Strojniški vestnik - Journal of Mechanical Engineering 67(2021)12, 682-691
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DOI:10.5545/sv-jme.2021.7406
Original Scientific Paper

Received for review: 2021-09-15
Received revised form: 2021-11-23
Accepted for publication: 2021-11-24

Extremal-Micro Genetic Algorithm Model for Time-Cost Optimization with Optimal Labour Productivity

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In a highly competitive manufacturing environment, it is critical to balance production time and cost simultaneously. Numerous attempts have been made to provide various solutions to strike a balance between these factors. However, more effort is still required to address these challenges in terms of labour productivity. This study proposes an integrated substitution and management improvement technique for enhancing the effectiveness of labour resources and equipment. Furthermore, in the context of time-cost optimization with optimal labour productivity, an extremal-micro genetic algorithm (Ex-μGA) model has been proposed. A real-world case from the labour-intensive medium-scale bus body fabricating industry is used to validate the proposed model performance. According to the results, the proposed model can optimize production time and cost by 34 % and 19 %, respectively, while maintaining optimal labour productivity. In addition, this study provides an alternative method for dealing with production parameter imbalances and assisting production managers in developing labour schedules more effectively.

Key words: labour productivity, equipment effectiveness, time-cost optimization, extremal optimization, micro genetic algorithm

Highlights

- *An integrated substitution and management improvement technique has been proposed for enhancing the effectiveness of labour resources and equipment.*
- *An extremal-micro genetic algorithm model has been proposed to optimize time and cost with optimal labour productivity.*
- *The proposed model provides optimal labour resource allocation for each activity in order to carry out work efficiently.*
- *This facilitates the production managers in developing an effective maintenance plan to enhance equipment effectiveness.*

0 INTRODUCTION

The most significant factors for planning and regulating labour-intensive projects are duration and cost analysis. The production manager is responsible for selecting various resources for the completion of an activity. Uncertainties and vulnerabilities in fabrication processes are taken into account throughout this decision-making process. In this regard, when discussing time-cost optimization, it is essential to review the terms 'crashing', 'fast-tracking', 'substitute', and 'management improvement techniques'. Crashing is a well-known project schedule compression technique that comprises taking action to shorten the overall project timeline after analysing several options. Shrinking schedule activity durations and increasing resource allocation on schedule activities are two popular crashing techniques [1]. However, crashing has negative consequences including congestion, overburdening workers, and fatigue. 'Fast-tracking' is a real-time way of analysing the volume and timeliness of assessments from start to finish [2]. Drawbacks to fast-tracking include defects, rework, and overloading. The third term, substitution, is the process of replacing resources and applying cutting-edge technology to increase a company's production within the time limits and budgets [3]. Its drawbacks such as over-costing, resistance and the time required to improve workforces. The fourth key term in time-cost optimization is management improvement techniques, such as skill enhancement training. The training programme is a strategy for enhancing an individual employee's knowledge and skills to perform given tasks flawlessly [4]. However, there are certain disadvantages to this method, including work interruption, separate improvement costs, and separate trainer employment costs.

The most crucial aspect of the optimization profession is figuring out how to meet deadlines on time and within budget. Numerous approaches are often used to investigate the optimization problem in terms of time and cost, including the fuzzy-based simulation annealing technique [5], critical path method, linear programming [6], non-dominated genetic algorithm [7], fuzzy logic with genetic algorithm [8], and learning curve methods [9]. Likewise, mathematical programming might be the most appropriate option. However, project managers are reluctant to employ it due to the difficulties in establishing projects with complex schedules. In

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addition, Peña-Mora and Li **[10]** developed a model to use system dynamics to accelerate building projects. They changed the labour productivity assumption, which had been used in earlier analyses as a constant. Productivity is estimated in the dynamic model as a function of schedule pressure and level of experience. Zhang et al. **[11]** used a heuristic technique to tackle construction projects' time-cost constraints. This method divides a project's activities into groups based on feasible combinations and then schedules all of the activities in the chosen group to reduce the project's time. A heuristic algorithm assesses all possible activity combinations and chooses the best one with the shortest project duration. The shortcoming of this technique is that it did not account for the impact of shorter project length on direct and overall project costs. Gerk and Qassim **[12]** introduced a mixed-integer non-linear programming model to assist automation enterprises in setting up time reduction projects. The time and cost savings are expected as a result of activity crashing, overlapping, and substitution. Lakshminarayanan et al. **[13]** considered a risk element to be an important aspect in the optimization of a building project. An ant colony optimization approach was used to handle the time-cost-risk trade off problem in the construction project. Based on the time-cost trade off problem, an objective function associated with each activity was developed using a set of quality indicators. The construction project risk was assessed and divided into several zones based on its importance. Likewise, Shrivastava et al. **[14]** devised a multi-objective optimization technique for the time-cost-quality-quantity problem in building projects based on the ant colony optimization technique. The objective functions were calculated in regards to the project's duration, overall cost, and quality. The drawback of this method is that the parameter they select is dependent on randomly chosen. Han et al. **[15]** proposed a system dynamics model to speed up construction projects. They concentrated on schedule delays caused by design flaws. The dynamic approach determines productivity as a function of scheduling pressure. Gracanin et al. **[16]** proposed value-stream optimization through lean strategies to reduce cost-time investment. This reduces the allocation of non-value-added overhead across the entire production process. Wood **[17]** used a fuzzy memetic optimization algorithm to investigate the stochastic duration-cost-quality trade off in the oil and gas industry. Taheri Amiri et al. **[7]** presented a non-dominated sorting genetic algorithm model for analysing concurrent cost and time minimization of projects with resource constraints. Jordan et al.**[18]** advocated the use of value stream analysis to reduce process waste and improve the economic efficiency of production. Lin and Lai **[19]** suggested a genetic algorithm model for multi-objective time-cost trade off analysis. Productivity is estimated using this method as a function of the management improvement strategy for labour training and the labour resource congestion factor. These investigations offered several efficient optimization models that may be used in various sectors. Most of these studies argued that shortening project length would invariably result in higher costs in a time-cost trade off context. Some of them also looked into labour productivity.

Furthermore, while heuristic approaches can predict the optimal level of activity acceleration and overlap in schedule compression, they cannot guarantee a global optimum. Dehghan et al. **[20]** assert that the genetic algorithm (GA) has given much more effective capacity to seek the optimal solution compared to traditional methodologies. Likewise, Trivedi and Namdev **[21]** investigated the heuristic, mathematical, and GA approaches for time-cost optimization, concluding that the genetic algorithm is the most adaptive meta-heuristic technique. Naseri **[22]** also compared linear programming to the GA model, concluding that GA can deliver a near-optimal solution. In a further study, Lin andLai **[19]** corroborate the superiority of GA in time-cost optimization. In contrast, the population size and parameter setting on the real-world problems significantly impact GA sampling capabilities. To address this issue, local search algorithms have been integrated with GA **[23]** and **[24]**. The key characteristic of GA is that it may easily be combined with various optimization techniques to enhance their performances.GA hybridized with other techniques has many advantages, including global optimization quality, efficiency, a guarantee of feasible solutions, and optimal control parameters **[25]**.

According to the literature, changing productivities are frequently employed in the time and cost optimization context, mainly focusing on large-scale projects. However, labour-driven medium-scale projects, such as bus bodybuilding, also face uncertainty in the duration and cost of operation due to decreased labour efficiency. Likewise, the impact of long-term viability on equipment and labour productivity has not been studied in terms of time-cost optimization. Therefore, this study provides an interesting perspective on the uncertainties of time and cost along with labour productivity. Furthermore, this study proposes an integrated substitution and management improvement technique for enhancing the effectiveness of labour resources and equipment. In addition, this study proposes a hybrid extremal-micro genetic algorithm (Ex-μGA) optimization model for determining an optimal solution for labour productivity and work schedules. Consequently, the model could shorten the duration of work and direct labour costs.

1 RESEARCH METHODOLOGY

The simple GA probably produces a global optimal solution. However, this will happen at a relatively slow rate. Hence, this is ineffective in real-world problem solving because it requires rapid convergence. For instance, during online optimization scenarios, the objective function might occur faster than the simple GA can find the best solution. In this sense, a rapid GA is essential for the online optimization process. The structure of the micro genetic algorithm (μGA) is identical to that of simple GA, and it is used to work with small populations. As a result, it necessitates fewer function evaluations than traditional GA [26]. The crossover operation is carried out in μGA. However, the mutation is not required, because sufficient variance had been maintained during micro population convergence. In contrast, the self-organized critical idea is at the heart of the extremal optimization technique. The most unfavourable variables in a suboptimal response are gradually replaced by newly produced random variables in this method. The physical instinct to streamline also can serve as a source of inspiration for extremal optimization. This path is commonly followed by its forerunners, such as simulated annealing and GA [27]. In this study, the μGA is combined with the extremal optimization technique to focus on improving optimization efficiency for small populations. The chromosome symbolizes the improving strategy, and the gene symbolizes the decision variable in this process. The time module reduces the amount of time spent within the original budget, while the cost module reduces the amount of money spent within a set amount of time.

1.1 Model Formulation

Management has provided a realistic and essential strategy for improving efficiency in bus body building operations. Improvement, in contrast, takes time and money. Hence, due to time and cost constraints, all viable improvement actions cannot be carried out. In the context of multi-objective decisions, decision-makers can prioritize the most appropriate alternative solutions while maintaining optimal time cost management. Consequently, the proposed model's goal is to assist decision-makers in recognizing a redesigned primary goal of improving efficiency while reducing time and direct labour expenses. The formulation and objective function of the mathematical model are presented in this section. The following assumptions are employed while developing the Ex-μGA optimization model.

1. The resources considered while optimizing the process is labour and equipment.
2. The external factors are inexact and inconsistent, so the model does not account for it.
3. The proposed model identifies that the original team is adequate and that the additional personnel is unnecessary.
4. The overtime strategy is not employed since it may increase costs and reduce efficiency.

The original project duration (PD) is expressed in Eq. (1),

$$PD = \sum\nolimits_{i=1}^{j} \left(AD_i^{L_U L_P Q} \right), \tag{1}$$

where, $AD_i^{L_U L_P Q}$ is the actual project duration of activity (i), number of activity (j) mostly on project scheduling using labour productivity (L_P) labour usage (L_U) to complete the quantity of work (Q). The optimal target is to minimize fabrication duration (D_F). The objective function is follows as in Eq. (2):

$$\text{Minimize } D_F = \sum\nolimits_{i}^{j} \left(AD_i^{L_U^* L_P^* Q} \right), \tag{2}$$

subject to $D_F < PD$.

Post optimization, according to the logical relationships and minimized process time, a new labour schedule composed for j operations could be created. Where $AD_i^{L_U^* L_P^* Q}$ is the new activity duration using optimal labour resource (L_U^*) with optimal productivity (L_P^*) to total the work quantity Q. The diverse elements that influence labour productivity could be classified using the factor model described by [20]. The labour time to complete (L_{TTC}) one quantity of work is computed as Eq. (3), and the labour productivity (L_P) computed as in Eq. (4),

$$L_{TTC} = \frac{mh}{q} = f\left(L_{EA}, E_{EL}\, \overline{R_S}, \overline{C_W} \right), \tag{3}$$

where mh is the input labour working hours, q is per work quantity, L_{EA} stands for labour environment allowance, which is used to constrain labour usage. E_{EL} is a management-identified equipment effectiveness improvement index as enhancing deliverables to constraint the labour productivity. R_S is the ability needed to perform the job, and C_W is the work content including such job role. R_S and

C_W are constants throughout this experiment since it is assumed that the worker is skilled to perform the job, and the work content is stated as a requirement for work, where n represents number of quantities completed with actual equipment effectiveness in a day and DMH represents daily man-hours utilized with respect to labour usage (L_U) in the actual scenario of work. In this study, the improvement factor as mentioned as improved equipment effectiveness (E_{EI}) is an index of measuring the improvement effect through management. The number of quantities (N) completed is a function of quantity (n) completed with actual equipment effectiveness (E_{EA}) versus improved equipment effectiveness (E_{EI}). The optimal labour productivity (L_P^*) after improvement through equipment effectiveness equals to amount of work (N) completed divided to daily man-hours with respect to optimal labour usage (L_U^*). The labour usage and improvement index are used as two sets of key decision variables that jointly decide the proposed Ex-μGA optimization model results. The relations among improved equipment effectiveness (E_{EI}), number of quantities (N) completed, optimal labour productivity (L_P^*), and FD are presented in the following Eqs. (5) to (8).

$$E_{EI} = f\left(E_A, E_P, W_Q\right), \tag{5}$$

$$N = f\left(n / E_{EA}, E_{EI}\right), \tag{6}$$

$$L_P^* = \left(\frac{N}{DMH}\right), \tag{7}$$

$$D_F = Q \times P / DMH, \tag{8}$$

where D_F is fabrication duration, Q is the quantity of work to be done, DMH is daily man-hours multiplied by daily straight hours (default: 8 hours). When Q is constant, fabrication duration is proportional to the labour productivity and inversely proportional to the man-hour. The fabrication cost (FC) with optimal duration has been estimated as Eq. (9).

$$FC = \sum_{x=1}^{n}\left[DLC_x^{L_U^* D_F} + C_I\right], \tag{9}$$

subject to $FC < PC$, where, $DLC_x^{L_U^* D_F}$ is direct labour cost with respect to optimal labour usage and optimal fabrication duration, C_I cost of improvement, and PC is proposed project cost.

2 CASE VALIDATION

The real-world problem has been utilized to propose an optimal model. This study has investigated uncertainties observed in a medium-scale bus body fabrication project carried out by a specific industry in Karur, Tamil Nadu, India. The chosen industry is recognized for fabricating city, school, tour, coach, and mini buses. It has 175 workers. This study has been done on the fabrication of city buses. A gemba crew of five professionals has been initially organized. The team includes educational specialists as well as production managers. The crew assesses the factors that influence the effectiveness of the equipment and measures the actual progress of the city bus fabrication process. In addition, the crew develops an improvement strategy.

The city bus body fabrication work consists of 11 distinct activities. There is no lag time in any of the relationships, according to the process, because they are determined by the characteristics of each activity. These are unaffected by the optimization process and have no influence on the final result. The suitable amount of available labour is determined based on the normal conditions for each task in terms of environmental allowance. Each activity's normal labour productivity is determined separately. The actual labour utilization is initially lower than the allowances for the working environment, because management strives to avoid workplace crowding. The production manager assigns labour with various skills to carry out the given activity. Furthermore, the labours cannot be swapped between different activities. The fabrication duration and cost are calculated using Eqs. (8) and (9), respectively, to provide the findings of this investigation. Table 1 shows the various activities and the initial progress of the fabrication process. Owing to the confidentiality of case project, the project labour cost was €1686.69. The work done per day with actual equipment effectiveness for all 11 activities was calculated as 879 units with labour usage of 54. The average L_{TTC} is 0.56 with average labour productivity of 1.95 units per man-hour. The total duration required to fabricate the city bus is 40 days.

2.1 Case Improvements

The improvement team thoroughly investigated the substituting and management improvement programme and decided to integrate those two techniques. The improvement index is identified as a means of increasing labour productivity. In general, the production manager may assign additional workers to speed up the schedule and reduce fabrication time if there is sufficient labour available. In contrast, when more employees are assigned, the working environment becomes increasingly crowded. Worker

Table 1. *Initial progress of the city bus fabrication process*

Activity	Activity name	Labour allowance	Labour usage	Labour productivity	Quantity [units]	Duration [days]	Cost [€]
1	Material preparation	5	5	2.38	950	10	380.31
2	Chassis preparation	5	5	1.89	400	5	202.07
3	Sheet metal preparation	7	6	1.89	150	2	88.40
4	Super structure fabrication	5	5	2.08	540	6	247.05
5	Frame assembly	4	4	2.04	190	3	88.73
6	Painting	6	6	2.63	675	5	244.49
7	Interior work	15	12	1.89	475	3	299.94
8	Window &glass fitting	4	4	2.04	124	2	57.92
9	Exterior work	4	4	2.08	120	2	54.90
10	Finishing	2	2	1.25	20	1	15.25
11	Inspection	1	1	1.25	10	1	7.63

productivity may decline as a result. The literature has demonstrated that crashing causes inefficiencies due to high labour density and congestion. Therefore, in this study, the environment labour allowance is taken as constraint to optimize labour usage. In addition, motivational techniques are used as part of an improvement programme. Short-term crew meetings and gemba walks are introduced to motivate workers, and this improves worker accountability and self-discipline. The cost of improvement for these management improvement strategies is low, because the same production manager is in charge of both. Therefore, the usual activities are unaffected by this integrated strategy.

Furthermore, optimal labour productivity (L_P^*) is associated with the improvement of overall equipment effectiveness (*OEE*). The resultant *OEE* is used to measure the effectiveness of the production system. From a wider perspective, total productive maintenance (*TPM*) can be characterized in terms of OEE **[28]** and **[29]**. The detailed list of research parameters, units, notation, and OEE estimation formula is in Table 2. These evaluations are essential to analyse the current situation in order to enforce the appropriate counter-measures. Self-maintenance techniques are the first line of defence. This entails adhering to the 5'S principles in order to maintain the proper equipment. Second, preventive maintenance has indeed been promoted in order to keep the unit up to date on a regular basis. A weekly source of power inspection by circulating air into the device, which lowers overheating and sporadic arc output, is one of the electrical maintenance remedies. Of course, the coolant level is controlled in order to prevent

Table 2. *Improvement parameters estimation*

Serial No	Parameter	Notation	Units	Calculation	Estimates (before TPM)	Estimates (after TPM)
1	Planned production time	T_p	[min]	measurement	395	395
2	Planned production speed	S_p	[weld /min]	measurement	1.2	1.2
3	Planned quantity	P_w	[-]	$T_p \times S_p$	474	474
4	Time per weld	T_w	[s]	measurement	50	50
5	Labour movement time	T_{lm}	[min]	measurement	16	8
6	Unscheduled break down time	T_b	[min]	measurement	48	15
7	Changeover & adjustment time	T_c	[min]	measurement	12	12
8	Scheduled stoppage duration	T_{ss}	[min]	measurement	50	50
9	Realized stoppage duration	T_{Lrs}	[min]	$T_{lm} + T_b + T_c + T_{ss}$	126	85
10	Total operating time	T_o	[min]	$T_p - T_{Lrs}$	269	310
11	Realized production speed	S_r	[weld / min]	measurement	0.5	1
12	Defects and rework	L_r	[-]	measurement	8	4
13	Total acceptable quantity	To_{aq}	[-]	$To_w - \mathrm{Lr}$	127	306
14	Total quantity of work	To_w	[-]	$S_r \times T_o$	135	310
15	Overall equipment effectiveness	OEE	[%]	$T_o \times S_r \times To_{aq} / (T_p \times S_p \times To_w)$	27	65

sludge from developing. There is a focus on generator welding machine maintenance, including changing the oil, filtration, air cleaners, and fuel filters. Finally, a load test is performed to check that weld output is accurate. In addition, for each selected parameter, countermeasures have been estimated and are listed in Table 2. The *OEE* rate has increased significantly (from 27 % to 65 %), since the TPM programme was implemented. Thus, the improvement factor is selected for the welding machine chosen to increase output work in the range of $27 < E_{EI} < 65$. Therefore, the work production quantity should increase as a result of the integrated improvement approach.

3 OPTIMIZATION RESULTS AND DISCUSSION

The parameters used in the proposed optimization method have been fine-tuned to achieve good results. The optimization is done with hybrid Ex-µGA. The optimization results are provided as the average of the ten best experiments with a maximum of 10,000 iterations. The run time for optimization is 7.91 s. The production manager could be able to enhance labour productivity by using the integrated improvement method. The results show that when improvement factor (E_{EI}) performs the maximum output is valued at an average of 86 %. Due to the improvement factor, the average optimal $L_{TTC}{}^{*}$is reduced from 0.56 to 0.46 (man-hours required to complete unit quantity of work). The optimal labour productivity ($L_P{}^*$) increased to 2.84 units per man-hour. The total fabrication duration (D_F) could be reduced from 41 days to 27 days with optimal cost of € 1372.80 and a congestion factor of 1. The congestion factor is computed using L_U/L_{EA}. It is used to assess workplace crowding and to avoid crashing. The fabrication duration, in contrast, will be reduced to 17 days if the production manager mobilizes all available labour to reduce the timeline. However, this mobilization raises the average congestion factor to 1.7, resulting in overcrowding and high labour costs. Furthermore, with improved productivity, actual labour usage could complete the fabrication in 28 days while spending less than the fabrication budget cost. However, compared to the optimal solution, these results in a lower congestion factor of 0.9 and a longer fabrication time. The optimized results are depicted in Table 3.

3.1 Improvement on Time and Cost

This is more beneficial than crashes in terms of reducing fabrication timelines by enhancing labour productivity. Similarly, the fabrication along with improvement costs is less than the actual budgeted direct labour cost. The consistency of maximum achieved effectiveness from the integrated improvement method cannot be achieved at all times. Therefore, the selective improvement index is concluded from the optimization using Ex-µGA. This enables for the most efficient use of labour resources and productivity, as well as providing the shortest bus fabrication duration. The results indicate an improvement of fabrication duration of 34 % and a cost improvement of 19 %with respect to the selected case. Figs. 1 and 2 demonstrate the comparison of time and cost of actual and optimized scenarios. This result acknowledges optimal acceleration as a method for balancing fabrication time and cost.

3.2 Improvement on Labour Productivity

In terms of labour productivity, when labour utilization exceeds the labour environment allowance, productivity diminishes as a result of overcrowding. In

Table 3. *Comparison of fabricating case study bus's basic with optimized information*

Activity	Equipment effectiveness after improvement, E_{EI}	Optimized labour usage	Optimized labour productivity	Quantity of work done [units]	Optimized duration [days]	Optimized fabrication cost [€]
1	0.59	5	5.22	950	5	213.69
2	0.57	5	4.02	400	3	139.66
3	1.00	7	1.62	150	2	88.40
4	0.65	5	4.99	540	3	158.34
5	0.61	4	4.65	190	2	92.58
6	1.00	6	2.63	675	5	244.49
7	1.00	15	1.51	475	3	299.94
8	1.00	4	2.04	124	2	57.92
9	1.00	4	2.08	120	2	54.90
10	1.00	2	1.25	20	1	15.25
11	1.00	1	1.25	10	1	7.63

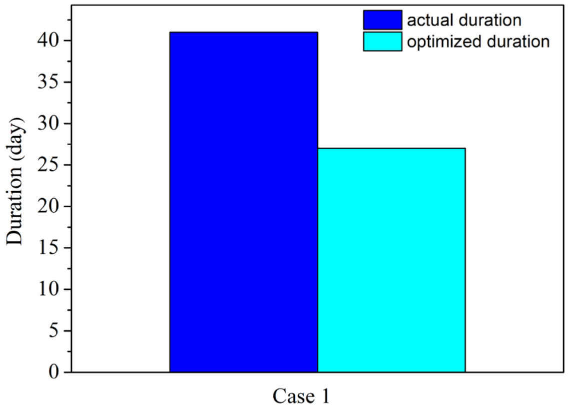

Fig. 1. *City bus body fabricating duration comparison*

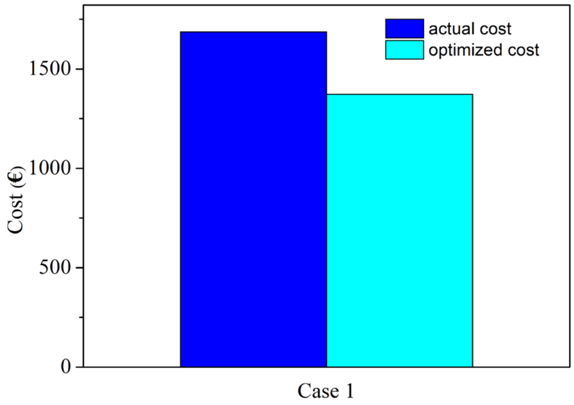

Fig. 2. *City bus body fabricating cost comparison*

the meantime, as labour usage slips below the labour environment allowance, production time increases. Therefore, optimum labour use can enhance labour productivity. Fig. 3 illustrates the growth of labour productivity. Table 4 demonstrates actual labour allocation as well as equipment effectiveness rates and four alternative optimized schedules. Furthermore, the optimal set of four with a 34 % acceleration rate is the best option for fabricating city buses within a fixed budget.

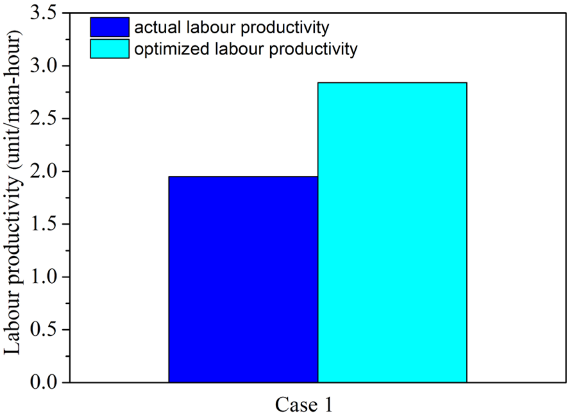

Fig. 3. *City bus body fabricating labour productivity comparison*

3.3 Statistical Hypothesis Test

This statistical test enables quantitative inferences to be drawn about the optimization model's outcomes. The paired *t*-test is employed for hypothesis testing because the mean difference between actual and optimized are paired observations. Table 5 demonstrates the paired *t*-test results. The calculated probability of obtaining the observed sample data is 0.076, 0.118, and 0.058. This confirms accepting the null hypothesis, which means the optimized values are suitable for completing this bus body fabrication work. This determined quantitative statistical evidence provides decisions to accept the hypothesis of the optimization process.

3.4 Comparison with Previous Techniques

The total cost in the preceding time-cost minimization context often consists of direct and indirect expenses that have been adversely and favourably associated with the production duration. The indirect expenses can be reduced when the duration is reduced, but the direct expenses are unavoidably increased due to inefficiency caused by crashing and fast-tracking. The

Table 4. *Paired t-test results*

Particulars	DF - Actual	DF -Optimized	FC - Actual	FC - Optimized	LP - Actual	LP - Optimized
N	11	11	11	11	11	11
Mean	3.636	2.636	13071	10638	1.947	2.842
STDEV	2.693	1.362	10781	8163	0.411	1.566
SE mean	0.812	0.411	3251	2461	0.124	0.472
Difference for 95 CI	(-0.124, 2.124)		(-735, 5599)		(-1.828, 0.039)	
t-value	1.98		1.71		2.14	
p-value	0.076		0.118		0.058	

direct cost, in contrast, has not been necessarily rising as a result of the timeline acceleration if resource usage efficiency is enhanced, as suggested by the proposed model. Table 5 compares the variation rate of time-cost optimization. This comparison demonstrates the significant differences in direct cost estimates between previous studies. This also shows the concept of critical approaches and methodologies. It also highlights how far the proposed model has advanced, which confirms that labour productivity enhancement can reduce time and cost simultaneously.

4 CONCLUSION

Most prior findings of time-cost optimization have been extensively carried out using techniques such as crashing, fast-tracking, costly substitution and management programs for labour improvements. However, simultaneous enhancement of existing resources such as machines and labours has not been encountered among those approaches. This study's primary importance is to apply an integrated improvement technique associated with time-cost optimization for enhancing productivity of machines as well as labours. The fabrication duration is significantly optimized as a result of productivity enhancement of available resources. This study also suggests that production managers could consider the proposed Ex-μGA optimization model initially in order to optimize fabrication process, which is also helpful for minimizing maintenance risk. Finally, the potential benefits of this integrated approach are sustainable for a long time. Hence, the proposed model provides important managerial insights into determining optimal labour resource allocation for each activity in order to carry out work efficiently. In addition, this facilitates the production managers to develop an effective maintenance plan to enhance equipment effectiveness. Furthermore, this facilitates communication between employees and their immediate superiors, resulting in a more harmonious working environment. The proposed time-cost optimization model has the potential to improve task performance significantly. However, future research will concentrate on the additional important factor of organizing flexible labour usage to accelerate schedules in the context of time-cost optimization using various optimization methodologies.

Table 5. *Optimal set for labour scheduling*

Activity	Actual		Optimal Set 1		Optimal Set 2		Optimal Set 3		Optimal Set 4	
	L_U	E_{EA}	L_U*	E_{EI}	L_U*	E_{EI}	L_U*	E_{EI}	L_U*	E_{EI}
1	5	0.27	4	0.37	5	0.45	5	0.59	5	0.59
2	5	0.27	4	0.40	4	0.43	5	0.57	5	0.57
3	6	1.00	5	1.00	7	1.00	6	1.00	7	1.00
4	5	0.27	5	0.38	5	0.47	5	0.65	5	0.65
5	4	0.27	4	0.39	4	0.48	4	0.61	4	0.61
6	6	1.00	6	1.00	5	1.00	6	1.00	6	1.00
7	12	1.00	14	1.00	13	1.00	12	1.00	15	1.00
8	4	1.00	4	1.00	4	1.00	4	1.00	4	1.00
9	4	1.00	4	1.00	4	1.00	4	1.00	4	1.00
10	2	1.00	2	1.00	2	1.00	2	1.00	2	1.00
11	1	1.00	1	1.00	1	1.00	1	1.00	1	1.00
Duration [days]	41		34		31		28		27	
Acceleration rate [%]	0		17		24		32		34	
Cost [€]	1686.68		1955.16		1486.26		1450.72		1372.79	

Table 6. *Comparison of optimization rates for various methodologies*

Reference	Time-cost optimization technique	Methodology	Variation on time optimization [%]	Variation on cost optimization [%]	Side effects
[19]	Management improvement	GAs	–4	–3	Interruption
[30]	Crashing	GAs	–35	+7	Congestion
[31]	Fast-tracking	nonlinear programming	–24	+13	Defects, rework, and overloading
This study case	Integrated substitution and management improvement	Ex-μGA	–34	–19	None

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