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Monitoring production time and cost performance by combining earned value analysis and adaptive fuzzy control

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ABSTRACT

This paper presents a new method for measuring and improving production time and cost performance by applying project management concepts and methods. In the context of production and manufacturing industries, we demonstrate how to improve production performance by considering production as a project with limited time and budget in order to track the production progress at any given point of time. The proposed approach is capable of monitoring cost and time of production implementation in an adaptive and real-time fashion. According to the fact that in the production and manufacturing environment, cost and time of fulfilling customer demand can be considered as a measure of production performance, this research applied Earned Value Analysis from project management and integrated it with Gain Scheduling Fuzzy Control to design an adaptive monitoring system to support real-time control of production cost and time. Gain Scheduling Fuzzy Control was used to adapt the monitoring system with different conditions of the production environment. To the best of authors' knowledge, this research is a new application of Fuzzy Adaptive Control in the literature of production and project cost-time performance monitoring. The proposed model in this paper is capable of online monitoring of cost and time performance for different products, at different production periods, and machine centers. The proposed method was implemented successfully in a case study. The results indicated a substantial improvement in production time and cost performance.

1. Introduction

Applying effective methods to support the control of production execution plays a crucial role in the success of any manufacturing system. Without applying sophisticated production performance monitoring systems, success of all production planning activities is in doubt. Looking at the current state of the research in both production planning and production monitoring reveals the fact that much less attention have been paid to developing production performance monitoring systems (Bagherpour & Noori, 2012). On-time and on-budget delivery to the customer is always critical in a successful manufacturing system. However, most of the time production performance is exposed to different kinds of risks and uncertainties (such as rework, failure of machines, lack of material, emergency situations. etc.) resulting in a deviation from plan that leads to delay and over-budget delivery of the products. Here, a real-time estimation of product's completion time and cost during production execution can pave the way for an early detection of any deviations from plans for implementing timely corrective actions.

Despite the advantages of considering time and cost of fulfilling customer demand as key production performance indicators (KPIs), this direction of research remains unexplored yet. However, the problem of monitoring and controlling production performance has been addressed from variety of other aspects. Qi-Zhi (1989) analyzed the fundamentals of an online production control system including control objectives, criteria for identifying potential problems in the forthcoming production period, in particular bottlenecks, and decision-making procedures. Their analysis resulted in the development of a framework for designing a decision support system for online control of production in the discrete manufacturing environments. Stevenson, Hendry, and Kingsman (2005) reviewed different production planning and control approaches including Manufacturing Resource Planning (MRP II), Kanban and Theory of Constrains (TOC), as well as techniques such as Workload Control (WLC), Constant Work In Process (CONWIP), Paired cell

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Overlapping Loops of Cards with Authorization (POLCA) and web- or e-based Supply Chain Management (SCM) solutions. The authors assessed the applicability of different approaches in make-to-order (MTO) industries. They claimed that workload control (WLC) is the most efficient solution for job shop systems. In order to decrease shop floor congestion, WLC applies a pre-shop group of orders which includes a series of short queues. Monostori, Kádár, Pfeiffer, and Karnok (2007) developed a framework for designing an advanced real-time production control, which not only reports on the deviations and problems of the manufacturing system but also suggests possible alternatives to handle them. For detection of changes and disturbances emerging during the daily production, the authors integrated information coming from the process, quality and production monitoring subsystems. Then, the integrated information forms the basis of rescheduling policies.

Another unexplored area in the literature of production monitoring and control is adjustability of such techniques in dynamic production environments. An efficient production performance monitoring technique should be capable of being adjusted to variety of production conditions as the production progresses through different stages. For instance, a performance monitoring approach which is suitable for the beginning of production, where the production is not fully stable, might not be suitable for an advanced stage of production where there is more stability. Few authors addressed the aforementioned problem. Among them, Csáji, Monostori, and Kádár (2006) addressed the limitations of conventional production control approaches in addressing the complexities of today's manufacturing environment such as unexpected tasks and events, non-linearities, and a multitude of interactions while attempting to control various activities in dynamic shop floors. Using machine learning, the authors developed an adaptive iterative distributed scheduling algorithm for a market based production control system considering machine and job as learning and cooperative agents. Xanthopoulos, Koulouriotis, and Gasteratos (2017) proposed two adaptive production control policies named Adaptive Extended Kanban and adaptive Generic Kanban to address problem of highly volatile manufacturing systems such high demand fluctuations. Their developed control policies is capable of adjusting the number of cards in the Kanban system with the aim of minimizing mean Work-In-Process, mean finished goods inventory and mean length of backorders queue under three different demand patterns.

In order to fulfill the aforementioned research gaps in the domain of production monitoring and control, this research aimed to develop a real-time and adaptive production performance monitoring technique by considering the estimation of final cost and completion date of customers' orders, based on actual performance up to any point in time, as two strong measures of production performance. To this end, this research applied Earned Value Analysis (EVA), a powerful project management method, and integrated it with Gain Scheduling Fuzzy Control method, a type of adaptive fuzzy control.

EVA is a method to measure the real physical progress of a project by integrating three critical elements of project management, which are scope, time and cost (PMBOK, 2004). This research applied EVA particularly to estimate cost and time of work at completion as two key measures of production performance. There are limited research on the application of EVA in the context of monitoring production performance. Vitner, Rozenes, and Spraggett (2006) evaluated the performance of a multi-project environment by applying Data Envelopment Analysis (DEA) through integrating an Earned Value Management System (EVMS) and a Multi-dimensional Project Control System (MPCS). As a useful contribution in the project management context, their proposed methodology is also capable of reducing the number of outputs and inputs in order not to exceed the number of projects. Noori, Bagherpour, and Zareei (2008) developed a novel method to control the EV performance indexes by using fuzzy logic and extended the traditional version of the control chart for controlling the trend of SPI/CPI. They addressed the main research gap of lacking a control mechanism that detects current progress of the project quantitatively (numerically via EVA formulas) and qualitatively (categorizing current progress linguistically). The research also contributed to a new application of EVA on a Multi Period-Multi Product production control problem. Noori, Bagherpour, and Zorriasatine (2008) focused exclusively on the Production Planning Problem (PPP) known as Multi Product Multi Period (MPMP) problem using their proposed method in Noori, Bagherpour, and Zareei (2008) without incorporating fuzzy logic since they considered known (certain) production operation sequence for their MPMP problem. Bagherpour, Zareei, Noori, and Heydari (2010) considered job processing time as a fuzzy triangular number in order to develop an EVA-based control technique. Their proposed method was feasible to be used through production control problems as well as project management problems. Their approach addressed the problem of measuring production performance during implementation of production processes. Prediction of the production completion time for delivery to customers is also addressed via their proposed approach. Project tracking as a key success/failure factor of projects is investigated by Vanhoucke (2011) in order to improve performance of project management activities. They presented a top-down and a bottom-up project tracking method that was applied to detect project problems. The bottom-up method was derived from schedule risk analysis and the top-down approach relied on EVA performance metrics. Using EVA, Bagherpour and Noori (2012) addressed cost management problem in production environment. They presented a method to convert the Multi-Period Multi-Product (MPMP) problem to a project management network first, and then after getting performance measures in the lowest level of work breakdown structure of the project, sending the results back to the production environment again. Analyzing the relevant literature revealed that none of the reviewed papers benefits from the potentials of EVA in measuring final cost and time of delivery to the customer as key performance measures of production. Moreover, the adaptability of the monitoring system is missing in the aforementioned works.

Fuzzy logic is applied in this research to deal with uncertainties related to the production environment. In this regards, fuzzy numbers were applied to deal with imprecise numerical quantities (e.g. process time) (Dijkman, Van Haeringen, & De Lange, 1983) and linguistic variables were applied to deal with values that represent linguistic concepts and could not be quantified easily (Zadeh, 1975) (e.g. small or large time variance). Gain Scheduling Fuzzy Control is a type of fuzzy adaptive appropriate for developing rule-based expert systems for the control of dynamic systems Chen and Pham (2000). Despite many successful application of gain scheduling fuzzy controller in the domain of control engineering, application of this method in the context of production cost and time management. However, few researchers applied adaptive fuzzy control in the dominion of production and operations management. Among them Liang and Zhu (2006) aimed at developing a customer loyalty measurement system. They measured and evaluated the degree of customer loyalty by recommending the notion of a loyalty coefficient which was obtained by fuzzy optimization theory. They applied the customer loyalty model to develop a customer loyalty adaptive control technique. Si and Lou (2009) demonstrated how a supply chain management agent is able to adapt itself to the dynamic situation of the market by controlling the profit margin and the target inventory level. They applied a fuzzy heuristic based agent that is capable of negotiating with suppliers and customers. The current research is expected to open a new field in the application of adaptive fuzzy controllers.

In order to assess the applicability of the proposed method, a monitoring system was developed using Matlab software and implemented in the company of case study. The production cost and time performance for two products, three machine centers and one production period were monitored using the data related to the four weeks of model implementation. The analysis of the result revealed a noticeable improvement in the production cost and time performance of the company. The remainder of the current paper is structured as follows.

Section 2 explains the main concepts and state of the art in EVA and Fuzzy Control theory and reviews some related works. In Section 3, the proposed monitoring approach is developed. Section 4 presents the implementation of the model using an illustrative case and the results are discussed. Finally, conclusions and directions for future research are discussed in Section 5.

2. Basic concepts

Before going through the proposed model, the main concepts and state-of-the-art in EVA and fuzzy control theory are briefly explained in this section.

2.1. Earned value analysis

Earned Value Analysis (EVA) method which is often referred to as Earned Value Management (EVM) is a method to measure the real physical progress of a project by integrating three critical elements of project management, which are scope, time and cost. In order to measure project performance, EVA applies several key parameters as follows:

- Planned Value (PV): sum of budgets for all work packages scheduled to be accomplished within a given time period ($PV = \text{percent complete (planned)} \times \text{project budget}$)
- Budget at Completion (BAC): sum of all the budgets allocated to a project.
- Schedule at Completion (SAC): total of all the durations allocated to a project.
- Earned Value (EV): the amount budgeted for performing the work that was accomplished by a given point in time ($EV = \text{percent complete (actual)} \times \text{project budget}$)
- Actual Cost (AC): the cumulative cost spent to a given point in time to accomplish an activity, work package or project and to earn the related value.

To assess the accomplishment level of work activities at any point in time, EVA applies the following performance measures:

- Cost variance ($CV = EV - AC$): the measure of the variance between Earned Value of the project and actual cost. Positive variance indicates an under budget situation.
- Schedule variance ($SV = EV - PV$): the variance between Earned Value and planned value. Positive variance indicates that a project is ahead of schedule.
- Time variance ($TV = \frac{SV}{PV\ \ Rate}$, $PV\ \ Rate = \frac{BAC}{SAC}$): time variance is the schedule variance in time units. The average planned value per time period is called the PV Rate.
- Cost Performance Index ($CPI = \frac{EV}{AC}$): an index showing the efficiency of resource utilization. A CPI value below 1 indicates that resource utilization is poor.
- Schedule Performance Index ($SPI = \frac{EV}{PV}$): an index that shows the efficiency of time utilized on a project from the aspect of schedule. An SPI value above 1 indicates that a project is very efficiently using the time allocated to a project.
- Critical Ratio ($CR = CPI \times SPI$): the indicator of the overall project health. It allows cost and time trade-offs based on project goals.

2.2. Forecasting in earned value analysis

The EVA method is particularly useful in forecasting the (expected) cost and time of the project at completion based on actual performance up to any given point in the project. Anbari (2003) presented different formulas for calculating the Cost Estimate At Completion (CEAC) and the Time Estimate At Completion (TEAC), each of them suitable for a specific condition regarding the future performance of the project. In this research, we focused on three of the conditions defined by Anbari (2003) as follows:

Condition (1)**:** *"when current analysis shows that past cost/schedule performance is not a good predictor of future cost/schedule performance, that problems or opportunities that affected performance in the past will not occur in the future, and that future performance will parallel the original plan"*. Then,

$$CEAC = AC + BAC - EV = BAC - CV \tag{1}$$

$$TEAC = SAC - TV \tag{2}$$

Condition (2)**:** *"when current analysis shows that past cost performance is a good predictor of future cost performance and schedule performance is a good predictor of the future schedule performance, that performance to date will continue into the future, and that efficiencies or inefficiencies observed to date will prevail to completion"*. Then,

$$CEAC = \frac{BAC}{CPI} \tag{3}$$

$$TEAC = \frac{SAC}{SPI} \tag{4}$$

Condition (3)**:** *"if the activity, work package, or project were behind schedule, additional cost would be incurred to bring the project back on schedule, through the use of overtime, additional resources, expediting shipments, and similar actions. On the other hand, if the activity, work package, or project were ahead of schedule, opportunities for significant cost savings may be pursued, although they may require more time as a result of using resources that are fewer in number, less experienced, and/or less skilled "*. The difference between condition (3) and condition (2) is that condition (3) refers to situations where there is a need for trade-offs between cost and time to meet the project's overall goal. However, such cost and time trade-offs are not necessary or applicable in condition (2). Then,

$$CEAC = \frac{BAC}{CR} \tag{5}$$

$$TEAC = \frac{SAC}{CR} \tag{6}$$

Fig. 1 demonstrates CEAC and TEAC trends over time (Anbari, 2003) in relation to a baseline. These figures provide a valuable indicator of the trend in project cost and time performance, and the impact of any corrective actions. Values above the BAC (SAC) baseline indicate a poor project cost (time) performance.

2.3. Fuzzy earned value analysis

In almost all previous research in the area of EVA, performance indexes have been taken into account as deterministic variables. However, in reality, the durations of the activities in a project have some degree of uncertainty that may come from a variety of sources such as rework, weather conditions, delays in supplying material, etc.

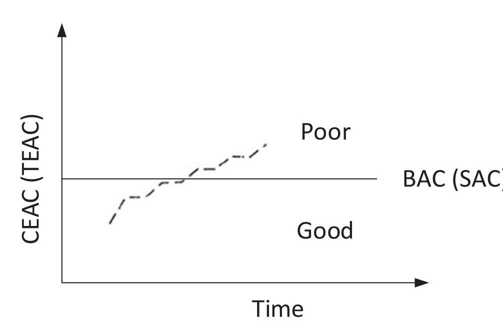

Fig. 1. CEAC (TEAC) trend over time (Anbari, 2003).

To deal with uncertainty related to activity duration when measuring project performance, Bagherpour et al. (2010) demonstrated that activity duration can be represented by a Triangular Fuzzy Number (TFN) shown by (a, b, c) in which a, b and c represent the optimistic, moderate and pessimistic duration of an activity respectively. The authors claimed that the cost of activity also could be considered as a TFN (C_a, C_b, C_c) since the activity duration and cost are related to each other. Here C_a represents the cost related to an optimistic activity duration, C_b represents the cost related to a moderate activity duration, and C_c represents the cost related to a pessimistic activity duration. They applied an α-cut operation to determine the value of the lower bound and the upper bound of the activity duration and its cost to make a crisp interval. The alpha cut of fuzzy number $\tilde{A}$ is shown by $\widetilde{A}^{\alpha}$ and described as follows:

$$\widetilde{A}^{a} = \{xi\colon \mu_{\widetilde{A}}(xi) \geq \alpha,\ xi \in X\}$$

$\widetilde{A}^{a}$ is the set of members of $\tilde{A}$ that have membership degree $(\mu_{\widetilde{A}})$ equal or greater than alpha. Set X represents universal set. The lower bound $(a^{a})$and upper bound (c^{a}) values provided by the alpha cut operation are determined as follows:

$$a^{a} = a + \alpha(b - a)$$

$$c^{a} = c - \alpha(c - b)$$

Thus the activity duration and activity cost of alpha cut equal to (a^{a}, b, c^{a}) and $(C_a^{\alpha}, C_b, C_c^{\alpha})$ respectively. Bagherpour et al. (2010) demonstrate that by changing the value of the alpha cut, the user can control the variation in the estimation of the duration. As it is shown in Fig. 2, higher alpha cut values results in a smaller range for the processing duration.

In the Bagherpour et al. (2010) paper, by considering activity duration and its related cost as TFN and applying them in EVA, three different PVs were generated and since budget at completion was the summation of planned values, three different BACs were calculated as well $(BAC_a^{\alpha}, BAC_b, BAC_c^{\alpha})$ which represented optimistic, moderate and pessimistic budget at completion respectively. Moreover, three different schedule at completion estimates were calculated as well, named SAC_a^{α}, SAC_b and SAC_c^{α} (optimistic, moderate and pessimistic schedule at completion). The EV, which is equals to the multiplication of BAC with the percentage of the work completed, was also extended as follows considering the above concept:

$$EV_{a^{\alpha}} = BAC_a^{\alpha} \times \%\ \text{complete},\quad EV_b = BAC_b \times \%\ \text{complete},\quad EV_{c^{\alpha}} = BAC_c^{\alpha} \times \%\ \text{complete}$$

Bagherpour et al. (2010) extended the EVA performance measures therefore as follows:

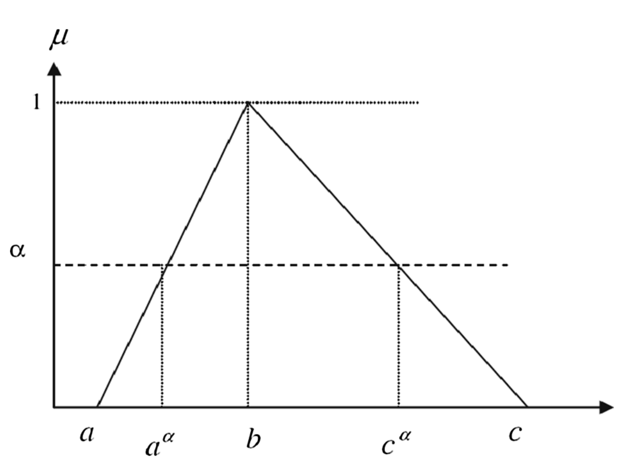

Fig. 2. Triangular fuzzy number (a,b,c) with the alpha-cut Bagherpour et al. (2010).

$$CV_{a^{\alpha}} = EV_{a^{\alpha}} - AC,\quad CV_b = EV_b - AC,\quad CV_{c^{\alpha}} = EV_{c^{\alpha}} - AC$$

$$CPI_{a^{\alpha}} = \frac{EV_a^{\alpha}}{AC},\quad CPI_b = \frac{EV_b}{AC},\quad CPI_{c^{\alpha}} = \frac{EV_c^{\alpha}}{AC}$$

$$SV_{a^{\alpha}} = EV_{a^{\alpha}} - PV_{a^{\alpha}},\quad SV_b = EV_b - PV_b,\quad SV_{c^{\alpha}} = EV_{c^{\alpha}} - PV_{c^{\alpha}}$$

$$SPI_{a^{\alpha}} = \frac{EV_a^{\alpha}}{PV_a^{\alpha}},\quad SPI_b = \frac{EV_b}{PV_b},\quad SPI_{c^{\alpha}} = \frac{EV_c^{\alpha}}{PV_c^{\alpha}}$$

$$TV_{a^{\alpha}} = \frac{SV_{a^{\alpha}}}{PVRate_{a^{\alpha}}},\quad TV_b = \frac{SV_b}{PVRate_b},\quad TV_{c^{\alpha}} = \frac{SV_{c^{\alpha}}}{PVRate_{c^{\alpha}}}$$

$$CR_{a^{\alpha}} = SPI_{a^{\alpha}} \times CPI_{a^{\alpha}},\quad CR_b = SPI_b \times CPI_b,\quad CR_{c^{\alpha}} = SPI_{c^{\alpha}} \times CPI_{c^{\alpha}}$$

2.4. Gain scheduling fuzzy control

Fuzzy control theory has been regarded as one of the greatest applications of theory of fuzzy sets and systems thanks to its successful performance in many industries (Wang, 1993). Adaptive fuzzy control is one of the extensions of the fuzzy control theory for developing controllers in uncertain systems or adjusting parameters of any control system. Gain scheduling, model reference adaptive system, self-tuning regulator, and dual control are demonstrated by Chen and Pham (2000) as four basic approaches of developing adaptive controllers. To control a dynamic system, Gain scheduling combines various controllers together, each one for a specific condition. Then a condition checking procedure is required to determine when each controller should be activated. Two set of rules must be developed in order to design a gain scheduling fuzzy controller: firstly, a set of fuzzy controllers that are effective under certain conditions of a dynamic system, and secondly, a set of meta rules to decide each controller must be activated under which circumstances and provide the most suitable control action based on the monitoring data. These meta rules are generally defined by experts (Chen & Pham, 2000).

3. Proposed model

In this research, the production performance monitoring system was developed by a combination of Earned Value Analysis and a Gain Scheduling Fuzzy Control. Fig. 3 represents the proposed methodology. The pseudo code of the methodology is represented in Algorithm 1. The details of the methodology are given in the following sections.

Algorithm 1: Pseudo code of the proposed methodology

```
Define control limits (see Algorithm 2)
Calculate the last EVA parameters (see Algorithm 3)
Calculate changes between two consequent monitoring (see Algorithm 4)
Switch (meta rules)
  Case past performance not good predictor of future performance :
    Define control rules from Tables 1 and 2
    Define future trends and degree of certainty from formulas 15–20
  Case past time/cost performance good predictor of future time/cost performance:
    Define control rules from Tables 3 and 4
      Define future trends and degree of certainty from Appendix B
    Case past time & cost performance together good predictor of future time/cost p-
erformance
      Define control rules from Tables 5 and 6
      Define future trends and degree of certainty from Appendix D
```

3.1. Define control limits

In line with Section 2.3, by considering activity duration and its related cost as TFN and by applying the alpha cut procedure, three different BACs and SACs were generated (Algorithm 2). Thus, the performance from the aspects of cost and time at completion can be evaluated based on three different control limits. In Fig. 4, the graph of CEAC over time considering three different BACs and consequently

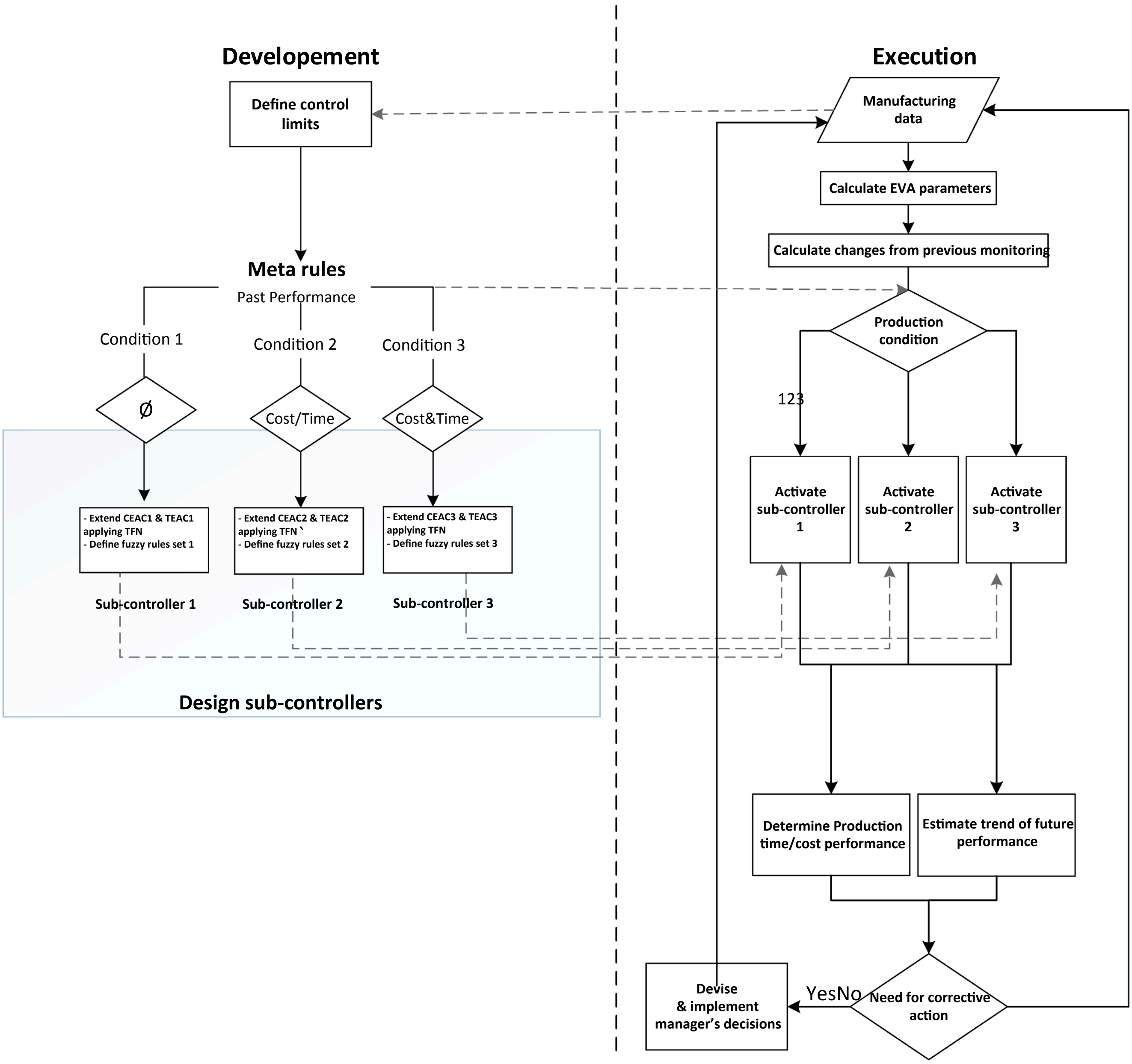

Fig. 3. Proposed methodology.

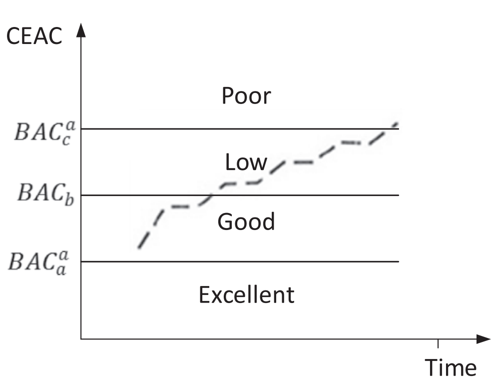

Fig. 4. Graph of CEAC over time considering three different BACs.

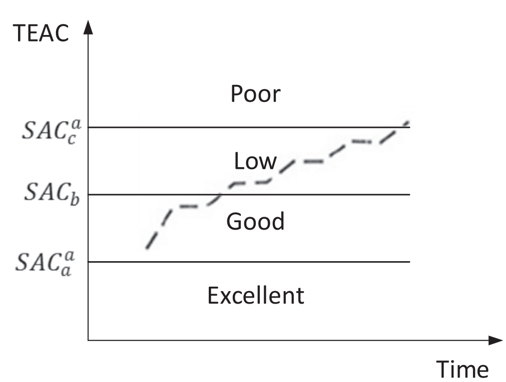

Fig. 5. Graph of TEAC over time considering three different SACs.

Table 1
Cost performance statuses vs. different states of moderate CV.

Moderate cost variance	$CV_b \leq BAC_b - BAC_c^{\alpha}$	$CV_b \leq 0$ and $BAC_b - BAC_c^{\alpha} < CV_b$	$CV_b > 0$ and $CV_b \leq BAC_b - BAC_a^{\alpha}$	$CV_b > BAC_b - BAC_a^{\alpha}$
Cost performance	Poor	Low	Good	Excellent

Table 2
Time performance statuses vs. different states of moderate TV.

Moderate time variance	$TV_b \leq SAC_b - SAC_c^{\alpha}$	$TV_b \leq 0$ and $SAC_b - SAC_c^{\alpha} < TV_b$	$TV_b > 0$ and $TV_b \leq SAC_b - SAC_a^{\alpha}$	$TV_b > SAC_b - SAC_a^{\alpha}$
Time performance	Poor	Low	Good	Excellent

different conditions of cost performance is represented. Fig. 5 illustrates TEAC over time by considering three different SACs and different condition of time performance.

Algorithm 2: Applying alpha-cut to BACs and SACs

Input: BAC_a, BAC_b, BAC_c, SAC_a, SAC_b, SAC_c
Output: Lower bound and upper bound of control limits
1 $BAC_a^{\alpha} = BAC_a + \alpha(BAC_b - BAC_a)$
2 $BAC_c^{\alpha} = BAC_c - \alpha(BAC_c - BAC_b)$
3 $SAC_a^{\alpha} = SAC_a + \alpha(SAC_b - SAC_a)$
4 $SAC_c^{\alpha} = SAC_c - (SAC_c - SAC_b)$

3.2. Developing meta rules

As mentioned earlier, a gain scheduling fuzzy controller consist of several sub-controllers, each of them suitable for a specific situation, and a set of meta rules that determine which sub-controller must be activated at the time of a control action. In developing the proposed control system, first the set of meta rules is developed based on three different conditions of production execution and methods of estimation at completion in each condition (see Section 2.2). These meta rules are as follows:

Meta rule 1: If in time of monitoring production performance, analysis of production processes shows that past cost/time performance is not a good demonstrator of the future cost/time performance (e.g., a situation where production is not stable such as at the beginning of production, new process set up, …) then controller 1 must be activated.

Meta rule 2: If in time of monitoring production performance, analysis of production processes shows that past cost/time performance is a good demonstrator of the future cost/time performance and the achieved performance (up to any point) would continue into the future (e.g., a situation where production is in a stable and routine stage) then controller 2 must be activated.

Meta rule 3: If in time of monitoring production performance, analysis shows that time management and cost management are inseparable and time and cost performance together are good demonstrators of the future cost/time performance (e.g., a situation where adherence to the schedule is important to the company and additional cost can be provided to the system whenever production is behind schedule), then controller 3 must be activated.

3.3. Sub-controller 1

The first sub-controller is designed for controlling production performance when the conditions of meta rule 1 is satisfied. In the first phase, Eqs. (1) and (2) were extended applying the concepts explained in Section 2.3. The extensions are as follows.

$$CEAC_a{}^{\alpha} = BAC_a^{\alpha} - CV_a{}^{\alpha} \tag{7}$$

$$CEAC_b = BAC_b - CV_b \tag{8}$$

$$CEAC_c{}^{\alpha} = BAC_c^{\alpha} - CV_c{}^{\alpha} \tag{9}$$

$$TEAC_a{}^{\alpha} = SAC_a^{\alpha} - TV_a{}^{\alpha} \tag{10}$$

$$TEAC_b = SAC_b - TV_b \tag{11}$$

$$TEAC_c{}^{\alpha} = SAC_c^{\alpha} - TV_c{}^{\alpha} \tag{12}$$

Since we have three different CEACs and TEACs, making a certain decision about the status of production performance is impossible. Based on Bagherpour et al. (2010), we can apply moderate cost and time estimate at completion($CEAC_b$, $CEAC_b$) since they are the most likely CEACs/TEACs at the time of control.

Now, we apply the control limits that are demonstrated in Figs. 4 and 5 to check the current state of cost and time at completion. As an illustration, If the value of $CEAC_b$falls under the BAC_a^{α} baseline (see Fig. 4), it can be concluded that production cost performance is Excellent ($CEAC_b < BAC_a^{\alpha}$). Also, when the value of $TEAC_b$falls under the SAC_a^{α} baseline, the production time performance also is Excellent ($TEAC_b < SAC_a^{\alpha}$). Applying Eqs. (8) and (11), different statuses of production performance versus moderate cost variance and time variance are determined and shown in Tables 1 and 2.

In the second phase, we measure the current cost/time trend by developing two new elements named ΔCV_b and ΔTV_b. These elements represent the difference between current and previous moderate cost/time variance and are calculated as follows.

$$\Delta CV_b = CV_b(t) - CV_b(t-1) \tag{13}$$

$$\Delta TV_b = TV_b(t) - TV_b(t-1) \tag{14}$$

To make it more understandable and applicable for managers in a real world manufacturing environment, ΔCV_b and ΔTV_b are considered as linguistic variables that have three values: small, positive large and negative large, which show a stable, positive and negative performance trend for the future, respectively. These values are described by triangular numbers and part of trapezoidal numbers. The membership functions of three different values of ΔCV_b and ΔTV_b are depicted in Figs. 6 and 7. Note that X% and Y% are values that create the border between small and (positive/negative) large values of ΔCV_b and ΔTV_b, respectively, and need to be determined based on expert knowledge (e.g., production/project manager) based on the characteristics of the production environments. For example, when X% is equal to 4%, up to 4% variation from BAC_b is considered as small. When ΔCV_b grows beyond 4% it would demonstrate a positive large ΔCV_b. The mathematical representation of the membership functions are as follows.

$$\mu_{\text{Negative large}}(\Delta CV_b) = \begin{cases} 1 & -\infty < (\Delta CV_b) \leq -X\%\ BAC_b \\ \frac{-\Delta CV_b}{X\%\ BAC_b} & -X\%\ BAC_b < (\Delta CV_b) \leq 0 \\ 0 & 0 < (\Delta CV_b) < \infty \end{cases} \tag{15}$$

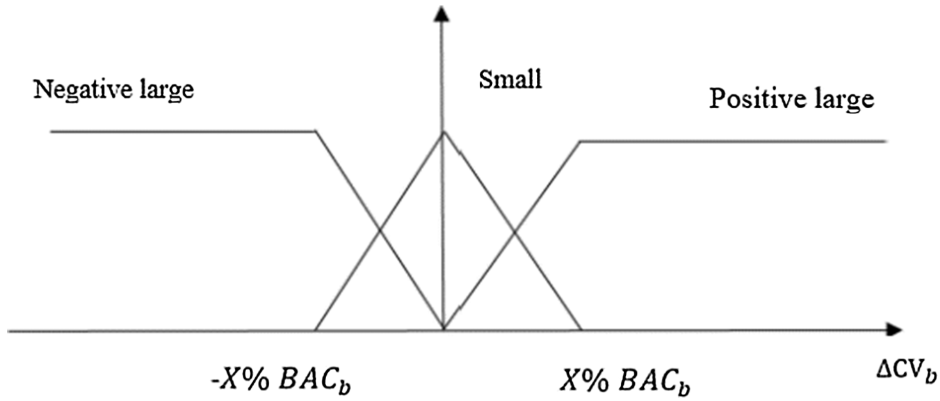

Fig. 6. Membership function of three different values of ΔCV_b.

$$\mu_{Small}\ (\Delta CV_b) = \begin{cases} \frac{(\Delta CV_b + X\%\ BAC_b)}{X\%\ BAC_b} & -X\%\ BAC_b < (\Delta CV_b) \le 0 \\ \frac{(X\%\ BAC_b - \Delta CV_b)}{X\%\ BAC_b} & 0 < (\Delta CV_b) \le X\%\ BAC_b \\ 0 & \text{else} \end{cases} \quad (16)$$

$$\mu_{Positive\ \ large}\ (\Delta CV_b) = \begin{cases} 1 & X\%\ BAC_b < (\Delta CV_b) < \infty \\ \frac{\Delta CV_b}{X\%\ BAC_b} & 0 < (\Delta CV_b) \le X\%\ BAC_b \\ 0 & -\infty < (\Delta CV_b) \le 0 \end{cases} \quad (17)$$

$$\mu_{Negative\ \ large}\ (\Delta TV_b) = \begin{cases} 1 & -\infty < (\Delta TV_b) \le -Y\%\ SAC_b \\ \frac{-\Delta TV_b}{Y\%\ SAC_b} & -Y\%\ SAC_b < (\Delta TV_b) \le 0 \\ 0 & 0 < (\Delta TV_b) < \infty \end{cases} \quad (18)$$

$$\mu_{Small}\ (\Delta TV_b) = \begin{cases} \frac{(\Delta TV_b + Y\%\ SAC_b)}{Y\% SAC_b} & -Y\%\ SAC_b < (\Delta TV_b) \le 0 \\ \frac{(Y\%\ SAC_b - \Delta TV_b)}{Y\%\ SAC_b} & 0 < (\Delta TV_b) \le Y\%\ SAC_b \\ 0 & \text{else} \end{cases} \quad (19)$$

$$\mu_{Positive\ \ large}\ (\Delta TV_b) = \begin{cases} 1 & Y\%\ SAC_b < (\Delta TV_b) < \infty \\ \frac{\Delta TV_b}{Y\%\ SAC_b} & 0 < (\Delta TV_b) \le Y\%\ SAC_b \\ 0 & -\infty < (\Delta TV_b) \le 0 \end{cases} \quad (20)$$

In the third phase, by considering CV_b and ΔCV_b as the input variables and production time/cost performance status and future trend as the output, two sets of fuzzy rules, each one includes 12 rules, are developed for controlling production performance. As an illustration the first three rules for cost performance are shown below.

$R^{(1)}$: If $CV_b > BAC_b - BAC_a^{\alpha}$ and ΔCV_b is small then production cost performance is Excellent and stable.
$R^{(2)}$: If $CV_b > BAC_b - BAC_a^{\alpha}$ and ΔCV_b is positive large then production cost performance is Excellent with positive trend.
$R^{(3)}$: If $CV_b > BAC_b - BAC_a^{\alpha}$ and ΔCV_b is negative large then production cost performance is Excellent with negative trend.

As an illustration, three rules for controlling time performance are as follows.

$R^{(13)}$: If $TV_b > SAC_b - SAC_a^{\alpha}$ and ΔTV_b is small then production time performance is Excellent and stable.
$R^{(14)}$: If $TV_b > SAC_b - SAC_a^{\alpha}$and ΔTV_b is positive large then production time performance is Excellent with positive trend.
$R^{(15)}$: If $TV_b > SAC_b - SAC_a^{\alpha}$ and ΔTV_b is negative large then production time performance is Excellent with negative trend.

A complete list of fuzzy rules is presented in Appen dix A. The membership function of each rule is calculated as a minimum of the membership value of individual inputs. For example the membership value for rules$R^{(1)}$, $R^{(2)}$, $R^{(3)}$are as follows:

$$\mu_{R^{(1)}}(CV_b, \Delta CV_b) = Min\{\mu_{Small}\ (\Delta CV_b),\ \ \mu(CV_b)\} \quad (21)$$

$$\mu_{R^{(2)}}(CV_b, \Delta CV_b) = Min\{\mu_{positive\ \ large}\ (\Delta CV_b),\ \ \mu(CV_b)\} \quad (22)$$

$$\mu_{R^{(2)}}(CV_b, \Delta CV_b) = Min\{\mu_{negative\ \ large}\ (\Delta CV_b),\ \ \mu(CV_b)\} \quad (23)$$

The rule membership function gives the truth degree of the rules and represents the certainty of the status proposed by the rule. In fact, it shows the strength of the rule in detecting the performance status. For example, if the production condition matches with the first rule ($R^{(1)}$) and the membership value of $R^{(1)}$ is equal to 0.8 then it can be concluded that production performance from the aspect of cost at completion is Excellent and stable with a truth degree of 0.8.

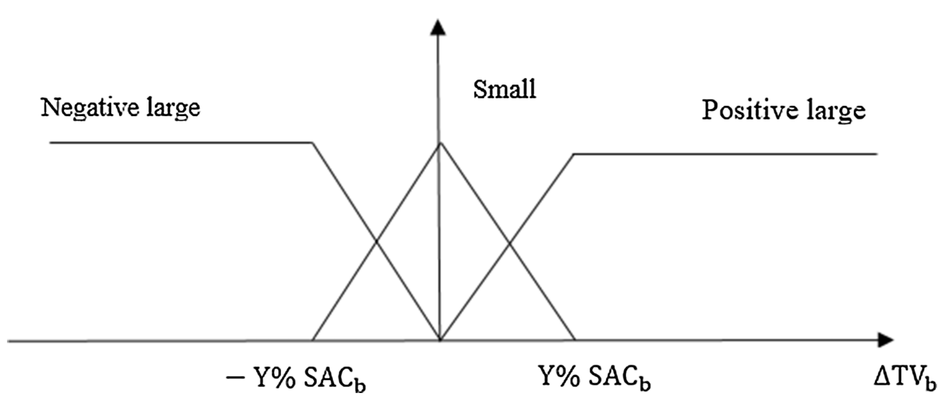

Fig. 7. Membership function of three different values of ΔTV_b.

Table 3
Cost performance statuses vs. different states of moderate CPI.

Moderate cost performance index	$CPI_b \leq \frac{BAC_b}{BAC_c^{\alpha}}$	$CPI_b \leq 1$ and $\frac{BAC_b}{BAC_c^{\alpha}} < CPI_b$	$CPI_b > 1$ and $\frac{BAC_b}{BAC_a^{\alpha}} \geq CPI_b$	$CPI_b > \frac{BAC_b}{BAC_a^{\alpha}}$
Cost performance	Poor	Low	Good	Excellent

Table 4
Time performance statuses vs. different states of moderate SPI.

Moderate schedule performance index	$SPI_b \leq \frac{SAC_b}{SAC_c^{\alpha}}$	$SPI_b \leq 1$ and $\frac{SAC_b}{SAC_c^{\alpha}} < SPI_b$	$SPI_b > 1$ and $\frac{SAC_b}{SAC_a^{\alpha}} \geq SPI_b$	$SPI_b > \frac{SAC_b}{SAC_a^{\alpha}}$
Time performance	Poor	Low	Good	Excellent

3.4. Sub-controller 2

The second sub-controller is activated when the conditions of meta rule 2 are satisfied. To design the second sub-controller, all three phases similar to the design procedure of the first sub-controller are applied. For the first phase, Eqs. (3) and (4) are used to come up with the following moderate forecasts:

$$CEAC_b = \frac{BAC_b}{CPI_b} \tag{24}$$

$$TEAC_b = \frac{SAC_b}{SPI_b} \tag{25}$$

In designing sub-controller 2, Eqs. (24) and (25) are used to determine different condition of production performance versus moderate cost and time performance indexes as shown in Tables 3 and 4.

In the second phase, ΔCPI_b and ΔSPI_b are determined. ΔCPI_brepresents the difference between the current and the previous moderate cost performance index and ΔSPI_b represents the difference between the current and the previous moderate time performance index. The formulas for calculating ΔCPI_b and ΔSPI_b are as follows.

$$\Delta CPI_b = CPI_b(t) - CPI_b(t-1) \tag{26}$$

$$\Delta SPI_b = SPI_b(t) - SPI_b(t-1) \tag{27}$$

$\Delta \mathrm{CPI}_b$ and ΔSPI_b are also linguistic variables with small, positive large and negative large values. The membership functions of the three different values of $\Delta \mathrm{CPI}_b$ and $\Delta \mathrm{SPI}_b$ are depicted in Figs. 8 and 9, respectively. The mathematical interpretation of membership functions are represented in Appendix B.

At the final phase, the fuzzy rules that determine production performance from the aspect of cost at completion using two input variables (CPI_b and ΔCPI_b) and one output variable (cost performance status) are 12 rules of which 3 are depicted below.

$R^{(1)}$: If $CPI_b > \frac{BAC_b}{BAC_a^{\alpha}}$ and $\Delta \mathrm{CPI}_b$ is small then production cost performance is Excellent and stable.
$R^{(2)}$: If $CPI_b > \frac{BAC_b}{BAC_a^{\alpha}}$ and $\Delta \mathrm{CPI}_b$ is positive large then production cost performance is Excellent with a positive trend.
$R^{(3)}$: If $CPI_b > \frac{BAC_b}{BAC_a^{\alpha}}$ and $\Delta \mathrm{CPI}_b$ is negative large then production cost performance is Excellent with a negative trend.

In the same manner, 12 fuzzy rules are also developed to detect production performance from the aspect of time at completion by considering SPI_b and ΔSPI_b as input variables and production time performance as the output variable. The first three are as follows.

$R^{(13)}$: If $SPI_b > \frac{SAC_b}{SAC_a^{\alpha}}$ and $\Delta \mathrm{SPI}_b$ is small then production time performance is Excellent and stable.
$R^{(14)}$: If $SPI_b > \frac{SAC_b}{SAC_a^{\alpha}}$ and $\Delta \mathrm{SPI}_b$ is positive large then production time performance
is Excellent with a positive trend.
$R^{(15)}$: If $SPI_b > \frac{SAC_b}{SAC_a^{\alpha}}$ and $\Delta \mathrm{SPI}_b$ is negative large then production time performance is Excellent with a negative trend.

As it is explained for controller 1, the membership function for a rule equals to the minimum of the memberships values of inputs variables. The complete set of rules of sub-controller 2 are given in Appendix C.

3.5. Sub-controller 3

The third controller is designed based on Eqs. (5) and (6). These equations are expanded as follows by considering job processing time and its cost as TFN:

$$CEAC_b = \frac{BAC_b}{CR_b} \tag{28}$$

$$TEAC_b = \frac{SAC_b}{CR_b} \tag{29}$$

In this controller, Eqs. (28) and (29) are applied to align with Tables 5 and 6. In designing the third controller a linguistic variable named ΔCR_b is introduced as the difference between current and previous moderate critical ratio.

$$\Delta CR_b = CR_b(t) - CR_b(t-1) \tag{30}$$

ΔCR_b can take small, positive large and negative large values. The membership function of the three different values of ΔCR_b is presented in Fig. 10 and its mathematical interpretation is given in Appendix D. Similar to X and Y in sub-controller 1 and 2, the value of Z also is determined by production managers.

Here, 24 fuzzy rules determine production cost and time performance (each one 12 rules). The first 3 rules for cost performance are as follows.

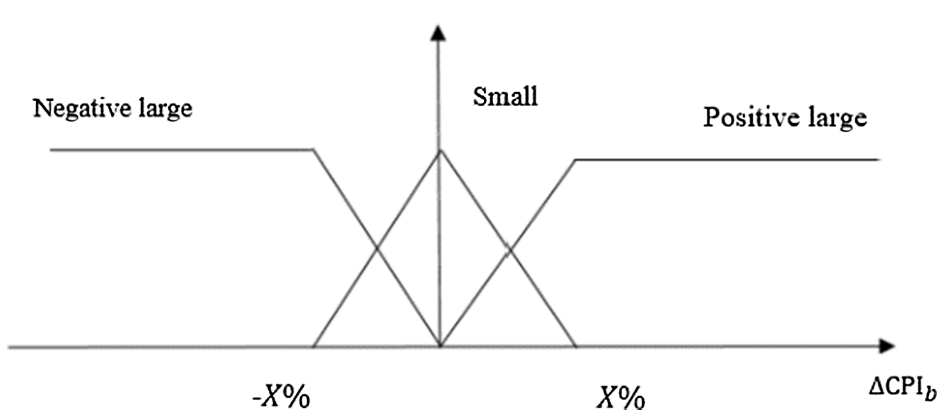

Fig. 8. Membership function of three different values of $\Delta \mathrm{CPI}_b$.

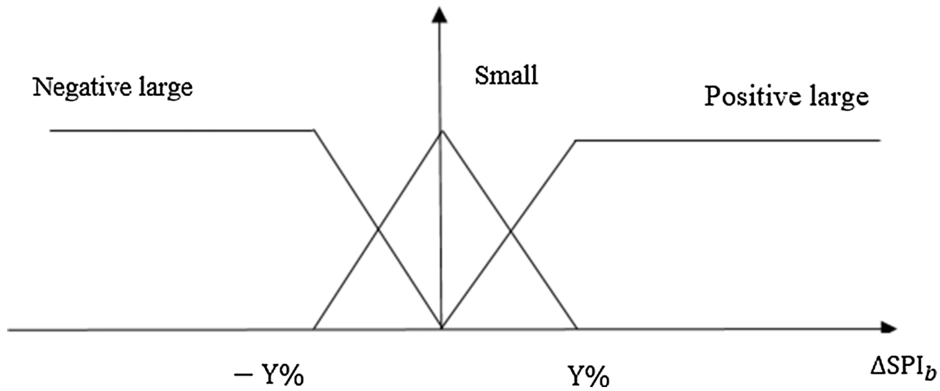

Fig. 9. Membership function of three different values of ΔSPI_b.

Table 5
Cost performance statuses vs. different states of moderate CR.

Moderate critical ratio	$CR_b \le \frac{BAC_b}{BAC_c^\alpha}$	$CR_b \le 1$ and $CR_b > \frac{BAC_b}{BAC_c^\alpha}$	$CR_b > 1$ and $CR_b \le \frac{BAC_b}{BAC_a^\alpha}$	$CR_b > \frac{BAC_b}{BAC_a^\alpha}$
Cost performance	Poor	Low	Good	Excellent

Table 6
Time performance statuses vs. different states of moderate CR.

Moderate critical ratio	$CR_b \le \frac{SAC_b}{SAC_c^\alpha}$	$CR_b \le 1$ and $CR_b > \frac{SAC_b}{SAC_c^\alpha}$	$CR_b > 1$ and $CR_b \le \frac{SAC_b}{SAC_a^\alpha}$	$CR_b > \frac{SAC_b}{SAC_a^\alpha}$
Time performance	Poor	Low	Good	Excellent

$R^{(1)}$: If $CR_b > \frac{BAC_b}{BAC_a^\alpha}$ and ΔCR_b is small then production cost performance is Excellent and stable.
$R^{(2)}$: If $CR_b > \frac{BAC_b}{BAC_a^\alpha}$ and ΔCR_b is positive large then production cost performance is Excellent with a positive trend.
$R^{(3)}$: If $CR_b > \frac{BAC_b}{BAC_a^\alpha}$ and ΔCR_b is negative large then production cost performance is Excellent with a negative trend.
$R^{(13)}$: If $CR_b > \frac{SAC_b}{SAC_a^\alpha}$ and ΔCR_b is small then production time performance is Excellent and stable.
$R^{(14)}$: If $CR_b > \frac{SAC_b}{SAC_a^\alpha}$ and ΔCR_b is positive large then production time performance is Excellent with positive trend.
$R^{(15)}$: If $CR_b > \frac{SAC_b}{SAC_a^\alpha}$ and ΔCR_b is negative large then production time performance is Excellent with negative trend.

Appendix E represents the full set of fuzzy rules for sub-controller 3.

Based on the information given by the developed monitoring system, three types of corrective actions might be recommended. If cost/time performance is Excellent/Good with stable/positive trend, no action is required. If cost/time performance is Poor/Low with negative trend, a major corrective action is required to detect the root of the problem as soon as possible and bring back the performance to the plan by making proper decisions. The cause and effect diagram, a powerful problem-solving tool, can help in this regard. In other situations, only a minor corrective actions are required to make sure that despite of the minor tolerances from original plan, the performance of the system still promises the on-time and on-budget delivery of the products.

3.6. Implementation of the proposed model using MATLAB

The proposed controller was coded in MATLAB software. After identifying the control limits (Algorithm 2), the developed system got the production data to calculate EVA parameters (see Algorithm 3). Defining the production condition, the monitoring system activated the appropriate controller to measure performance (see Algorithm 1). In addition, the system predicted the future trend of the production performance applying Algorithm 4.

Algorithm 3: Calculate the last EVA parameters

Input: $AC(T)$, $PV_b(T)$, $EV_b(T)$
Output: Moderate EVA parameters
1 $CV_b(T) = EV_b(T) - AC(T)$
2 $CPI_b(T) = \frac{EV_b(T)}{AC(T)}$
3 $SV_b(T) = EV_b(T) - PV_b(T)$
4 $SPI_b(T) = \frac{EV_b(T)}{PV_b(T)}$

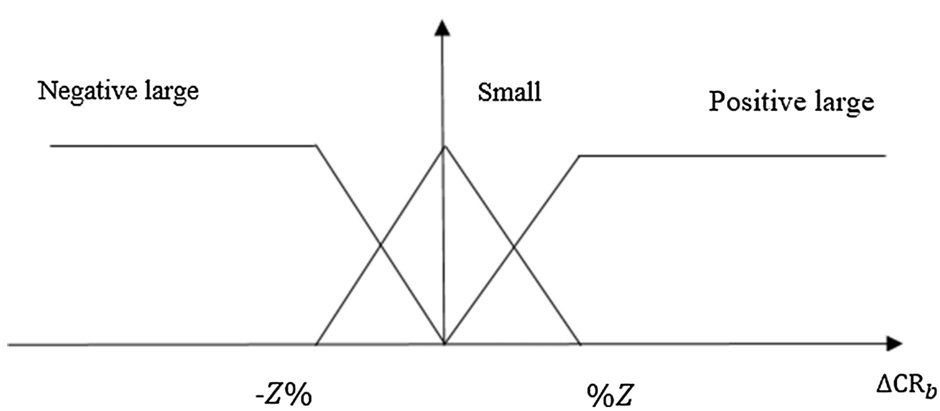

Fig. 10. Membership function of three different values of ΔCR_b.

Algorithm 3: Calculate the last EVA parameters

$PVRate_b(T) = \frac{BAC_b(T)}{SAC_b(T)}$

$TV_b(T) = \frac{SV_b(T)}{PVRate_b(T)}$

$CR_b(T) = SPI_b(T) \times CPI_b(T)$

Algorithm 4: Calculate changes between two consequent monitoring

Input: $EVA\ parameters\ (T),\ EVA\ parameters\ (T-1)$
Output: Δ EVA parameters
For T > 1
$\Delta CV_b = CV_b(T) - CV_b(T-1)$
$\Delta TV_b = TV_b(T) - TV_b(T-1)$
$\Delta CPI_b = CPI_b(T) - CPI_b(T-1)$
$\Delta SPI_b = SPI_b(T) - SPI_b(T-1)$
$\Delta CR_b = CR_b(T) - CR_b(T-1)$

4. Case study

In this section, the implementation of the proposed model in the company of the case study is given, and the results are discussed.

4.1. Implementation of the case study

A manufacturer of different kinds of hydraulic lifts and barriers was selected for implementation of the proposed model. The company had both Make-To-Stock (MTS) and Make-To-Order (MTO) policies to respond to market demand. Since the developed model in this study is useful for pull production systems, two MTO products named A and B were selected for implementation of the proposed model. These two products had to be produced during one production period (four weeks). The demand of each product is illustrated in Table 7. Each product was processed in three machine centers. The route of processes for each product is shown in Table 8. The processing time of each product in each machine center was considered as a triangular fuzzy number and is shown in Table 9. Triangular unit production cost is depicted in Table 10. Four-week data related to Earned Value metrics for period 1, product A, product B, machine center 1, machine center 2 and machine center 3 are illustrated in Table 11. The production condition (see Section 3.2) for each week of monitoring was determined through discussion with production managers of the company and is shown in Table 11 as well. More over the values of X and Y (see Section 3.3) were determined through brainstorm with a group of experts within the company including sales manager, production manager, and company manager. The data for each week was provided to the developed monitoring system and it determined production cost and time performance for each product, each machine center, and the period 1 separately. Table 12 represents the output of the monitoring system at the end of 4 weeks. The graphs of CEACs and TEACs over time are represented in Figs. 11–16.

4.2. Discussion of the results

In this section the results of week 1 and 2 of production monitoring are discussed as an illustration. At the early stages of production execution, there were several problems (Production condition (1): not expected to continue in the future) such as delay in receiving raw materials, preparing machines, preparing parts drawings and specifications, etc. This situation resulted in the activation of sub-controller 1 for determining production performance at the end of week 1 of production. In this week, machine center 1 (MC1) had a Good performance from the aspect of cost performance. It implied that CEAC for MC1 in week 1 was more than its optimistic budget at completion and less than its moderate budget at completion and it was expected that production in MC1 would have a cost lower than the baseline budget. The monitoring system represented the degree of certainty of the proposed performance as well. For MC1 the certainty of a Good performance was 100%. Moreover, from the aspect of time performance MC1 showed a Low performance during week 1, which means that the estimated time at completion for MC1 in week 1 is more than its moderate schedule at completion and less than its pessimistic schedule at completion and it was predicted that production in MC1 would take a longer time than planned. The certainty of the Low performance was 100%. The Low time performance in MC1 was an indicator of a problem in that machine center. The investigation detected a problem with Low performance of a less skilled operator in this center. It must be mentioned that monitoring of the production performance started in week 1 and there was not any previous information about production performance, so it was impossible to detect the trend of performance in week 1 and it could only be determined from week 2 onward. Moreover, since there was not any production plan for machine center 2 and machine center 3 in week 1, only the performance of machine center 1 was determined. For the products, the cost performance of producing both product A and B were Good which implied that products A and B were produced with a price similar or lower than the baseline budget. Also, the certainty of having a Good performance was 100%. However, the time performance for both products A and B were Low with a certainty of 100%. Such a Low time performance was the result of the Low performance in machine center 1. For the period 1, cost performance was Good and time performance was Low with a certainty of 100%.

At the end of week 2 of production, sub-controller 2 was activated to measure performance since the production was more stable and it was estimated that performance of that week was a good predictor for future performance. For the machine centers, the monitoring system detected that in machine center 1, cost performance was Low and stable with truth degree of 0.043. Moreover, there was a possibility of Low cost performance with a negative trend with a truth degree of 0.95 which implied that the situation of cost performance would be getting worse in future with certainty of 95 percent. This was an indicator of a serious

Table 7
Customer demand for period 1.

Period product	1
A	11
B	12

Table 8
Machine center processing order.

Product	Machine Center		
A	MC1	MC2	MC3
B	MC1	MC2	MC3

Table 9
Triangular processing time in machine centers (hour).

Machine Center Product	MC1	MC2	MC3
A	(18,21,24)	(15,18,21)	(17,21,25)
B	(7,9,11)	(5,7,8)	(6,8,11)

Table 10
Triangular unit production cost.

Product	Unit production cost
A	(7200,7500,7800)
B	(1100,1300,1500)

Table 11
Detailed information of production during 4 weeks (period1).

Week	Dimension	AC	PV_b	EV_b	BAC_a	BAC_b	BAC_c	SAC_a	SAC_b	SAC_c	Condition
1	Machine center 1	21,900	23,100	22,400	33,645	34,725	36,017	282	339	396	1
1	Machine center 2	0	0	0	27,427	29,300	30,540	225	282	327	1
1	Machine center 3	0	0	0	31,328	34,075	37,243	259	327	407	1
1	Product A	17,800	19,200	18,900	79,200	82,500	85,800	550	660	770	1
1	Product B	4100	3900	3500	13,200	15,600	18,000	216	288	360	1
1	Period 1	21,900	23,100	22,400	92,400	98,100	103,800	766	948	1130	1
2	Machine center 1	32,400	34,725	31,900	33,645	34,725	36,017	282	339	396	2
2	Machine center 2	21,100	21,964	20,700	27,427	29,300	30,540	225	282	327	2
2	Machine center 3	0	0	0	31,328	34,075	37,243	259	327	407	2
2	Product A	44,900	47,437	44,400	79,200	82,500	85,800	550	660	770	2
2	Product B	8600	9252	8200	13,200	15,600	18,000	216	288	360	2
2	Period 1	53,500	56,689	52,600	92,400	98,100	103,800	766	948	1130	2
3	Machine center 1	34,100	34,725	33,800	33,645	34,725	36,017	282	339	396	2
3	Machine center 2	26,800	29,300	27,500	27,427	29,300	30,540	225	282	327	2
3	Machine center 3	21,600	22,662	21,700	31,328	34,075	37,243	259	327	407	2
3	Product A	69,600	72,825	70,500	79,200	82,500	85,800	550	660	770	2
3	Product B	12,900	13,862	12,500	13,200	15,600	18,000	216	288	360	2
3	Period 1	82,500	86,687	83,000	92,400	98,100	103,800	766	948	1130	2
4	Machine center 2	35,000	34,725	34,725	33,645	34,725	36,017	282	339	396	3
4	Machine center 3	28,300	29,300	28,900	27,427	29,300	30,540	225	282	327	3
4	Machine center 1	24,800	34,075	29,300	31,328	34,075	37,243	259	327	407	3
4	Product A	74,500	82,500	78,175	79,200	82,500	85,800	550	660	770	3
4	Product B	13,600	15,600	14,750	13,200	15,600	18,000	216	288	360	3
4	Period 1	88,100	98,100	92,925	92,400	98,100	103,800	766	948	1130	3

problem in MC1 and triggered the managers for applying a major corrective action in this center. They replaced the low skilled operator with another operator which resulted in a stable (rather than a negative) trend, and a positive cost performance trend in weeks 3 and 4 respectively. The company's experts confirmed that the production performance status proposed by the monitoring system were compatible with the actual performance of the system to a degree of around 90%. By using this technique in the manufacturing environment, the production performance trend can be monitored easily, and managers are able to analyze production performance and detect any unusual or negative performance. In this case study, the fluctuation in the production time and cost performance came from variety of sources of uncertainty related to the manufacturing environment such as machine break downs, less skilled workers, delay in receiving materials from suppliers, modification in product design, etc. Analyzing the information generated by the proposed system helps manager in executing early corrective actions can improve the production performance effectively. In order to show the effectiveness of the proposed method, historical data of four weeks of production, prior to implementation of the proposed approach, were analyzed and compared with the production data of the four weeks of model implementation. As it was shown in Table 13, the application of the proposed approach resulted in the improvement of cost and time of delivery to the customer significantly. Although this research applied the data related to only four weeks of production, due to the research constraints, the prediction of the future performance can be made more effectively using the moving average.

5. Conclusions

This paper proposed a real-time and adaptive time-cost performance measurement system for manufacturing organizations by integrating EVA from the domain of project management and gain scheduling fuzzy control. This monitoring system estimates time and cost at completion based on actual performance up to any point of time continuously during production execution to detect any over-time or over-budget performance of production. In order to incorporate uncertainties in the estimation of cost and time at completion, activity duration and its related costs were considered as fuzzy numbers. The adaptiveness of the proposed system refers to its ability to adjust the control parameters based on different conditions of production execution (e.g. stable, uncertain). In this regard, the Gain Scheduling Fuzzy Control method was applied to develop a set of fuzzy rules based on different methods of calculating CEAC and TEAC. Then a set of meta rules were defined to determine which set of rules must be activated at each time based on the condition of production execution. In developing the fuzzy rules, linguistic variables were used to deal with variables which are hard to quantify.

This research represents a novel application of project management methods and concepts in manufacturing and production area. Looking at production environment from project management perspective enabled us to come up with a novel method to monitor and consequently improve cost and time at completion significantly. The model ensures on-time and on-budget delivery of the product to the customers. With the help of the proposed method, significant improvements achieved for the case company. Average over-budget decreased from 25% to 7%. Average over-time (late delivery) also improved from 20% to 4%. Both figures demonstrated substantial improvements in time and cost progress in the case company.

The proposed method in this study has a remarkable role in practice. Considering uncertainties of the production and manufacturing environment, the proposed technique helps production and manufacturing managers to monitor conformity of production progress to the planned budget and schedule and perform timely actions when production is going to go out of budget or delayed. Also, decision makers can check whether there is enough money and time to fulfill customer demand whenever needed. The last but not least viable assistance for production managers is the ability to measure production time and cost performance for different products, in different machine center and different periods.

This study can be extended in the following directions:

- A user interface can be designed to apply the proposed model which helps production managers in monitoring the production performance continuously during production implementation.
- The efficiency of different production planning methods can be measured by applying the proposed monitoring approach in order to determine which one is the most efficient system for having an on-time and on-budget delivery to the customers.

Table 12
Output of the proposed system in 4 weeks (period1).

		Week 1			Week 2			Week 3			Week 4		
		Performance	Future trend	Degree of certainty	Performance	Future trend	Degree of certainty	Performance	Future trend	Degree of certainty	Performance	Future trend	Degree of certainty
MC1	**Cost**	Good	–	1	Poor	Stable	0.04	Poor	Stable	0.83	Poor	Stable	0.32
						Negative trend	0.96		Positive trend	0.17		Positive trend	0.68
	Time	Poor	–	1	Worse	Negative trend	1	Poor	Positive trend	1	Poor	Stable	0.32
												Positive trend	0.68
MC2	**Cost**	–	–	1	Poor	–	1	Good	Positive trend	1	Good	Stable	0.08
												Positive trend	0.92
	Time	–	–	1	Poor	–	1	Poor	Stable	0.90	Good	Stable	0.08
										0.10		Positive trend	0.92
MC3	**Cost**	–	–	1	–	–	1	Good	–	1	Good	Positive trend	1
	Time	–	–	1	–	–	1	Poor	–	1	Good	Positive trend	1
Product A	**Cost**	Good	–	1	Poor	Negative trend	1	Good	Stable	0.40	Poor	Stable	0.73
									Positive trend	0.60		Positive trend	0.27
	Time	Poor	–	1	Poor	Negative trend	1	Poor	Stable	0.20	Poor	Stable	0.73
									Positive trend	0.80		Positive trend	0.27
Product B	**Cost**	Good	–	1	Poor	Positive trend	1	Poor	Stable	0.61	Good	Positive trend	1
									Positive trend	0.39			
	Time	Poor	–	1	Worse	Stable	0.72	Poor	Stable	0.61	Good	Positive trend	1
						Negative trend	0.38		Positive trend	0.39			
Period 1	**Cost**	Good	–	1	Poor	Stable	1	Good	Stable	0.43	Poor	Stable	0.16
									Positive trend	0.57		Positive trend	0.84
	Time	Poor	–	1	Poor	Negative trend	1	Poor	Stable	0.26	Poor	Stable	0.16
									Positive trend	0.74		Positive trend	0.84

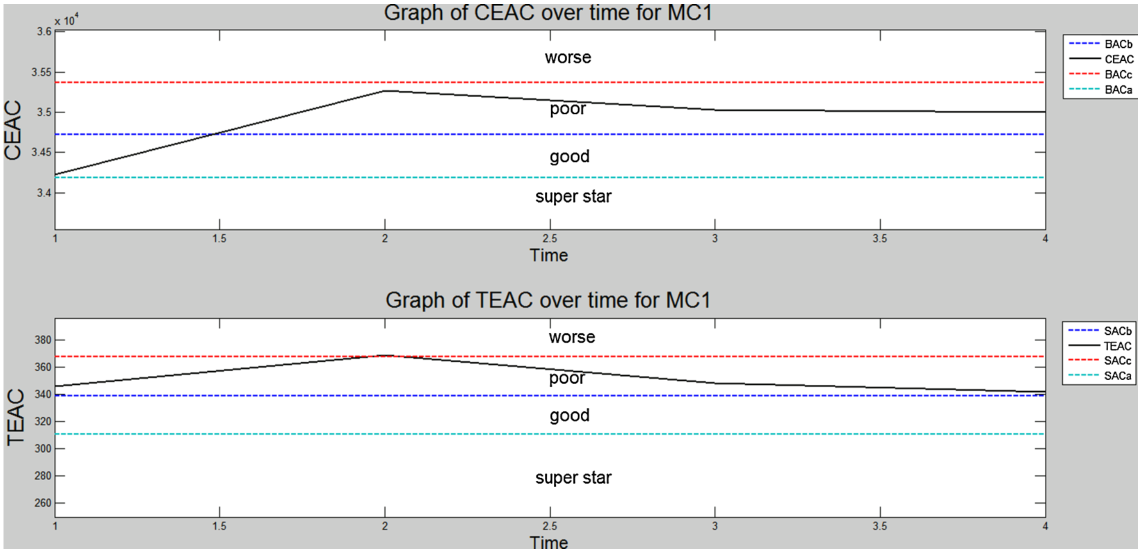

Fig. 11. Graph of CEAC and TEAC over time for machine center 1.

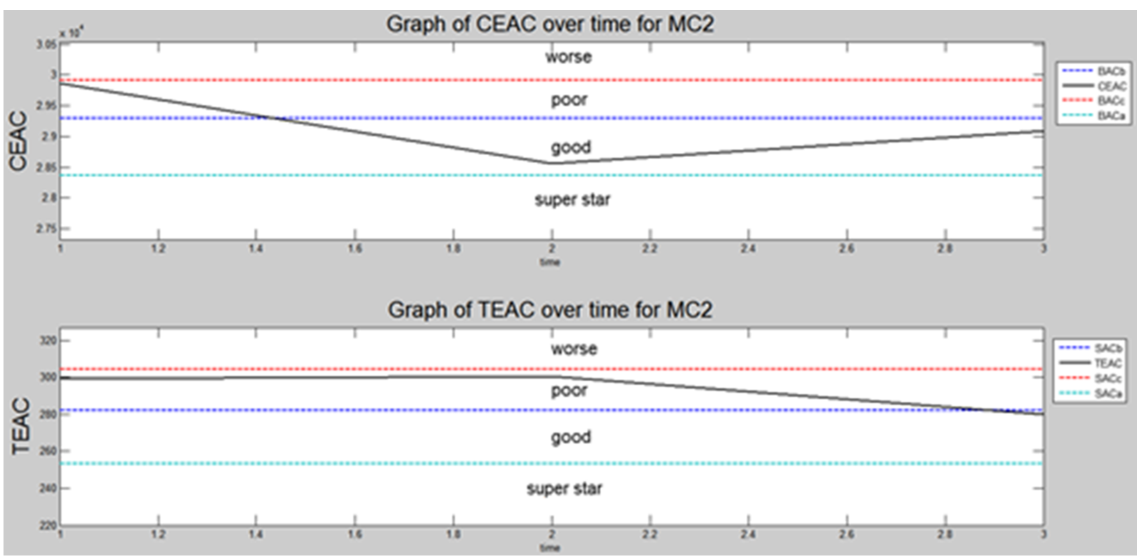

Fig. 12. Graph of CEAC and TEAC over time for machine center 2.

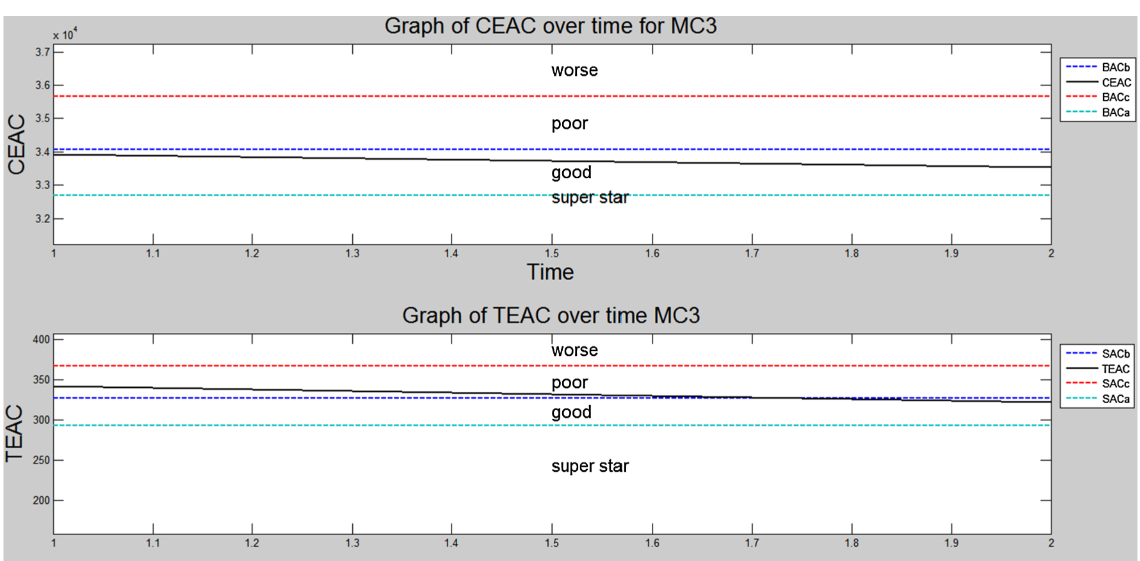

Fig. 13. Graph of CEAC and TEAC over time for machine center 3.

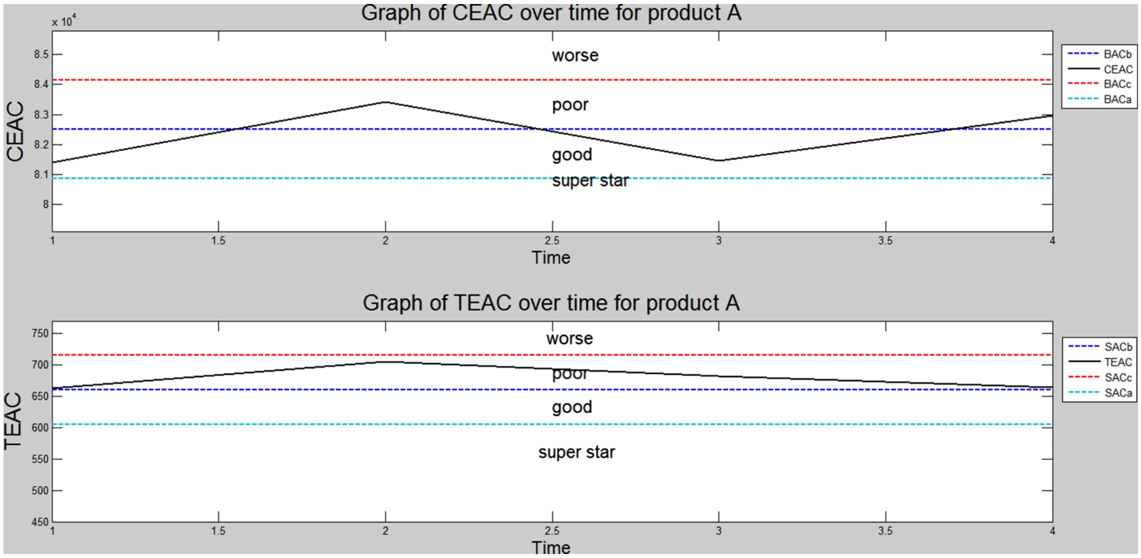

Fig. 14. Graph of CEAC and TEAC over time for product A.

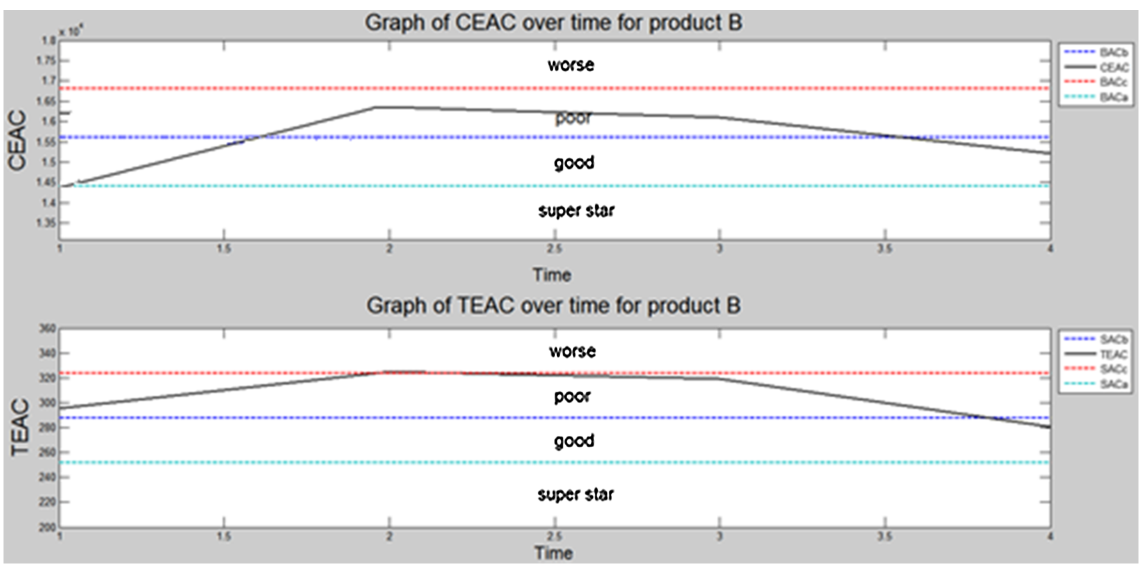

Fig. 15. Graph of CEAC and TEAC over time for product B.

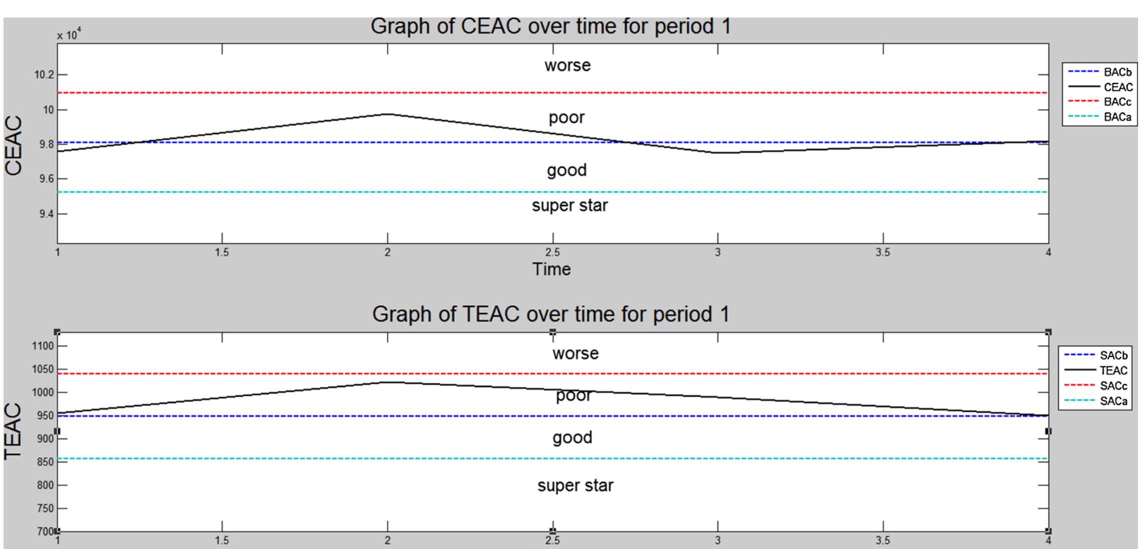

Fig. 16. Graph of CEAC and TEAC over time for period 1.

Table 13
Comparison of production performance at the end of a 4-week period before and after applying the proposed method.

Production performance measure	With proposed method	Without proposed method
Cost at completion	Average 7% over-budget	Average 25% over-budget
Time at completion	Average 5% delay in delivery time	Average 20% delay in delivery time

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Appendix A. Complete set of rules of sub-controller 1

$R^{(1)}$: If $CV_b > BAC_b - BAC_a^a$ and ΔCV_b is small then production cost performance is excellent and stable.
$R^{(2)}$: If $CV_b > BAC_b - BAC_a^a$ and ΔCV_b is positive large then production cost performance is excellent with positive trend.
$R^{(3)}$: If $CV_b > BAC_b - BAC_a^a$and ΔCV_b is negative large then production cost performance is excellent with negative trend.
$R^{(4)}$: If $0 < CV_b \le BAC_b - BAC_a^a$ and ΔCV_b is small then production cost performance is good and stable.
$R^{(5)}$: If $0 < CV_b \le BAC_b - BAC_a^a$ and ΔCV_b is positive large then production cost performance is good with positive trend.
$R^{(6)}$: If $0 < CV_b \le BAC_b - BAC_a^a$ and ΔCV_b is negative large then production cost performance is good with negative trend.
$R^{(7)}$: If $BAC_b - BAC_c^a < CV_b \le 0$ and $\Delta CV_b$is small then production cost performance is low and stable.
$R^{(8)}$: If $BAC_b - BAC_c^a < CV_b \le 0$ and $\Delta CV_b$is positive large then production cost performance is low with positive trend.
$R^{(9)}$: If $BAC_b - BAC_c^a < CV_b \le 0$ and $\Delta CV_b$is negative large then production cost performance is low with negative trend.
$R^{(10)}$: If $CV_b \le BAC_b - BAC_c^a$and ΔCV_b is small then production cost performance is poor and stable.
$R^{(11)}$: If $CV_b \le BAC_b - BAC_c^a$ and ΔCV_b is positive large then production cost performance is poor with positive trend.
$R^{(12)}$: If $CV_b \le BAC_b - BAC_c^a$ and ΔCV_b is negative large then production cost performance is poor with negative trend.
$R^{(13)}$: If $TV_b > SAC_b - SAC_a^a$ and ΔTV_b is small then production time performance is in excellent and stable condition
$R^{(14)}$: If $TV_b > SAC_b - SAC_a^a$and ΔTV_b is positive large then production time performance is excellent with positive trend.
$R^{(15)}$: If $TV_b > SAC_b - SAC_a^a$and ΔTV_b is negative large then production time performance is excellent with negative trend.
$R^{(16)}$: If $0 < TV_b \le SAC_b - SAC_a^a$ and ΔTV_b is small then production time performance is good and stable.
$R^{(17)}$: If $0 < TV_b \le SAC_b - SAC_a^a$ and ΔTV_b is positive large then production time performance is good with positive trend.
$R^{(18)}$: If $0 < TV_b \le SAC_b - SAC_a^a$ and ΔTV_b is negative large then production time performance is good with negative trend.
$R^{(19)}$: If $SAC_b - SAC_c^a < TV_b \le 0$ and $\Delta TV_b$is small then production time performance is low and stable.
$R^{(20)}$: If $SAC_b - SAC_c^a < TV_b \le 0$ and $\Delta TV_b$is positive large then production time performance is low with positive trend.
$R^{(21)}$: If $SAC_b - SAC_c^a < TV_b \le 0$ and $\Delta TV_b$is negative large then production time performance is low with negative trend.
$R^{(22)}$: If $TV_b \le SAC_b - SAC_c^a$ and ΔTV_b is small then production time performance is poor and stable.
$R^{(23)}$: If $TV_b \le SAC_b - SAC_c^a$ and $\Delta TV_b$is positive large then production time performance is poor with positive trend.
$R^{(24)}$: If $TV_b \le SAC_b - SAC_c^a$ and $\Delta TV_b$is negative large then production time performance is poor with negative trend.

Appendix B. Mathematical interpretation of membership function of three different values of ΔCPI_b and ΔSPI_b

$$\mu_{\text{Negative large}}(\Delta \mathrm{CPI_b}) = \begin{cases} 1 & -\infty < (\Delta \mathrm{CPI_b}) \le -X\% \\ \frac{-\Delta \mathrm{CPI_b}}{X\%} & -X\% < (\Delta \mathrm{CPI_b}) \le 0 \\ 0 & 0 < (\Delta \mathrm{CPI_b}) < \infty \end{cases}$$

$$\mu_{\text{Small}}(\Delta \mathrm{CPI_b}) = \begin{cases} \frac{(\Delta \mathrm{CPI_b} + X\%)}{X\%} & -X\% < (\Delta \mathrm{CPI_b}) \le 0 \\ \frac{(X\% - \Delta \mathrm{CPI_b})}{X\%} & 0 < (\Delta \mathrm{CPI_b}) \le X\% \\ 0 & \text{else} \end{cases}$$

$$\mu_{\text{Positive large}}(\Delta \mathrm{CPI_b}) = \begin{cases} 1 & X\% < (\Delta \mathrm{CPI_b}) < \infty \\ \frac{\Delta \mathrm{CPI_b}}{X\%} & 0 < (\Delta \mathrm{CPI_b}) \le X\% \\ 0 & -\infty < (\Delta \mathrm{CPI_b}) \le 0 \end{cases}$$

$$\mu_{\text{Negative large}}(\Delta \mathrm{SPI_b}) = \begin{cases} 1 & -\infty < (\Delta \mathrm{SPI_b}) \le -Y\% \\ \frac{-\Delta \mathrm{SPI_b}}{Y\%} & -Y\% < (\Delta \mathrm{SPI_b}) \le 0 \\ 0 & 0 < (\Delta \mathrm{SPI_b}) < \infty \end{cases}$$

$$\mu_{\text{Small}}(\Delta \mathrm{SPI_b}) = \begin{cases} \frac{(\Delta \mathrm{SPI_b} + Y\%)}{Y\%} & -Y\% < (\Delta \mathrm{SPI_b}) \le 0 \\ \frac{(Y\% - \Delta \mathrm{SPI_b})}{Y\%} & 0 < (\Delta \mathrm{SPI_b}) \le Y\% \\ 0 & \text{else} \end{cases}$$

$$\mu_{\text{Positive large}}(\Delta\text{SPI}_b) = \begin{cases} 1 & Y\% < (\Delta\text{SPI}_b) < \infty \\ \frac{\Delta\text{SPI}_b}{Y\%} & 0 < (\Delta\text{SPI}_b) \le Y\% \\ 0 & -\infty < (\Delta\text{SPI}_b) \le 0 \end{cases}$$

Appendix C. Complete set of rules of sub-controller 2

$R^{(1)}$: If $CPI_b > \frac{BAC_b}{BAC_a^{\alpha}}$ and ΔCPI_b is small then production cost performance is excellent and stable.
$R^{(2)}$: If $CPI_b > \frac{BAC_b}{BAC_a^{\alpha}}$ and ΔCPI_b is positive large then production cost performance is excellent with positive trend.
$R^{(3)}$: If $CPI_b > \frac{BAC_b}{BAC_a^{\alpha}}$ and ΔCPI_b is negative large then production cost performance is excellent with negative trend.
$R^{(4)}$: If $1 < CPI_b \le \frac{BAC_b}{BAC_a^{\alpha}}$ and ΔCPI_b is small then production cost performance is good and stable.
$R^{(5)}$: If $1 < CPI_b \le \frac{BAC_b}{BAC_a^{\alpha}}$ and ΔCPI_b is positive large then production cost performance is good with positive trend.
$R^{(6)}$: If $1 < CPI_b \le \frac{BAC_b}{BAC_a^{\alpha}}$ and ΔCPI_b is negative large then production cost performance is good with negative trend.
$R^{(7)}$: If $\frac{BAC_b}{BAC_c^{\alpha}} < CPI_b \le 1$ and $\Delta\text{CPI}_b$is small then production cost performance is low and stable.
$R^{(8)}$: If $\frac{BAC_b}{BAC_c^{\alpha}} < CPI_b \le 1$ and $\Delta\text{CPI}_b$is positive large then production cost performance is low with positive trend.
$R^{(9)}$: If $\frac{BAC_b}{BAC_c^{\alpha}} < CPI_b \le 1$ and $\Delta\text{CPI}_b$is negative large then production cost performance is low with negative trend.
$R^{(10)}$: If $CPI_b \le \frac{BAC_b}{BAC_c^{\alpha}}$ and ΔCPI_b is small then production cost performance is poor and stable.
$R^{(11)}$: If $CPI_b \le \frac{BAC_b}{BAC_c^{\alpha}}$ and ΔCPI_b is positive large then production cost performance is poor with positive trend.
$R^{(12)}$: If $CPI_b \le \frac{BAC_b}{BAC_c^{\alpha}}$ and ΔCPI_b is negative large then production cost performance is poor with negative trend.
$R^{(13)}$: If $SPI_b > \frac{SAC_b}{SAC_a^{\alpha}}$ and ΔSPI_b is small then production time performance is excellent and stable.
$R^{(14)}$: If $SPI_b > \frac{SAC_b}{SAC_a^{\alpha}}$ and ΔSPI_b is positive large then production time performance is excellent with positive trend.
$R^{(15)}$: If $SPI_b > \frac{SAC_b}{SAC_a^{\alpha}}$ and ΔSPI_b is negative large then production time performance is excellent with negative trend.
$R^{(16)}$: If $1 < SPI_b \le \frac{SAC_b}{SAC_a^{\alpha}}$ and ΔSPI_b is small then production time performance is good and stable.
$R^{(17)}$: If $1 < SPI_b \le \frac{SAC_b}{SAC_a^{\alpha}}$ and ΔSPI_b is positive large then production time performance is good with positive trend.
$R^{(18)}$: If $1 < SPI_b \le \frac{SAC_b}{SAC_a^{\alpha}}$ and ΔSPI_b is negative large then production time performance is good with negative trend.
$R^{(19)}$: If $\frac{SAC_b}{SAC_c^{\alpha}} < SPI_b \le 1$ and $\Delta\text{SPI}_b$is small then production time performance is low and stable.
$R^{(20)}$: $\frac{SAC_b}{SAC_c^{\alpha}} < SPI_b \le 1$ and $\Delta\text{SPI}_b$is positive large then production time performance is low with positive trend.
$R^{(21)}$: $\frac{SAC_b}{SAC_c^{\alpha}} < SPI_b \le 1$and $\Delta\text{SPI}_b$is negative large then production time performance is low with negative trend.
$R^{(22)}$: If $SPI_b \le \frac{SAC_b}{SAC_c^{\alpha}}$ and ΔSPI_b is small then production time performance is poor and stable.
$R^{(23)}$: If $SPI_b \le \frac{SAC_b}{SAC_c^{\alpha}}$ and ΔSPI_b is positive large then production time performance is poor with positive trend.
$R^{(24)}$: If $SPI_b \le \frac{SAC_b}{SAC_c^{\alpha}}$ and ΔSPI_b is negative large then production time performance is poor with negative trend.

Appendix D. Mathematical interpretation of membership function of three different values of ΔCR_b

$$\mu_{\text{Negative large}}(\Delta\text{CR}_b) = \begin{cases} 1 & -\infty < (\Delta\text{CR}_b) \le -Z\% \\ \frac{-\Delta\text{CR}_b}{Z\%} & -Z\% < (\Delta\text{CR}_b) \le 0 \\ 0 & 0 < (\Delta\text{CR}_b) < \infty \end{cases}$$

$$\mu_{\text{Small}}(\Delta\text{CR}_b) = \begin{cases} \frac{(\Delta\text{CR}_b + Z\%)}{Z\%} & -Z\% < (\Delta\text{CR}_b) \le 0 \\ \frac{(Z\% - \Delta\text{CR}_b)}{Z\%} & 0 < (\Delta\text{CR}_b) \le Z\% \\ 0 & \text{else} \end{cases}$$

$$\mu_{\text{Positive large}}(\Delta\text{CR}_b) = \begin{cases} 1 & Z\% < (\Delta\text{CR}_b) < \infty \\ \frac{\Delta\text{CR}_b}{Z\%} & 0 < (\Delta\text{CR}_b) \le Z\% \\ 0 & -\infty < (\Delta\text{CR}_b) \le 0 \end{cases}$$

Appendix E. Complete set of rules of sub-controller 3

$R^{(1)}$: If $CR_b > \frac{BAC_b}{BAC_a^{\alpha}}$ and ΔCR_b is small then production cost performance is excellent and stable.
$R^{(2)}$: If $CR_b > \frac{BAC_b}{BAC_a^{\alpha}}$ and ΔCR_b is positive large then production cost performance is excellent with positive trend.
$R^{(3)}$: If $CR_b > \frac{BAC_b}{BAC_a^{\alpha}}$and ΔCR_b is negative large then production cost performance is excellent with negative trend.
$R^{(4)}$: If $1 < CR_b \le \frac{BAC_b}{BAC_a^{\alpha}}$ and ΔCR_b is small then production cost performance is good and stable.

$R^{(5)}$: If $1 < CR_b \leq \frac{BAC_b}{BAC_a^{\alpha}}$and ΔCR_b is positive large then production cost performance is good with positive trend.

$R^{(6)}$: If $1 < CR_b \leq \frac{BAC_b}{BAC_a^{\alpha}}$ and ΔCR_b is negative large then production cost performance is good with negative trend.

$R^{(7)}$: If $\frac{BAC_b}{BAC_c^{\alpha}} < CR_b \leq 1$ and ΔCR_b is small then production cost performance is low and stable.

$R^{(8)}$: If $\frac{BAC_b}{BAC_c^{\alpha}} < CR_b \leq 1$ and ΔCR_b is positive large then production cost performance is low with positive trend.

$R^{(9)}$: If $\frac{BAC_b}{BAC_c^{\alpha}} < CR_b \leq 1$ and ΔCR_b is negative large then production cost performance is low with negative trend.

$R^{(10)}$: If $CR_b \leq \frac{BAC_b}{BAC_c^{\alpha}}$ and ΔCR_b is small then production cost performance is poor and stable.

$R^{(11)}$: If $CR_b \leq \frac{BAC_b}{BAC_c^{\alpha}}$ and ΔCR_b is positive large then production cost performance is poor with positive trend.

$R^{(12)}$: If $CR_b \leq \frac{BAC_b}{BAC_c^{\alpha}}$ and ΔCR_b is negative large then production cost performance is poor with negative trend.

$R^{(13)}$: If$CR_b > \frac{SAC_b}{SAC_a^{\alpha}}$ and ΔCR_b is small then production time performance is excellent and stable.

$R^{(14)}$: If $CR_b > \frac{SAC_b}{SAC_a^{\alpha}}$ and ΔCR_b is positive large then production time performance is excellent with positive trend.

$R^{(15)}$: If $CR_b > \frac{SAC_b}{SAC_a^{\alpha}}$ and ΔCR_b is negative large then production time performance is excellent with negative trend.

$R^{(16)}$: If $1 < CR_b \leq \frac{SAC_b}{SAC_a^{\alpha}}$ and ΔCR_b is small then production time performance is good and stable.

$R^{(17)}$: If $1 < CR_b \leq \frac{SAC_b}{SAC_a^{\alpha}}$ and ΔCR_b is positive large then production time performance is good with positive trend.

$R^{(18)}$: If $1 < CR_b \leq \frac{SAC_b}{SAC_a^{\alpha}}$ and ΔCR_b is negative large then production time performance is good with negative trend.

$R^{(19)}$: If $\frac{SAC_b}{SAC_c^{\alpha}} < CR_b \leq 1$and ΔCR_b is small then production time performance is low and stable.

$R^{(20)}$: If $\frac{SAC_b}{SAC_c^{\alpha}} < CR_b \leq 1$ and ΔCR_b is positive large then production time performance is low with positive trend.

$R^{(21)}$: If $\frac{SAC_b}{SAC_c^{\alpha}} < CR_b \leq 11$ and ΔCR_b is negative large then production time performance is low with negative trend.

$R^{(22)}$: If $CR_b \leq \frac{SAC_b}{SAC_c^{\alpha}}$ and ΔCR_b is small then production time performance is poor and stable.

$R^{(23)}$: If $CR_b \leq \frac{SAC_b}{SAC_c^{\alpha}}$ and ΔCR_b is positive large then production time performance is poor with positive trend.

$R^{(24)}$: If $CR_b \leq \frac{SAC_b}{SAC_c^{\alpha}}$ and ΔCR_b is negative large then production time performance is poor with negative trend.

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