

Integrating Quality Control Charts with Maintenance: A Brief Literature Review

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Abstract

During last decade, there has been a significant interest to integrate maintenance management with Statistical Process Control (SPC). The research on integrating SPC with maintenance is not adequately discussed in literature. In this paper, a brief overview of the existing literature on the integration of the SPC charts with maintenance has been discussed. Based on the literature review, few research gaps have been identified, and possible future research opportunities have been addressed.

Keywords

Economic Design of Control Charts, Preventive Maintenance, Statistical Process Control

1. Introduction

The planning and implementation of preventive maintenance programs plays a critical role in maintaining the desired reliability and availability of engineering assets. The ultimate goal of any maintenance program is to reduce or eliminate system breakdowns which in returns will improve and ensure effective system reliability. Reliability monitoring of engineering assets is an important tool to monitor maintenance effectiveness. The integration of maintenance management and assets' reliability monitoring may provide more benefits to organizations (see Alsayouf et al., 2016).

In recent years, there has been a significant interest to integrate maintenance management with SPC. More and more practitioners and academicians recognize that there is strong relationship between product quality, process quality and equipment maintenance (Zhou, et. al., 2007), the growing interrelationship between quality control and maintenance planning forces organizations to develop integrated management systems, which requires an increased level of coordination among management practices (Xiang, 2013).

Control charts are the most commonly used SPC tools. Many researchers have addressed the integration of control charts with maintenance management. However, the research on integrating SPC and maintenance is not adequately discussed in the literature. The purpose of this paper is to provide a brief review of existing literature on the integration of control charts with maintenance management, and to suggest some possible future research directions.

2. Control charts and maintenance

It is commonly argued that preventive maintenance (PM) policies can contribute significantly in increasing equipment reliability, as well as in reducing the maintenance-related costs (Panagiotidou et al., 2009). Models and policies of maintenance can be found in (Sharma et al., 2011; Garg & Deshmukh, 2006; Chien, Sheu & Zhang, 2012; Moghaddam, 2008; Henry, et al., 2012; Liu, Xie and Kuo, 2016; Endrenyl et al., 1998; Taghicipour and Banjevic, 2011; Mckone & Weiss, 1998; Wang, 2002; Afefy, 2010). During the last decade, practitioners and academicians recognized that there is a strong relationship between product quality and equipment maintenance (Amal et al., 2016). For a deteriorating single-machine manufacturing system, preventive maintenance (PM) is an effective way to improve the machine reliability and product quality. In conventional PM models, however, quality improvement has seldom been considered, which may lead to loss of economic benefits (Lu et al., 2016). The close relationship between

quality and maintenance of manufacturing systems has contributed to the development of integrated models, which use the concept of SPC and maintenance. Such models not only help to improve quality of products but also lead to lower maintenance cost (Mehrafrooz & Noorossana, 2011). These two tools are traditionally separated (both in science and in business practice). But their goals overlap a great deal (Zhou & Zhu, 2008).

The design of control chart that takes into account the economic issues and parameters involved in the monitoring process of the control chart is usually called "Economic design of control charts". Much of the research in the development of economic models of control charts has been devoted to the X-Bar chart. The interest of analysts in this control chart follows directly from its widespread use in practice. (Montgomery, 2009). Duncan (1956) proposed the first model for the economic design of X-Bar control chart. (cited by Wei-Shing Chen, et al, 2011). His work stimulated most of the work on the economic design of control charts. (Wei-Shing Chen, et al, 2011) addressed an interesting literature review of the economic design of X-Bar control charts. Additionally, See ((Raj, 2010; DAS & JAIN, 1997; and Wu et al., 2004)).

On the other hand, Shewhart control charts may face some practical problems when the process fraction of nonconforming is very low, say, at parts per million (ppm) or even parts per billion (ppb) levels (Liu et al., 2006). However, when dealing with high-quality processes, the traditional control charts may face some practical difficulties, such as meaningless control limits, too many false alarms and failure in detecting process improvement. An effective way to solve these problems is to employ time-between-events charts. Time-between-events charts monitor the time between successive occurrences of events, e.g. nonconforming items or nonconformities (Liu et al., 2004). A few researchers have discussed the economic design of time-between-events control charts. In 2010, (Zahang, et al., 2010) proposed an economic control chart system that consists of several individual times-between-events control charts for monitoring the multistage production processes. However, in 2011, (Zahang, et al., 2011) extended their approach of economic design of time-between-events control charts by considering the random characteristics of the process shift which in return will better reflects the real process conditions. Out of the investigated articles presented in this paper, only four papers discussed the economic design of time-between-events control charts. See (Zhang, et al., 2011; Zhang et al., 2005; & Zhang et al., 2010; & Zhang et al., 2007). A few authors addressed the economic design of control charts other than the X-Bar, and time between events. For example (WU et al, 2004) developed an algorithm for the optimization design of control charts based on probability distribution of the random process shift. The design objective of their model is to minimize the overall mean of Taguchi's loss function per out-of-control case. They denoted their developed chart as ML, however, their algorithm can be applied to different charts such as CUSUM and EWMA. (Serel, & Moskowitz, 2008) presented an exponentially weighted moving average (EWMA) cost optimization model to design the joint control scheme based on pure economic or both economic and statistical performance criteria.

The economic design of control charts and the optimization of preventive maintenance policies are two research areas that have recently received a great deal of attention in the quality and reliability literature. Both of these research areas are focused on reducing the costs associated with operating manufacturing processes. However, these two research areas are rarely integrated. (Cassady et al., 2000).

A literature review on SPC-Maintenance models has been conducted utilizing few papers that discussed the combination of maintenance with quality improvement using statistical process control tools, mainly quality control charts. It was found that most of the investigated papers addressed the integration of maintenance and \bar{X} control chart, (around 52%), however, different types of control charts have also been discussed such as: exponentially weighted moving average (EWMA). On the other hand, most of the papers discussed the use of control charts for product quality monitoring which is also affected by equipment deterioration or reliability. Moreover, there is a lack of integrating time between events control charts with maintenance management for the purpose of reliability monitoring of engineering assets. Most of the investigated papers considered the economic consequences while integrating SPC with maintenance management. (See table 1: appendix 1)

In the following sub-sections, a brief discussion on the investigated papers is presented.

2.1 \bar{X} Control chart and maintenance:

Many authors addressed the integration of maintenance with \bar{X} control chart. The interest of analysts in this control chart follows directly from its widespread use in practice as highlighted earlier. (Ben-Daya, 1999) developed an integrated model for the joint optimization of the economic production quantity, the economic design of \bar{X} control

chart, and the optimal maintenance level. In his model, preventive maintenance activities (PM) reduce the shift rate to an out of control state which is proportional to the level of PM. He used pattern search technique of Hooke and Jeeves in order to minimize the cost function of his model. He compared the case with no preventive maintenance with his proposed model and found that lower control costs can be achieved using his proposed model. However, in 2000, (Ben-Daya & Rahim) developed an integrated model for the joint optimization of maintenance level and the economic design of \bar{X} control chart without considering the economic production quantity. He intended to investigate the effect of maintenance level on quality control costs. He found that higher PM levels lead to more reduction in quality control costs, and if the savings in these costs compensate for the added maintenance cost, the overall cost will be reduced compared to the no PM case. (Cassady et al., 2000) proposed a combined control chart-preventive maintenance strategy for a process which shifts to an out of control state due to machine failure. He used \bar{X} control chart with age replacement policy in order to achieve lower operating costs. He used a simulation-optimization strategy for optimizing the parameters of the control chart and the preventive maintenance policy. However, his model does not take into account the situation of shifting to an out of control state due to causes other than machine failure. (Lee, & Rahim, 2001) proposed an integrated model for the economic design of \bar{X} control chart and age replacement policy. They concluded that a joint approach to quality control and preventive maintenance results in cost savings. Although they considered both age-dependent maintenance costs and salvage value of the equipment in their economic model, they have assumed constant replacement cost for equipment which is usually variable in practice.

(Linderman et al., 2005) developed a generalized analytic model named Monitoring-Maintenance model in order to coordinate SPC and planned maintenance to minimize expected costs. They utilized Hooke and Jeeves search technique to reach the optimal values. In their model, SPC monitors the equipment and provide signals indicating equipment deterioration, while planned maintenance is scheduled at specified intervals in order to prevent equipment failures. If the process is stated as unstable by the SPC an early reactive maintenance will be conducted in order to return the equipment to its intended level. Otherwise, a planned maintenance will be conducted at its pre-specified time. Figure 1 provides a presentation of Monitoring-Maintenance model.

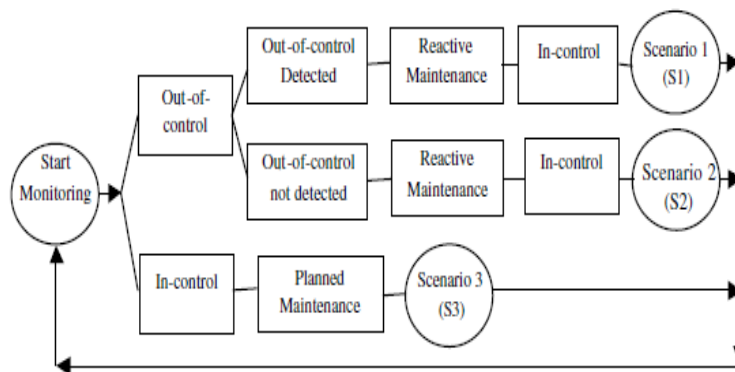


Figure 1: Three monitoring-maintenance scenarios (adapted from ((Linderman et al., 2005))

However, (Zhou, & Zhu, 2008) extended (Linderman et al., 2005) model and suggested an integrated model of control chart and maintenance management with four possible scenarios. They used grid search approach to find the optimal values of their model. A general presentation of their model is summarized in figure 2.

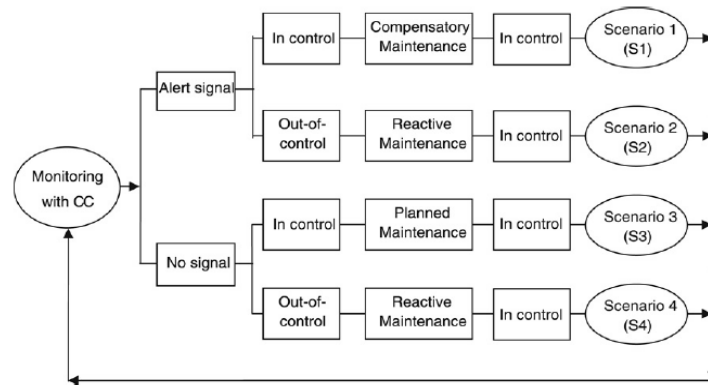


Figure 2: Integrated model of CC and MM. (adapted from (Zhou, & Zhu, 2008))

(Mehrafrooz, & Noorossana, 2011) presented an integrated model of SPC and maintenance which considers complete failure and planned maintenance simultaneously with six different scenarios. However, due to the complexity of their model, the solution procedure used in (Linderman et al., 2005) and in (Zhou, & Zhu, 2008) is not applicable, therefore, they proposed a new solution procedure which is based on all states related to each scenario. Figure 3 presents (Mehrafrooz, & Noorossana, 2011) model scenarios.

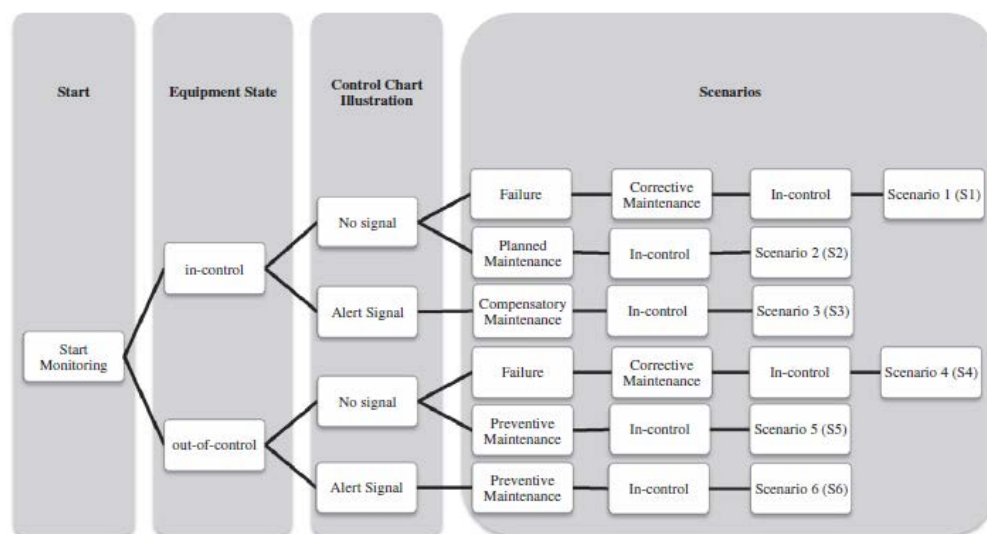


Figure 3 Integrated Model Scenarios (Adopted from (Mehrafrooz, & Noorossana, 2011))

(Chen & Yu, 2011) presented an integrated model for preventive maintenance and the economic design of \bar{X} control chart using Toguchi loss function. Their model assumes that preventive maintenance is performed on the basis of sampling characteristic. It can only reduce failure rates, but it does not return the system as good as new.

(Pandey et al., 2011) developed a model for joint optimization of maintenance planning, process quality and production scheduling. They firstly combined SPC with preventive maintenance block replacement policy by developing a model that captures the costs associated with the manufacturing process which are affected by quality control policies and maintenance planning. In addition, they modified Duncan (1956) model to capture the costs associated with the manufacturing process which are affected by quality control policies and maintenance planning. These costs comprise of cost of poor quality, cost of sampling/inspection, cost of preventive maintenance, cost of downtime and fixed cost of repair/restoration. (Xiang, 2013) has also presented an integrated model for the joint optimization of economic \bar{X} control chart and age-dependent preventive maintenance policy. The model is developed for a production process that deteriorates according to a discrete Markov Chain and it is assumed that inspection, corrective and preventive maintenance are instantaneous and there is no sampling delay. However, (Liu et al., 2013)

presented an economic statistical designs of \bar{X} control chart for two identical unit series systems with condition-based maintenance. The system process is described using five state continues time Markov chain. (Yin et al., 2015) developed an integrated model of SPC and maintenance decision. In their model, the process starts in an in-control state, and the \bar{X} control chart is used to monitor the key quality characteristic of the product, and if the control chart signals an out of control state, which implies probable deterioration of equipment, both the failure rate of the equipment and the production cost per unit time are supposed to be higher than that of the in control state, hence, predictive maintenance and corrective maintenance are performed to deal with the true alert signal and equipment failure respectively. However, preventive maintenance is performed at scheduled intervals. They relaxed the assumption of (Xiang, 2013) of no sampling delay by proposing a delayed monitoring (DM) policy, which postpones sampling process till a scheduled time. The (DM) policy will reduce the total production cost by reducing the frequency of sampling.

2.2 EWMA Control chart and maintenance:

The exponentially weighted moving average (EWMA) control chart is a good alternative to the Shewhart control chart when we are interested in detecting small shifts (Montgomery, 2009). Out of the investigated papers, only two articles discussed the combination between maintenance and EWMA control chart.

(Charongrattanasakul, & Pongpullponsak, 2011) developed an integrated model between SPC and planned maintenance of the EWMA. A mathematical model was developed to analyze the costs involved in the integrated and genetic algorithm is then used to find the optimal values of six variables that minimize the hourly cost. Their work presents an extension of (Zhou, & Zhu, 2008) approach of four scenarios integrated model which was based on (Linderman et al., 2005) three policies (scenarios) model discussed in the previous sub-section (see section 2.1). The warning limit is considered to increase the policies from four to six scenarios which are warning limit signal and warning limit no signal. Figure 4 presents the different scenarios of the developed integrated model.

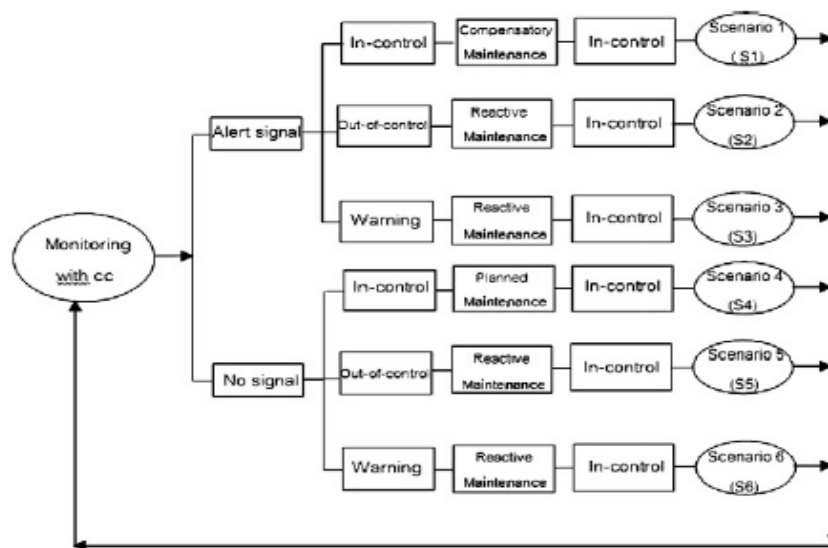


Figure 4 Six monitoring maintenance scenarios of the integrated model (adapted from (Charongrattanasakul, & Pongpullponsak, 2011))

Despite the univariate case of EWMA control chart discussed in the previous paragraph, (Abouei Ardakan et al., 2015) proposed a hybrid model for the economic design of multivariate EWMA control chart under maintenance policies. In their model, the MEWMA control chart is used to control process variability, the maintenance plan can stop the process at specific times and check process state. However, if control chart signals out of control state before the scheduled maintenance time, a reactive maintenance is conducted in order to restore the process to its in control state. They used Hooke and Jeeves search technique in order to find the optimal values of their policy variables.

2.3 Times between events (TBE) control chart and maintenance:

An effective way to control high-quality processes is to employ time-between-events charts. Time-between-events charts monitor the time between successive occurrences of events, e.g. nonconforming items or nonconformities (Liu et al., 2004).

A few authors have addressed the combination of maintenance with times between events control charts. The research in this area is still limited. Out of the investigated papers, two papers have discussed the combination of maintenance with TBE control chart. (Michael & Xie., 2008) proposed the use of times between events chart in monitoring of the lifetime of a regularly maintained Weibull distributed system. Their mathematical model presents an integration between maintenance decisions with SPC. They assumed that the system consists of only one component which is rarely the case in engineering applications. However, (Alsyouf et al., 2016) presented the use of time between events chart in monitoring times-between-failures of a multi-component repairable systems. They proposed a step-by-step procedure which help decision makers to periodically monitor and improve system reliability. Figure 5 presents a summary of their suggested procedure.

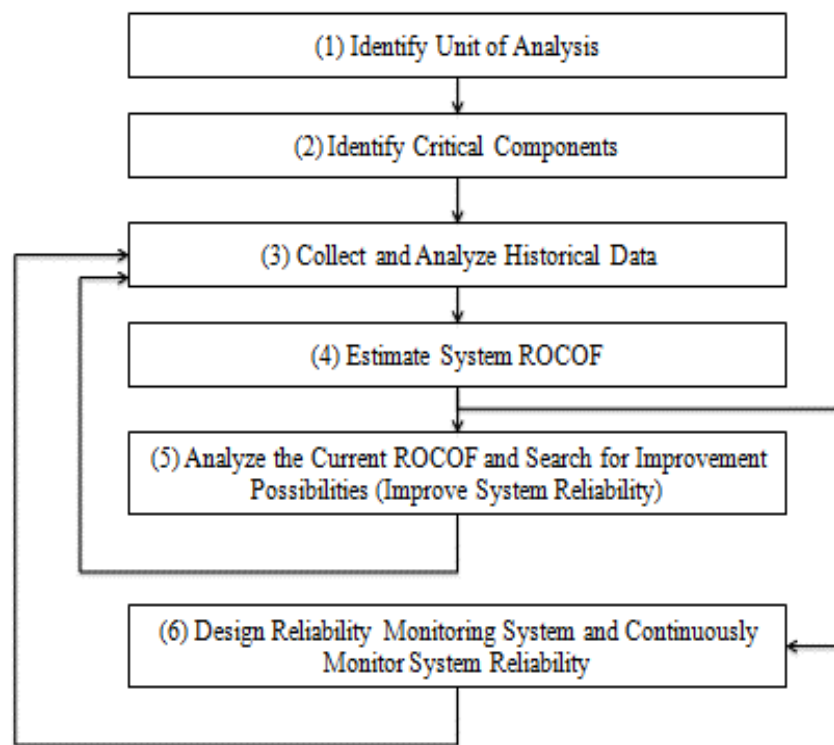


Figure 5 Procedure for improving and monitoring the reliability of a repairable system (Adopted from , (Alsyouf et al., 2016))

A comparative classification of investigated papers considering six characteristics; control chart type, maintenance policy employed, integration method/solution procedure, area of application, control chart monitoring purpose, and whether economic consequences has been considered or not, is illustrated in table 1 (Appendix 1)

3. Future Research

Nearly all papers discussed the SPC-Maintenance combination for production systems and processes, only two papers (Alsyof et al., 2016) and (Michael & Xie., 2008) discussed SPC-Maintenance combination for repairable systems and maintained systems in general, however both papers did not consider economic design of control charts. Based on the literature review and this finding, a possible research opportunity has been identified:

1. A possible future research is to develop an integrated model for economic design of time between events control chart under maintenance management of engineering assets. The model should have the flexibility to be implemented to any engineering/repairable assets such as: fleet of vehicles, fleet of air planes, construction equipment's, or any other engineering assets. A discussion of using time-between-events control charts in reliability monitoring is discussed in (Zhang, et al., 2005; Zhang et al., 2007, and Xie et al., 2002)

4. Conclusion

In this paper, we conducted a literature review utilizing some of the existing literature on the field of integrating statistical process control with maintenance, focusing mainly on integrating control charts with maintenance. Based on the literature review, few research gaps in this area have been noted. For example, most of the investigated papers addressed the integration of maintenance and X-Bar control chart. However, other control charts have also been addressed. On the other hand, nearly all papers discussed the SPC-Maintenance integration for production systems and processes except two papers which discussed SPC-Maintenance combination for repairable and maintained systems in general. Finally, based on the conducted literature review, one main future research opportunity has been identified.

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References

- Abouei Ardakan, M., Zeinal Hamadani, A., Sima, M. and Reihaneh, M. A hybrid model for economic design of MEWMA control chart under maintenance policies. *The International Journal of Advanced Manufacturing Technology*, 83(9-12), pp.2101-2110. (2015).
- Pandey, D., Kulkarni, M. S., & Vrat, P., A methodology for joint optimization for maintenance planning, process quality and production scheduling. *Computers & Industrial Engineering*, 61(4), 1098-1106. doi:10.1016/j.cie.2011.06.023, (2011).
- Panagiotidou, S., & Nenes, G. An economically designed, integrated quality and maintenance model using an adaptive Shewhart chart. *Reliability Engineering & System Safety*, 94(3), 732-741. doi:10.1016/j.res.2008.07.003, (2009).
- Ching, C., Hsiang C., Yuan-Du H., & Fong-Jung Y. Effect of Preventive Maintenance on the Economic Design of X-Bar Control Chart. 13th IFAC Symposium on Information Control Problems in Manufacturing. doi:10.3182/20090603-3-ru-2001.00284, (2009).
- Azizi, A., Evaluation Improvement of Production Productivity Performance using Statistical Process Control, Overall Equipment Efficiency, and Autonomous Maintenance. *Procedia Manufacturing*, 2, 186-190. doi:10.1016/j.promfg.2015.07.032, (2015).
- Lu, B., Zhou, X., & Li, Y. Joint modeling of preventive maintenance and quality improvement for deteriorating single-machine manufacturing systems. *Computers & Industrial Engineering*, 91, 188-196. doi:10.1016/j.cie.2015.11.019, (2016).
- Xiang, Y. Joint optimization of control chart and preventive maintenance policies: A discrete-time Markov chain approach. *European Journal of Operational Research*, 229(2), 382-390. doi:10.1016/j.ejor.2013.02.04, (2013).

Bouslah, B., Gharbi, A., & Pellerin, R. Joint production, quality and maintenance control of a two-machine line subject to operation-dependent and quality-dependent failures. *International Journal of Production Economics*, 195, 210-226. doi:10.1016/j.ijpe.2017.10.016, (2017).

Lesage, A., & Dehombreux, P. Maintenance & Quality Control: A First Methodological Approach for Maintenance Policy Optimization. *IFAC Proceedings Volumes*, 45(6), 1041-1046. doi:10.3182/20120523-3-ro-2023.00382, (2012).

Panagiotidou, S., & Tagaras, G., Optimal integrated process control and maintenance under general deterioration. *Reliability Engineering & System Safety*, 104, 58-70. doi:10.1016/j.res.2012.03.019, (2012).

Deloux, E., Castanier, B., & Bérenguer, C., Predictive maintenance policy for a gradually deteriorating system subject to stress. *Reliability Engineering & System Safety*, 94(2), 418-431. doi:10.1016/j.res.2008.04.002, (2009).

Tasias, K. A., & Nenes, G., Optimization of a fully adaptive quality and maintenance model in the presence of multiple location and scale quality shifts. *Applied Mathematical Modelling*, 54, 64-81. doi:10.1016/j.apm.2017.09.014, (2017).

Kurniati, N., Yeh, R., & Lin, J., Quality Inspection and Maintenance: The Framework of Interaction. *Procedia Manufacturing*, 4, 244-251. doi:10.1016/j.promfg.2015.11.038, (2015).

Yin, H., Zhang, G., Zhu, H., Deng, Y., & He, F. An integrated model of statistical process control and maintenance based on the delayed monitoring. *Reliability Engineering & System Safety*, 133, 323-333. doi:10.1016/j.res.2014.09.020, (2015).

Liu, L., Yu, M., Ma, Y., & Tu, Y. Economic and economic-statistical designs of an control chart for two-unit series systems with condition-based maintenance. *European Journal of Operational Research*, 226(3), 491-499. doi:10.1016/j.ejor.2012.11.031, (2013).

Ben-Daya, M., Integrated production maintenance and quality model for imperfect processes. *IIE Transactions*, 31(6), 491-501. doi:10.1080/07408179908969852, (1999).

Chen, W. S., & Yu, F. J. Economic design of x-bar charts under preventive maintenance and Taguchi loss functions. *Journal of Applied operational Research*, 3(2), 103-109. doi:10.1201/9781315210469-20, (2011).

Charongrattanasakul, P., & Pongpullponsak, A. Minimizing the cost of integrated systems approach to process control and maintenance model by EWMA control chart using genetic algorithm. *Expert Systems with Applications*, 38(5), 5178-5186. doi:10.1016/j.eswa.2010.10.044, (2011).

Lee, B. H., & Rahim, M. A., An Integrated Economic Design Model For Quality Control, Replacement, And Maintenance. *Quality Engineering*, 13(4), 581-593. doi:10.1080/08982110108918688, (2001).

Linderman, K., Mckone-Sweet, K. E., & Anderson, J. C., An integrated systems approach to process control and maintenance. *European Journal of Operational Research*, 164(2), 324-340. doi:10.1016/j.ejor.2003.11.026, (2005).

Ben

Engineering, 1(1), 20-26. doi:10.1108/13552519510083110, (1995).

Ben-Daya, M., & Al-Emrouss, S. Maintenance and quality

Cassady, C. R., Bowden, R. O., Liew, L., & Pohl, E. A. Combining preventive maintenance and statistical process control: a preliminary investigation. *IIE Transactions*, 32(6), 471-478. doi:10.1080/07408170008963924, (2000).

Mehrafrooz, Z., & Noorossana, R. An integrated model based on statistical process control and maintenance. *Computers & Industrial Engineering*, 61(4), 1245-1255. doi:10.1016/j.cie.2011.07.017, (2011).

Zhou, W. and Zhu, G., Economic design of integrated model of control chart and maintenance management. *Mathematical and Computer Modelling*, 47(11-12), pp.1389-1395, (2008).

Zhong, J., & Ma, Y., An integrated model based on statistical process control and maintenance for two-stage dependent processes. *Communications in Statistics - Simulation and Computation*, 46(1), 106-126. doi:10.1080/03610918.2014.957841, (2014).

Alsyouf, I., Shamsuzzaman, M., Abdelrahman, G. and Taha, M., Improving reliability of repairable systems using preventive maintenance and time-between-failures monitoring. *European J. of Industrial Engineering*, 10(5), p.596, (2016).

Ben-Daya, M. and Rahim, M., Effect of maintenance on the economic design of \bar{x} -control chart. *European Journal of Operational Research*, 120(1), pp.131-143, (1998).

Amal Gouiaa-Mtibaa, So_ene Dellagi, Zied Achour, Walid Erray. Joint optimization for maintenance planning and quality deterioration. X_eme Conf_erence Internationale : Conception et Production Int_egr_ees, Dec 2015, Tanger, Morocco.

Sharma, A., Yadava, G. and Deshmukh, S. A literature review and future perspectives on maintenance optimization. *Journal of Quality in Maintenance Engineering*, 17(1), pp.5-25, (2011).

Garg, A. and Deshmukh, S., Maintenance management: literature review and directions. *Journal of Quality in Maintenance Engineering*, 12(3), pp.205-238, (2006).

Chien, Y., Sheu, S. and Zhang, Z., Optimal maintenance policy for a system subject to damage in a discrete time process. *Reliability Engineering & System Safety*, 103, pp.1-10, (2012).

Moghaddam, K., Preventive Maintenance and Replacement Scheduling: Models and Algorithms. *University of Louisville, Kentucky, USA*, (2008).

Henry, A. J., & Nachlas, J. A., An equivalent age model for condition-based maintenance. *2012 Proceedings Annual Reliability and Maintainability Symposium*. doi:10.1109/rams.2012.6175484, (2012).

Liu, B., Xie, M. and Kuo, W., Reliability modeling and preventive maintenance of load-sharing systems with degrading components. *IIE Transactions*, 48(8), pp.699-709, (2016).

Endrenyi, J., Anders, G. and Leite da Silva, A., Probabilistic evaluation of the effect of maintenance on reliability. An application [to power systems]. *IEEE Transactions on Power Systems*, 13(2), pp.576-583, (1998).

Taghipour, S. and Banjevic, D., Optimum inspection interval for a system under periodic and opportunistic inspections. *IIE Transactions*, 44(11), pp.932-948, (2011).

MCKONE, K. and WEISS, E., TPM: PLANNED AND AUTONOMOUS MAINTENANCE: BRIDGING THE GAP BETWEEN PRACTICE AND RESEARCH. *Production and Operations Management*, 7(4), pp.335-351, (1998).

Wang, H., A survey of maintenance policies of deteriorating systems. *European Journal of Operational Research*, 139(3), pp.469-489, (2002).

Afey, I., Reliability-Centered Maintenance Methodology and Application: A Case Study. *Engineering - Scientific Research*, 02(11), pp.863-873, (2010).

Raj, A., Economic design of control chart (In partial fulfillment of the requirements of Bachelor of Technology (Mechanical Engineering)). *National Institute of Technology Rourkela-769008 Orissa*, (2010).

Zhang, H., Shamsuzzaman, M., Xie, M. and Goh, T., Design and application of exponential chart for monitoring time-between-events data under random process shift. *The International Journal of Advanced Manufacturing Technology*, 57(9-12), pp.849-857, (2011).

DAS, T. and JAIN, V., An economic design model for X charts with random sampling policies. *IIE Transactions*, 29(6), pp.507-518, (1997).

Zhang, C., Xie, M. and Goh, T., Economic design of exponential charts for time between events monitoring. *International Journal of Production Research*, 43(23), pp.5019-5032, (2005).

Zhang, H., Xie, M., Goh, T., & Shamsuzzaman, M., Economic design of time-between-events control chart system. *Computers & Industrial Engineering*, 60(4), 485-492. doi:10.1016/j.cie.2010.11.008, (2010).

Zhang, C. W., Xie, M., Liu, J. Y., & Goh, T. N., A control chart for the Gamma distribution as a model of time between events. *International Journal of Production Research*, 45(23), 5649-5666. doi:10.1080/00207540701325082, (2007).

Xie, M., Goh, T., & Ranjan, P., Some effective control chart procedures for reliability monitoring. *Reliability Engineering & System Safety*, 77(2), 143-150. doi:10.1016/s0951-8320(02)00041-8v, (2002).

Serel, D. A., & Moskowitz, H., Joint economic design of EWMA control charts for mean and variance. *European Journal of Operational Research*, 184(1), 157-168. doi:10.1016/j.ejor.2006.09.084, (2008).

Wu, Z., Shamsuzzaman, M., & Pan, E. S., Optimization design of control charts based on Taguchis loss function and random process shifts. *International Journal of Production Research*, 42(2), 379-390. doi:10.1081/00207540310001614169, (2004).

Liu, J. Y., Xie, M., Goh, T. N., & Sharma, P. R., A Comparative Study of Exponential Time between Events Charts. *Quality Technology & Quantitative Management*, 3(3), 347-359. doi:10.1080/16843703.2006.11673120, (2006).

Liu, J., Xie, M., Goh, T., & Ranjan, P. (n.d.). Time-between-events charts for on-line process monitoring. *IEEE International Engineering Management Conference (IEEE Cat. No.04CH37574)*. 2004
doi:10.1109/iemc.2004.1408854

Montgomery, D. C. *Introduction to Statistical Quality Control*, (6th ed.). Danvers, MA.: John Wiley & Sons, . (2009).

Khoo, M. and Xie, M., A study of time-between-events control chart for the monitoring of regularly maintained systems. *Quality and Reliability Engineering International*, 25(7), pp.805-819, (2009).

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Appendix 1

Table 1: A Summary of the Literature review on SPC-Maintenance Models

Integration Method/Solution Procedure	Publication	Quality Control Chart Type / SPC Tool						Economic	Application Quality Monitoring Purpose	Maintenance Policy Employed
	(Author(s), Year)	X-Bar Chart	MEWMA	EWMA	Time-Between-Events	Adaptive Shewart	Other			
Hooke and Jeeves algorithm	(Abouei Ardakan et al., 2015)		x					Yes	Production System Process Quality - Equipment Deterioration	Planned Maintenance Reactive Maintenance
Dancun (1956) approach with Maintenance Cost Parameters	(Pandey et al., 2011)	x						Yes	Production System Quality Characteristic	Block Replacement Policy
Markove Chain (7 States)	(Panagiotidou et al., 2009)					x		Yes	Production System Process Quality	Condition Based Maintenance
Dancun (1956) approach with Maintenance Cost Parameters	(Ching et al., 2009)	x						Yes	Production System Product Quality	Preventive Maintenance
Basic Input-Output Integration	(Azizi, 2015)						x SPC	No	Production System Product Quality, Productivity, etc	Autonomous Maintenance

	Publication	Quality Control Chart Type / SPC Tool	EC		
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Integration Method/Solution Procedure	(Author(s), Year)	X-Bar Chart	MEWMA	EWMA	Time-Between-	Adaptive Shewart	Other		Application Quality Monitoring Purpose	Maintenance Policy Employed
Proposed Framework of integrated variables, and models	(Lu et al., 2016)						x Quality Improvement	Yes	Production System - Product Quality- Machine Reliability	Preventive Maintenance Decision Making
discrete-time Markov Chain	(Xiang, 2013)	x						Yes	Production System Product Quality	age based preventive maintenance (Imperfect)
Combined Mathematics and Simulation Based Modeling framework	(Bouslah, 2017)						X Quality Control (Inspection)	Yes	Production System Product Quality - Machine Reliability	Age Replacement Policy
Methodological Approach (Procedure)	(Lesage, et al., 2012)	x						Yes	Production System Quality Parameters	Quality Based Maintenance Policy
Optimization of different models and the combination model	(Panagiotidou, 2012)						X General Standard Control Chart	Yes	Production System Quality Parameters	Preventive Maintenance Corrective Maintenance Minimal Maintenance

	Publication	Quality Control Chart Type / SPC Tool	Econ	Application Quality	
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Integration Method/Solution Procedure	(Author(s), Year)	X-Bar Chart	MEWMA	EWMA	Time-Between-	Adaptive Shewart	Other		Monitoring Purpose	Maintenance Policy Employed
Mathematical Model	(Deloux, 2009)						X (SPC) Classical Control Chart	Yes	Production System Quality Parameter	Condition Based Maintenance
bi-objective optimization: Quality and maintenance-related cost minimization criterion along with a long-run expected availability maximization criterion and constraints.	(Tasias, & Nenes, 2017)					x		Yes	Production System Process Quality	Preventive Maintenance Corrective Maintenance
General framework of integration between quality inspection and maintenance	(Kurniati et al., 2015)						X Quality Inspection	No	Production System Quality Characteristic	Preventive Maintenance Corrective Maintenance
Genetic algorithm	(Yin et al., 2015)	x						Yes	Production System Product Quality	Predictive Maintenance Preventive Maintenance Corrective Maintenance
Continuous time Markov Chain (5 States)	(Liu et al., 2013)	x						Yes	Production System Product Quality-Machine Deterioration	Condition Based Maintenance

	Publication	Quality Control Chart Type / SPC Tool	Econ Quality	Application Quality	
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Integration Method/Solution Procedure	(Author(s), Year)	X-Bar Chart	MEWMA	EWMA	Time-Between-	Adaptive Shewart	Other		Monitoring Purpose	Maintenance Policy Employed
Optimization using pattern search technique of Hooke and Jeeves	(Ben-Daya, 1999)	x						Yes	Production System Product Quality	Preventive Maintenance
Taguchi loss functions	(Chen & Yu, 2011)	x						Yes	Production System Product Quality	Preventive Maintenance
Genetic algorithm	(Charongrattanasakul, and Pongpullponsak, 2011)			x				Yes	Production System Product Quality	Planned Maintenance Reactive Maintenance Compensatory Maintenance
Hooke and Jeeves Search Technique - Mathematical Models	(Lee, & Rahim, 2001)	x						Yes	Production System Product Quality	Age Replacement Policy
Hooke and Jeeves pattern search algorithm	(Linderman et al., 2005)	x Other Control Charts can also be used						Yes	Production System Equipment Deterioration	Planned Maintenance Reactive Maintenance

	Publication	Quality Control Chart Type / SPC Tool	ECON	Application Quality	
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Integration Method/Solution Procedure	(Author(s), Year)	X-Bar Chart	MEWMA	EWMA	Time-Between-	Adaptive Shewart	Other		Monitoring Purpose	Maintenance Policy Employed
Simulation Optimization Approach	(Cassady et al., 2000)	x						Yes	Production System Product Quality	Age Replacement Policy
Mathematical Model (6 Scenarios)	(Mehrafrooz , & Noorossana, 2011)	x						Yes	Production System Product Quality	Planned Maintenance Reactive Maintenance Compensatory Maintenance
Grid-search approach	(Zhou, & Zhu, 2008)	x Other Control Charts can also be used						Yes	Production System Equipment Deterioration	Planned Maintenance Reactive Maintenance Compensatory Maintenance
Mathematical Model Framework (8 scenarios) Taguchi loss function	(Zhong and Ma, 2014)						x Shewart individual-residual joint control chart	Yes	Production System Equipment Deterioration	Planned Maintenance Reactive Maintenance Compensatory Maintenance
Procedure	(Alsayouf et al., 2016)				x			No	Repairable Systems System Reliability	Age Replacement Policy
Hooke and Jeeves Search Technique	(Ben-Daya and Rahim, 2000)	x						Yes	Production System Product Quality	Preventive Maintenance
Mathematical Model	(Michael & Xie., 2008)				x				Maintained Systems System Lifetime	Planned Maintenance Reactive Maintenance

