Concurrent tolerance allocation and scheduling for complex assemblies

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Abstract

Traditionally, tolerance allocation and scheduling have been dealt with separately in the literature. The aim of tolerance allocation is to minimize the tolerance cost. When scheduling the sequence of product operations, the goal is to minimize the makespan, mean flow time, machine idle time, and machine idle time cost. Calculations of manufacturing costs derived separately using tolerance allocation and scheduling separately will not be accurate. Hence, in this work, component tolerance was allocated by minimizing both the manufacturing cost (sum of the tolerance and quality loss cost) and the machine idle time cost, considering the product sequence. A genetic algorithm (GA) was developed for allocating the tolerance of the components and determining the best product sequence of the scheduling. To illustrate the effectiveness of the proposed method, the results are compared with those obtained with existing wheel mounting assembly discussed in the literature.

Keywords: Tolerance allocation; Scheduling; Lagrange’s multiplier method; Genetic algorithm; Tolerance cost model; Tolerance machining time model; Quality loss cost

1. Introduction

There has been extensive research on tolerance allocation due to its relationship with product cost, quality, and functionality. Tolerance allocation involves allocating a component’s tolerance based on its known critical dimension tolerance to meet the functional requirements of a product. There are an infinite number of combinations of component part tolerance values within process tolerance limit that can satisfy functional equations. However, some combinations of part tolerances are better than others. The aim of tolerance allocation is to compute the best possible combination of component part tolerances based on a given set of objectives associated constraints.

Methodologies: Various methodologies have been used to solve the tolerance allocation problem in the literature. The most frequent methods, namely Lagrange multiplier, heuristics, and metaheursitic methods, are dealt with in the following section.

Lagrange multiplier method: This method is the most popular among analytical methods for allocating the tolerances of component parts for a known assembly tolerance value. It is most suited to single-process optimization problems. This method eliminates the need for multiple-parameter iterative solutions and allows consideration of alternative cost–tolerance models. It can handle both worst-case and statistical tolerance accumulation models [1 – 6]. Details of the available models are discussed later in this section. The drawbacks that limit its usage are (i) the allocated tolerance values may be beyond the process precision limits, (ii) it cannot be easily adopted to alternative process selection; and (iii) it is a time-consuming and tedious process. Siva Kumar et al. [7] developed a closed-form equation for tolerance allocation and compared its performance with that of Lagrange multiplier method

Heuristic method: In this method, the best combination of component part tolerances is determined using nonmathematical techniques, such as rules of thumb, past practices, and current standards [8-9]. As this method is only suited to limited cases, very few studies have used it to solve optimum tolerance allocation problems. However, a considerable number of studies have used other methods, such as the Branch and Bound algorithm [10] and Design of Experiments [11], to minimize the manufacturing costs of assemblies.

Metaheuristic method: In this method, near optimal allocated tolerances of component parts are obtained by dividing the process tolerance limits into a number of discrete points and randomly selecting a discrete tolerance for each component. The assembly tolerance is then determined with a tolerance accumulation model. The mathematical function and its constants of tolerance cost models are well known before the allocation. Two metaheuristic methods used extensively in the literature are simulated annealing [12] and genetic algorithms (GAs) [1, 13-22].

Cost function model: Various cost-function models have been proposed to calculate manufacturing costs. These include reciprocal [23], reciprocal squared [24], reciprocal power [25], exponential [26], reciprocal power/exponential hybrid, polynomial and fourth-order polynomial [27], reciprocal power with setup cost [2], and exponential with constant [28]. These functions can be classified into two categories: a discrete cost function (DCF) and a continuous cost function (CCF). DCF models [2, 29-32] have a relatively large number of model fitting errors, do not consider the value range of cost tolerance curves, and require manual formulation. Therefore, most studies have focused on the CCF tolerance model, which provides a closed-form solution to the optimization problem.

Taguchi introduced the concept of quality loss of a product. According to this concept, all the critical parameters (including the dimensions) of a product should be at their target values to ensure the product's best performance. If parameters deviate from their target values, the performance of the product deteriorates, and the product loses quality. A large number of studies have considered the sum of quality loss and manufacturing cost as an objective function [13, 30-31, 33-43].

Tolerance accumulation model: The tolerance accumulation model is a mathematical model that estimates the combined effect of component part tolerances on assembly tolerance. A number of tolerance accumulation models are available, and they are classified into two groups: (i) worst-case (WC) models and (ii) statistical models. The WC tolerance accumulation model considers the possibility that all the component part dimensions are at their extreme limits (i.e., maximum or minimum) simultaneously; thus, it is based on the worst-case scenario. Statistical tolerance accumulation models are based on the premise that the chance that all the component part dimensions will be at their extreme limits simultaneously is very small. Consequently, a statistical model places little significance on dimensions that have a low probability of occurring. As a result, individual tolerance values are greater when a statistical model is applied than when a WC model is applied. Statistical tolerance accumulation, such as the root sum square (RSS) method, has been used by a number of researchers [5-6, 31-33, 44].

Example product type: The ability of tolerance allocation methods to determine tolerance differs according to the product type. For example, the Lagrange multiplier method is more suited to a simple product than a complex product. Only a few authors [13-15, 66-67, 33] have considered simple assembly products comprised of only two mating component parts as an example problem. To evaluate functional performance requirements, most researchers have focused on complex assemblies that have several critical dimensions and are controlled simultaneously within certain variation ranges [1, 4-5, 10, 12, 16, 22, 28, 36, 45-56] . A relatively small number of authors have examined nonlinear assembly products that consist of more than two components and are arranged nonlinearly [1-2, 10, 17-19, 32, 40, 57].

Process planning and scheduling: Process planning and scheduling functions play a vital role in the profitability, utilization, and delivery time of a product [58]. The method proposed by the authors was applicable to Holonic manufacturing system with dynamic changes in volume and a variety of products. Xinyu et al. [59] suggested a GA-based approach for the integration and optimization of process planning and scheduling. Li et al. [60] developed three strategies (i.e., Pareto, Nash, and Stackelberg) for computer-automated process planning and scheduling in a systematic way. Guo et al. [61] used both a combinatorial optimization model and a modern evolutionary algorithm, the particle swarm optimization (PSO) algorithm, to solve integrated process planning and scheduling problems. Hengyun et al. [62] proposed a particle swam algorithm to minimize production makespan. Xinyu et al. [63] developed a hybrid approach (a GA and a local search strategy) to solve integrated process planning and scheduling problems. Xinyu et al. [64]introduced an integrated process planning and scheduling mathematical model.

In the literature, tolerance allocation and scheduling problems are usually dealt with separately. Many papers of tolerance allocation have focused on either minimizing the tolerance cost [1-6, 8-13, 15-29, 31-32,] or minimizing the tolerance cost and quality loss cost [13, 31, 33-38, 40-43]. As a result, later scheduling [58-65] produces a non optimum solution because the machining time and processing time of a component play a vital role in the scheduling process, which depends on the allocated tolerance of the components. Considering the tolerance allocation and scheduling separately provides misleading information about the manufacturing cost because tolerance allocation aims to minimize the tolerance cost based on the distribution of tolerance among the components of an assembly.

However, in scheduling, the machining time plays a vital role in determining the machine idle time cost. Only a few authors [14, 36] have considered both tolerance costs and machining time when allocating tolerance to components. No significant effort has been made to simultaneously address tolerance allocation in the context of job-shop scheduling. Therefore, in the present study, both the tolerance cost and machine idle time cost were optimized by considering the component/operation sequence. Singh et al. [28], Prabhaharan et al. [17], Singh et al. [46], Sivakumar et al. [47], and Li et al. [63] showed that the GA provided a good solution to tolerance allocation and scheduling problems as compared with other optimization techniques. The ability of a GA to identify different solutions, given the same objective value, offers engineers a range of solutions from which they can then select the optimal one. Moreover, realizing the complexity of the problem, a GA algorithm is introduced both in allocating the best tolerance for each component of an assembly and in obtaining the best product sequence.

2. Problem Definition

Heavy competition in the global market forces manufacturers to reduce their manufacturing costs and improve their productivity. It is a challenging task for engineers to find the ways and means to solve the above problem. Selection of tolerance within the known process tolerance limits in a given process-machine combination influences the manufacturing cost and the productivity of the known complex assembly’s critical tolerance. Infinite number of tolerance values between the process tolerance limits makes the problem a non polynomial hard problem. Besides the tolerance cost, the specified tolerance values determine the machining time required to make the component in a machine. The sequence of operations performed on each machine determines the idle time of all the other machines. Therefore, the problem of the sequence of operations is treated as a non polynomial hard problem.

3. Mathematical Formulation

The allocation of tolerance among the components of an assembly affects the manufacturing cost and machining time for a given tolerance-cost and tolerance-machining time relationship. The sequence of the product/operation to be performed on a specified machine influences other factors, including the makespan, mean flow time, machine idle time, machine idle time, and cost. The objective of the proposed method, represented in Eq. (1), is to minimize the sum of the manufacturing cost and the total machine idle time cost. The reciprocal tolerance cost model and worst-case method are used in the proposed method to allocate component's tolerance. The sum of the tolerance cost and the quality lost cost is expressed in Eq. (2). The tolerance cost is determined using Eq. (3), where the tolerances are allocated using a GA.

$$Z = C_{MC} + C_{ITC} \tag{1}$$

$$C_{MC} = C_{TTC} + C_{QL} \tag{2}$$

$$C_{TCi} = \eta_i (a_i + \frac{b_i}{t_i}) \tag{3}$$

$$MT_i = \eta_i (X_i + \frac{Y_i}{t_i}) \tag{4}$$

$$C_{TTC} = \sum_{i=1}^{nc} C_{TCi} \tag{5}$$

$$C_{QL} = \frac{C_{RC}}{\Delta^2} (y - m)^2 \tag{6}$$

$$C_{ITC} = \sum_{j=1}^{nm} IT_j IC_j \tag{7}$$

$$t_{asy} = \sum_{i=1}^{nc} t_i \tag{8}$$

Constraints:

$$t_a \geq \sum_{i=1}^{nc} t_i \tag{9}$$

$$t_{\min} \leq t_i \leq t_{\max} \tag{10}$$

Where,
Z - Objective function
C_{MC} - Manufacturing cost in \$
C_{ITC} - Total idle machine time cost
C_{TCi} - Tolerance cost of the i^{th} component in \$
C_{QL} - Cost of quality loss in \$
η_i - Efficiency factor for the i^{th} component
a_i, b_i - Cost function constant for the i^{th} component
X_i, Y_i - Time function constant for the i^{th} component
t_i - Allocated tolerance for the i^{th} component
C_{RC} - Cost of repairing the product in \$
y - Target value in mm
m - Deviation from the target in mm
Δ - Required specification of the product in mm
IT_j - j^{th} Machine idle time in min
IC_j - j^{th} Machine idle time cost in \$
nc - Number of components
nm - Number of machines
MT_i - Machining time of the i^{th} component
t_a - Given assembly tolerance in mm
t_{asy} - Calculated assembly tolerance in mm
t_{min} - Minimum process tolerance in mm
t_{max} - Maximum process tolerance in mm

4. Methodology

The proposed method consists of two stages: (i) the allocation of tolerance for each operation based on a known assembly tolerance value and computation of the individual component's tolerance cost and machining time and (ii) determining the best product sequence and its total machine idle time cost. A GA is implemented in both stages to achieve the objective value. In the first stage, the tolerance for each operation/component (t_i) is selected randomly from the process tolerance limits using Eq. (11). The assembly tolerance (t_{asy}) is calculated using Eq. (8) based on the worst-case method and checked against the known value. If the constraint given in Eq. (9) is satisfied, then the tolerance cost (C_{TCi}) based on the reciprocal tolerance cost model and machining time (MT_i) for each t_i are calculated using Eq.(3) and (4), respectively. The total tolerance cost and the quality loss cost are determined using Eq. (5) and (6), respectively. In the second stage, the best component sequence is determined according to the minimum machine idle time cost using

Eq. (7). Using the concurrent tolerance allocation and scheduling, the best tolerances of the components/operations, taking account of the sum of the tolerance cost, quality loss cost, and the machine idle time cost, is obtained, along with the best product sequence. The scheme for the proposed method is shown in Figure 1.

$$t_i = t\min_i + rand()*(t\max_i - t\min_i)\,. \tag{11}$$

5. Numerical Illustration

To demonstrate the proposed method, it was initially applied to an existing problem (wheel-mounting assembly) discussed by Geetha et al. [36], where the product sequence is not considered. The components of the assembly are shown in Figure 2, and its manufacturing details are presented in Tables 1 and 2, respectively. Eq. (12) and (13) represent the critical dimensions, and Eq. (14) and (15) represent the tolerances of the critical dimensions. The sum of the tolerance of each operation to obtain the critical dimensions Y1 and Y2 is calculated using Eq. (16) and (17).

$$Y1 = X2 - X4 \tag{12}$$

$$Y2 = X5 - X1 - X2 - X3 \tag{13}$$

$$t_{Y1} = t_{X2} + t_{X4} \tag{14}$$

$$t_{Y2} = t_{X1} + t_{X2} + t_{X3} + t_{X5} \tag{15}$$

$$t_{Y1} = t_{O3} + t_{O7} + t_{O8} \tag{16}$$

$$t_{Y2} = t_{O1} + t_{O2} + t_{O4} + t_{O5} + t_{O6} + t_{O7} + t_{O8}\,. \tag{17}$$

Table 3 represents the details of the allocated tolerance, machining time, process number, and the machine number obtained by Geetha et al. [36]. In this paper, to demonstrate the need to consider the product sequence, the machine idle time cost was calculated for a different product sequence for the allocated tolerance, process number, and the machine number obtained by Geetha et al. [36].The inclusion of the product sequence reduced the machine idle time cost. Thus, the product sequence was included in the present work. Hence, in this paper, for the same process number and machine number for each operation of wheel mounting assembly and the subassembly tolerance, the different tolerance has been distributed among the components for different product sequence, which gives different tolerance cost and machining time.

Figures 3 and 4 present the least machine idle time and the best product sequence with different objectives, with and without considering quality loss costs. The countable savings (i.e., the effectiveness of the proposed work) is shown in Figure 5 where the machine idle time cost obtained with the proposed method is compared with that obtained with the existing method. The results show that more cost savings can be achieved by manufacturing the components in sequence.

5.1 Implementation of the GA

The representation of the problem using genes and chromosomes in stage 1 and 2 of the work is presented in Table 4. The basic concepts and working principles of the GA were described by Deb [65]. Table 5 represents the values of the GA parameters assumed in the present work.

Tables 6 and 7 represent the process number, machine number, and subassembly tolerances considered in Geetha et al. [36]. In the proposed method, for each objective function, the tolerance of the components/operations is allocated to satisfy the known subassembly tolerance values in the first stage. For the allocated tolerance values obtained in the first stage, the best product/component sequence is to determine to minimize the machine idle time cost in the second stage. The distribution of a component’s tolerance corresponding to the subassembly tolerances, t_{y1} and $t_{y2,}$ are shown in Figures 6 and 7 respectively. The tolerance cost and machining time of each operation for various objective functions are presented in Table 8. The best product/component sequence, operation sequence, total tolerance cost, total machine idle time cost, and total cost are shown in Table 9. Figures 8 and 9 represent the distribution of the components/operation tolerance of t_{y1} and t_{y2}while considering the quality loss. The tolerance cost and machining time of an individual operation for different objectives are shown in Figures 10 and 11, together with the quality loss cost. The best product sequence for considering the quality loss cost is tabulated in Table 10.

6. Results and Discussion

The total cost comparison of the existing and proposed method is shown in Figure 12. As clear from Figure 12, for all objective functions without considering the quality loss cost, the inclusion of the component/operation sequence results in considerable cost savings in product production. With regard to quality loss costs, considerable cost savings are possible with all the objective functions, other than objective function Z3, when the component/operation is carried out in sequence. The cost savings are due to the ability to make components with a wider tolerance applying a process with higher manufacturing cost. The total cost is almost equal in objective function Z3because only the machine idle time cost is considered an objective function. The component/operation sequence does not have any role in minimizing the total machine idle cost. Thus, considerable savings cannot be made in the total cost value of objective function Z3.

7. Conclusion

Most previous studies of tolerance allocation problems have concentrated on minimizing manufacturing costs, quality loss, or a combination of the two, with scarce attention paid to machining time, an important manufacturing parameter. In this paper, the machining time was considered, along with the manufacturing cost, in optimum tolerance allocation of complex assemblies, thereby representing a more realistic product development scenario. Alternative machine and process selections with component/operation sequence consideration make this problem cumbersome and complex.

Therefore, we developed a new methodology, which consists of two stages, and applied a GA to obtain the lowest total cost when manufacturing a product. The results presented in this paper demonstrate that the proposed methodology can reduce tolerance costs and machining time in less computation time.

The proposed method is also suitable for solving two- and three-dimensional problems. As a further extension of this work, the operation sequence, machine sequence, or both could be considered with additional objectives, such as the minimization of mean flow time, makespan, total investment cost of machines, idle time of machines, idle cost of machines, and number of machines required for manufacturing a product.

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Table 1: Dimension and tolerance symbol of wheel mounting assembly

Name of the Components /Particulars	Dimension No.	Operation / Sub stage No.	Tolerance symbol	Tolerance stack-up
Left side support	X1	O1 and O2	t_{X1}	$t_{O1}+ t_{O2}$
Wheel	X4	O3	t_{X4}	t_{O3}
Right side support	X3	O4 and O5	t_{X3}	$t_{O4}+ t_{O5}$
Shaft	X5	O6	t_{X5}	t_{O6}
Spacer	X2	O7 and O8	t_{X2}	$t_{O7} + t_{O8}$
Critical dimension 1	Y1		t_{Y1}	$t_{O3} +t_{O7} + t_{O8}$
Critical dimension 2	Y2		t_{Y2}	$t_{O1}+ t_{O2}+t_{O4}+ t_{O5}+ t_{O6} +t_{O7} + t_{O8}$

Table 2: Cost and Time Function Constants for WMA

Process number	Cost function constant		Time function constant		Process capability limits in mm		Cost and Time manipulating Factor Machine Numbers			
	ai	bi	Xi	Yi	t_{min}	t_{max}	M1	M2	M3	M4
P1	1.4	0.24	2	0.4	0.01	0.08	0.8	0	1.15	0
P2	1.5	0.22	5	0.2	0.03	0.09	0	0.85	1	0
P3	0.9	0.18	3	0.8	0.02	0.07	0.85	0	0.9	1.02
P4	2.5	0.23	4.5	0.5	0.03	0.13	0	1.11	0.95	0
P5	1.9	0.15	3	0.2	0.009	0.1	1.08	1.01	0	0.8

Table 3: Details of allocated tolerance in Geetha et al. [23]

Objective	As per Table 10 in Geetha et al.					As per Table 12 in Geetha et. al.			
	O. No.	P.No.	M. No.	t_j	MTi	P.No.	M. No.	t_j	MTi
Z1	O1	4	2	0.077843	12.12	2	2	0.0534	7.43
	O2	1	1	0.070941	6.11	5	1	0.0532	7.30
	O3	2	2	0.062235	6.98	2	3	0.0526	8.80
	O4	5	4	0.035051	6.96	3	3	0.0657	13.65
	O5	1	1	0.038	10.02	1	1	0.0427	9.09
	O6	2	3	0.081529	7.45	5	4	0.0581	5.16
	O7	3	4	0.048824	19.77	3	1	0.0659	12.87
	O8	2	3	0.066706	8.00	1	1	0.0748	5.88
Z2	O1	2	3	0.083176	7.40	1	1	0.0376	10.12
	O2	1	1	0.024275	14.78	5	4	0.0353	6.94
	O3	2	2	0.071176	6.64	2	2	0.0369	8.85

	O4	5	4	0.081443	4.36	5	2	0.0737	5.77
	O5	1	1	0.056392	7.27	1	1	0.062	6.76
	O6	2	3	0.063176	8.17	5	4	0.0748	4.54
	O7	3	4	0.064706	15.67	4	2	0.0511	15.85
	O8	2	3	0.031647	11.32	2	3	0.0785	7.55
Z3	O1	4	3	0.064118	11.68	4	3	0.1005	9.00
	O2	1	1	0.047333	8.36	1	1	0.03	12.25
	O3	2	2	0.079412	6.39	2	3	0.0687	7.91
	O4	5	4	0.048969	5.67	3	4	0.0317	28.78
	O5	1	1	0.048706	8.17	4	2	0.0544	15.20
	O6	2	3	0.045059	9.44	5	1	0.0167	16.20
	O7	3	4	0.062941	16.02	3	3	0.066	13.61
	O8	2	3	0.060824	8.29	2	2	0.0422	8.28
Z1Z2	O1	1	1	0.060784	6.86	2	2	0.0392	8.58
	O2	1	1	0.061882	6.77	3	4	0.0697	14.77
	O3	2	2	0.039412	8.56	2	3	0.0415	9.81
	O4	5	4	0.041831	6.22	5	4	0.0393	6.48
	O5	1	1	0.055569	7.36	1	1	0.0579	7.12
	O6	2	3	0.070471	7.84	5	4	0.0967	4.05
	O7	3	4	0.062745	16.07	3	1	0.0525	15.51
	O8	2	3	0.056824	8.52	2	2	0.047	7.87
Z1Z3	O1	1	1	0.064078	6.59	1	3	0.0679	9.08
	O2	1	1	0.05502	7.42	3	3	0.0364	22.48
	O3	2	2	0.075176	6.51	4	2	0.0836	11.64
	O4	5	4	0.050753	5.55	3	1	0.0642	13.14
	O5	1	1	0.028667	12.76	1	1	0.056	7.32
	O6	2	3	0.035176	10.69	2	2	0.0447	8.05
	O7	3	4	0.048627	19.84	3	4	0.0298	30.41
	O8	2	3	0.075882	7.64	2	2	0.0734	6.57
Z2Z3	O1	2	3	0.039176	10.11	2	3	0.0485	9.12
	O2	1	1	0.072314	6.03	5	1	0.0779	6.01
	O3	2	2	0.045294	8.00	2	3	0.0772	7.59
	O4	5	4	0.041475	6.26	3	4	0.034	27.09
	O5	1	1	0.061333	6.82	1	3	0.0691	8.95
	O6	2	3	0.045059	9.44	5	1	0.0443	8.11
	O7	3	4	0.069412	14.82	4	2	0.0347	21.00
	O8	2	3	0.05	9.00	2	2	0.0732	6.57
Z1Z2Z3	O1	1	3	0.057765	10.26	1	3	0.0396	13.93
	O2	1	1	0.046235	8.52	5	1	0.054	7.24
	O3	2	2	0.058941	7.13	2	3	0.0537	8.73
	O4	5	4	0.075376	4.52	5	2	0.0615	6.31
	O5	1	1	0.040745	9.45	1	1	0.0505	7.94
	O6	2	3	0.047882	9.18	5	1	0.0506	7.51
	O7	3	4	0.065686	15.48	3	4	0.05	19.37
	O8	2	3	0.070706	7.83	2	2	0.0619	7.00

Table 4: GA Representation of the Problem

Particulars	Stage 1								Stage 2				
Representation of Gene	A random number between 0 and 1 for each operation								Product number				
Example for Gene	0.6546								0.4				
Representation of chromosome	No. of random number between 0 and 1 equal to no. of operation								Sequence of Product number				
Example for chromosome	0.66	0.22	0.03	0.13	0.70	0.21	0.23	084	3	2	1	4	5

Table 5: GA Parameter's Value

Particulars	Stage 1	Stage 2
Population Size	40	20
Selection Process	Roulette wheel selection	
Cross over probability	0.45	0.4
Cross over method	Single point	
Mutation probability	0.03	0.025
Replacement strategy	Complete replacement	
Stopping criteria	1000 iterations or no change in 50 consecutive iteration's fitness value	500 Iteration or no change in 50 consecutive iteration's fitness value

Table 6: Process and machine number for different operation without C_{QL}

Objective function	O1		O2		O3		O4		O5		O6		O7		O8		Y1	Y2
	P.No.	M.No.	P.No.	M.No.	P.No.	M.No.	P.No.	M.No.	P.No.	M.No.	P.No.	M.No.	P.No.	M.No	P.No.	M.No.		
Z1	4	2	1	1	2	2	5	4	1	1	2	3	3	4	2	3	0.177765	0.418894
Z2	2	3	1	1	2	2	5	4	1	1	2	3	3	4	2	3	0.167529	0.404816
Z3	4	3	1	1	2	2	5	4	1	1	2	3	3	4	2	3	0.203176	0.377949
Z1Z2	1	1	1	1	2	2	5	4	1	1	2	3	3	4	2	3	0.15898	0.410106
Z1Z3	1	1	1	1	2	2	5	4	1	1	2	3	3	4	2	3	0.199686	0.358204
Z2Z3	2	3	1	1	2	2	5	4	1	1	2	3	3	4	2	3	0.164706	0.378769
Z1Z2Z3	1	3	1	1	2	2	5	4	1	1	2	3	3	4	2	3	0.195333	0.404396

Table 7: Process and machine number for different operation with C_{QL}

Objective function	O1		O2		O3		O4		O5		O6		O7		O8		Y1	Y2	C_{QL}
	P.No	M.No.	P.No.	M.No.	P.No.	M.No.	P.No.	M.No.	P.No.	M.No.	P.No.	M.No.	P.No.	M.No.	P.No.	M.No.			
Z1	2	2	5	1	2	3	3	3	1	1	5	4	3	1	1	1	0.19322	0.41379	0.68
Z2	1	1	5	4	2	2	5	2	1	1	5	4	4	2	2	3	0.16659	0.41303	4.33
Z3	4	3	1	1	2	3	3	4	4	2	5	1	3	3	2	2	0.17686	0.34145	9.49
Z1Z2	2	2	3	4	2	3	5	4	1	1	5	4	3	1	2	2	0.14102	0.40225	11.15
Z1Z3	1	3	3	3	4	2	3	1	1	1	2	2	3	4	2	2	0.18677	0.37233	3.8
Z2Z3	2	3	5	1	2	3	3	4	1	3	5	1	4	2	2	2	0.18500	0.38170	3.08
Z1Z2Z3	1	3	5	1	2	3	5	2	1	1	5	1	3	4	2	2	0.16554	0.36808	7.54

Table 8: Tolerance cost and machining time of proposed method without C_{QL}

	Z1		Z2		Z3		Z1Z2		Z1Z3		Z2Z3		Z!Z2Z3	
O.No.	TC_i	MT_i	TC_i	MT_i	TC_i	MT_i	TC_i	MT_i	TC_i	MT_i	TC_i	MT_i	TC_i	MT_i
O1	4.78	9.35	7.96	10.87	6.12	12.42	9.36	15.33	8.15	13.31	6.31	9.37	7.97	12.89
O2	6.67	10.85	3.75	5.99	6.22	10.09	3.77	6.02	3.94	6.29	4.19	6.71	4.43	7.12
O3	3.75	6.5	4.41	7.1	3.35	6.14	6.38	8.89	3.35	6.14	4.56	7.23	3.35	6.14
O4	2.79	4.1	2.93	4.28	2.84	4.16	2.84	4.16	2.91	4.25	2.84	4.15	2.73	4.01
O5	7.52	12.27	4.59	7.39	6.05	9.82	3.92	6.26	6.39	10.38	6.61	10.75	6.38	10.37
O6	8.76	11.6	5.95	9.05	7.15	10.13	8.3	11.18	8.82	11.66	7.53	10.48	5.05	8.23
O7	3.58	14.87	3.61	15.02	4.25	17.87	3.59	14.95	3.61	15	3.63	15.12	4.07	17.07
O8	8.11	11.01	7.05	10.05	5.29	8.44	5.6	8.72	6.82	9.84	6.99	9.99	6.17	9.25

Table 9: The best product sequence and its total cost without C_{QL}

Obj. No.	**P.Seq**	**O.Seq**	**TTC**	**ITC**	**TLC**
Z1	1 4 5 2 3	1 2 3 6 7 8 4 5	45.97	76.03	122.00
Z2	3 1 4 5 2	4 5 1 2 3 6 7 8	40.25	23.1	63.35
Z3	3 1 4 5 2	4 5 1 2 3 6 7 8	41.27	22.46	63.73
Z1Z2	1 4 5 2 3	1 2 3 6 7 8 4 5	43.75	29.37	73.12
Z1Z3	1 4 5 2 3	1 2 3 6 7 8 4 5	43.98	26.1	70.08
Z2Z3	3 1 4 5 2	4 5 1 2 3 6 7 8	42.65	22.43	65.08
Z1Z2Z3	3 1 4 5 2	4 5 1 2 3 6 7 8	40.16	21.66	61.82

Obj. No. – Objective function number; P.Seq. – Product sequence; O.Seq. – Operation sequence; TTC – Total tolerance cost in $; ITC – Total machine idle time cost in $; TLC – Total cost in $

Table 10: The best product sequence and its total cost with C_{QL}

Obj. No.	P.Seq	O.Seq	TTC	TMIDC	C_{QL}	TLC
Z1	2 1 3 4 5	7 8 1 2 4 5 3 6	32.80	0	0.68	33.5
Z2	5 1 3 2 4	6 1 2 4 5 7 8 3	44.11	123.16	4.33	172
Z3	3 5 1 2 4	4 5 6 1 2 7 8 3	45.52	68.03	9.49	123.04
Z1Z2	3 4 5 1 2	4 5 3 6 1 2 7 8	39.29	83.46	11.15	134
Z1Z3	1 3 4 5 2	1 2 4 5 3 6 7 8	39.00	0	3.8	42.8
Z2Z3	5 1 3 4 2	6 1 2 4 5 3 7 8	52.23	0	3.08	55.3
Z1Z2Z3	5 1 3 4 2	6 1 2 4 5 3 7 8	45.83	7.41	7.54	60.8

Figure

Fig. 1: Scheme of proposed method

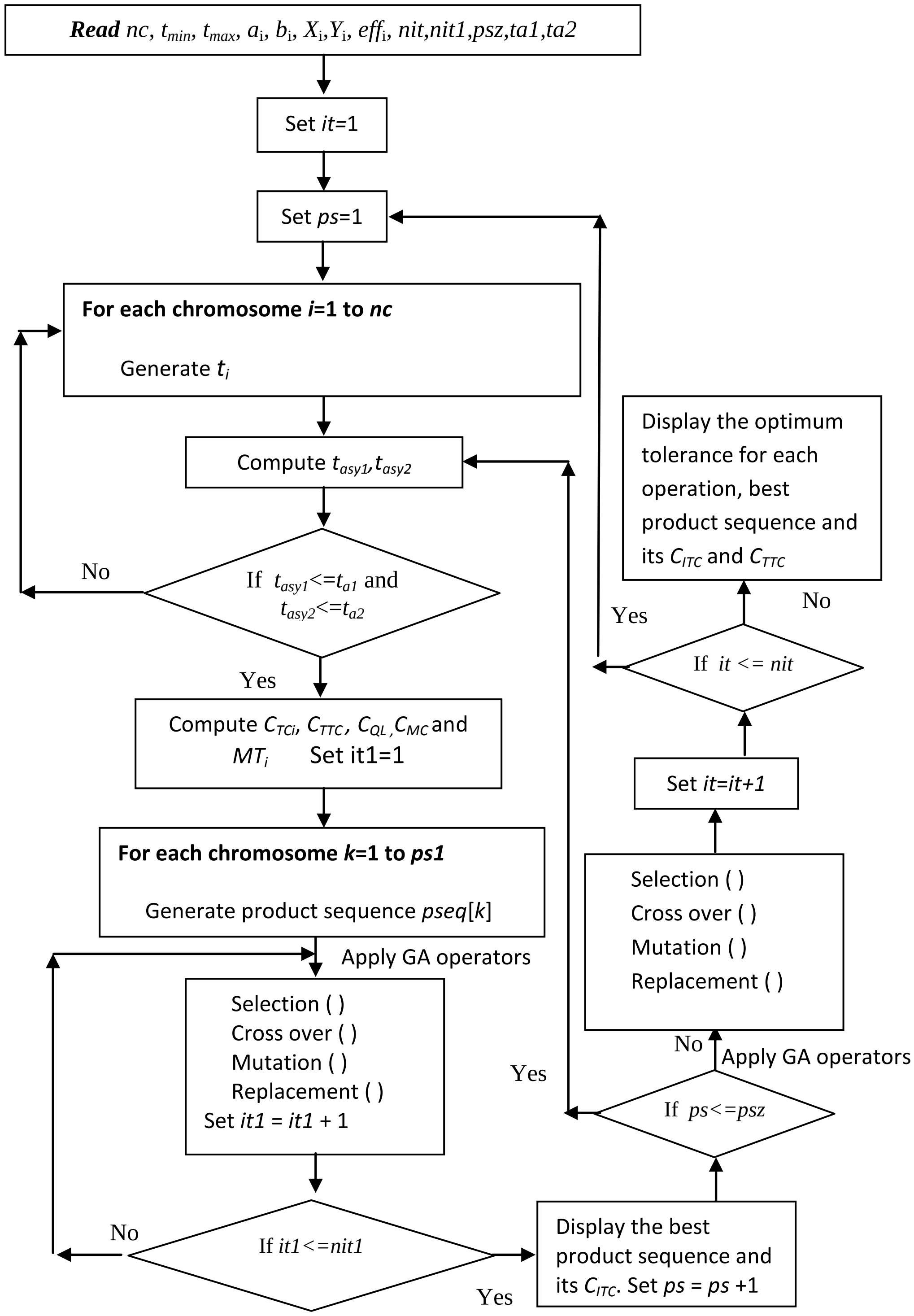


Fig. 2: Wheel mounting assembly

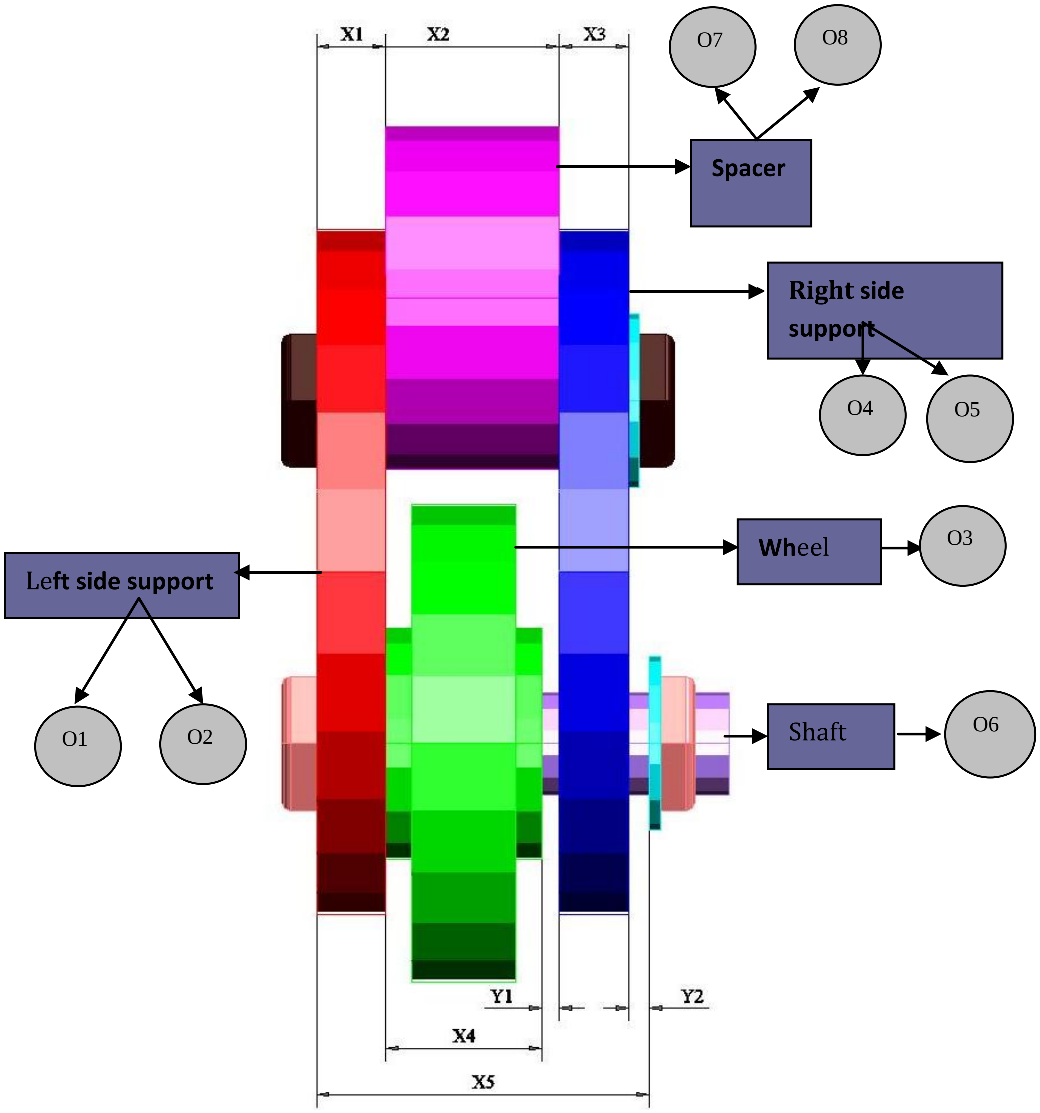
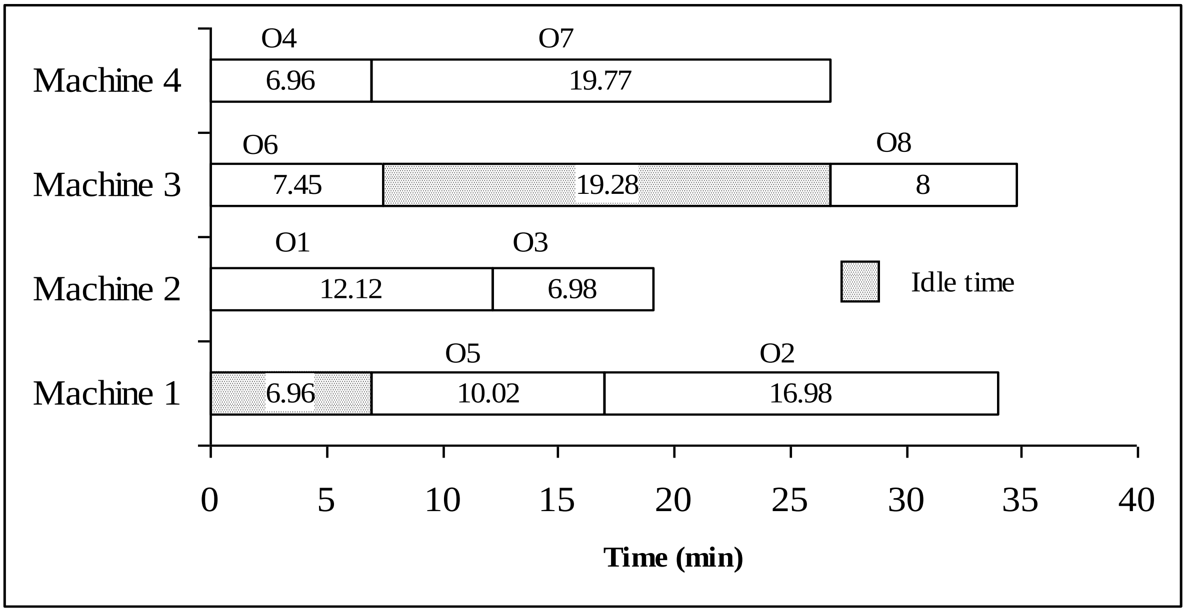
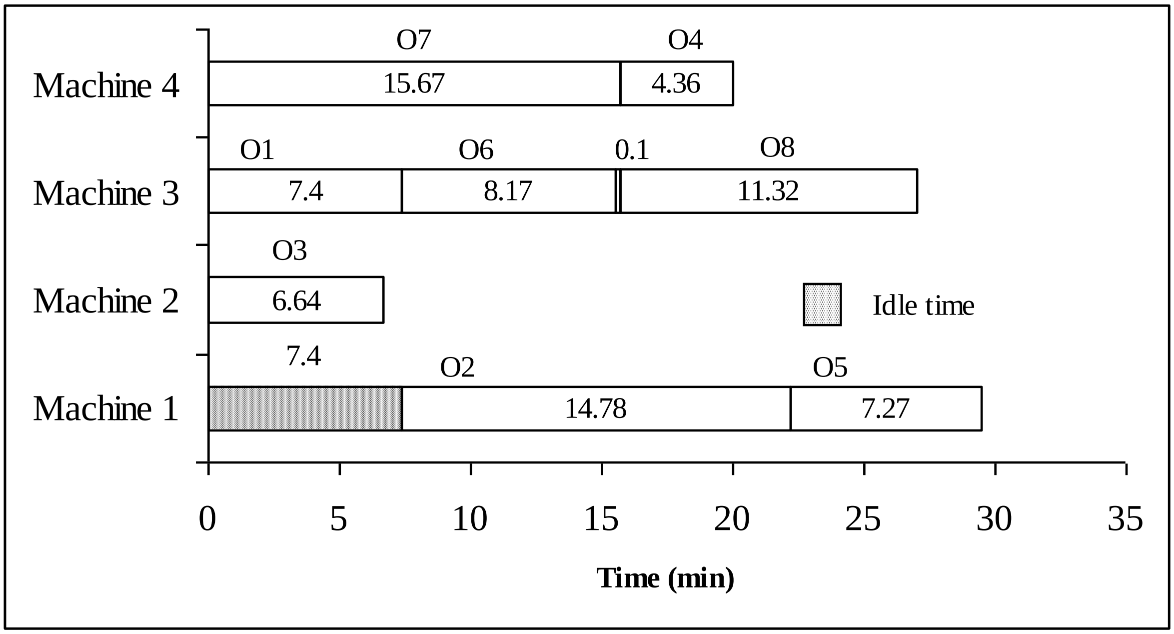


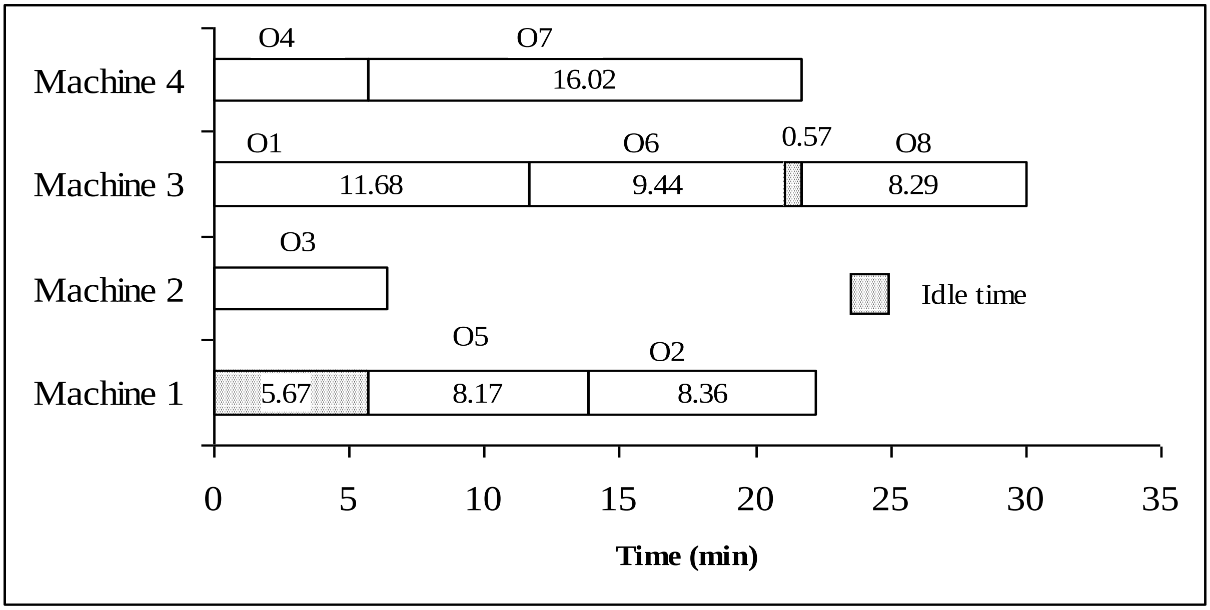
Fig. 3: Machine idle time for the best product sequence of each objective function without C_{QL}



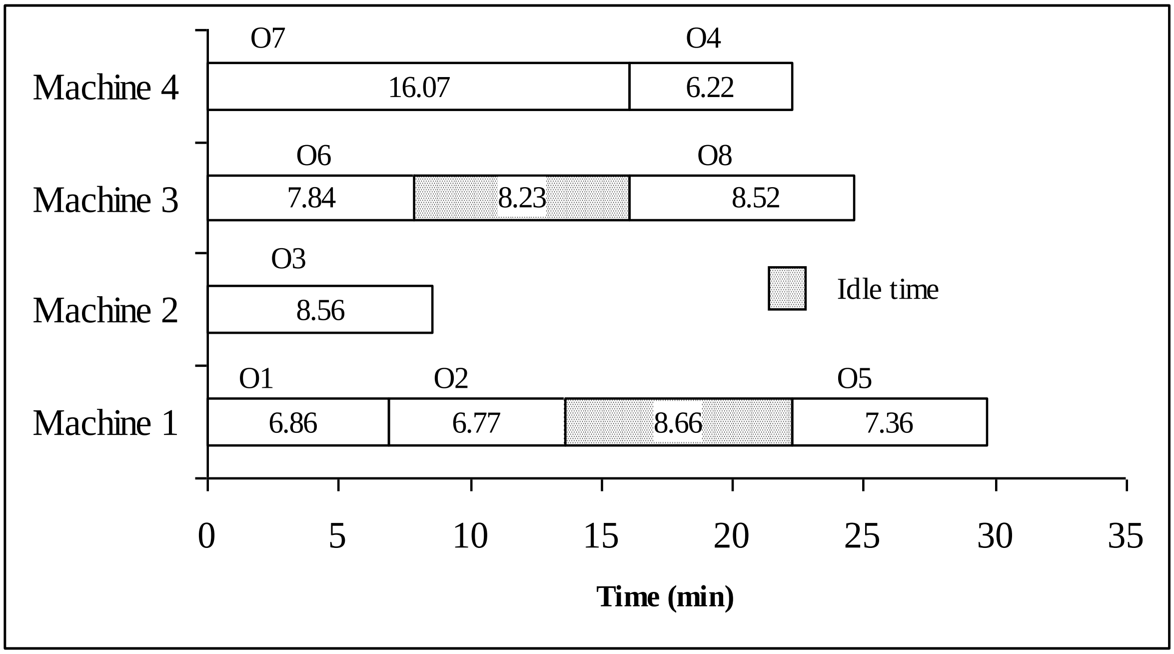
(a) Z1 without C_{QL} (Best product sequence X3X1X4X5X2)



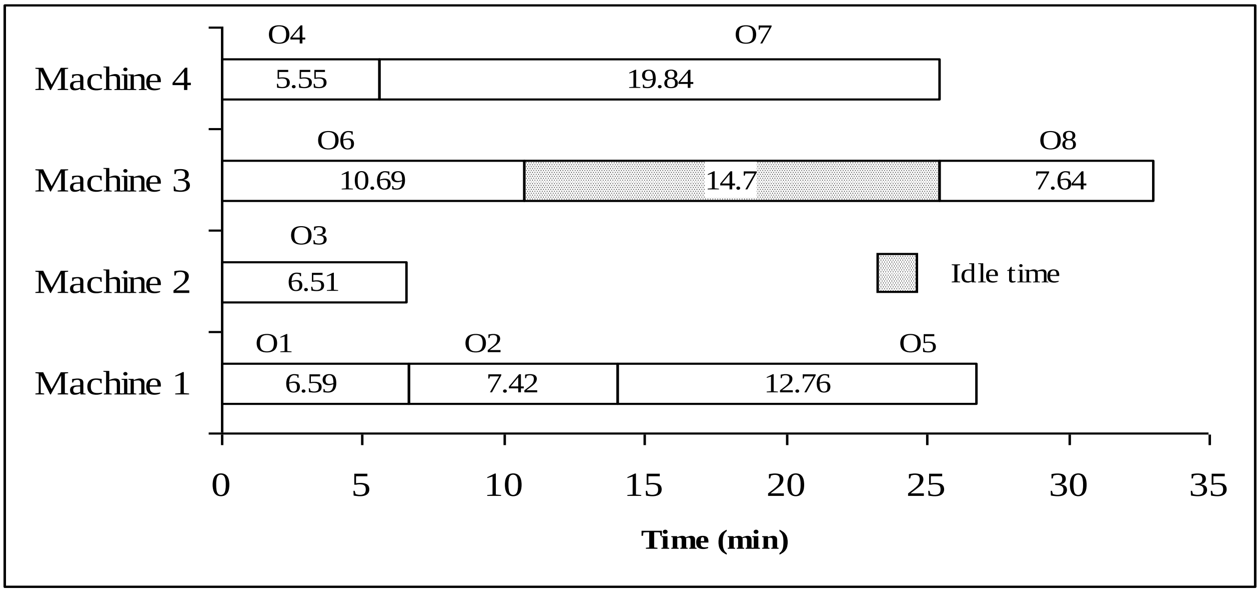
(b) Z2 without C_{QL} (Best product sequence X1X4X5X2X3)



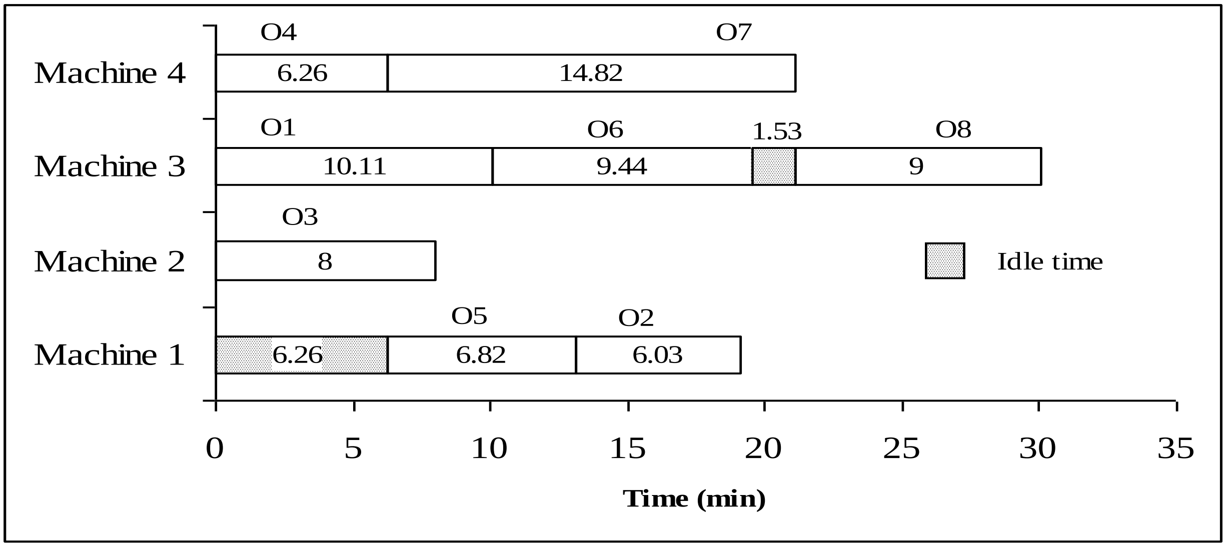
(c) Z3 without C_{QL} (Best product sequence X3X1X4X5X2)



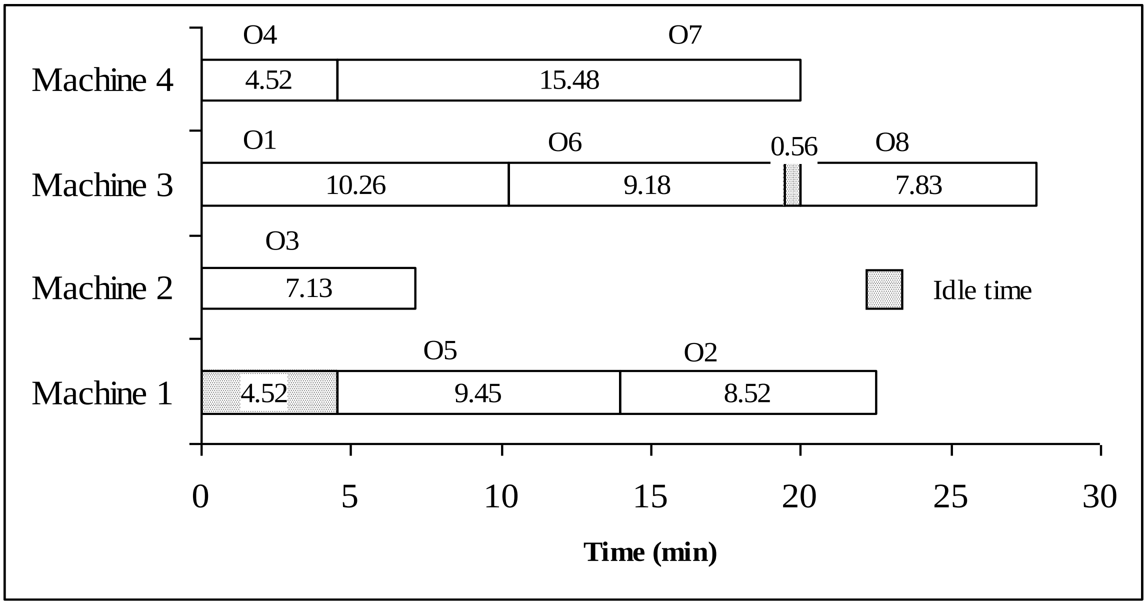
(d) Z1Z2 without C_{QL} (Best product sequence X1X4X5X2X3)



(e) Z1Z3 without C_{QL} (Best product sequence X1X3X4X5X2)

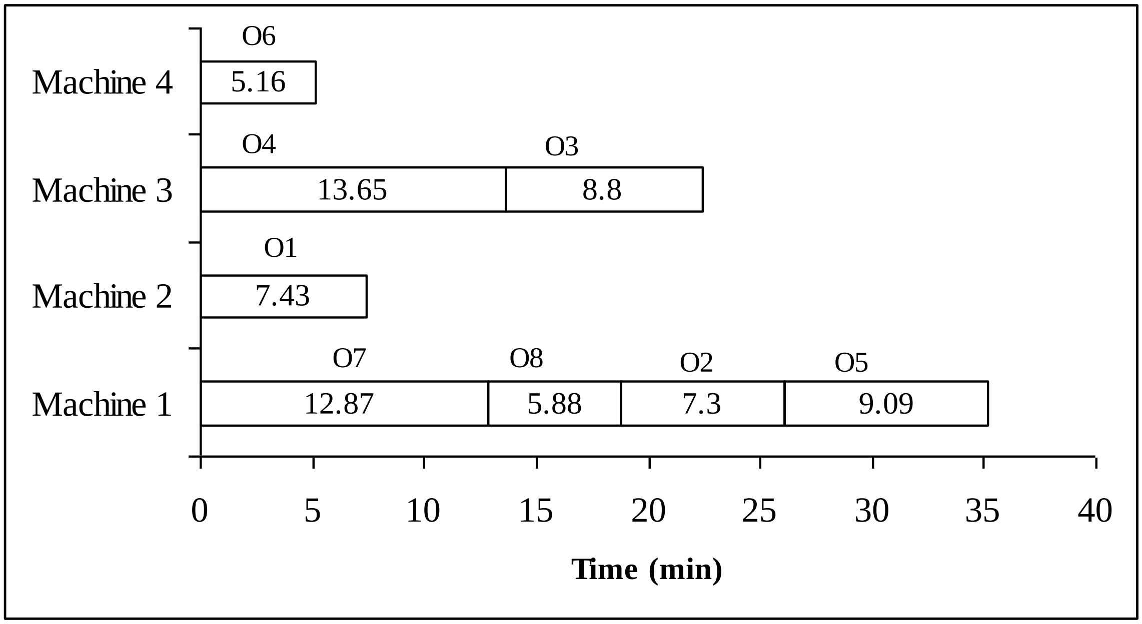


(f) Z2Z3 without C_{QL} (Best product sequence X3X1X4X5X2)

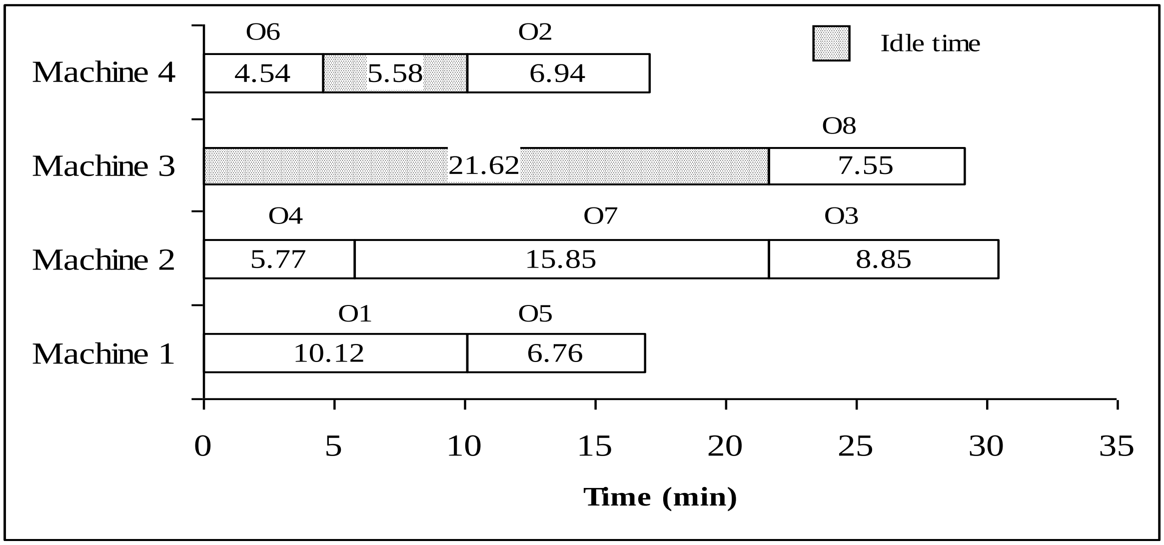


(g) Z1Z2Z3 without C_{QL} (Best product sequence X3X1X4X5X2)

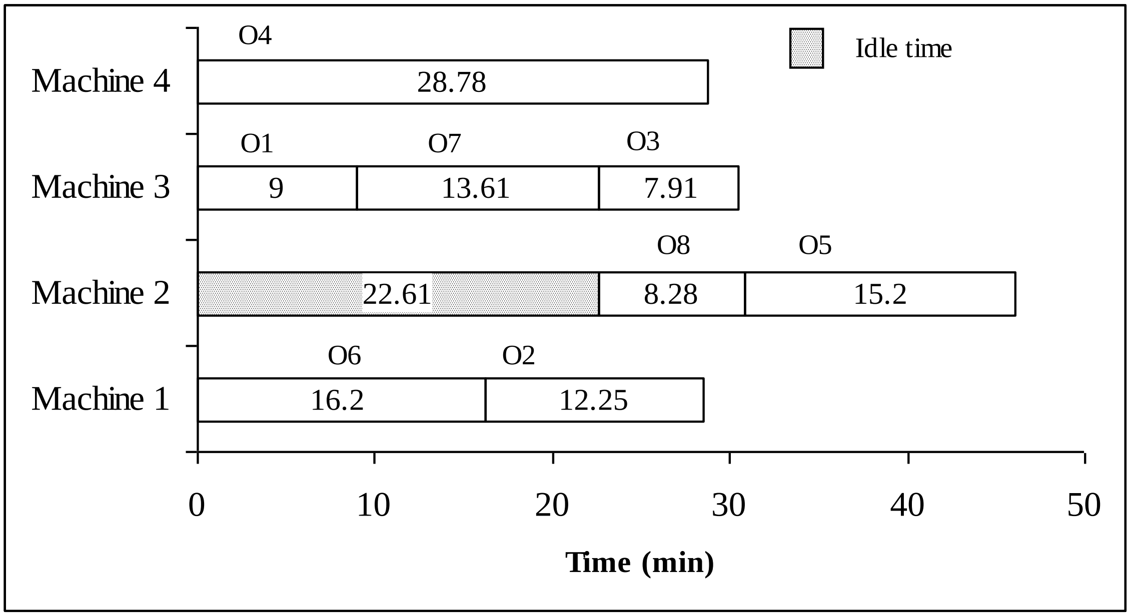
Fig. 4: Machine idle time for the best product sequence of each objective function with C_{QL}



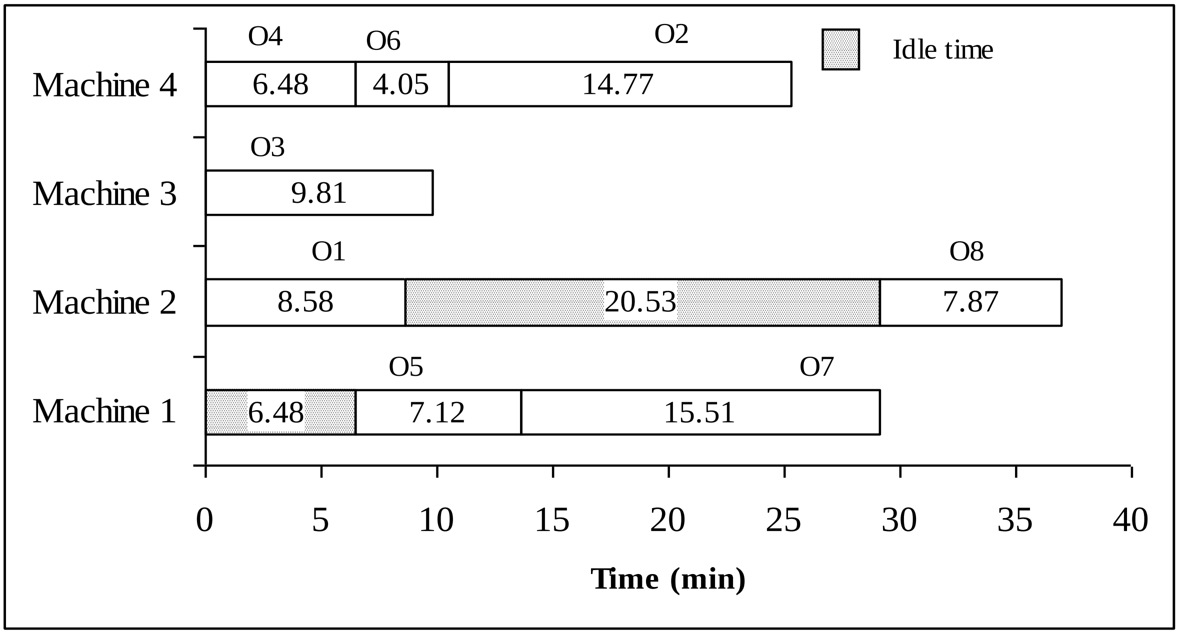
(a) Z1 with C_{QL} (Best product sequence X2X1X3X4X5)



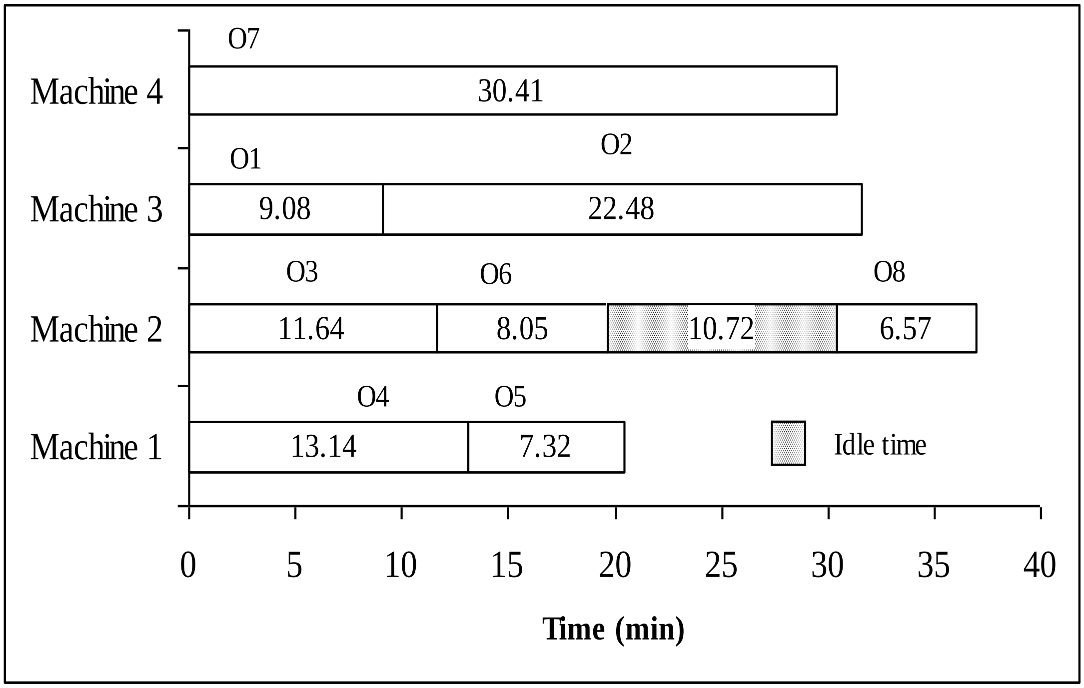
(b) Z2 with C_{QL} (Best product sequence X5X1X3X2X4)



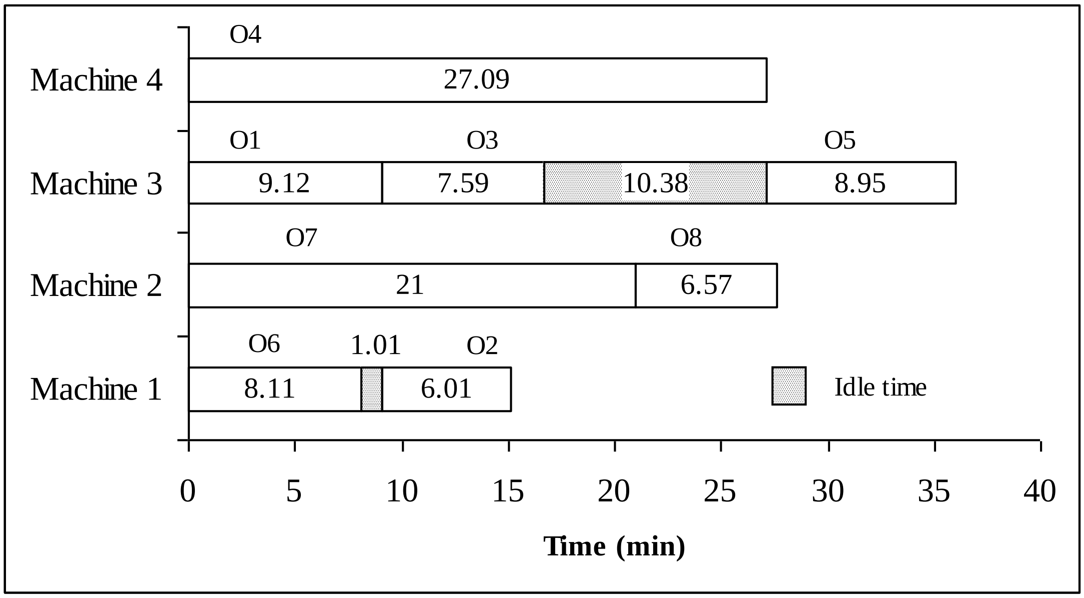
(c) Z3 with C_{QL} (Best product sequence X5X1X2X4X3)



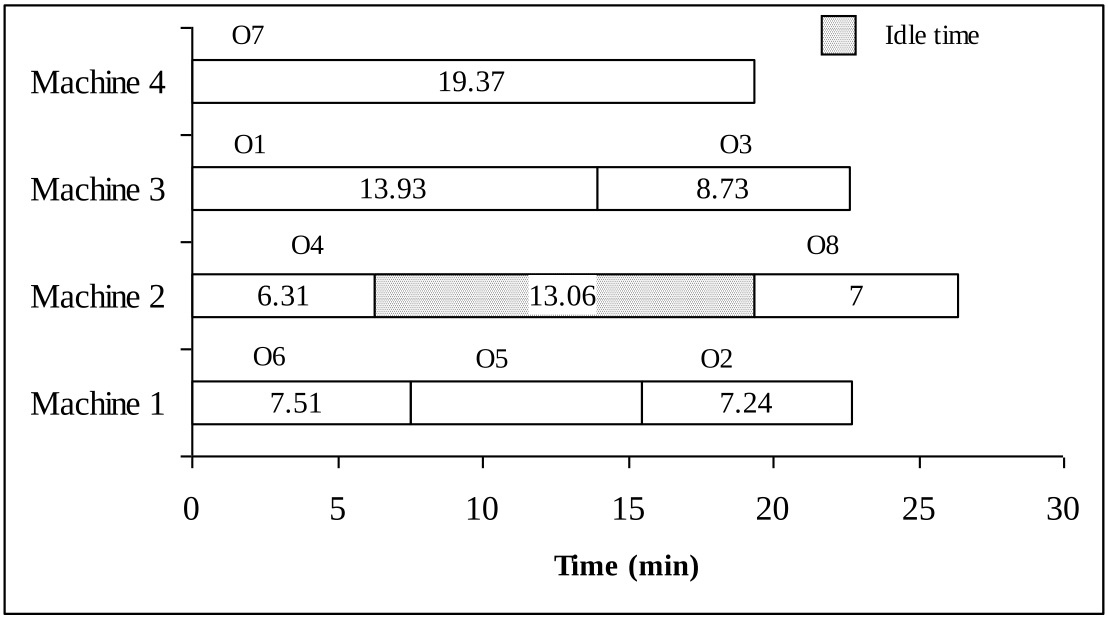
(d) Z1Z2 with C_{QL} (Best product sequence X3X4X5X1X2)



(e) Z1Z3 with C_{QL} (Best product sequence X1X3X4X5X2)



(f) Z2Z3 with C_{QL} (Best product sequence X2X5X1X4X3)



(g) Z1Z2Z3 with C_{QL} (Best product sequence X5X3X2X1X4)

Fig. 5: Comparison of total machine idle time cost

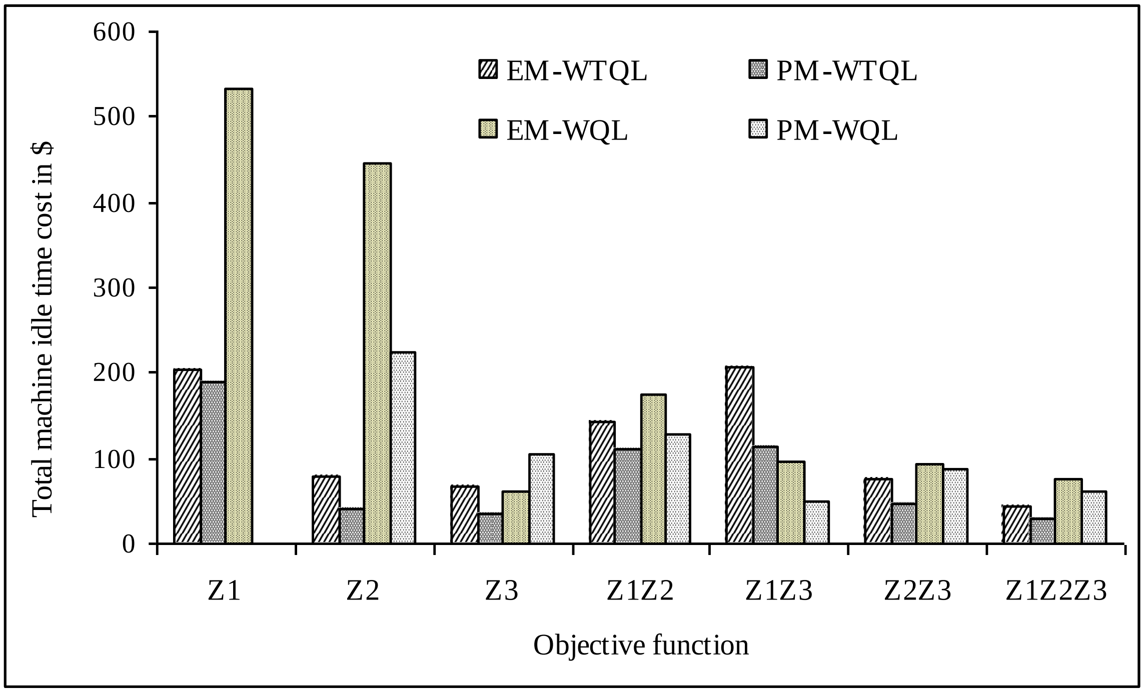


Fig. 6: Distribution of component's tolerance in each operation for t_{y1} without C_{QL}

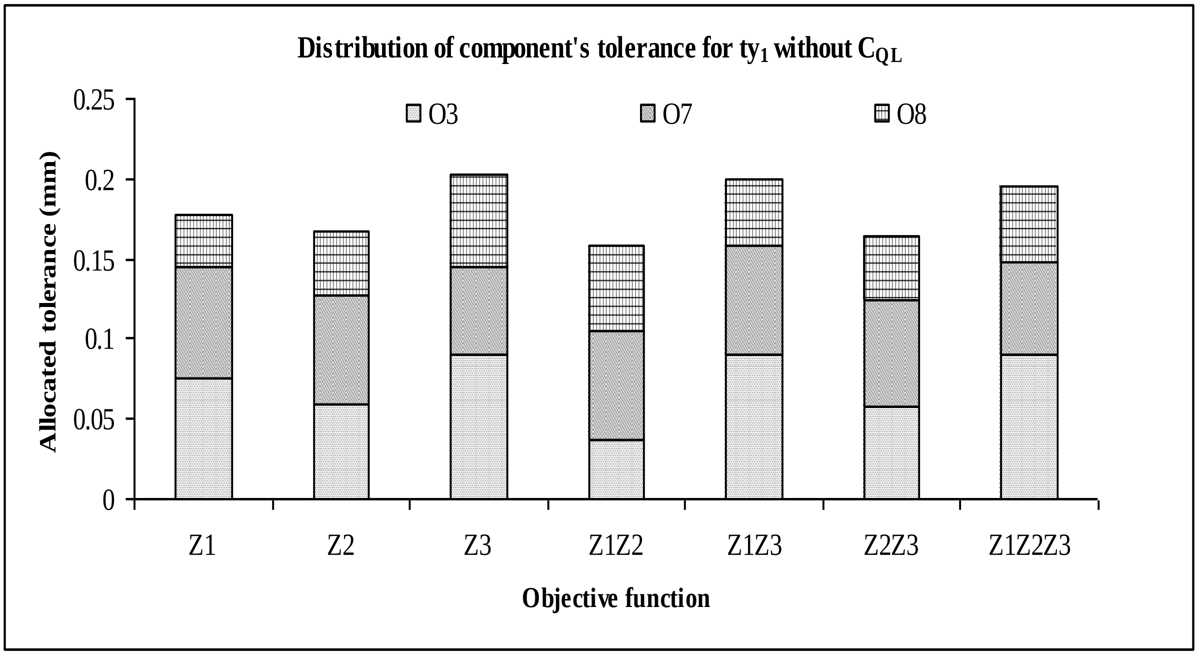


Fig. 7: Distribution of component's tolerance in each operation for t_{y2} without C_{QL}

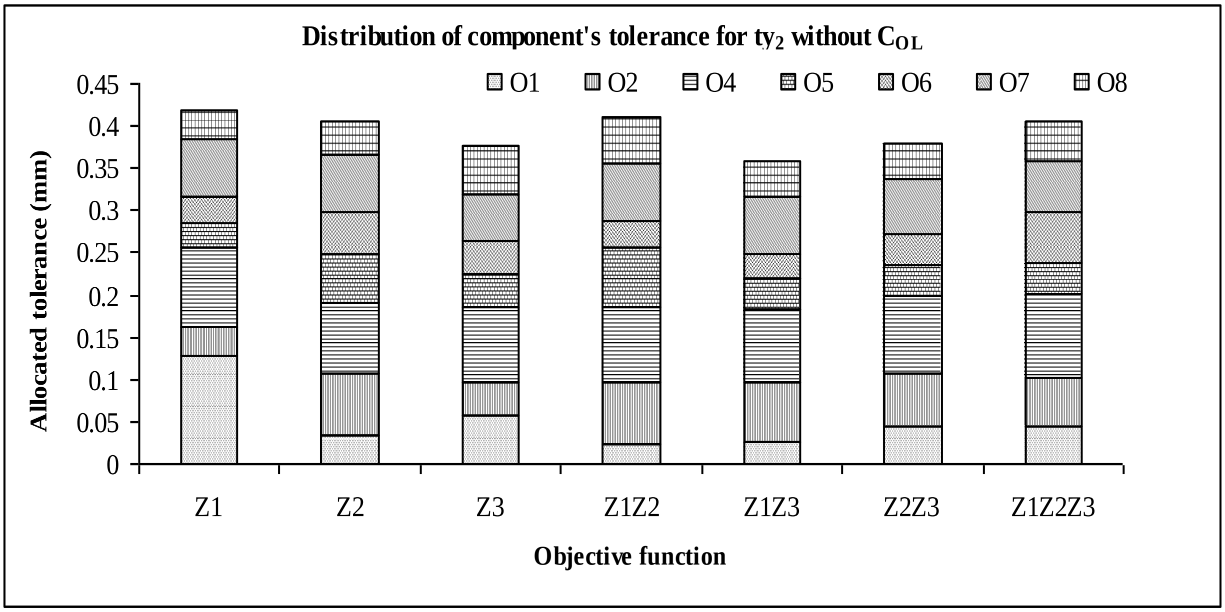


Fig. 8: Distribution of component's tolerance in each operation for t_{y1} with C_{QL}

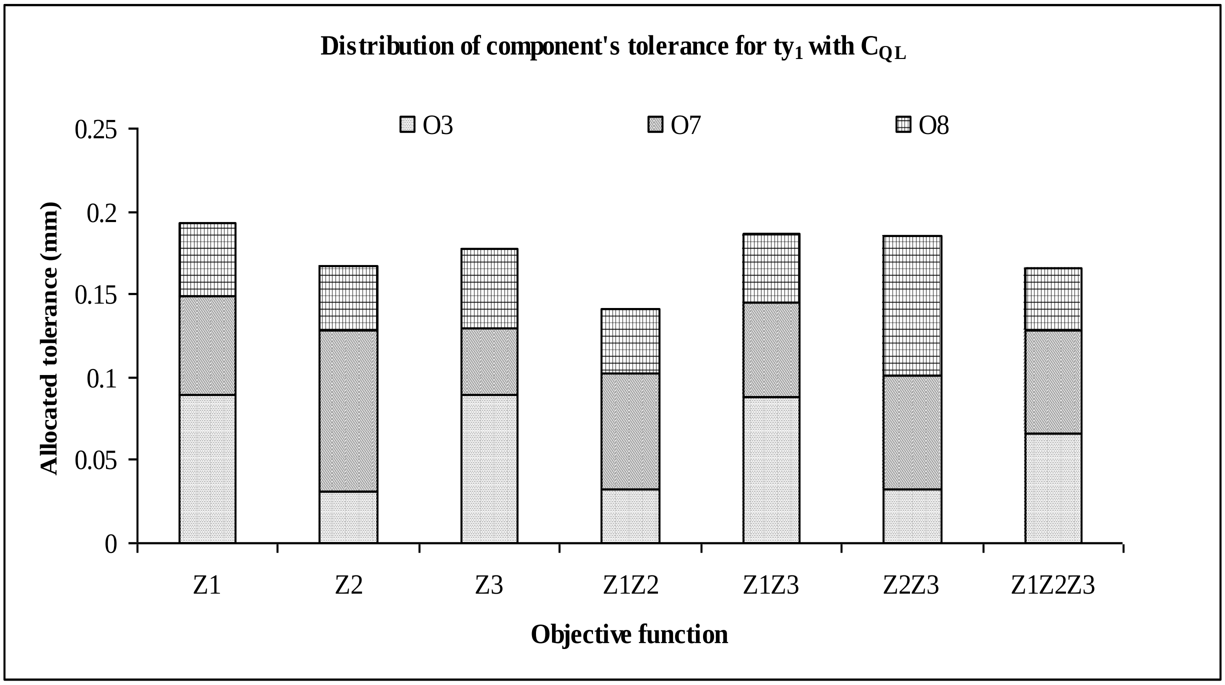


Fig. 9: Distribution of component's tolerance in each operation for t_{y2} with C_{QL}

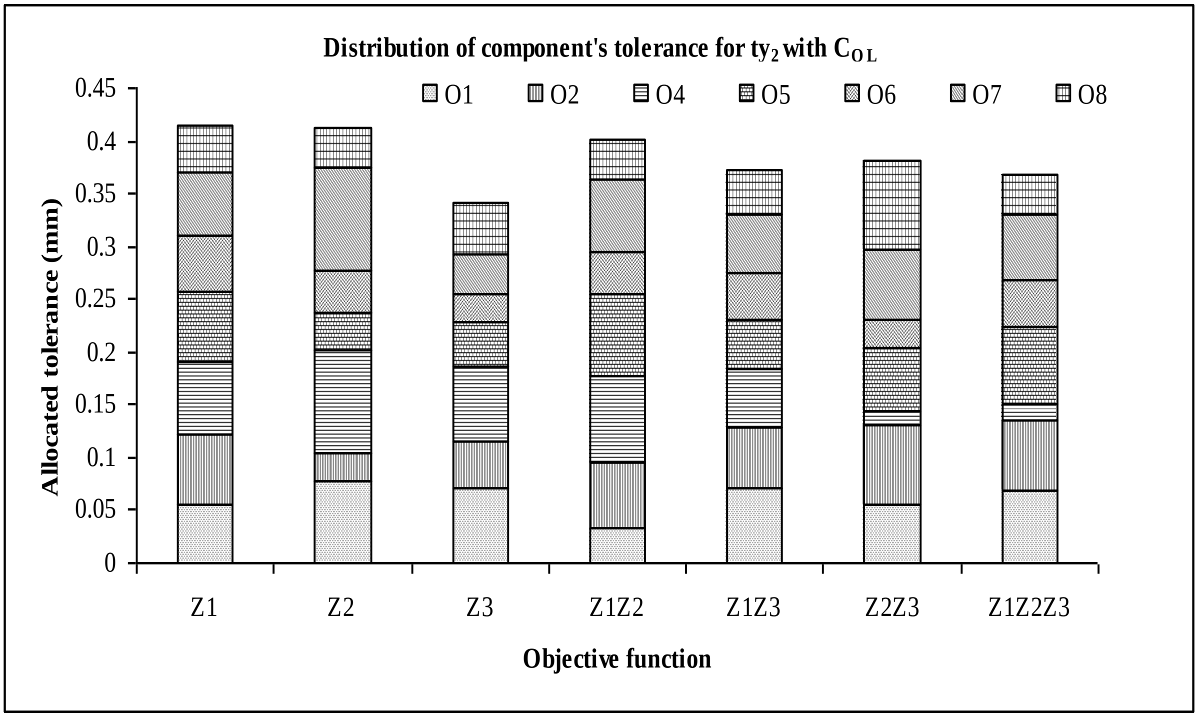


Fig. 10: Machining time of each operation with C_{QL}

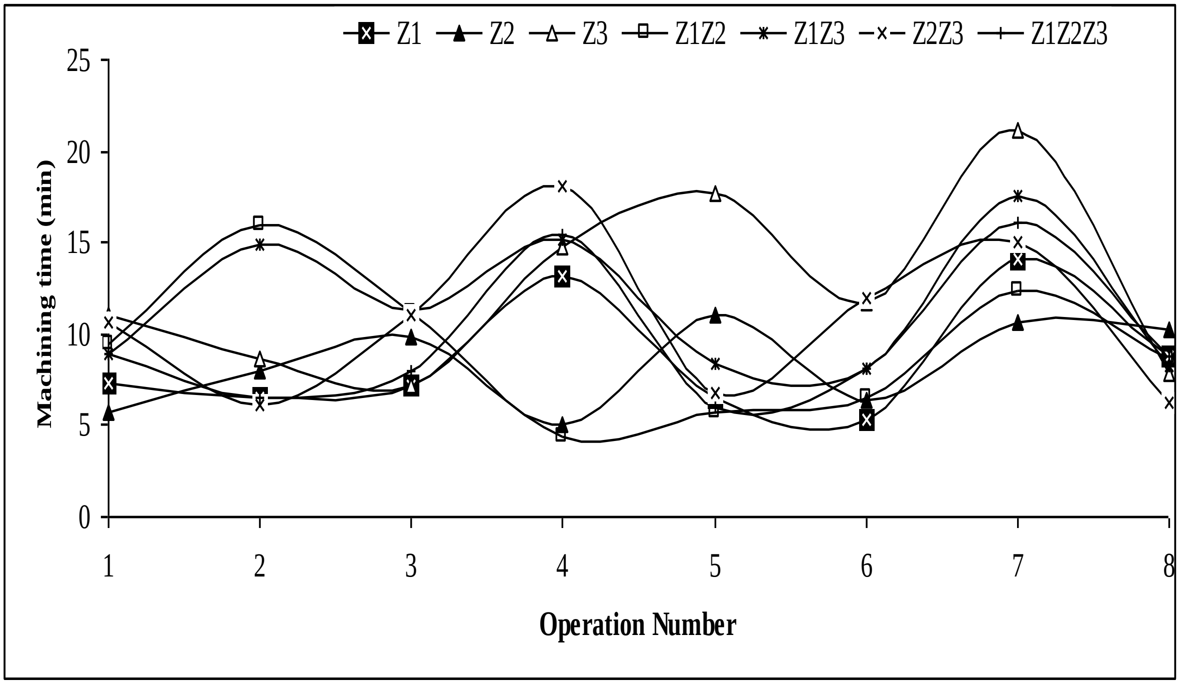


Fig. 11: Tolerance cost of each operation with C_{QL}

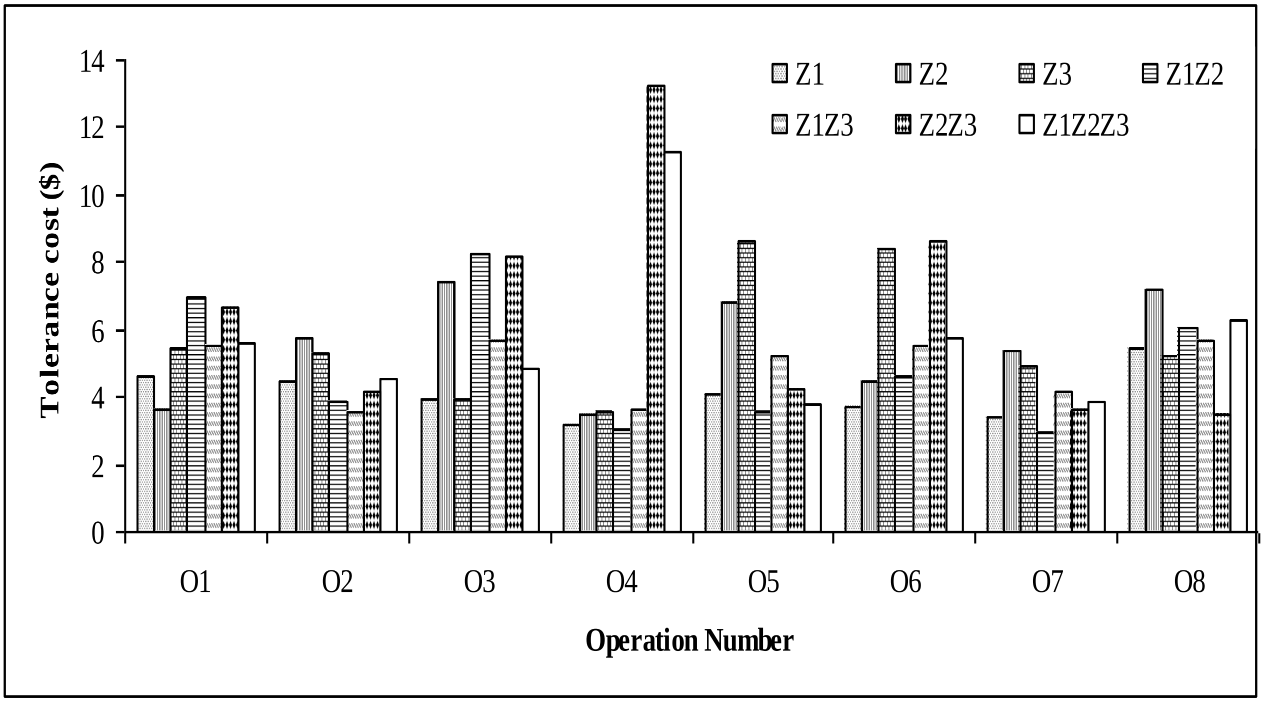


Fig. 12: Comparision of total cost between exisiting and proposed method