International journal of innovation in Engineering

journal homepage: www.ijie.ir

Research Paper

Adaptive Project Monitoring and Control with Variable Reviewing Intervals

Seyed Taha Hossein Mortaji[a], Siamak Noori[b]*, Morteza Bagherpour[c]

[a] *PhD, Industrial Engineering Department, Iran University of Science and Technology, Tehran, Iran.*

[b] *Associate Professor, Industrial Engineering Department, Iran University of Science and Technology, Tehran, Iran*

[c] *Assistant Professor, Industrial Engineering Department, Iran University of Science and Technology, Tehran, Iran.*

ARTICLE INFO

Received: 25 September 2021

Reviewed: 11 October 2021

Revised: 17 October 2021

Accepted: 29 October 2021

Keywords:

Statistical Project Control, Variable Reviewing Intervals, Adaptive Control Points, Earned Value Management, Project Monitoring and Control

ABSTRACT

This paper presents a managerial project control scheme in which the time between the control points is not fixed but instead is a function of the distance between the planned and the current performance levels. Varying the reviewing interval improves the efficiency of the project monitoring and control process and allows project managers to obtain the required information more quickly. To evaluate the effectiveness of the proposed scheme, a systematic computational experiment is carried out. Besides, a practical case study is given to illustrate the applicability of the proposed scheme. The results reveal the satisfactory performance of the adaptive control scheme.

1. Introduction

Today, projects are becoming more and more complex since they are unique undertakings with varying degrees of uncertainty and unpredictability executing in a context full of assumptions and constraints. These uncertainties affect the project's objectives so that few projects finish without time and/or cost overruns (Qazi, Dikmen, & Birgonul, 2020; Mortaji, Noori, & Bagherpour, 2021; Mortaji, Bagherpour, & Noori, 2013). That is why the project monitoring and control process, which includes those activities required to track, review, and regulate the project progress, is of particular importance and needs to be effectively applied throughout the project life cycle (Hussain, Barber, & Hussain, 2009). The main objective of this process is to evaluate the project performance level to minimize deviations from the project's objectives and meet the time, cost, and quality requirements. For this purpose, projects need to be regularly monitored to detect possible deviations and take preventive and/or corrective measures (such as re-baselining and re-scheduling) in a timely manner. Therefore, the use of an efficient project control system is required to keep the project on the right track (Patanakul, Shenhar, & Milosevic, 2012; Aminian, Rahimi Nejad, Mortaji, & Bagherpour, 2016).

The main objectives of an efficient project control system are twofold. On the one hand, it aims to provide project managers with information on the current performance level as well as information about the future project trends (Orgut, Batouli, Zhu, Mostafavi, & Jaselskis, 2020). In this regard, Earned Value Management (EVM) is the most well-known project control system which has attracted a lot of attention both in practice and research. On the other hand, since the project monitoring and control process is cost-wise prohibitive, a project control system should be able to determine the appropriate number and timing of control points (Mortaji, Bagherpour, & Mahdavi Mazdeh, 2013). In this regard, there are few studies and the problem has received scant attention in the research literature (Mortaji & Hosseinzadeh, 2021).

There are different schemes for the application of a project control system. The standard control scheme requires that a set of performance indicators be calculated in the fixed reviewing intervals. In this scheme, which has been recently improved with the use of statistical control charts, project performance is monitored at some pre-specified fixed control points. However, from a practical point of view, it is more efficient to change the level of control according to the performance level. As the level of control increases, potential failures such as project cost overruns and delays can be avoided by taking preventive actions at appropriate times. However, the cost and duration of those activities required to track, review, and regulate the progress will be substantially increased. Decreasing the level of control may also be risky, because it may result in a failure to achieve the project objectives. Therefore, determining the appropriate timing of control points is one of the most important parts of an efficient control system.

By paying close attention to the project-specific characteristics and using statistical techniques, this paper proposes an adaptive control scheme in which the time between control points is not fixed but instead is a function of the distance of the current performance level from the target value. The idea behind the adaptive control scheme is to dynamically deal with the possible dynamics that exist in the project life cycle. For this purpose, if the current performance level is close enough to the target value so that there is no indication of possible disruption, the time to the next control point will be lengthened. Otherwise, as the performance level deviates from the target, it might be reasonable to reduce the time to the next control point.

2. Literature Review

Earned value management (EVM) is one of the most well-known project control systems which has attracted a lot of attention both in practice and research (Fleming & Koppelman, 2010; Armani, Gibson Jr, El Asmar, & Cho, 2021). EVM measures both the project time and cost performance by providing a set of straightforward metrics. EVM key parameters include planned value (PV) or the budgeted cost of work scheduled, earned value (EV) or the budgeted cost of work performed, and the actual cost (AC) of work performed. Using these key parameters, EVM performance indicators are obtained including cost performance index (CPI), that is the ratio of EV to AC, i.e. CPI=EV/AC, and schedule performance index (SPI), that is the ratio of EV to PV, i.e. SPI=EV/PV. Considering the current project performance, EVM also predicts the future project trends by summing up the incurred cost (or the passed time) and the planned cost (or the planned time of work remaining) (Leon, Osman, Georgy, & Elsaid, 2018).

In recent years, EVM and its extensions have been widely used in practice due to their applicability in evaluating the current and future performance of the projects (Lipke, 2009; Khamooshi & Golafshani, 2014; Dodson, Defavari, & Carvalho, 2015; Khesal, Saghaei, Khalilzadeh, Rahiminezhad Galankashi, & Soltani, 2019; Mortaji, Noori, & Bagherpour, 2021). Also, there has been an increasing interest in the use of statistical control charts for monitoring project performance which has led to a relatively large volume of published papers in this context (Willems & Vanhoucke, 2015). Statistical project control charts make it possible to discriminate between acceptable and non-acceptable variations and also allow project managers to take preventive and corrective actions more quickly and at a lower cost. In these charts, while the project performance falls within the acceptable area, the project is assumed to be in control. Otherwise, a warning signal is generated if the project performance deviates from the target value. In this case, if there is a negative gap, corrective and/or preventive actions are taken to bring the project back on the right track. On the contrary, actions such as re-baselining can be taken to exploit the possible opportunities.

Much of the current literature on the statistical project control pays particular attention to the use of univariate control charts (such as individuals, individuals-moving range, and cumulative sum control charts) to monitor the project's cost and schedule performance indicators (Lipke & Vaughn, 2000; Bauch & Chung, 2001; Wang, Jiang, Gou, Che, & Zhang, 2006; Leu & Lin, 2008; Aliverdi, Moslemi Naeni, & Salehipour, 2013; Mortaji, Noorossana, & Bagherpour, 2015; Salehipour, Naeni, Khanbabaei, & Javaheri, 2016; Mortaji, Noori, Noorossana, & Bagherpour, 2017). However, Some researchers have adopted a broader perspective and attempted to simultaneously monitor performance indicators by the use of multivariate control charts (such as Hotelling's T^2 control chart) (Sogandi, Mousavi, & Amiri, 2018; Hadian & Rahimifard, 2019).

Despite the importance of determining the appropriate number and timing of control points, which is one of the most important parts of an efficient project control system, the literature in this context is still scarce and only a few numbers of researchers have sought to address this topic. For example, Partovi and Burton (1993) evaluated the effectiveness of five different control-timing policies using computer simulation. De Falco and Macchiaroli (1998) proposed a nonlinear effort function of the total number of active operations at each interval and the total slack time. Tareghian and Salari (2009) determined the number and timing of control points with the use of simulation-optimization methods. Raz and Erel (2000) used dynamic programming to determine the timing of control points based on the assumption that the passage of time leads to the loss of some information. To determine the optimal control efforts, Kogan et al. (2002) developed a continuous model based on the relationship between control efforts and deviations related to the cost of projects. Sabeghi et al. (2015) developed a customized version of the facility-location model to determine the optimal timing of control points in the project lifecycle. They also proposed a model to simulate possible disruptions between the start of the project and the first control point whereby the maximum control coverage is achieved (Sabeghi & Tareghian, 2020).

3. Methodology

The above-reviewed literature suggests a role for the application of statistical control charts in the project monitoring and control process. However, much of the current literature on this topic has a static control scheme on determining the number and timing of control points wherein the time between control points is constant and specified at the beginning of the project. Project managers usually prefer to have continuous monitoring and control to quickly identify any areas requiring special attention. This type of control seems to be the most effective type of control. However, it is time-consuming and very expensive. On the other hand, decreasing the level of control may also be costly, because it significantly increases the risk of not achieving the project's objectives and failing to meet the time, budget, and quality constraints (Sols, 2018). Thus, the most important question that needs to be addressed is to determine the time of control points in such a way that the project performance is appropriately monitored while the control efforts remain minimal. In the following, this paper seeks to address this question by paying close attention to the current performance level of the project and using statistical techniques. For this purpose, a simple but effective control scheme is proposed in which the time to the next control point is defined as a function of the current performance level. In this control scheme, if there is evidence that the project performance is off-target, it makes sense to increase the level of control. Hence, the time until the next control point will be shortened. Otherwise, by approaching the project performance to the target, there is no need to evaluate the project performance immediately. Hence, the time until the next control point will be lengthened. It is expected that the use of adaptive control points improves the project monitoring and control process by obtaining the required information more quickly. It is also expected to reduce the control efforts needed to track, review, and regulate the progress, whereby the project's objectives can be achieved at a lower cost.

4. Adaptive Project Monitoring and Control with Variable Reviewing Intervals

The proposed control scheme is based on the geometric moving average (GMA) statistic which incorporates information from all the previous control points. GMA statistic at time t, say z_t, is defined as:

$$z_t = \lambda \sum_{j=0}^{t-1} (1-\lambda)^j PI_{t-j} + (1-\lambda)^t z_0 \quad (1)$$

Equation (1) can be simplified to:

$$z_t = \lambda PI_t + (1-\lambda) z_{t-1} \quad (2)$$

in which $0 \leq \lambda \leq 1$ is a constant, PI_t is the performance indicator at control point t, and the starting value (z_0) is the performance target (Montgomery, 2013). Since project managers prefer to be on-budget (CPI=1) and on-schedule (SPI=1), the target value is assumed to be equal to 1 meaning that the actual progress is expected to be equal to the planned progress.

The proposed adaptive control chart is then constructed by plotting z_t versus t (or the elapsed time) at each control point. The centerline, and the lower and upper control limits for the adaptive control chart are also defined as follows:

$$LCL = Target - k\sigma_{z_t} \tag{3}$$

$$CL = Target \tag{4}$$

$$UCL = Target + k\sigma_{z_t} \tag{5}$$

where k is a constant indicating the width of the control limits and σ_{z_t} represents the standard deviation of z_t which is calculated as follows in which $\hat{\sigma}$ is the desired standard deviation of the performance level.

$$\sigma_{z_t} = \hat{\sigma}\sqrt{\left(\frac{\lambda}{2-\lambda}\right)[1-(1-\lambda)^{2t}]} \tag{6}$$

In the standard control scheme, the length of the time between control points is assumed to be fixed. However, as stated earlier, it is intuitively reasonable to vary the length of the time between control points concerning the current performance level. For this purpose, assume that we have a finite number of interval lengths $d_1, \ldots, d_m$ where $0 < d_1 \leq d_2 \leq \cdots \leq d_m$. The minimum possible interval length of the time between two control points can be determined by physical considerations such as the shortest amount of time that is required to record the actual progress, while the maximum possible interval length can be determined by the longest amount of time that is reasonable to continue the project without monitoring its actual progress. For the sake of simplicity, consider the case where the distance between the upper and lower control limits splits into two parts, such that

$$LCL \leq LWL \leq CL \leq UWL \leq UCL \tag{7}$$

in which LWL and UWL are the lower and upper warning limits, respectively. If the value of z_t at a particular control point falls between LWL and UWL, it means that the project performance tends to be around the target and there is no indication of a possible performance change. Hence the longest possible reviewing interval should be selected for the next control point. Otherwise, if $LCL \leq z_t \leq LWL$ or $UWL \leq z_t \leq UCL$, there may be some indications of a possible performance change. Hence, the shortest possible reviewing interval should be selected for the next control point. This two-state adaptive control scheme for the timing of control points is formulated by the following function and displayed in Figure 1.

$$Reviewing\ Interval = \begin{cases} L & LCL < z < LWL \\ S & LWL \leq z \leq UWL \\ L & UCL < z < UWL \end{cases} \tag{8}$$

where L is the longest possible reviewing interval and S is the shortest possible reviewing interval. The lower and upper warning limits are also calculated from:

$$LWL = Target - k'\sigma_{z_t} \tag{9}$$

$$UWL = Target + k'\sigma_{z_t} \tag{10}$$

in which k' indicates the control level controlling the preventive sensitivity of the adaptive control chart. By adding this adaptive feature to the statistical project control, the time required to detect unacceptable performance variations will be substantially reduced. Besides, the cost and duration of those activities required to track, review, and regulate the progress will be reduced, and therefore the overall quality of the project can be significantly improved.

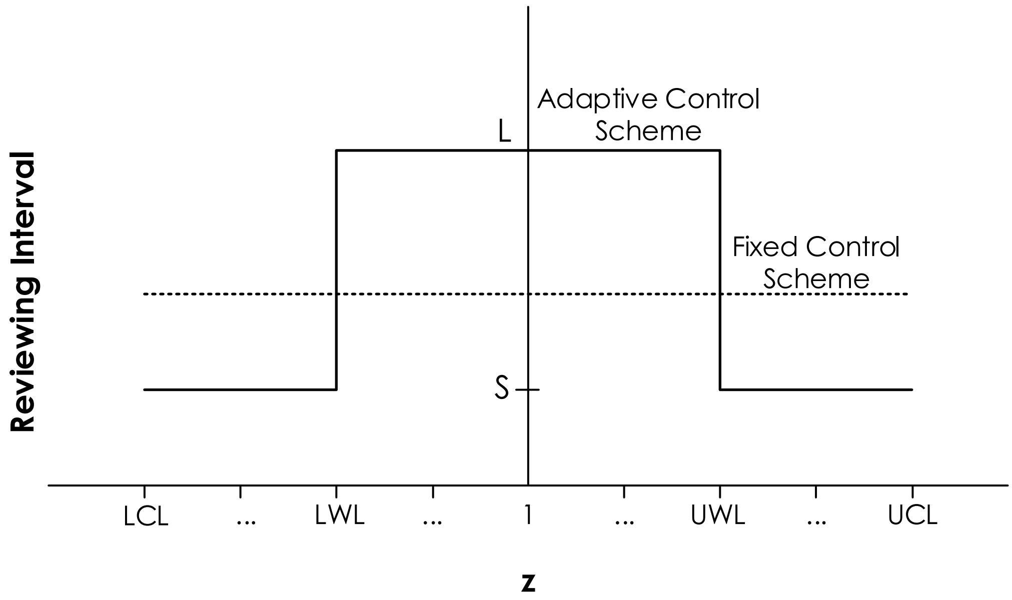

Figure 1. Reviewing interval functions for adaptive and fixed control schemes.

5. Case Study: A Construction Project

In the next section, a comprehensive experimental design will be developed to shed light on the various aspects of the proposed approach. However, to address the dynamics of the real projects, the performance of the proposed approach needs to be examined from both theoretical and practical points of view. To this end, this section illustrates how the cost performance of a construction project is monitored through the adaptive control scheme. This project is a medium residential construction project in which condos and townhomes have been constructed in 200 working days. For illustrative purposes, the cost performance indicators of this project have been calculated in the 5-day periods and the results have been summarized in Table 1.

Table 1. Cost performance indicators of the project in 5-day periods.

Day	*CPI*	*Day*	*CPI*	*Day*	*CPI*	*Day*	*CPI*
5	0.993	55	0.956	105	1.030	155	0.763
10	0.985	60	0.950	110	0.958	160	0.794
15	1.010	65	0.898	115	0.959	165	0.753
20	1.034	70	0.845	120	0.960	170	0.712
25	1.047	75	0.857	125	1.018	175	0.701
30	1.059	80	0.868	130	1.077	180	0.689
35	1.032	85	0.937	135	1.053	185	0.863
40	1.004	90	1.006	140	1.030	190	1.037
45	0.984	95	1.054	145	0.881	195	0.910
50	0.963	100	1.102	150	0.732	200	0.783

Starting from day 140, the main contractor has been changed resulting in a decrease in the cost performance level. To compare the efficiency of the fixed and adaptive control schemes in the early detection of this change with the minimal control activities, individuals, moving range and GMA control charts (with both the fixed and adaptive control points) are going to be drawn. For this purpose, the parameters of the adaptive control scheme are chosen to be $\lambda = 0.3$, $k = 2.925$, $S = 5$ days, $L = 20$ days, $\hat{\sigma} = 0.1$, and $k' = 0.664$ to have an in-control average time to signal approximately equal to 370. Also, the target value is assumed to be $z_0 = 1$. In the fixed control scheme, the time between control points is constant and the performance level is examined in 10-day intervals, i.e. day=10, 20, …, 200. However, the adaptive control scheme determines the time until the next control point as a function of the current performance level. In this regard, if the performance level at the first control point (day=10) be close enough to the target value, the longest possible reviewing interval, i.e. 20 days, is selected and the next control point is on day=10+20=30. Otherwise, if the performance level deviates from the target value and falls outside the warning limits, the next control point is on day=10+5=15. Table 2 provides the information needed to construct the adaptive control chart.

Table 2. Details of the adaptive control scheme.

t	*Day*	*CPI*	σ_{z_t}	*LCL*	*LWL*	*UWL*	*UCL*	z_t	*Next Control Point (Day)*
0	0	-	-	-	-	-	-	1	-
1	10	0.985	0.03	0.912	0.980	1.020	1.088	0.996	30
2	30	1.059	0.036	0.893	0.976	1.024	1.107	1.015	50
3	50	0.963	0.03946	0.885	0.974	1.026	1.115	0.999	70
4	70	0.845	0.04078	0.881	0.973	1.027	1.119	0.953	75
5	75	0.857	0.041411	0.879	0.973	1.027	1.121	0.924	80
6	80	0.868	0.041717	0.878	0.972	1.028	1.122	0.907	85
7	85	0.937	0.041866	0.878	0.972	1.028	1.122	0.916	90
8	90	1.006	0.041939	0.877	0.972	1.028	1.123	0.943	95
9	95	1.054	0.041974	0.877	0.972	1.028	1.123	0.976	115
10	115	0.959	0.041992	0.877	0.972	1.028	1.123	0.971	120
11	120	0.950	0.042	0.877	0.972	1.028	1.123	0.965	125
12	125	1.018	0.042004	0.877	0.972	1.028	1.123	0.981	145
13	145	0.881	0.042006	0.877	0.972	1.028	1.123	0.951	150
14	150	0.732	0.042007	0.877	0.972	1.028	1.123	0.885	155
15	155	0.763	0.0420	0.877	0.972	1.028	1.123	0.848	-

As is apparent from Table 2, while the performance level is around the target, there is no reason to shorten the reviewing interval. By understanding this concept, the reviewing intervals in the first 70 days, in which the performance levels fall between the lower and upper warning limits, have been increased to 20 days. By doing so, the control efforts have been significantly reduced compared to the fixed reviewing interval control scheme in which the project progress is measured in 10-day intervals. However, once the performance level falls outside the warning limits but inside the control limits, the natural inclination is to shorten the reviewing interval as much as possible. For example, since $z_4 = 0.953$ (day 70) is outside the warning limits but inside the control limit, the next reviewing interval has been shortened to 5 days and the next control point ($t = 5$) is on the 75th day. For illustrative purposes, Figure 2 displays the constructed control charts with both fixed and adaptive control schemes.

Figure 2. Individuals, moving range, and GMA control charts with fixed and adaptive control points.

The most striking result to emerge from this Figure is that the proposed adaptive control scheme reduces the control efforts needed to track, review, and regulate the progress, and therefore the associated control costs can be arguably reduced if the project performance level is around the target value. For example, unlike the fixed control scheme, wherein there are seven control points in the first 70 days, the proposed control scheme only requires four control points to monitor the project's performance at the same time. Examination of Figure 2 also reveals that although the I control chart and GMA control chart with fixed reviewing interval require four and three control points (i.e. 40 and 30 days) to detect the change in performance level arising from the contractor's change on the 140th day, the proposed control chart with the adaptive control scheme detects this change in 15 days after the change has taken place (at day 140) and a signal has been generated at day 155.

6. Performance Evaluation

To evaluate the effectiveness of the proposed control chart in detecting the abnormal behavior of project performance, it is important to show how quickly this control chart detects a change in the project performance level. It is also important to have a low false alarm rate, which happens when the control chart indicates an out-of-control situation in the project performance level, while no assignable cause is present. An efficient way to evaluate this effectiveness is to measure the average time to signal (ATS) of the proposed control chart, which is the expected time to generate an out-of-control signal when the project is out-of-control. ATS can also be used as a measure to indicate the false alarm rate if it is calculated when a project is in control. ATS is calculated by multiplying the average run length (ARL) that is the expected number of points that must be plotted before a point indicates an out-of-control state, and the reviewing interval, as follows:

$$ATS = ARL \times h \tag{11}$$

For the sake of convenience, it is reasonable to take the reviewing interval as the unit of time. For example, if the project control team reviews the project performance biweekly, then the time unit can be considered as a two-week period. By doing so, the numerical value of ARL will be the same as the numerical value of ATS. When the project performance level is near the target value, ATS should be increased to avoid false alarms. Similarly, when the project performance level tends to deviate from the target, ATS should be decreased to reveal the possible deviations.

The method usually used for obtaining the average time to signal of a control chart is the Markov chain method in which the interval between the lower and upper control limits is discretized into $2m+1$ states, E_j, $j=-m,\dots,0,\dots,m$. Then, GMA statistic at the control point t, say z_t, is assumed to be in-control only if $z_t \in E_j$. Otherwise, z_t is in the out-of-control state, E_a. Therefore, the average time to signal would be defined as follows:

$$ATS = \boldsymbol{p}^{\boldsymbol{T}}(I-R)^{-1}\boldsymbol{b} = \boldsymbol{p}^{\boldsymbol{T}}Q\boldsymbol{b} \quad (12)$$

where $\boldsymbol{p}$ represents the transition probability matrix containing the one-step transition probabilities, $\boldsymbol{p}^{\boldsymbol{T}}$ is the initial probability vector containing the probabilities that the GMA statistic starts in a particular state, I is the identity matrix, R is a submatrix of the in-control one-step transition probabilities, and $\boldsymbol{b}$ is the vector of control points corresponding to the discretized states of the Markov chains.

Equation (12) assumes that the time to signal is started one interval before the first control point. However, in practice, the time to signal should be evaluated starting from the first control point. As a result, the zero state ATS is defined as follows:

$$ATS_{Zero\ State} = \boldsymbol{p}^{\boldsymbol{T}}Q\boldsymbol{b} - \boldsymbol{p}^{\boldsymbol{T}}\boldsymbol{b} \quad (13)$$

Table 3 shows the experimental data on the effectiveness of the adaptive control chart compared to other common statistical project control charts, such as individuals (I), moving range (MR), individuals-moving range (I-MR), and non-adaptive GMA control charts. For the sake of fairness, the control limits of the charts have been adjusted to approximately give the same in-control ATS value. Also, the magnitude of the change in the mean of the project performance level is computed as follows:

$$\delta = \frac{|\mu-\mu_0|}{\sigma} \quad (14)$$

For example, $\delta = 2$ indicates that the project performance level has been changed from μ_0 to $\mu = \mu_0 \pm 2\sigma$. Columns 2 to 4 of this table give the three-sigma ATS values of the I, MR, and I-MR control charts, respectively. The ATS values of the proposed control chart with fixed and variable reviewing interval (FRI and VRI) control schemes and different parameter values are also displayed in the next columns of this table.

Table 3. Comparison of the Time to Signal for Different Control charts.

δ	*I*	*MR*	*I-MR*	*GMA with Fixed and Variable Reviewing Intervals*										
0.00	370.4	370.4	370.4	FRI	369	369	369	369	369	369	369	369	369	369
				VRI	369	369	369	369	369	369	369	369	369	369
0.25	280.7	369.3	310.3	FRI	280	242	195	173	148	135	120	88.3	72.2	67.1
				VRI	274	233	183	159	132	118	102	68.5	52.3	47.9
0.50	154.7	366.5	199.2	FRI	154	109	70.7	57.5	45.6	40.1	35.2	27.2	25.5	26.1
				VRI	141	94.1	55.4	42.3	30.7	25.6	21.1	14.9	14.4	15.4
1	43.4	365.2	61.9	FRI	42.9	24.5	14.2	11.7	9.90	9.25	8.80	8.74	9.74	10.8
				VRI	29.9	14.3	6.50	4.85	3.81	3.53	3.41	3.80	4.78	5.71
1.5	14.5	360.0	19.7	FRI	14	7.68	4.99	4.47	4.21	4.18	4.23	4.80	5.75	6.62

				VRI	6.49	2.67	1.42	1.26	1.22	1.26	1.34	1.79	2.50	3.17
2	5.8	348.6	7.5	FRI	5.30	3.14	2.42	2.35	2.39	2.46	2.59	3.18	3.98	4.67
				VRI	1.53	0.70	0.51	0.51	0.54	0.58	0.64	0.96	1.48	2.00
3	1.5	298.7	1.8	FRI	1.00	0.79	0.85	0.95	1.09	1.19	1.31	1.76	2.35	2.83
				VRI	0.14	0.10	0.11	0.12	0.14	0.16	0.18	0.30	0.53	0.83
4	0.9	185.3	1.1	FRI	0.19	0.19	0.30	0.39	0.55	0.67	0.81	1.14	1.57	1.97
				VRI	0.02	0.02	0.03	0.04	0.06	0.07	0.08	0.12	0.20	0.31
5	0.5	106.3	0.5	FRI	0.02	0.03	0.06	0.10	0.18	0.27	0.41	0.89	1.10	1.39
				VRI	0.00	0.00	0.01	0.01	0.02	0.03	0.04	0.09	0.11	0.15
				k	3.000	2.997	2.978	2.959	2.925	2.898	2.859	2.701	2.490	2.302
				λ	1.000	0.750	0.500	0.400	0.300	0.250	0.200	0.100	0.050	0.030
				k'	0.671	0.670	0.668	0.667	0.664	0.662	0.660	0.647	0.624	0.599

It is apparent from the table that the proposed control scheme with variable reviewing interval has a better performance to detect the small, medium, and large shifts in the project performance level. For example, for a 1.5σ shift in the project performance level, the adaptive control chart with $k = 2.925$, $\lambda = 0.300$, and $k' = 0.664$ requires 1.22 periods to detect the change, which is much lower than the ATS values of I, MR, I-MR, and even non-adaptive GMA control charts (i.e. 14.5, 360, 19.7, and 4.21 periods, respectively). Closer inspection of the table also reveals that the ability of the adaptive control chart in detecting the small to moderate shifts is affected by different λ values. An optimal λ value can be chosen concerning the control policy of project managers. However, as a rule of thumb, it is recommended to set small to moderate (large) λ values to detect small to moderate (large) shifts in the performance level. For the sake of simplicity, the interested readers can refer to the R function *spc.region* to compute the zero state average run length of the GMA control with their own parameters, which is available in The Comprehensive R Archive Network: CRAN.

7. Discussions

This section aims to discuss some of the practical implications of the implementation of the proposed control scheme. First of all, it needs to be pointed that the GMA statistic is insensitive to the normality assumption meaning that moderate departures from normality have little impact on the effectiveness of the GMA control chart to detect assignable causes. Therefore, unlike the existing statistical project control charts such as individuals and moving range control charts, it is not required to normalize the performance indicators. The second point to bear in mind is the predictive ability of the adaptive control chart to predict the project performance level at the next control point. In addition to the ability of the adaptive control chart to quickly detect performance changes with minimal control efforts, it also provides a forecast of where the project performance level will be at the next control point. For this purpose, note that λPI_t in Equation (2) can be viewed as a forecast of the project performance level at review period t. Then, let $PI_t - z_{t-1}$ be defined as the forecast error e_t of period t. Thus, the GMA statistic for period $t+1$ would be equal to the GMA statistic for period t plus a proportional adjustment which is defined as a fraction λ_1 of e_t for the performance level at period $t+1$. To enhance the prediction ability of the GMA statistic, we can also add an integral adjustment as the sum of the errors accumulated to time $t+1$, and a differential adjustment as the first difference of the errors. The project performance level at time instance $t+1$ is then:

$$z_{t+1} = z_t + \lambda_1 e_t + \lambda_2 \sum_{j=1}^{t+1} e_j + \lambda_3 (e_{t+1} - e_t) \tag{15}$$

To give the best forecasting performance λ_1, λ_2, and λ_3 would be chosen as weighting factors of the three terms added for adjusting the performance level at the next control point, respectively.

Another point to be taken into consideration is to determine an appropriate number of reviewing interval lengths. Changing the number of reviewing interval lengths may affect both the effectiveness and applicability of the control chart. From a practical point of view, it seems reasonable to define only two reviewing intervals that are spaced far apart. In the following of this section, we represent a simplified proof to show the optimality of two reviewing intervals based on the theory of Markov chains. For this purpose, consider μ as the mean of the project performance level, and R_μ as the sub-matrix of one-step transition probabilities corresponding to the in-control state, E_j. If $\boldsymbol{b} = b_j$ is the vector of reviewing intervals associated with the in-control state E_j, then the average time to signal is defined as follows:

$$ATS_\mu = (1 - R_\mu)^{-1} \boldsymbol{b} = Q_\mu \boldsymbol{b} \tag{16}$$

Suppose that the interval length at reviewing period j, say b_j, is calculated according to the following piecewise function:

$$b_j = \begin{cases} b_L, & \dfrac{q_{ij}(0)}{q_{ij}(\mu)} > k \\ b_S, & \dfrac{q_{ij}(0)}{q_{ij}(\mu)} \leq k \end{cases} \tag{17}$$

in which b_L and b_S denote the longest and shortest possible reviewing intervals, respectively. Let $j_S = \{j: b_j = b_S\}$ and $j_L = \{j: b_j = b_L\}$, and without any loss of generality choose $b_S = 0$. Then, for all $\{j \in j_L\}$ we have:

$$ATS_0(k) = \sum_j b_L q_{ij}(0) \tag{18}$$

in which $ATS_0(k)$ is defined as a step function of k. The desired in-control ATS can now be obtained by changing the value of k. For this purpose, let $\boldsymbol{b}^* = (b_j^*)$ to be a representative reviewing interval length such that $b_S \leq b_j^* \leq b_L$. By equating the in-control ATS equations, we will have:

$$0 = ATS_0 - ATS_0^* \tag{19}$$

$$\sum_j b_j q_{ij}(0) - \sum_j b_j^* q_{ij}(0) = \sum_j (b_j - b_j^*) q_{ij}(0) \tag{20}$$

$$= \sum_{jL} (b_L - b_j^*) q_{ij}(0) - \sum_{jS} b_j^* q_{ij}(0) \tag{21}$$

According to Equation (17), when the shortest possible reviewing interval is selected in this piecewise function, we will have $\frac{q_{ij}(0)}{q_{ij}(\mu)} \leq k$ that implies $q_{ij}(\mu) \geq \frac{1}{k} q_{ij}(0)$. Hence, the ATS equations can be modified as follows:

$$\begin{aligned} &ATS_\mu - ATS_\mu^* = \\ &\sum_{jL} (b_L - b_j^*) q_{ij}(\mu) - \sum_{jS} b_j^* q_{ij}(\mu) < \frac{1}{k} \sum_{jL} (b_L - b_j^*) q_{ij}(0) - \frac{1}{k} \sum_{jS} b_j^* q_{ij}(0) \\ &= \frac{1}{k} \left[\sum_{jL} (b_L - b_j^*) q_{ij}(0) - \sum_{jS} b_j^* q_{ij}(0) \right] = 0 \end{aligned} \tag{22}$$

Therefore, the minimum out of control average time to signal is achieved using only two reviewing intervals. Practical experiences also show that the reviewing intervals should be as far apart as possible. For this purpose, the short reviewing interval can be determined by taking into account the physical considerations such as the shortest amount of time that is required to record the actual progress, while the long reviewing interval length can be determined by the longest amount of time that is reasonable to continue the project without monitoring its actual progress.

8. Implications for Engineering Managers

The theoretical and practical implications of the findings in this research are primarily intended for engineering managers who are responsible for monitoring and control of status and performance of the project. However, project managers and other relevant interested parties such as contractors, clients, theoreticians, and practitioners can also apply the findings of this study. The proposed approach is a simple but effective managerial control scheme that can be applied to any organization or project, regardless of its type, size, or the products and services it delivers. The application of the proposed control scheme may lead to the effective implementation of project monitoring and control process by significantly reducing the control efforts. Therefore, the proposed adaptive control scheme, in an existing or partially modified form can serve theoreticians in their research, and project managers and other relevant interested parties in reducing the cost and duration of those activities required to track, review, and regulate the progress. Moreover, since the proposed control scheme reduces the time required to detect unacceptable performance variations, it helps project managers and other related interested parties to ensure the completion of all project activities without time and/or cost overruns at the desired level of performance. Furthermore, the proposed approach can be used as a predictor of the project performance level at the next control point whereby the project manager can promptly make necessary corrective and preventive measures to keep the project on the right track. The proposed control scheme is based on the EVM performance indicators (such as CPI and SPI), which is one of the most widely accepted control systems used by practitioners in the project management field. However, project managers can apply the proposed control scheme with their own performance indicators.

9. Conclusions

This study was set out to develop a simple but effective control scheme with adaptive control points in which the reviewing interval is a function of the distance of the current performance level from the targeted level of performance. The most obvious finding to emerge from this study is that while the project performance is around the target and the performance level is stable, there is no reason to immediately review the project progress. Therefore, it would be reasonable to increase the time length to the next control point. Otherwise, by approaching the project performance to the control limits, the time until the next control point should be shortened to examine the project performance as soon as possible. To examine the effectiveness of the proposed control scheme, a comprehensive simulation study was conducted. In addition, to address the dynamics of the real projects, the performance of the proposed approach was illustrated by monitoring the cost performance of a construction project through the adaptive control scheme. Analysis of the obtained results complements the findings of earlier studies about the applicability of the statistical project control and suggests a role for the use of the adaptive control scheme. Further studies seem to be carried out to develop the proposed adaptive control scheme in the multivariate control charts wherein the cost and schedule performance levels are examined simultaneously. Besides, to fully understand the practical implications of the proposed control chart, readers are encouraged to implement the proposed approach to their real-life projects.

Conflict of Interest Statement

This is to confirm that the authors do not have any conflict of interest to the best of their knowledge in pursuing the research that is being presented in the paper.

Funding Information

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

References

- Aliverdi, R., Moslemi Naeni, L., & Salehipour, A. (2013). Monitoring project duration and cost in a construction project by applying statistical quality control charts. International Journal of Project Management, 31(3), 411-423.
- Aminian, V., Rahimi Nejad, A., Mortaji, S., & Bagherpour, M. (2016). A modified earned value management using activity based costing. Journal of project management, 1(12), 41-54.
- Armani, V., Gibson Jr, G., El Asmar, M., & Cho, N. (2021). Earned Value Management System State of Practice: Identifying Critical Subprocesses, Challenges, and Environment Factors of a High-Performing EVMS. Journal of Management in Engineering, 37(4), 04021031.
- Bauch, G. T., & Chung, C. A. (2001). A statistical project control tool for engineering managers. Project Management Journal, 32, 37-44.
- De Falco, M., & Macchiaroli, R. (1998). Timing of control activities in project planning. International Journal of Project Management, 16(1), 51-58.
- Dodson, M., Defavari, G., & Carvalho, V. D. (2015). Quality: the third element of earned value management. Procedia Computer Science, 64, 932-939.
- Fleming, Q. W., & Koppelman, J. M. (2010). Earned Value Project Management. Newtown Square: Project Management Institute.
- Hadian, H., & Rahimifard, A. (2019). Multivariate statistical control chart and process capability indices for simultaneous monitoring of project duration and cost. Computers & Industrial Engineering, 130, 788-797.
- Hussain, Z., Barber, K., & Hussain, N. (2009). An Intranet based system as an enabler in effective project management and implementation of quality standards: A case study. Journal of Engineering and Technology Management, 26(3), 196-210.
- Khamooshi, H., & Golafshani, H. (2014). EDM: Earned Duration Management, a new approach to schedule performance management and measurement. International Journal of Project Management, 32(6), 1019-1041.
- Khesal, T., Saghaei, A., Khalilzadeh, M., Rahiminezhad Galankashi, M., & Soltani, R. (2019). Integrated cost, quality, risk and schedule control through earned value management (EVM). Journal of Engineering, Design and Technology, 17(1), 183-203.
- Kogan, K., Raz, T., & Elitzur, R. (2002). Optimal control in homogeneous projects: analytically solvable deterministic cases. Iie Transactions, 34(1), 63-75.
- Leon, H., Osman, H., Georgy, M., & Elsaid, M. (2018). System dynamics approach for forecasting performance of construction projects. Journal of Management in Engineering, 34(1), 04017049.
- Leu, S.-S., & Lin, Y.-C. (2008). Project performance evaluation based on statistical process control techniques. Journal of Construction Engineering and Management, 134(10), 813-819.
- Lipke, W. H. (2009). Earned Schedule. Chicago: Lulu.
- Lipke, W. H., & Vaughn, J. (2000). Statistical process control meets earned value. CrossTalk: The Journal of Defense Software Engineering, 13.
- Montgomery, D. C. (2013). Introduction to Statistical Process Control. New York: John Wiley and Sons.
- Mortaji, S., & Hosseinzadeh, M. (2021). A Competitive Nature-Inspired Cuckoo Search Algorithm for Solving the Resource Constrained Project Scheduling Problem. International Journal of Innovation in Engineering, 1(3), 48-64.
- Mortaji, S., Bagherpour, M., & Mahdavi Mazdeh, M. (2013). Fuzzy time-driven activity-based costing. Engineering Management Journal, 25(3), 63-73.
- Mortaji, S., Bagherpour, M., & Noori, S. (2013). Fuzzy earned value management using LR fuzzy numbers. Journal of Intelligent & Fuzzy Systems, 24(2), 323-332.
- Mortaji, S., Noori, S., & Bagherpour, M. (2021). Directed earned value management based on ordered fuzzy numbers. Journal of Intelligent & Fuzzy Systems, 40(5), 10183-10196.

- Mortaji, S., Noori, S., & Bagherpour, M. (2021). Directed earned value management based on ordered fuzzy numbers. Journal of Intelligent & Fuzzy Systems, 40(5), 10183-10196.

- Mortaji, S., Noori, S., Noorossana, R., & Bagherpour, M. (2017). An ex ante control chart for project monitoring using earned duration management observations. Journal of Industrial Engineering International, 1-14.
- Mortaji, S., Noorossana, R., & Bagherpour, M. (2015). Project completion time and cost prediction using change point analysis. Journal of Management in Engineering, 31(5), 04014086.

- Orgut, R. E., Batouli, M., Zhu, J., Mostafavi, A., & Jaselskis, E. J. (2020). Critical Factors for Improving Reliability of Project Control Metrics throughout Project Life Cycle. Journal of Management in Engineering, 36(1), 04019033.
- Partovi, F. Y., & Burton, J. (1993). Timing of monitoring and control of CPM projects. IEEE Transactions on Engineering Management, 40(1), 68-75.
- Patanakul, P., Shenhar, A. J., & Milosevic, D. Z. (2012). How project strategy is used in project management: Cases of new product development and software development projects. Journal of Engineering and Technology Management, 29(3), 391-414.
- Qazi, A., Dikmen, I., & Birgonul, M. (2020). Mapping uncertainty for risk and opportunity assessment in projects. Engineering Management Journal, 32(2), 86-97.
- Raz, T., & Erel, E. (2000). Optimal timing of project control points. European Journal of Operational Research, 127(2), 252-261.
- Sabeghi, N., & Tareghian, H. (2020). Using the generalized maximum covering location model to control a project's progress. Computational Management Science, 17(1), 1-21.
- Sabeghi, N., Tareghian, H., Demeulemeester, E., & Taheri, H. (2015). Determining the timing of project control points using a facility location model and simulation. Computers & Operations Research, 61, 69-80.
- Salehipour, A., Naeni, L. M., Khanbabaei, R., & Javaheri, A. (2016). Lessons Learned from Applying the Individuals Control Charts to Monitoring Autocorrelated Project Performance Data. Journal of Construction Engineering and Management, 142(5), 04015105.
- Sogandi, F., Mousavi, S., & Amiri, A. (2018). Self-starting control chart and post signal diagnostics for monitoring project earned value management indices. Journal of Industrial and Systems Engineering, 11(2), 85-100.
- Sols, A. (2018). A comprehensive approach to dynamic project risk management. Engineering Management Journal, 30(2), 128-140.
- Tareghian, H., & Salari, M. (2009). On the optimal frequency and timing of control points in a projects's life cycle. International Journal of Industrial Engineering & Production Research, 20(3), 96-102.
- Wang, Q., Jiang, N., Gou, L., Che, M., & Zhang, R. (2006). Practical experiences of cost/schedule measure through earned value management and statistical process control. In Software Process Change (pp. 348-354). Berlin: Springer.
- Willems, L. L., & Vanhoucke, M. (2015). Classification of articles and journals on project control and earned value management. International Journal of Project Management, 33(7), 1610-1634.