc_{i+1}},$$
$$CA_i + l_{ab_i} + t_i + u_{ab_i} + B_i + l_{bc_i} + g_i + u_{bc_i} + C_i, CC_{i-1} + C_i\} + C_{i+1}$$
$$CC_{i+1} = \max\{CA_{i-1} + A_i + A_{i+1} + l_{ab_{i+1}} + t_{i+1} + u_{ab_{i+1}} + B_{i+1} + l_{bc_{i+1}} + g_{i+1} + u_{bc_{i+1}} + C_{i+1},$$
$$CA_{i-1} + A_i + l_{ab_i} + t_i + u_{ab_i} + B_i + l_{bc_i} + g_i + u_{bc_i} + C_i + C_{i+1}, CC_{i-1} + C_i + C_{i+1}\} \quad (5)$$

Similarly

$$C'C_{i+1} = \max\{C'A_{i-1} + A'_i + A'_{i+1} + l'_{ab_{i+1}} + t'_{i+1} + u'_{ab_{i+1}} + B'_{i+1} + l'_{bc_{i+1}} + g'_{i+1} + u'_{bc_{i+1}} + C'_{i+1},$$
$$C'A_{i-1} + A'_i + l'_{ab_i} + t'_i + u'_{ab_i} + B'_i + l'_{bc_i} + g'_i + u'_{bc_i} + C'_i + C'_{i+1}, C'C_{i-1} + C'_i + C'_{i+1}\} \quad (6)$$

Comparing the sequences S and S', it is obvious that

$$\begin{gathered} CA_{i-1} = C'A_{i-1}, CC_{i-1} = C'C_{i-1} \\ X_i = X'_{i+1}, X_{i+1} = X'_i \left(X = A, B \text{ or } C \right) \\ t_i = t'_{i+1}, t_{i+1} = t'_i, g_i = g'_{i+1}, g_{i+1} = g'_i \\ l_{ab_i} = l'_{ab_{i+1}}; l_{ab_{i+1}} = l'_{ab_i}; l_{bc_i} = l'_{bc_{i+1}}; l_{bc_{i+1}} = l'_{bc_i} \\ g_{ab_i} = g'_{ab_{i+1}}; g_{ab_{i+1}} = g'_{ab_i}; g_{bc_i} = g'_{bc_{i+1}}; g_{bc_{i+1}} = g'_{bc_i} \end{gathered} \tag{7}$$

Writing (4) for $p = i + 1$ and using (7), we get

$$\begin{aligned} &\max\{CA_{i-1} + A_i + A_{i+1} + l_{ab_{i+1}} + t_{i+1} + u_{ab_{i+1}} + B_{i+1} + l_{bc_{i+1}} + g_{i+1} + u_{bc_{i+1}} + C_{i+1}, \\ &\quad CA_{i-1} + A_i + l_{ab_i} + t_i + u_{ab_i} + B_i + l_{bc_i} + g_i + u_{bc_i} + C_i + C_{i+1}, CC_{i-1} + C_i + C_{i+1}\} \\ &< \max\{CA_{i-1} + A_{i+1} + A_i + l_{ab_i} + t_i + u_{ab_i} + B_i + l_{bc_i} + g_i + u_{bc_i} + C_i, CA_{i-1} + A_{i+1} + l_{ab_{i+1}} + \\ &\quad t_{i+1} + u_{ab_{i+1}} + B_{i+1} + l_{bc_{i+1}} + g_{i+1} + u_{bc_{i+1}} + C_{i+1} + C_i, CC_{i-1} + C_{i+1} + C_i\} \end{aligned} \tag{8}$$

Subtracting last term from both sides and further subtracting $CA_{i-1} + A_i + A_{i+1} + l_{ab_i} + t_i + u_{ab_i} + l_{ab_{i+1}} + t_{i+1} + u_{ab_{i+1}} + l_{bc_i} + g_i + u_{bc_i} + l_{bc_{i+1}} + g_{i+1} + u_{bc_{i+1}} + B_i + B_{i+1} + C_i + C_{i+1}$ from each side, we get

$$\begin{aligned} &\max\left\{-l_{ab_i} - t_i - u_{ab_i} - l_{bc_i} - g_i - u_{bc_i} - B_i - C_i, -A_{i+1} - l_{ab_{i+1}} - t_{i+1} - u_{ab_{i+1}} - l_{bc_{i+1}} - g_{i+1} - u_{bc_{i+1}} - B_{i+1}\right\} \\ &< \max\left\{-l_{ab_{i+1}} - t_{i+1} - u_{ab_{i+1}} - l_{bc_{i+1}} - g_{i+1} - u_{bc_{i+1}} - B_{i+1} - C_{i+1}, -A_i - l_{ab_i} - t_i - u_{ab_i} - l_{bc_i} - g_i - u_{bc_i} - B_i\right\} \end{aligned} \tag{9}$$

$$\begin{aligned} &\min\left\{A_i + l_{ab_i} + t_i + u_{ab_i} + l_{bc_i} + g_i + u_{bc_i} + B_i, l_{ab_{i+1}} + t_{i+1} + u_{ab_{i+1}} + l_{bc_{i+1}} + g_{i+1} + u_{bc_{i+1}} + B_{i+1} + C_{i+1}\right\} \\ &< \min\left\{A_{i+1} + l_{ab_{i+1}} + t_{i+1} + u_{ab_{i+1}} + l_{bc_{i+1}} + g_{i+1} + u_{bc_{i+1}} + B_{i+1}, l_{ab_i} + t_i + u_{ab_i} + l_{bc_i} + g_i + u_{bc_i} + B_i + C_i\right\} \end{aligned} \tag{10}$$

Algorithm 1 The utility of above theorem can be summarized into following steps to give us decomposition algorithm, that is, numerical method to obtain optimal schedule minimizing total elapsed time for a 3-machine, n-job sequencing problem where loading, transportation and unloading times are taken into account. Our problem can be represented in tableau form as follows:

Item i	Machine A (A_i)	l_{ab_i}	t_i	u_{ab_i}	Machine B (B_i)	l_{bc_i}	g_i	u_{bc_i}	Machine C (C_i)
1	A_1	l_{ab_1}	t_1	u_{ab_1}	B_1	l_{bc_1}	g_1	u_{bc_1}	C_1
2	A_2	l_{ab_2}	t_2	u_{ab_2}	B_2	l_{bc_2}	g_2	u_{bc_2}	C_2
.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.
n	A_n	l_{ab_n}	t_n	u_{ab_n}	B_n	l_{bc_n}	g_n	u_{bc_n}	C_n

Where A_i, B_i, C_i are the service times on A, B & C respectively. l_{ab_i}, u_{ab_i} and l_{bc_i}, u_{bc_i} are respectively the loading and unloading times for transport agent in transporting the item from machines A to B and B to C respectively. t_i, g_i are the transportation times of item i from machine A to B and B to C respectively satisfying one of the two structural relationships:

i) $\min\left(A_i + l_{ab_i} + t_i + u_{ab_i}\right) \geq \max\left(B_i + l_{ab_i} + t_i + u_{ab_i}\right)$

ii) $\min\left(C_i + l_{bc_i} + g_i + u_{bc_i}\right) \geq \max\left(B_i + l_{bc_i} + g_i + u_{bc_i}\right)$

The result of Theorem 1 gives the following procedure for an optimal or near optimal sequence:

1 Assume there are two fictitious machines $(G \& H)$ in place of A & B respectively. Assume that the service times for these fictitious machines are given by G_i and H_i where

$$G_i = A_i + l_{ab_i} + t_i + u_{ab_i} + l_{bc_i} + g_i + u_{bc_i} + B_i, \quad H_i = l_{ab_i} + t_i + u_{ab_i} + l_{bc_i} + g_i + u_{bc_i} + B_i + C_i$$

2 Applying Johnson's (1954) rule to the fictitious machine times $G \& H$ constructed in step 1, we obtain the optimal sequence.

Flow-shop scheduling also involving job weights and break-down intervals of machines:-

Let job i be assigned with the weight w_i according to its relative importance for performance in the given sequence. The performance measure studied is weighted mean flow time defined by:

$$\bar{F}_w = \frac{\sum_{i=1}^{n} w_i f_i}{\sum_{i=1}^{n} w_i}$$, where f_i is the flow time of i^{th} job.

Let the break-down interval (a,b) is already known to us, i.e., deterministic nature and the break-down interval length is $b-a$, which is known. Then our aim is to find out optimal or near optimal sequence of jobs so as to minimize the total elapsed time.

Algorithm 2 The given problem in the tabular form may be stated as follows:

Item i	Machine A (A_i)	l_{ab_i}	t_i	u_{ab_i}	Machine B (B_i)	l_{bc_i}	g_i	u_{bc_i}	Machine C (C_i)	w_i
1	A_1	l_{ab_1}	t_1	u_{ab_1}	B_1	l_{bc_1}	g_1	u_{bc_1}	C_1	w_1
2	A_2	l_{ab_2}	t_2	u_{ab_2}	B_2	l_{bc_2}	g_2	u_{bc_2}	C_2	w_2
.	.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.	.
n	A_n	l_{ab_n}	t_n	u_{ab_n}	B_n	l_{bc_n}	g_n	u_{bc_n}	C_n	w_n

Then the steps are as follows:

1 Modifying problem into two machines flow-shop problem using fictitious machine $G \& H$ as in Algorithm 1, the modified problem in the tabular form is:

Item i	Machine G $G_i = A_i + l_{ab_i} + t_i + u_{ab_i} + l_{bc_i} + g_i + u_{bc_i} + B_i$	Machine H $H_i = l_{ab_i} + t_i + u_{ab_i} + l_{bc_i} + g_i + u_{bc_i} + B_i + C_i$	Weight w_i
1	G_1	H_1	w_1
2	G_2	H_2	w_2
.	.	.	.
.	.	.	.
n	G_n	H_n	w_n

2 Find $\min(G_i, H_i)$

i) If $\min(G_i, H_i) = G_i$ then define $G'_i = G_i - w_i$ and $H'_i = H_i$.

ii) If $\min(G_i, H_i) = H_i$ then define $G'_i = G_i$ and $H'_i = H_i + w_i$.

3 Define a new reduced problem in the tabular form as:

Item i	G'_i	H'_i
1 2 . . n	G'_1/w_1 G'_2/w_2 . . G'_n/w_n	H'_1/w_1 H'_2/w_2 . . H'_n/w_n

4 Determine the optimal sequence by using Johnson's algorithm for the new reduced problem obtained in step 3 and see the effect of break-down interval (a,b) on different jobs.

5 Formulate a new problem with processing time A'_i, B'_i & C'_i where

$A'_i = A_i + (b-a)$, $B'_i = B_i + (b-a)$ and $C'_i = C_i + (b-a)$, if (a,b) affected on job i.

And $A'_i = A_i$, $B'_i = B_i$, $C'_i = C_i$, if (a,b) has no effect on job i.

6 Now repeat the procedure to get the optimal sequence.

This sequence is either optimal or near optimal for the original problem. By this sequence we can determine the total elapsed time and weighted mean-flow time.

Example 3 Let a machine tandem queuing problem be given in the following tableau form:

Item i	Machine A (A_i)	l_{ab_i}	t_i	u_{ab_i}	Machine B (B_i)	l_{bc_i}	g_i	u_{bc_i}	Machine C (C_i)	w_i
1	4	2	6	2	3	2	2	3	5	3
2	6	3	4	1	4	3	6	4	7	5
3	4	2	7	2	3	2	3	3	8	4
4	9	4	3	3	2	5	8	2	8	2

Solution Now $\min\left(A_i + l_{ab_i} + t_i + u_{ab_i}\right) = 14$

$$\max\left(B_i + l_{ab_i} + t_i + u_{ab_i}\right) = 14$$

Hence, Structural condition (i) is satisfied. Now, using the step 1, the reduced problem is:

Item i	Machine G $G_i = A_i + l_{ab_i} + t_i + u_{ab_i} + l_{bc_i} + g_i + u_{bc_i} + B_i$	Machine H $H_i = l_{ab_i} + t_i + u_{ab_i} + l_{bc_i} + g_i + u_{bc_i} + B_i + C_i$	Weight w_i
1	24	25	3
2	31	32	5
3	26	30	4
4	36	35	2

Using steps 2 to 4 and applying Johnson's rule, the optimal sequence is (2,3,1,4). Now the effects of break-down interval (12,18) on sequence (2,3,1,4) is read as follows:

Item i	A In-out	l_{ab_i}	t_i	u_{ab_i}	B In-out	l_{bc_i}	g_i	u_{bc_i}	C In-out	w_i
2	0-6	3	4	1	**14-18**	3	6	4	31-38	5
3	6-10	2	7	2	21-24	2	3	3	38-46	4
1	**10-14**	2	6	2	24-27	2	2	3	46-51	3
4	**14-23**	4	3	3	33-35	5	8	2	51-59	2

Hence, with effect of break-down interval the original problem gets modified to a new problem (as per step 5).

Item i	Machine A (A_i)	l_{ab_i}	t_i	u_{ab_i}	Machine B (B_i)	l_{bc_i}	g_i	u_{bc_i}	Machine C (C_i)	w_i
1	10	2	6	2	3	2	2	3	5	3
2	6	3	4	1	10	3	6	4	7	5
3	4	2	7	2	3	2	3	3	8	4
4	15	4	3	3	2	5	8	2	8	2

Now, repeating the procedure, we get the sequence (3,2,4,1) which is optimal or near optimal and the final table is:

Item i	A In-out	l_{ab_i}	t_i	u_{ab_i}	B In-out	l_{bc_i}	g_i	u_{bc_i}	C In-out	w_i
3	0-4	2	7	2	15-18	2	3	3	26-34	4
2	4-10	3	4	1	18-28	3	6	4	41-48	5
4	10-25	4	3	3	35-37	5	8	2	52-60	2
1	25-35	2	6	2	45-48	2	2	3	60-65	3

Mean weighted flow time is

$$= \frac{34\times 4+(48-4)\times 5+(60-10)\times 2+(65-25)\times 3}{4+5+2+3}$$

$= 41.14$ hrs.

Hence, the total elapsed time is 65 hrs and mean weighted flow time is 41.14 hrs.

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