Multi - Objective Assembly Job Shop Scheduling Problems: A Mixed Integer Model

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This paper presents a mixed integer linear programming model for scheduling an assembly job shop in a multi-objective environment. The objectives considered are minimization of makespan and total tardiness simultaneously. This work determines the extent of problem size for which exact solution can be generated for different product structures. Further, this work analyses the computational aspects with changes in the input parameters such as number of products, number of machines, and number of operations and level of structure. The other input parameters include processing time, precedence constraints of all components and product due date. The system consists of M machines, with N products to be manufactured. The components are first processed in a machine shop and then assembled in the assembly shop. Each component requires a given number of precedence constrained operations to be performed. The problem size analyzed in this study varies from three products and four machines to ten products and fifteen machines. The product structures considered in this study are single level assembly structure, two level assembly structure and three level assembly structure. The result shows the exact solution for each problem instance considered in this study and the range of problem level variation for which exact solution can be obtained.

Keywords: Assembly Job Shop, Scheduling, Multi-Objective, LINGO

1. Introduction

For maintaining competitive advantage, an organization has to ensure proper scheduling of jobs and activities. Effective scheduling can improve profitability in terms of reduced lead time, on-time delivery, utilization of resources and reduced inventory. Scheduling problems are classified as single machine scheduling, flow shop scheduling, job shop scheduling problems, etc. In a job shop, there are '*n*' jobs and '*m*' machines. A job may need some or all these machines in a specific sequence according their requirement. In the literature, it is found that most of the studies focus only on conventional job shop system which processes 'string type' jobs only. However, Scheduling assembly job shop which have serial, assembly operations and multi-level jobs is relatively less investigated (Pereira, 2011).

A number of solution techniques to handle the Assembly Job Shop Scheduling Problem (AJSSP) have been developed over the years. The solution techniques include mixed integer programing, dispatching rules, constructive heuristics and meta-heuristics. It is found that almost all the studies on AJSSP focus on single objective optimization only. No significant research has been reported in the area of scheduling of an assembly job shop with multi-objective criteria. In the literature, it is also found that most of the studies on AJSSP uses approximation based techniques namely, dispatching rules and meta-heuristics for solving the problem. Research on AJSSP using optimization techniques such as mixed integer programing is very few compared to other techniques.

Tharumarajah et al. (1998) study the effect of distributed scheduling in a static environment by using mixed integer programming along with lower and upper boundaries. The objective of the work is to minimize the total tardiness. Guo et al. (2006) develop a universal mathematical model for the job shop scheduling problem in a mixed and multi-product assembly environment based on an apparel industry. A genetic optimization process is proposed to solve the model which includes a new chromosome representation, a heuristic initialization process and modified crossover and mutation operators. Dimyati (2007) addresses a problem of scheduling in a make-to-order job shop with product assembly consideration. A mixed integer linear programming model is developed to solve the model in with the objective of makespan minimization.

Gomes et al. (2009) describe the problem of scheduling a flexible job shop with recirculation and assembly. They develop two mixed integer linear programming models and solve the problems using a due-date based objective function. The model adopts discrete and continuous approaches both in the modeling of time as well as in the assignment of jobs to machines.Saeid et al. (2012) propose a mixed integer linear programming model which includes process planning and scheduling tasks simultaneously in a flexible assembly job shop with sequence dependent setup times. The objective of this study is minimizing maximum completion time (makespan) of final products. The products structures consider have three stage assembly structures.

The present work proposes a mixed integer linear programming model for scheduling an assembly job shop in a multi-objective environment. The objective of this work is to minimize makespan and total tardiness simultaneously. This work determines the extent of problem size for which exact solution can be generated for different product structures. Further this work analyses the computational aspects with the changes in the input parameters such as number of products, number of machines, number of operations and level of structure. Processing time, precedence constraints of all components and product due date are the other input parameters considered. In this study, the problem size varies from three products and four machines (3x4) to ten products and fifteen machines (10x15). The mathematical model of the assembly job shop is developed using the software LINGO (version 11.0). The product structures considered in this study are single level assembly structure, two level assembly structure and three level assembly structure

The rest of the paper is organized as follows: Section 2 describes the problem formulation. Section 3 presents the mathematical model. Section 4 provides the results and analysis. Conclusions are presented in section 5.

2. Problem Formulation

In a real manufacturing environment, scheduling of jobs is done by satisfying many objectives and considering many constraints simultaneously. However, it is important to develop an optimum methodology to solve multi-objective assembly job shop scheduling problems. The minimization of cost and maximization of customer satisfaction are two major issues in practice (Lei, 2008). A completion time related objective, namely, makespan aims to reduce production time and increase facility utilization which is a critical factor towards minimizing cost. The due date related objective of minimizing total tardiness aims to meet on-time delivery which is a critical factor towards realizing customer satisfaction. (Dileeplal, 2012). Hence, the objectives considered in this work are simultaneous minimization of makespan and total tardiness.

2.1 Problem Environment

This problem environment considers a classical assembly job shop similar to many previous studies. The data includes the due dates of different products, the processing time of different operations, precedence constraints of all components, assembly level structure of different products and performance measures selected for the study. The system consists of two divisions, a machining shop and an assembly shop. Assembly starts only after all machining operations of an item are completed. Each component requires a given number of precedence constrained operations to be performed. Each operation can start only when its preceding operations are completed. The machining work center queue and assembly work center queue are assumed to have an infinite capacity. The final product moves out of the assembly work center when the assembly at the highest level is completed.

The routing of products is generated randomly such that each machining work center for processing has the same probability of being chosen. The processing times and the assembly operation times follow uniform distribution in the range 1-20 and 5-20 respectively. The number of operations for each item or subassembly follows uniform distribution in the range 2-7. The due-date of an arriving job *i* is determined using the method proposed by Adam et al. (1993) using the critical path length (l_i), the allowance factor (c) and job arrival time (t_i), i.e., $d_i = t_i + c \times l_i$. The allowance factor considered in all problems is 1.5.

Three types of product structure are used in this study:

- Single level assembly structure
- Two level assembly structure
- Three level assembly structure

The three different job types and their configurations are listed in Figure 2.1 and Table 2.1

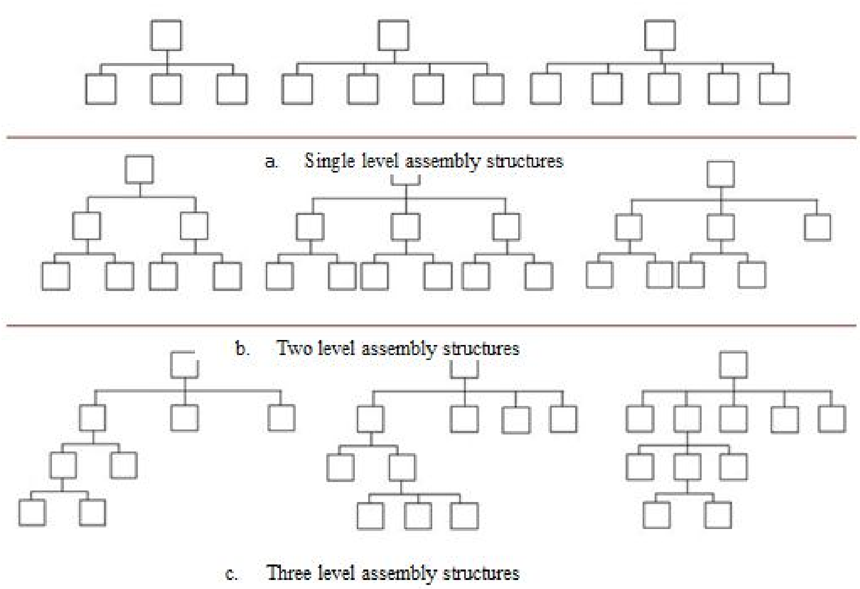

Figure 2.1 *Types of Job Structures*

Table 2.1 *Details of Jobs with Different Configurations*

Job type	Number of subassemblies at level 2	Number of Subassemblies at level 3	Number of Subassemblies at level 4
1 (Flat)	[2-5]	0	0
2 (Complex)	[2-5]	[4-6]	0
3 (Complex)	[3-5]	[2-3]	[2-3]

2.2 Assumptions

The assumptions made in this study are listed hereunder:

- Each machine can perform only one operation at a time.
- Preemption of jobs is not allowed.
- Precedence relationship between operations should be followed.
- In a given level of assembly, a job visits a machine only once.
- There are no alternative routes for jobs.
- Due date and job structure of each product are known in advance.
- Flow time includes processing time and waiting time only; setup, transport and loading times are assumed to be negligible.
- Machines are continuously available, i.e., there are no breakdowns

2.3 Mathematical Formulation

A Mathematical model that sequences the set of 'N' products over a set of 'M' is developed. Objective function is the minimization of the weighted sum of Makespan and tardiness simultaneously.ie

The notations used are:

p: Product index
i: Operation index
j: Precedence operation index
k: Machine index
S: Start time
C: Completion time
p_t: Processing time
D: Due date
h : Weight assigned
H: High positive integer
T: Tardiness
X: Decision variable for generating a sequence between operations on the same machine

Minimization of $Z = h$ (tardiness) + $(1 - h)$ (Makespan) (1)

$$= h \times \sum_{p=1}^{N} (Tp) + (1 - h)\,(\max(C_p)) \quad (2)$$

Subjected to:

$$S_{ik} >= 0 \ \forall i = 1, \ldots, N \quad (3)$$

$$C_{ik} - S_{ik} = t_{ik} \ \forall i = 1, \ldots, N \quad (4)$$

$$S_{ik} >= C_{jk} \ \forall i (P_i \neq \emptyset) \text{ and } \forall j \in P_i \quad (5)$$

$$S_{ik} >= C_{jk} - H * X_{ijk} \quad \forall k = 1, \ldots, M \text{ where } k_i = k_j = k \quad (6)$$

$$X_{ijk} + X_{jik} = 1 \quad \forall k = 1, \ldots, M \text{ where } k_i = k_j = k \quad (7)$$

$$X_{ijk} \in \{0, 1\} \quad \forall k = 1, \ldots, M \text{ where } k_i = k_j = k \quad (8)$$

$$\text{Max}(C_p) >= (C_{ik}) \ \forall i = 1, \ldots, N \quad (9)$$

$$T_p = \max(0, C_p - D_p) \quad (10)$$

The Constraint (3) ensures that the starting time of operation is positive. Constraint (4) ensures that the processing time of an operation is equal to the difference between its start and completion times, i.e., once an operation has started, it cannot be pre-empted until its completion. Constraint (5) means the starting time of one operation must be greater than or equal to the completion time of the previous operation. Constraint (6) ensures that no two operations can be processed simultaneously on the same machine. Constraints (7) and (8) ensure that the value of '*X*' will always be 1 or 0 and the sum of the '*X*' values for any operations *i*, *j* on the same machine will be always zero. Constraint (9) ensures that the makespan is the maximum completion time of all operations to manufacture the product. Constraint (10) defines the tardiness of each product as the difference between the completion time and due date.

3. Mathematical Model

3.1 Illustrative Problem

A problem given by Dilleplal (2012) is considered for explaining the model. The objective is minimization of total weighted sum of tardiness and makespan. The specification of the problem instance is two products, six machines, and fifteen operations with two level product structures with seven components. Figure 3.1 shows the product structure 1 and figure 3.2 shows the product structure 2. Table 3.1 describes the operations which have to be scheduled on respective machines. 'P_t' gives the processing time of each operation. The due date for product 1 is set as 16 and for product 2 as 21. The weight is set as 0.5.

Table 3.1 *Operations in Respective Machines*

Machines	Operations
1	1, 2 , 3
2	4, 5, 6
3	7, 8, 9
4	10, 11
5	12, 13, 14

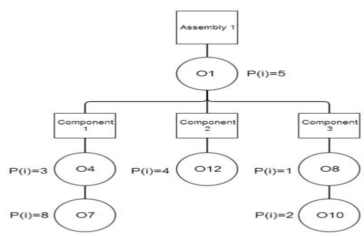

Figure 3.1 *Product structure 1*

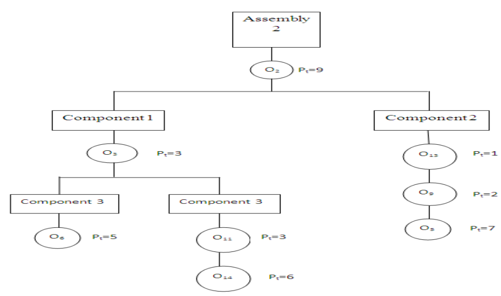

Figure 3.2 *Product Structure 2*

The Solver LINGO (version11.0) is used for solving the problem. The system configuration is Intel i5 3.30 GHz processor, 4 GB RAM and 1 GB graphics card. The results obtained are as follows: makespan = 28; total tardiness = 7; flow time of Product 1 = 16; flow time of Product 2 = 28. All the values are in time units. The weighted value of makespan and tardiness is 17.5 with equal weights which are found to be the minimum possible value. The result of the program is validated with the results from the literature. The Gantt chart presented in Figure 3.3 shows the machine sequence of different operations.

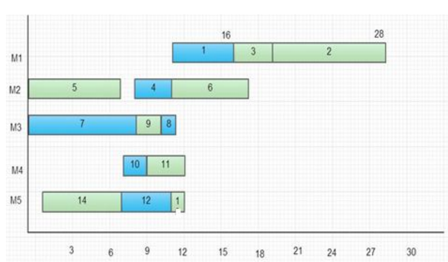

Figure 3.3 *Gantt Chart*

3.2 Numerical Examples

The performance of the proposed mathematical model is evaluated for various instances of multi-objective assembly job shop scheduling problem. Twenty five different problem instances based on the literature are considered and the problem sizes vary from 3 products and 4 machines to 15 products and 15 machines. Three types of product structures used in the present study are single level assembly structure, two level assembly structure and three level assembly structure (Natarajan et al., 2007). The list of problem instances is given in Table 3.2. These problem instances are solved for all the three types of product structures with the condition that the Solver generates a global optimum solution before the specified interruption time. The interruption time of solver set as one hour.

Table 3.2 *List Of Problem Instances*

Problem No.	Number of products	Number of machines	Number of operations
1	3	4	20
2	3	4	30
3	3	6	30
4	3	6	45
5	3	8	45
6	4	8	45
7	4	10	45
8	4	10	60
9	5	10	60
10	5	12	60
11	6	12	60
12	6	12	100
13	6	12	150
14	7	12	150
15	7	15	150
16	7	15	200
17	8	15	200
18	8	15	250
19	9	15	250
20	9	15	300
21	10	12	300
22	10	15	300
23	12	12	300
24	15	12	300
25	15	15	300

4. Results and Discussion

4.1 Three Levels Of Structures Under Equal Weights

Seventy five problem instances (25 problem instances in each level) under equal weight are considered. It is found that optimal solution could be generated for only 29 problems within the specified interruption time of one hour. Table 4.1 provides the weighted output value of makespan and tardiness for the problem instances involving single level product structure.

Table 4.1 *Weighted output of single level structure*

Problem No.	Number of products	Number of machines	Number of operations	Makespan	Tardiness	Weighted O/P
1	3	4	20	69	0	34.5
2	3	4	30	151	27.0	89.0
3	3	6	30	110	0	55.0
4	3	6	45	125	5.0	65.0
5	3	8	45	106	44.0	75.0
6	4	8	45	107	0	53.5
7	4	10	45	105	0	52.5

8	4	10	60	140	0	70.0
9	5	10	60	124	6.0	65.0
10	5	12	60	100	9.0	54.5
11	6	12	60	131	59.0	95.0
12	6	12	100	Interrupted		

The results shown in Table 4.1 reveals that in the case of single level structure, the model generates optimum solution for small size problems (3 products-4 machines and 4 products-8 machines) and medium size problems (5 products-10 machines and 5 products 12 machines). When the number of operations increases from 60 to 100 in the case of 6 products 12 machines, the Solver does not produce optimum result.

Table 4.2 provides the weighted output value of makespan and tardiness for the problem instances involving two level product structure.

Table 4.2 *Weighted Output of Two Level Structures*

Problem No.	Number of products	Number of machines	Number of operations	Makespan	Tardiness	Weighted O/P
1	3	4	20	77	19	48.0
2	3	4	30	113	83	98.0
3	3	6	30	95	33	64.0
4	3	6	45	131	9	70.0
5	3	8	45	115	12	63.5
6	4	8	45	94	14	54.0
7	4	10	45	89	5	47.0
8	4	10	60	117	6	61.5
9	5	10	60	97	0	48.5
10	5	12	60	93	3	48.0
11	6	12	60	105	81	93.0
12	6	12	100	Interrupted		

The results shown in Table 4.2 reveal that in two level structures, as in the case of single level structure, for small size and medium size problems (5 products-10 machines, 5 products-12 machines), the model generates optimum solution. When the number of operations increases from 60 to 100 (for example, in the case of 6 products-12 machines), the Solver is unable not able to produce the optimal solution.

Table 4.3 provides the weighted output value of makespan and tardiness for the problem instances involving three level product structure.

Table 4.3 *Weighted Output of three Level Structures*

Problem No.	Number of products	Number of machines	Number of operations	Makespan	Tardiness	Weighted O/P
1	3	4	20	82	2	42
2	3	4	30	128	34	81
3	3	6	30	112	24	68
4	3	6	45	106	37	71.5
5	3	8	45	112	13	62.5
6	4	8	45	107	51	79
7	4	8	60	Interrupted.		

From Table 4.3, it is evident that for smaller size problems (3 products-4 machines) only, the Solver generates optimum solution for three level structures. In the case of problems with 4 products-8 machines, the Solver generates solution for the instance containing 45 operations only. When the number of operations increases from 45 to 60, the Solver is unable to generate optimal solution within the specified time.

4.2 Effect of Different Weights

In this study, ten problem instances of single level structure under different weights are analysed. The different weights considered are 0.3, 0.5, and 0.7. The weighted output values of makespan and tardiness are summarized in Table 4.4. The results show that weights can be varied depending upon the requirements of a given situation.

Table 4.4 *Weighted Output Details for Different Problems*

Problem No.	Weight for tardiness = 0.3			Weight for tardiness = 0.5			Weight for tardiness = 0.7		
	Makespan	Tardiness	Weighted O/P	Makespan	Tardiness	Weighted O/P	Makespan	Tardiness	Weighted O/P
1	69	0	48.3	69	0	34.5	69	0	20.7
2	131	53	107.6	151	27	89	151	27	64.2
3	107	4	76.1	110	0	55	110	0	33
4	122	2	86	125	5	65	135	0	40.5
5	106	44	87.4	106	44	75	138	18	54
6	105	4	74.7	107	0	53.5	107	0	32.1
7	97	14	72.1	105	0	52.5	105	0	31.5
8	140	0	98	140	0	70	140	0	42
9	111	44	90.9	124	6	65	118	22	50.8
10	100	9	72.7	100	9	54.5	109	28	52.3

4.3 Sensitivity Analysis

Sensitivity analysis aids in determine how computational complexity varies with number of operations, number of products and levels of product structures. For this analysis, the first eleven problems of single level structure and two level structures are selected. Table 4.5 and Table 4.6 provide the computational time taken for solving these problems. Problem instances P 1 to P 11 are single level assembly structure and P 12 to P 22 two level assembly structures. Figure 4.1, 4.2 and 4.3 show the changes in computational time when the variables such as number of operations, number of levels and number of products are changed.

Table 4.5 *Computational Time of Single Level Structure*

Problem No.	Number of products	Number of machines	Number of operations	Execution time hh:mm:sec
P1	3	4	20	00:00:17
P2	3	4	30	00:02:56
P3	3	6	30	00:00:17
P4	3	6	45	00:09:03
P5	3	8	45	00:02:17
P6	4	8	45	00:02:35
P7	4	10	45	00:02:40
P8	4	10	60	00:16:51
P9	5	10	60	00:19:44
P10	5	12	60	00:18:25
P11	6	12	60	01:00:20

Table 4.6 *Computational Time of Two Level Structures*

Problem No.	No. of products	No. of machines	No. of operations	Execution time hh:mm:sec
P12	3	4	20	00:01:21
P13	3	4	30	00:55:18
P14	3	6	30	00:07:40
P15	3	6	45	00:59:04
P16	3	8	45	00:17:52
P17	4	8	45	00:28:39
P18	4	10	45	00:16:13
P19	4	10	60	00:18:33
P20	5	10	60	00:20:21
P21	5	12	60	00:48:58
P22	6	12	60	01:00:56

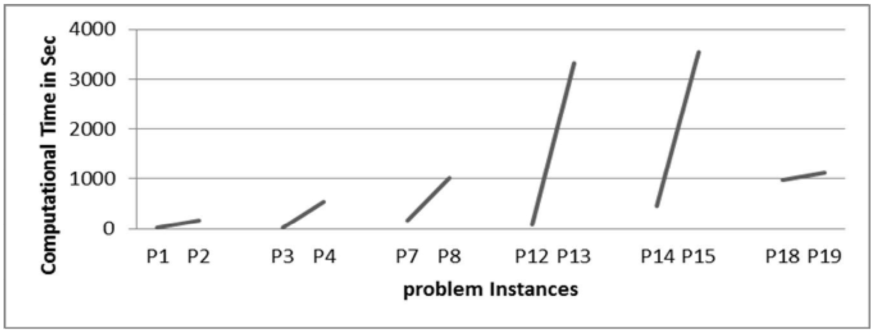

Figure 4.1 *Computational Time Changes Vs. Number of Operations*

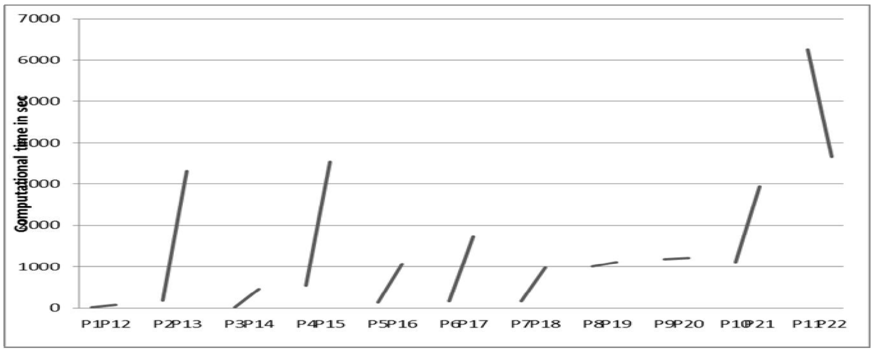

Figure 4.2 *Computational Time Changes Vs. Number Of Levels*

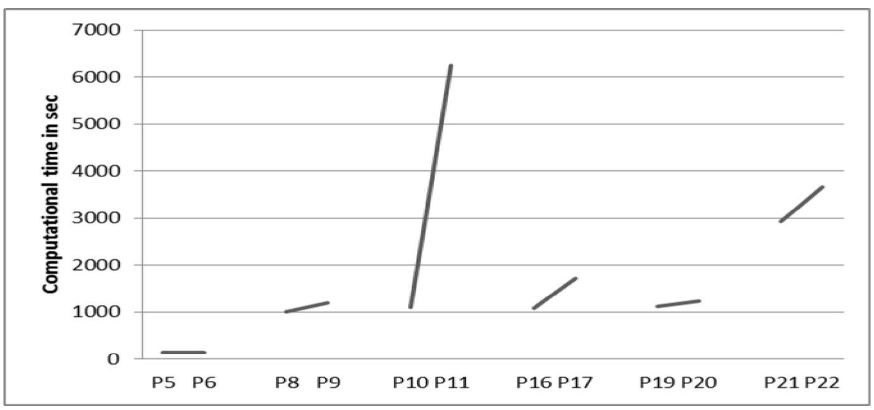

Figure 4.3 *Computational Time Changes Vs. Number of Products*

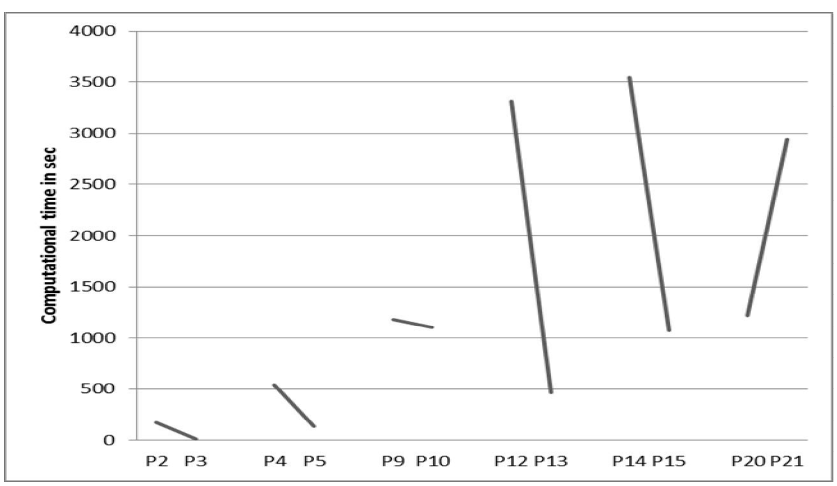

Figure 4.4 *Computational Time Changes Vs. Number of Machines*

The following are the inferences drawn from Tables 4.5and 4.6 and from Figures 4.1, 4.2, 4.3 and 4.4:

- When there is an increase in number of operations, number of products and number of levels, computational time also increases. This means that these factors affect the computational complexity.
- When number of machines increases, it reduces computational time in almost all cases because it reduces the number of comparisons for selecting an operation on each machine. This establishes the relevance of priority rules for selecting a job on each machine.

5. Conclusion

Assembly Job shop scheduling problem is one of the relevant problems in operations research, which is continuously being updated in accordance with the results of the newest approaches. An exhaustive literature survey is conducted and it reveals that the scheduling of assembly job shop with multiple objectives is seldom considered by the researchers though it has significant practical interest. A detailed computational study is conducted to prove the efficiency of the proposed mixed integer programming model. Variables such as number of operations, level of structure, number of machines and number of products have significant effect on computational complexity. With an increase in the number of products, number of operations, and number of levels, the product complexity increases. The computational time drastically increases with the increase of product complexity. Mixed integer programming model is good to get exact solution for small sized problems and medium sized problems for single level and two level structure problems. For more complicated large sized problems, approximation based methods need to be used. This study proves the relevance of priority rules for large sized problems to reduce computational time.

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