Investigating economic replacement policy under uncertainty for managerial application based on grey-reliability approach using QCC

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Abstract

Purpose – The main purpose of present study is to model the replacement policy under uncertainty for managerial application based on grey-reliability approach by considering the subjective views of quality control circle (QCC). The study objectively links the optimality between individual replacement and group replacement policies for determining the minimum operational costs. The integrated framework between QCC, replacement theory, grey set theory and supply chain management is presented to plan replacement actions under uncertainty.

Design/methodology/approach – The study proposes the concept of grey-reliability index and built a decision support model, which can deal with the imprecise information for determining the minimum operational costs to plan subsequent maintenance efforts.

Findings – The findings of the study establish the synergy between individual replacement and group replacement policies. The computations related to the numbers of failures, operational costs, reliability index and failure probabilities are presented under developed framework. An integrated framework to facilitate the managers in deciding the replacement policy based on operational time towards concerning replacement of assets that do not deteriorate, but fails suddenly over time is presented. The conceptual model is explained with a numerical procedure to illustrate the significance of the proposed approach.

Originality/value – A conceptual model under the framework of such items, whose failures cannot be corrected by repair actions, but can only be set by replacement is presented. The study provides an important knowledge based decision support framework for crafting a replacement model using grey set theory. The study captured subjective information to build decision model in the ambit of replacement.

Keywords Grey set theory, Replacement, Uncertainty, Failure probability, Maintenance, Quality control circle

Paper type Technical paper

1. Introduction

The main intention of every business is to earn more profit. Profit derives satisfaction and stimulates organizations resources to be more productive. The organization resources require optimization related with variables, factors and drivers for their better performance (Chemweno *et al.*, 2016; Petrillo *et al.*, 2019). It is required by the organizations to remain

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competitive and profitable for sustainability (Wang *et al.*, 2019; Bag *et al.*, 2021a), where maintenance and replacement is one of the decision making field. Replacement of assets is required in organization due to numerous decision factors like price fluctuation, replacement cost, generation of repetitive maintenance, safety, depreciation, power consumptions etc (Duan *et al.*, 2018; Golmakani, 2022). Replacement plays an important function in achieving organization goals such as productivity enrichment, loss reduction, acceptable consumer's response, profit maximization and better enterprises image (Wang *et al.*, 1997; Sahu *et al.*, 2016).

Researchers have developed abundant decision making techniques for estimating and planning micro and macroeconomic activities and have furnished numerous decision support models for selecting industrial robots, developing irrigation strategies, traffic control, transportation control, production management, quality management, environment protection, supplier selection, shipping logistic management, forecasting etc. In recent time, replacement is identified as an important decision making field and requires concentration of the researchers to develop new approaches, as it implicates huge human resources as well as capitals and machines etc (Avakh Darestani *et al.*, 2022; Gandhare and Akarte, 2022). Replacement is required, when the working units become less effective, unbeneficial and unprofitable; owing to sudden failure, wear, tear etc. by the passage of time (Tuyet and Chou, 2018; Algabroun *et al.*, 2022). The numerous maintenance costs can be significantly reduce and optimize by replacing working units with innovative ones at optimum interval (Ahmadi *et al.*, 2016; Rezaei, 2017).

Determining the optimum replacement interval for working units is important and requires development of various clusters of techniques by the researchers (Shagluf *et al.*, 2018; Sigsgaard *et al.*, 2022). In this study, development of a grey-reliability approach for the replacement of working units; that fails suddenly is considered. The obligatory requirement of improved productivity by the working units, costs reduction and safety provisions also requires decision making approaches for setting up replacement policies (Naji *et al.*, 2019; Peimbert-García *et al.*, 2022). Accordingly; the present work advocates the replacement policy derived from grey set theory (GST) to minimize the operational costs of the system, while dealing with uncertainty and impreciseness. The present study is conducted by the authors to report the below mentioned Research Questions (RQ):

RQ1. How the integrated framework between quality control circle, replacement theory, grey set theory and supply chain management can be developed.

RQ2. How the subjective information can be utilize to plan and schedule replacement actions under uncertainty.

RQ3. How the optimality can be achieved between individual replacement and group replacement policies for determining the minimum operational costs.

It has been observed that the performance and efficiency of the working units of a system decline over time (Staffell and Green, 2014). To restore their performance characteristics and efficiency, it is essential to replace or provide certain degree of maintenance (Rana and Emosi, 2018; Avakh Darestani *et al.*, 2022). However, a state will arrive, when it will be optimal to replace them with innovative one, as maintenance of them will become awfully expensive (Kurian *et al.*, 2019; Bashar *et al.*, 2022). Sahu *et al.* (2016) depicted a group of reasons, which strategically suggested the replacement of assets over time. They presented a depreciation-replacement framework to operate the working units with least expenditure. In lots of situations, the performance and efficiency of the working units do not decline over time, but fails suddenly. Consequently; in this study, a conceptual model under the context of such items whose failures cannot be corrected by repair actions, but can only be set by replacement is presented. The study considers developing a computation model for replacement via exploring the concept of GST, so as to deal with the uncertain and imprecise information, because acquiring true and precise information from the real working system is complicated.

The present study is explained in six sections, where in the first section; introduction is presented. In second section, literature review is discussed. In section three, methodological guidelines and decisive fields for preparing integrated framework are discussed. In section four, computation procedure is discussed, which is followed by results and sensitivity analysis in section five. Section six of the study is reporting the conclusions section.

2. Literature review

2.1 Concepts and linkages

Researchers have discovered that the computational models can assist in portraying effective replacement strategies for drafting replacement decisions (Ighravwe and Ayoola Oke, 2017; Kundu *et al*., 2022). It is found that both theoretical and numerical analyses of the system are required to predict system behavior and problem solutions (Zhang and Huang, 2019). Probability models are found significant in describing and predicting various real world problems (Marthin and Rao, 2020). The same are flexible and compatible to reveal real world issues to enable generalization (Marthin and Rao, 2020). It is also found that the dynamic nature of the system can be understood by system modeling and that can be effectively done by importing probabilistic techniques (Guo, 2007; Sahu *et al*., 2020). Probabilistic techniques can assist in identifying the significant possible choices. Additionally, it is found that the average cost for a unit can be decreased by developing a reliability constraint, which included components reliability, system reliability, the periodicity of preventive replacements and the costs of their preventive and corrective replacements (Darghouth *et al*., 2016). Safety and risk assessment in addition to quality, productivity and profitability is nowadays required by manufacturing companies (Alizadeh and Sriramula, 2018) and that can be assess by reliability analysis. It is also found that the cost related decisions of any project prominently helps in identifying best practices for the system (Langston, 2016). It is found that the development of holistic frameworks, computational methods etc. based on the reliability analysis is needed for defining a critical safe system, which can account systems degradation and failure behaviors, their dependencies, the external influencing factors and the associated uncertainties (Zio, 2016). It is profitable to appraise decisive outputs for assuming effectiveness and efficacy from implicated resources (He *et al*., 2021; Guo *et al*., 2022). Consequently, a knowledge based decision support model based on reliability, grey set theory, quality control concept and economic cost to plan sustainable maintenance efforts is presented in the study.

Reliability analysis greatly signifies in designing product architectures and planning maintenance efforts (Zhang *et al*., 2018). Reliability and other related performance parameters should have to be assessed based on actual customer use and failure data to define the quality of a complex system (Crow, 1990). Carlson (2014) stated that Failure Mode and Effects Analysis (FMEA) potentially exercised high reliability in products and processes and easily executed during the product life cycle, which can result in significant improvements to reliability, safety, quality, delivery and cost. Carlson (2012) utilized FMEA to define and identify the quality and reliability in corporations worldwide. Adhikary *et al.* (2016) suggested that improvement in system efficiency can be achieved with reduction in the maintenance cost to consequently increase profit. Wua and Liu (2009) and Liu *et al.* (2014) depicted the potential domain of grey system theory to be utilized in a system under incomplete information. Allen and Ching (2005) modeled a single machine replacement problem based on cost for generalizing their work and proposed renewal theory to solve replacement problem of machine. Li *et al.* (2015) presented a structural logical grey system theory to predict the nature of the system, which is based on an improved grey clustering technique. Alta *et al.* (2015) have stressed to quantify the performance of the system based on operational cost savings and Crowder and Lawless (2007) have exploited costs for examining the wear on an element, replacing an element and allowing an element to fail before being replaced and thus a decision support model underlying minimum operational costs to plan subsequent maintenance efforts is presented by the authors in the present work.

2.2 Critical analysis

The concept of grey system has been utilized by researchers to approximate the probabilistic thinking. He *et al.* (2015) compared conventional statistical tools with grey system theory and declared three superiorities of the grey system theory, i.e. (a) provides easy calculation (b) requires few sample size (c) have exact accuracy for prediction. Bezuglov and Comert (2016) found that the prediction errors can be lowered as well as prediction accuracy can be improved by structuring models through grey system theory. The study revealed that Mean Absolute Percent Errors and Mean Squared Errors on an average can be improved about 50%; by using grey system theory. Guo and Guo (2009) proposed fuzzy credibility measure theory for grey system modeling and suggested that an appropriate mathematical foundation is required for grey system modeling. Sahu *et al.* (2017) build a Multi Criteria-Material Handling System (MC-MHS) hierarchical module based on grey information, which have integrated ecological and fiscal criteria in a closed loop to benchmark the MC-MHS alternatives. Their study reported the effectiveness of grey system modeling in attaining robust decision.

Liu *et al.* (2015b) applied grey system theory accompanied with expert panel method to compute evaluation index of a system for assessing supplier performance at production and development stage of Commercial Aircraft Corporation of China Ltd (COMAC). The study utilized Grey cluster evaluation model based on triangular end-point and weight function to evaluate significant vendors to undertake the development task. Tang (2015) projected a new approach, which is based on grey relational analysis and Dempster–Shafer theory of evidence for solving decision making problem. Sahu *et al.* (2018a) utilized grey theory and presented a Grey- DEMATEL (Decision-Making Trial and Evaluation Laboratory) approach to recognize the most significant enabler, creating E-Waste by the replacement of working mobile phones. Luo *et al.* (2015) extended the application scope of grey theory by making the theory of grey analysis significant in practical application. Wang *et al.* (2016) suggested that grey theory have strong strength and the extent of uncertainty in information can be easily characterized by conceptualizing grey numbers. Sahu *et al.* (2018b) constructed the advanced hierarchical structural (AHS) chain of macro-micro parameters and developed a grey number based scorecard model to solve their presented AHS chain, in order to define the performances of fruit supply bazaars (FSBs).

Memon *et al.* (2015) merged grey system theory and uncertainty theory to develop a novel tool for evaluating supplier selection problem. Liu *et al.* (2015a) presented a fractional reverse accumulative grey Verhulst model to improve the stability and the prediction accuracy of the system characteristics. Chu *et al.* (1998) decided the system maintenance policy based on predictive maintenance by developing a global approach to determine the optimal policy for maintenance. Liu *et al.* (2016) suggested grey numbers as a kind of outline, where one can recognize the range of information in his work by utilizing them.

Quality control tools are nowadays used to monitor and control process variability. Hodkiewicz and Ho (2016) stated that the quality issues can be identified using reliability analysis in maintenance management systems as it defines significant information. Gouiaa *et al.* (2018) stated that degraded system affects the quality of the system and integrated maintenance strategies are required to be used for accounting the system degradation and its impact on the quality of output product. Their study assessed imperfect maintenance actions and developed analytical models to understand the economic impacts due to maintenance and reworking activities. Oyedepo *et al.* (2015) worked in the direction of reducing the costs linked with operations, maintenance, investment, safety, fuel etc. It is found that, in many situations, the working units do not fails over time but fails suddenly, which thereby leads to system failure instantly. Sometime the failure in the sub-unit is responsible for complete collapse of the system, in these cases; the cost of failure is higher than the actual cost of sub-unit that fails in reality.

Sheu (1998) highlighted the consequences and impact of failure in the overall performance of the system and found that the failure should be avoid at every stage during actual operation, as the failure of any sub-element in the system can be responsible for closing down the entire system and may possibly cause severe loss in production, idle labor, overhead costs, interruption in continuity of service and thus such an events are costly or dangerous. Sheu (1999) presented a generalized replacement model and minimized the estimated cost rate in their considered case. He talked about the types of failure, which responsible for deteriorating a system. Liu (2016) presented a ranking method to determine the ranking preference of the decision makers. They built a novel graph model with grey information to solve equilibrium states and decision paths. Sahu *et al.* (2014) utilized grey set theory in multi indices decision making model to benchmark CNC machine tool. They portrayed the procedural steps to built decision support system based on grey set theory. Additionally, It is found that Kumar and Westberg (1997) developed age replacement policy by a computational approach based on reliability and system variables to forecast the feasible replacement time period. Accordingly, in present study reliability index is built by utilizing grey system theory.

2.3 Trends and concerns

Maintenance management is a skill based management discipline, which stresses on eradicating waste for producing breakthrough performance by the system (Singh and Ahuja, 2017). Maintenance activities are planned on the basis on cost, time or failure and research based on mathematical formulation, artificial intelligence, matrix formation, simulation, critical analysis and multi criteria techniques are required to be developed by the researchers for influencing maintenance decisions (Basri *et al.*, 2017; Hemmati *et al.*, 2018; Jamkhaneh *et al.*, 2018). The rapid modernization and requirement of higher productivity needs developed maintenance tool and techniques for operating sophisticated and complex machines and equipments (Singh and Ahuja, 2017; Krotov, 2016; Navas *et al.*, 2017). Industries are using Preventive Maintenance (PM) to maintain the life of system components, which in turn demands the level of repair decisions such as repair/move/discard (Rawat and Lad, 2017). Maintenance managers should effort in studying the reliability of the repairable systems and their recurrent failures instead of collecting and adapting maintenance needs for the system (Navas *et al.*, 2017).

The reliability analysis can effectively assess and classifies the maintenance trends. Patil *et al.* (2017) presented an approach to be utilized in industries, where reliability, safety, maintainability and availability play an important role. The reliability and availability of production facilities can be increased by mounting valuable maintenance strategy in an organization (Awad and Rami, 2016). An imperfect preventive maintenance (PM) policy based on performing number of imperfect PM actions before undertaking a perfect one is established by Gouiaa *et al.* (2018) to minimize the repairs at failures and to slow down the degradation process of the manufacturing system. It is found that Failure analysis of new complex equipment is important but difficult (Peeters *et al.*, 2018). Peng *et al.* (2018) stated that the failures related with one mode may impact the occurrences of other modes and attributed failure as unacceptable occurrences. Peeters *et al.* (2018) stated that failure behavior should be accurately understood before designing a maintenance programme and disclosed it superior to execute preventive maintenance (PM) before a failure occurs, but that requires good predictions of the failure behavior of the system, which can be prepared by utilizing grey set theory (Sahu *et al.*, 2018a).

The corrective actions are needed to be incorporated in responding to failures during test operations (Crow, 2017). The reliability analysis can help in defining the failure trend and the associated realistic milestones, which in turn can assist in curtailing maintenance efforts. Awad and Rami (2016) prepared a reliability centered maintenance implementation model for prioritizing maintenance actions to opt the most significant subset actions relating time and budget constraints. Gupta and Mishra (2016) used strengths, weaknesses, opportunities and threats (SWOT) analysis to define the noteworthy factors for reliability centered maintenance implementation plan. Mirjalili *et al.* (2016) utilized grey concepts to develop a Multi-Objective Grey Wolf Optimizer for handling multiple objectives optimization problems. Mei *et al.* (2016) presented Grey-DEMATEL approach to identify and evaluate criterions and alternatives during uncertainty and incomplete information. Tan and Raghavan (2008) built a MSS (Multi State Systems) framework module for scheduling predictive maintenance work. Results of the study revealed that maintenance has an effect on quality characteristics. They recommended planning of maintenance schedules of the system by estimating the overall system failure times.

It is found that the Decision Support System (DSS) can assists in defining the behavior of the system and thus, a knowledge based decision support system based on grey set theory is presented in this study to define the significant replacement policy under maintenance. The study revealed that a less attentive work is done by the researchers in drafting a replacement policy for those assets, which cannot be rectified after failure. Moreover, low attentive work is found by the authors, which have addressed reliability, grey set theory, QCC and replacement under a sole arena. Accordingly, in this study, the authors proposed a reliability index for defining the maintenance policy of such products, whose component failures cannot be rectified through repair actions, but can only be fixed by replacement.

3. Methodological guidelines

This study aimed at developing a framework to suggest the importance of replacement and built a decision support system based on reliability to determine the minimum operational cost. The study developed the concept of grey-reliability index to deal with uncertainty and impreciseness in the domain of replacement. The study incorporates subjective information to build module in the ambit of replacement. The concept of GST is explored in conjunction with replacement theory and quality control circle for replacing street lights under uncertainty in the present work. A conceptual model under the framework of such items whose failures cannot be corrected by repair actions, but can only be set by replacement is presented in this study.

3.1 Grey set theory (GST) – mathematical basis

Grey set theory is an interval number theory, where grey set is a collection of grey numbers. Grey numbers act as a kind of outline, where one can recognize the range of information in his work by utilizing them. Deng (1989) affirmed that, on the basis of grey relations, grey elements and grey numbers; one can identify Grey System, where "grey" means poor, incomplete, uncertain etc. In present study, authors have used grey numbers to reproduce

Grey System. Grey set is interval number used for the purpose of solving problems dealing with uncertainty, discrete data and incomplete information (Deng, 1989; Sifeng *et al.*, 2012). The Grey set theory or grey number theory is utilized by numerous researchers and becomes a very successful theory for solving problems dealing with uncertainty and discrete data (Deng, 1989; Sifeng *et al.*, 2012). Grey system theory assists in modeling a dynamic system, which only possesses poor and uncertain information for investigating the concerned system (Deng, 1982; Guo and Guo, 2009). Grey theory categorizes the system dynamics into three categories: white, black and grey based on the degree of information completeness (Guo, 2007). Satisfactory results can be obtained by grey theory and additionally, this theory possesses the potential to develop new tool, methods and alternatives approaches for decision making (Wu *et al.*, 2016; Mehrjerdi, 2014; Li *et al.*, 2016). Grey theory is applied to various areas, i.e. production management, forecasting, transportation management, system control and decision making (Cui *et al.*, 2016; Li *et al.*, 2016; Guo *et al.*, 2016). Some basic definitions for representing grey system, grey set and grey number in grey theory are as follows (Khuman *et al.*, 2016; Liu *et al.*, 2015a; Datta *et al.*, 2013):

Definition 1. Grey set theory is an estimation methodology, which assists in projecting and revealing the state of a system by representing it in terms of grey number and grey variables to embrace uncertain information.

Definition 2. Let X be the universal set. Then a grey set ($\otimes$) of X is defined by its two mappings

$$\begin{cases} \overline{a}(x) : x \rightarrow [0, 1] \\ \underline{a}(x) : x \rightarrow [0, 1] \end{cases} \tag{1}$$

$\overline{a}(x) \geq \underline{a}(x)$, $x \in X$, $\overline{a}(x)$ and $\underline{a}(x)$ are the degrees of upper and lower membership functions in $\otimes$ respectively. When $\overline{a}(x) = \underline{a}(x)$, the $\otimes$ turns into a fuzzy set. It reveals that grey set theory own fuzziness and is flexible capable to deal with the fuzzy circumstances.

Definition 3. Grey number represents an entity, whose true value is unknown, whereas the upper and the lower boundaries are identified. In general the grey number is represented as

$$\otimes \in [\underline{a}, \overline{a}], \ \underline{a} < \overline{a}$$

Definition 4. If only the lower boundary of $\otimes$ is identified, then $\otimes$ is known as lower limit grey number and $\otimes \in [\underline{a}, \infty]$.

Definition 5. If only the upper boundary of $\otimes$ is identified, then $\otimes$ is known as upper limit grey number and $\otimes \in [-\infty, \overline{a}]$.

Definition 6. If two boundaries known as lower and upper limits of $\otimes$ are identified, then $\otimes$ is termed as interval grey number

$$\otimes \in [\underline{a}, \overline{a}].$$

Definition 7. The fundamental operations between grey numbers $\otimes a_1 \in [\underline{a}_1, \overline{a}_1]$ and $\otimes a_2 \in [\underline{a}_2, \overline{a}_2]$ can be articulated as:

$$\otimes a_1 + \otimes a_2 = [\underline{a}_1 + \underline{a}_2, \overline{a}_1 + \overline{a}_2] \tag{2}$$

$$\otimes a_1 - \otimes a_2 = [\underline{a}_1 - \underline{a}_2, \bar{a}_1 - \bar{a}_2] \tag{3}$$

$$\otimes a_1 \times \otimes a_2 = [\underline{a}_1 \times \underline{a}_2, \bar{a}_1 \times \bar{a}_2] \tag{4}$$

$$\otimes a_1 \div \otimes a_2 = [\underline{a}_1, \bar{a}_1] \times \left[\frac{1}{\underline{a}_2}, \frac{1}{\bar{a}_2}\right] \tag{5}$$

Definition 8. The extent of grey number $\otimes$ can be computed by utilizing Equation (6).

$$L(\otimes) = [\underline{a} - \bar{a}] \tag{6}$$

Definition 9. If $\otimes a_1 \in [\underline{a}_1, \bar{a}_1]$ and $\otimes a_2 \in [\underline{a}_2, \bar{a}_2]$ are two sets of grey number then, the Euclidean equation distance between two grey sets $\otimes a_1$ and $\otimes a_2$ can be computed by utilizing Equation (7).

$$d(\otimes a_1, \otimes a_2) = \sqrt{\frac{1}{2}\left[(\underline{a}_1 - \underline{a}_2)^2 + (\bar{a}_1 - \bar{a}_2)^2\right]} \tag{7}$$

Definition 10. If $\otimes a_1 \in [\underline{a}_1, \bar{a}_1]$ and $\otimes a_2 \in [\underline{a}_2, \bar{a}_2]$ are an arbitrary interval number, the distance from $\otimes a_1$ and $\otimes a_2$ can be computed by utilizing Equation (8).

$$|\otimes a_1 - \otimes a_2| = \max\left(|\underline{a}_1 - \underline{a}_2|, |\bar{a}_1 - \bar{a}_2|\right) \tag{8}$$

Let $\otimes_{jk} = [\underline{a}_{jk}, \bar{a}_{jk}]$, represents the valuation of the alternative (A_j) by member of the Quality Control Circle (QCC), where $\otimes_{jk}$, represents grey rating of the alternative A_j by k member of QCC, then the aggregated grey rating $\widehat{\otimes}_{jk} = [\widehat{\underline{a}}_{jk}, \widehat{\bar{a}}_{jk}]$ of alternatives can be calculated by employing Equation (9).

$$\widehat{\otimes}_{jk} = \left[\widehat{\underline{a}}_{jk} = \frac{1}{K}\sum_{k=1}^{K} \underline{a}_{jk}, \widehat{\bar{a}}_{jk} = \frac{1}{K}\sum_{k=1}^{K} \bar{a}_{jk}\right] \tag{9}$$

3.2 Decisive fields embraced in this study

Generally, quality of any decision model is determined by the degree of its actual response in contrast with the predicted behavior (Bag *et al.*, 2021b; Kang *et al.*, 2022). The accuracy of any built decision model can be increase by increasing the number of variables affecting and participating in generating decision solution. In the present work, the authors built a bridge between the below mentioned sections to built a robust decision support system in the arena of replacement.

3.2.1 Supply chain management. Supply chain management or network deals with the effective execution of flow of goods and services from the origin of products to its end-users (Wong and Wong, 2008). The supply chain includes planning and scheduling of all those activities, which are connected and associated with movement of goods from the raw materials stage to the end users (Simatupang and Sridharan, 2004). The present study focuses on the margin of profit acquired by different stuffs due to logistics, handling, storage activities etc. at the different stages of the supply chain network, as the degree of their involvement at different stages by supplier, manufacturer, distributor, retailer etc. are responsible for increasing the cost of the products. This study aimed at checking optimality for mass purchasing of street lights from the manufacturer directly via determining the dominancy between group replacement and individual replacement policy. Figure 1 illustrates the general supply chain network and depicted that by decreasing the number of elements at each elementary stage, incurred costs can be reduced. The main intention of this study is to develop a computational model for planning purchasing activities.

3.2.2 Replacement. All industrial units, house hold units, military units etc. gets worn out, decreased in efficiency or fails by the passage of time due to their continuous usage over intended function and needs replacement. Working units also favors replacement due to obsolescence, i.e. new discoveries and better equipment design etc (Fekri Sari and Avakh Darestani, 2019; Tuyet and Chou, 2018). The main intension of replacement is to minimize the total operating cost of the units, improved productivity and safety provisions. Usually, the replacement is required for those units, which depreciates due to wear and tear over time, fails gradually, and their maintenance and other overhead cost increases with time (Ding and Kamaruddin, 2015; Inyiama and Oke, 2021). Secondly replacement is required for those units that fail suddenly and unexpectedly. The present study drafted a replacement framework, which can assists in deciding the economic operational time concerning with replacement of those assets that do not deteriorate; but fails suddenly over time. The present work considers the replacement case of street lights, which fails unexpectedly. The concept of grey-reliability index is projected by building a decision support model based on reliability to determine the minimum operational cost via capturing the uncertain and imprecise information. The technical implication of the present study is shown by Figure 2. This study incorporated subjective information to build a decision module in the ambit of replacement.

3.2.3 Quality control circle (QCC). Quality circles also known as quality control circles are popular amongst industrial and manufacturing organizations throughout the world. Quality circles are suggested as a technique for enhancing employee's quality of work life and satisfaction with their work (Elizur, 1990). QCC exploited the tremendous potential of the workers for improving system quality and productivity. These circles are generally small group of workers doing analogous and repetitive work and solve work related problems, which stresses them during actual operation. It work on the assumption that the workers, who are engaged in work, better knows the problem and can develop facts and solutions about the problem efficiently. It is way of capturing the creative and innovative potential that

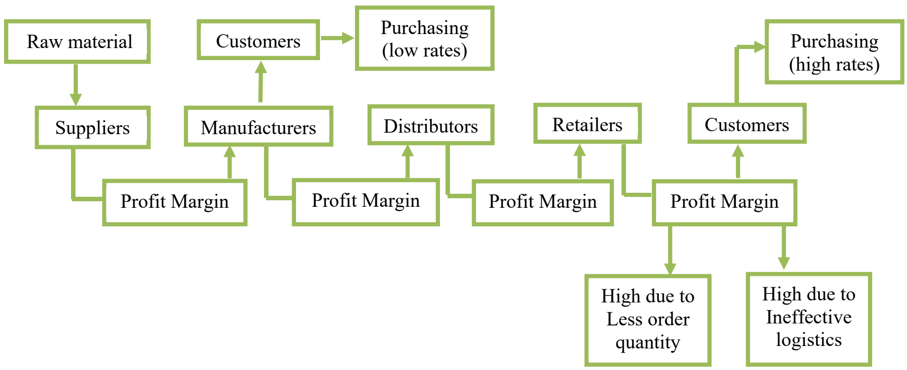

Figure 1.
Illustration of supply chain network and its elements

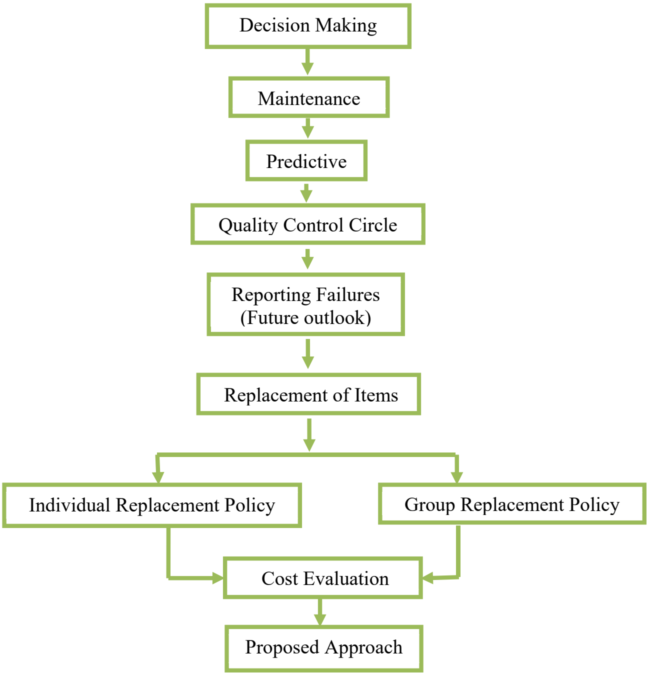

Figure 2.
Technical analysis of the present study

remains within the work force. It follows the concept that, suggestion concerning the work place should come from those individuals, who perform the actual job because they have the greatest knowledge of it.

Speakman (1991) described the concept of quality circles, highlighted their principle, background and history. The study embraces its utility based on the participation of the members from the maintenance department to form a quality circle. The members, who are discharging their duties and posses a degree of good experience in zone of maintenance activities executed during breakdown or getting complaints are required for instituting QCC. Figure 3 depicts the importance of the proposed approach in the zone of replacement.

3.2.4 Grey reliability index. Reliability analysis entails the computation of the failure probability of a component or system at any stage of his life. The analytical computation of the failure probability is usually difficult and that can be done by approximation methods (Xu and Kong, 2018). Defining systems momentary behavior under time varying inputs accompanied by cluster of coupling variables possesses significant computational challenges in reliability analysis (Hu and Mahadevan, 2017). Eryilmaz (2018) declared that the reliability of the system defined the probability that the performance of the system will be at least to that given level. Sharp research in the field of reliability engineering will aids in effectively utilizing and developing the existing and novel engineering tools and methodologies for improving quality of product or process. Reliability usually represents quality in the product over time, if the manufactured product does not fail in performing indeed function for which it is made; it is admired as reliable product and reciprocates the class of qualitative product.

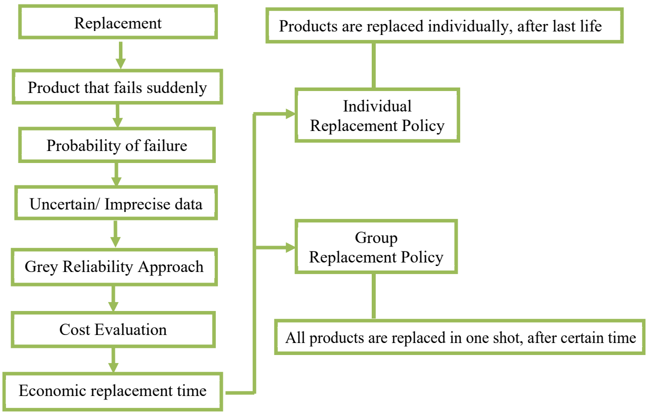

Figure 3.
Grey reliability approach implication in replacement loop

The reliability of the system can be computed by the inherent volatility of some variables, which can further assist in providing a reliable estimation of those variables (Krotov, 2016). Reliability analysis of a multidisciplinary system is computationally intensive due to the involvement of multiple variables and coupling between them (Hu and Mahadevan, 2017). The time-dependent reliability indices and probabilities of failure are needed to be obtained to evaluate structural reliability over a certain design lifetime (Zhang *et al.*, 2017). The nature of the system can be changed by estimating its reliability (Navas *et al.*, 2017). Reliability Centered Maintenance (RCM) frameworks can support the academicians and practitioner in making strategic decision for an organization (Gupta and Mishra, 2016). The reflection of the aggregate subjective ratings of the reliability assessed by the members of the quality control circle is termed as reliability index in this study. Equation (10) is employed to calculate reliability index in the present work, which realizes the whitened value of the accumulated grey sets. The whitened value of grey set is a deterministic quantity with its value existing between the lower and upper boundaries of $\otimes$ (Datta *et al.*, 2013).

$$R_{\otimes jk}^{index} = [(\beta)\underline{\widehat{a}}_{jk} \oplus (1-\beta)\overline{\widehat{a}}_{jk}] \quad (10)$$

here; β signify the value of whitening coefficient, such that $\beta \in [0, 1]$. The whitening coefficient indicates the degree of direction of $\otimes$ towards lower and upper boundaries. Based on the similarity with whitening coefficient, Equation (10) can also be written as:

$$R_{\otimes jk}^{index} = [(1-\beta)\underline{\widehat{a}}_{jk} \oplus (\beta)\overline{\widehat{a}}_{jk}] \quad (11)$$

$$R_{\otimes jk}^{index} = \frac{1}{2}[\underline{\widehat{a}}_{jk} \oplus \overline{\widehat{a}}_{jk}]\,; \ \approx \beta = 0.5 \quad (12)$$

If $\otimes a_1 \in [\underline{a}_1, \overline{a}_1]$ and $\otimes a_2 \in [\underline{a}_2, \overline{a}_2]$ are two sets of grey number. Then; the signed distance amongst $\otimes a_1$ and $\otimes a_2$ can be computed by utilizing Equation (13).

$$\begin{aligned} d(\otimes a_1, \otimes a_2) &= \left[\frac{(\underline{a}_1 - \overline{a}_1)}{2}\right] - \left[\frac{(\underline{a}_2 - \overline{a}_2)}{2}\right] \\ &= \frac{1}{2}[(\underline{a}_1 - \underline{a}_2) \oplus (\overline{a}_2 - \overline{a}_1)] \end{aligned} \quad (13)$$

The reliability index assists in calculating the failure index of street lights. The subjective assessments by member of the QCC are aggregated using Equation (9). Let $\widehat{\otimes}_{jk} = [\underline{\widehat{a}}_{jk}, \overline{\widehat{a}}_{jk}]$ denotes an aggregated grey set, and then $R^{index}_{\otimes_{jk}}$ can be calculated by using Equation (10). The various nomenclatures associated with the calculations can be identify in Appendix.

4. Computational approach and modeling

This study aimed at developing a decision support framework (DSS) for defining a replacement policy. The developed DSS is explained with illustrative numerical case based on below mentioned four steps for determining the operational cost for maintaining street lights with minimum operational expenditure. A knowledge based decision support system based on grey information is presented in this study to define the significant replacement policy for those assets, which cannot be corrected by repair actions, but can only be set by replacement. A decision support system is built and based on reliability index the minimum operational cost is determined as per the methodological flow chart presented in Figure 4. This study adopts the following procedural steps:

Step 1: Data Compilation

The numerical case considered in this study initiated with the collection of grey linguistic ratings from decision makers. Grey theory is utilized as a data compilation tool to estimate the perceptions of the decision makers. In this study, the grey theory is used to characterize the linguistic preferences under uncertainty. Grey ratings are collected from the members of the QCC, where the grey reliability model is build by considering the subjective reliability. Linguistic scale exploited by Sahu *et al.* (2017) is utilized in this study to evaluate the subjectivity in data collection. The linguistic preferences of the decision makers is collected based on grey theory to reproduce approximate situations and to avoid

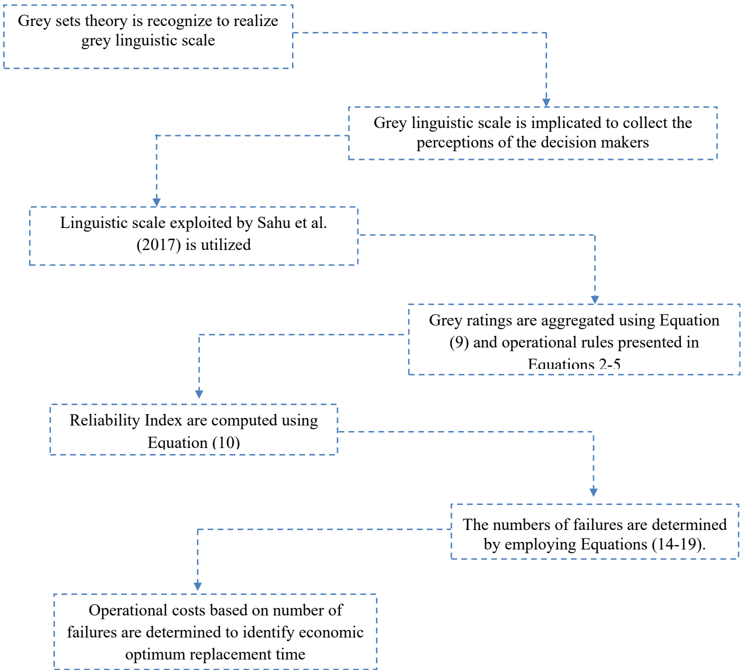

Figure 4.
Methodological flow chart of present study

vagueness and uncertainty in describing the nature of the system based on their perceptions.

Step 2: Determination of Reliability Index

The linguistic ratings are transformed into mathematical grey data sets for defining the reliability index in this study. The same are shown in Table 1. Table 1 represents the values of grey sets, which are converted on the basis of linguistic perceptions of QCC for three years under an assessment time of six months. The converted subjective reliability is acquired from decision makers, which are aggregated by using Equation (9). Later, the aggregated ratings are exploited to calculate the reliability index.

The aggregated grey ratings are disclosed in Tables 2–4. In this study, considering the values of whitening coefficient under a domain from 0.5–07, based on aggregated score, the values of Reliability Index are computed and disclosed by Tables 2–4. The same are computed by importing Equation (10) considering time duration of six months up to three years. Tables 2–4 depict the calculated values of reliability index. Next, the failure index is determined to define the failure probability. The determined failure probabilities are depicted in Figure 5. It can be observed from Figure 5, that the probability of failure for light bulbs is low in early periods and high in last periods, which discloses that the reliability of the system decreases over time. The values of failure probabilities for distinguish time periods are also

	Time period					
Experts assessment	6 Months (δ_1)	12 Months (δ_2)	18 Months (δ_3)	24 Months (δ_4)	30 Months (δ_5)	36 Months (δ_6)
(ξ_1)	[0.9, 1.0]	[0.6, 0.9]	[0.6, 0.9]	[0.4, 0.5]	[0.3, 0.4]	[0.1, 0.3]
(ξ_2)	[0.6, 09]	[0.5, 0.6]	[0.5, 0.6]	[0.4, 0.5]	[0.1, 0.3]	[0.0, 0.1]
(ξ_3)	[0.9, 1.0]	[0.9, 1.0]	[0.6, 1.0]	[0.4, 0.5]	[0.3, 0.4]	[0.1, 0.3]
(ξ_4)	[0.9, 1.0]	[0.6, 0.9]	[0.4, 0.5]	[0.3, 0.4]	[0.1, 0.3]	[0.0, 0.1]
(ξ_5)	[0.6, 0.9]	[0.6, 0.9]	[0.5, 0.6]	[0.5, 0.6]	[0.4, 0.5]	[0.3, 0.4]
(ξ_6)	[0.6, 0.9]	[0.5, 0.6]	[0.4, 0.5]	[0.4, 0.5]	[0.3, 0.4]	[0.1, 0.3]
(ξ_7)	[0.6, 0.9]	[0.5, 0.6]	[0.4, 0.5]	[0.3, 0.4]	[0.1, 0.3]	[0.0, 0.1]
(ξ_8)	[0.9, 1.0]	[0.6, 0.9]	[0.5, 0.6]	[0.4, 0.5]	[0.4, 0.5]	[0.1, 0.3]
(ξ_9)	[0.9, 1.0]	[0.9, 1.0]	[0.4, 0.5]	[0.3, 0.4]	[0.3, 0.4]	[0.0, 0.1]

Table 1. Grey ratings assigned by QCC

Time period	(δ_1)	(δ_2)	(δ_3)	(δ_4)	(δ_5)	(δ_6)
Aggregated Grey Score	[0.77, 0.96]	[0.63, 0.82]	[0.48, 0.62]	[0.38, 0.48]	[0.26, 0.39]	[0.08, 0.22]
Reliability Index	0.861	0.728	0.550	0.428	0.322	0.150
Failure Index	0.139	0.272	0.450	0.572	0.678	0.850
Failure Probability	0.047	0.092	0.152	0.193	0.229	0.287

Table 2. Aggregated grey score, reliability index and failure index for $\beta = 0.5$

Time period	(δ_1)	(δ_2)	(δ_3)	(δ_4)	(δ_5)	(δ_6)
Aggregated Grey Score	[0.77, 0.96]	[0.63, 0.82]	[0.48, 0.62]	[0.38, 0.48]	[0.26, 0.39]	[0.08, 0.22]
Reliability Index	0.880	0.747	0.564	0.438	0.336	0.164
Failure Index	0.120	0.253	0.436	0.562	0.664	0.836
Failure Probability	0.042	0.088	0.152	0.196	0.232	0.291

Table 3. Aggregated grey score, reliability index and failure index for $\beta = 0.6$

tabulated in Tables 2–4, where cumulative of them explicates that all lights will fail up to the end of third year, which is their predicted last life.

Step 3: Determination of number of Failures

The computed failure probabilities of distinguished periods are used to determine the number of failures during that period by employing Equations (14)–(19). For the sake of computation and to highlight the execution of the proposed approach, thousand street lights are initially assumed replaced up. Let $f_{end}^{i^{th}}$ be the individual replacement done by the end of δ_i period and γ_{fp}^{i} be the probability of failure for i^{th} time period.

$$f_{end}^{1^{st}} = f_{initial} \otimes \gamma_{fp}^{1}\,, \; \in f_{initial} = 1000 \tag{14}$$

$$f_{end}^{2^{nd}} = f_{initial} \otimes \gamma_{fp}^{2} \oplus f_{end}^{1^{st}} \otimes \gamma_{fp}^{1} \tag{15}$$

$$f_{end}^{3^{rd}} = f_{initial} \otimes \gamma_{fp}^{3} \oplus f_{end}^{1^{st}} \otimes \gamma_{fp}^{2} \oplus f_{end}^{2^{nd}} \otimes \gamma_{fp}^{1} \tag{16}$$

$$f_{end}^{4^{th}} = f_{initial} \otimes \gamma_{fp}^{4} \oplus f_{end}^{1^{st}} \otimes \gamma_{fp}^{3} \oplus f_{end}^{2^{nd}} \otimes \gamma_{fp}^{2} \oplus f_{end}^{3^{rd}} \otimes \gamma_{fp}^{1} \tag{17}$$

$$f_{end}^{5^{th}} = \xi_{initial} \otimes \gamma_{fp}^{5} \oplus f_{end}^{1^{st}} \otimes \gamma_{fp}^{4} \oplus f_{end}^{2^{nd}} \otimes \gamma_{fp}^{3} \oplus f_{\;end}^{\;3^{rd}} \otimes \gamma_{fp}^{2} \oplus f_{end}^{4^{th}} \otimes \gamma_{fp}^{1} \tag{18}$$

$$f_{end}^{6^{th}} = f_{initial} \otimes \gamma_{fp}^{6} \oplus f_{end}^{1^{st}} \otimes \gamma_{fp}^{5} \oplus f_{end}^{2^{nd}} \otimes \gamma_{fp}^{4} \oplus f_{end}^{3^{rd}} \otimes \gamma_{fp}^{3} \oplus f_{end}^{4^{th}} \otimes \gamma_{fp}^{2} \oplus f_{end}^{5^{th}} \otimes \gamma_{fp}^{1} \tag{19}$$

Step 4: Evaluation of Economic Cost

The numbers of failures are determined based on failure probabilities. The determined number of failures support in identifying the economic operational policy. Accordingly,

Table 4.
Aggregated grey score, reliability index and failure index for $\beta = 0.7$

Time period	(δ_1)	(δ_2)	(δ_3)	(δ_4)	(δ_5)	(δ_6)
Aggregated Grey Score	[0.77, 0.96]	[0.63, 0.82]	[0.48, 0.62]	[0.38, 0.48]	[0.26, 0.39]	[0.08, 0.22]
Reliability Index	0.899	0.766	0.579	0.448	0.349	0.179
Failure Index	0.101	0.234	0.421	0.552	0.651	0.821
Failure Probability	0.036	0.084	0.151	0.199	0.234	0.295

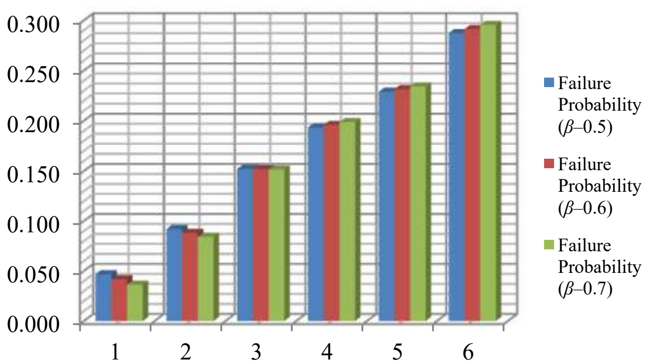

Figure 5.
Determined failure probabilities

operational cost of the street lights for different periods are determined based on group replacement in the initial first period followed by individual replacement in the subsequent periods. The determined numbers of failures for the distinguish values of whitening coefficients are represented by Tables 5–7. Operational costs originated by number of failures and distinguish purchasing cost segments for the whitening value of 0.5 is represented by Table 5. For the whitening values of 0.6 and 0.7, the related values of number of failures and operational costs are represented by Tables 6 and 7. Average cost for the period is examined to identify the economic operational policy for replacement of street lights. The minimum average cost is accepted as the economic replacement instant. Tables 5–7 are used to respond towards the average costs to determine the cost benefits and optimum replacement time.

4.1 Results and discussions

This study presents a knowledge based cost effective theoretical decision making framework towards defining an economic policy for the replacement of street lights. It is found that a replacement framework that can capture uncertain and imprecise real life information to facilitate the managers in deciding the economic operational time is momentous (Sahu *et al.*, 2020). A core policy for the replacement of street lights via checking the capability of individual replacement and group replacement policies is fabricated in this study. Investigation of the cost to be spent by the replacement of street lights by the individual replacement policy and group replacement policy is presented in this study. A technical framework, which can incorporate uncertainty and vagueness in defining the replacement policy is presented in this study to frame

Duration	$f_{end}^{1^{st}}$	$f_{end}^{2^{nd}}$	$f_{end}^{3^{rd}}$	$f_{end}^{4^{th}}$	$f_{end}^{5^{th}}$	$f_{end}^{6^{th}}$
Number of Failures	46.922	94.169	160.761	216.655	277.317	373.488
Average cost per period, 37 INR	41,692	25,555	22,395	22,213	23,316	25,655
Average cost per period, 38 INR	42,692	26,055	22,728	22,463	23,516	25,822
Average cost per period, 39 INR	43,692	26,555	23,062	22,713	23,716	25,989
Average cost per period, 40 INR	44,692	27,055	23,395	22,963	23,916	26,155

Table 5. Quantitative solution, when $\beta = 0.5$

Duration	$f_{end}^{1^{st}}$	$f_{end}^{2^{nd}}$	$f_{end}^{3^{rd}}$	$f_{end}^{4^{th}}$	$f_{end}^{5^{th}}$	$f_{end}^{6^{th}}$
Number of Failures	41.812	90.018	159.216	216.845	276.486	373.313
Average cost per period, 37 INR	41,181	25,091	22,035	21,947	23,088	25,461
Average cost per period, 38 INR	42,181	25,591	22,368	22,197	23,288	25,628
Average cost per period, 39 INR	43,181	26,091	22,702	22,447	23,488	25,795
Average cost per period, 40 INR	44,181	26,591	23,035	22,697	23,688	25,961

Table 6. Quantitative solution, when $\beta = 0.6$

Duration	$f_{end}^{1^{st}}$	$f_{end}^{2^{nd}}$	$f_{end}^{3^{rd}}$	$f_{end}^{4^{th}}$	$f_{end}^{5^{th}}$	$f_{end}^{6^{th}}$
Number of Failures	36.371	85.655	157.661	217.108	275.605	373.113
Average cost per period, 37 INR	40,637	24,601	21,656	21,670	22,848	25,259
Average cost per period, 38 INR	41,637	25,101	21,990	21,920	23,048	25,425
Average cost per period, 39 INR	42,637	25,601	22,323	22,170	23,248	25,592
Average cost per period, 40 INR	43,637	26,101	22,656	22,420	23,448	25,759

Table 7. Quantitative solution, when $\beta = 0.7$

a policy decision based on replacement costs of the street lights by the decision making authority. The results of the study revealed that after passing a peak duration, the lights start failing with high probability as compared to previous years and examined that the last life of lights are not more than three years, i.e. all lights fails before attaining this age. It is assumed that if replacement is performed individually after failure, then it costs INR 100 per light owning to small purchasing from retailer. Moreover, if replacements of all street lights are performed at predetermined (fixed) interval; after passing peak duration, then it costs between INR 37–40 per light due to mass purchasing from the producer directly. The replacement of street lights can be completed by implementing three choices, i.e. individual replacement policy or group replacement policy or linking individual cum group replacement policy. Consequently, an operational replacement modeling, which will economically help him in making a replacement decision and to assist in prior determining the optimal instant for replacing street lights individually or entirely is presented in this study. The cost benefits that can be achieved by exploiting the proposed modeling are recognized as a decision yardstick for accepting the replacement policy. The authors developed the concept of grey-reliability index under the arena of replacement, which can deal with uncertainty and vagueness in the captured information. Based on the proposed approach, the authors computed the operational costs after every six months subjected to the linked group replacement and individual replacement policies. The computation of operational costs are discussed in previous section and the same are also revealed by Tables 5–7. Additionally, Figures 6–8 are plotted considering the values of operational costs from Tables 5–7 to represent the decreased value of operational cost for distinguish values of whitening coefficient. The same assist in ease understanding the low values of operational costs for replacement policy. Figures 6–8 illustrate the operational cost computed for different time period by the built grey reliability framework.

4.2 Sensitivity analysis

Sensitivity analysis was carried out and it is depicted in Figures 9–12 to show the optimal operational cost by undertaking the distinguish values of whitening coefficient. Figures 9–12 are representing the line charts and are plotted with the intension to understand the trend of operational costs and to determine the sensitivity of whitening coefficient. It can be observed from said figures that the average operational cost for all the values of whitening coefficient is found low in fourth period of time. Average cost for the period is observed to identify the economic operational policy for replacement of street lights. Aforesaid figures are explicating that the minimum operational cost can be achieved by supporting replacement at the end of fourth time period. The operational cost charts over time indicates a pattern, which warns

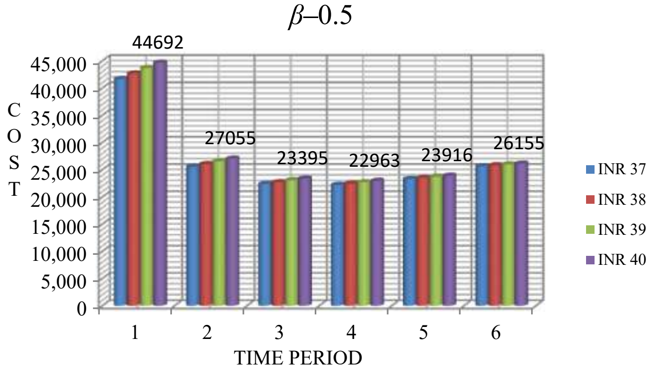

Figure 6.
Cost illustrations during different periods for β-0.5

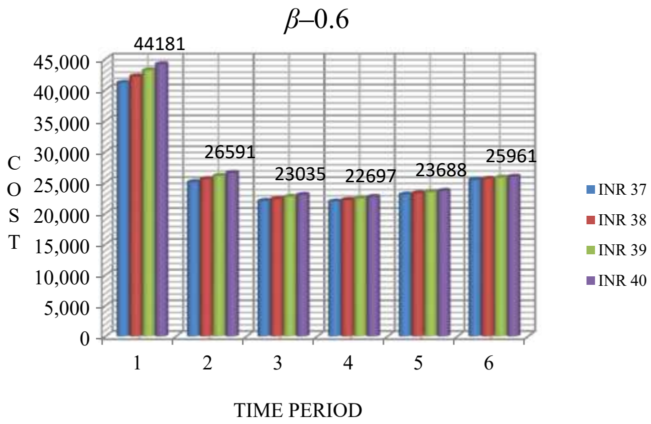

Figure 7. Cost illustrations during different periods for β-0.6

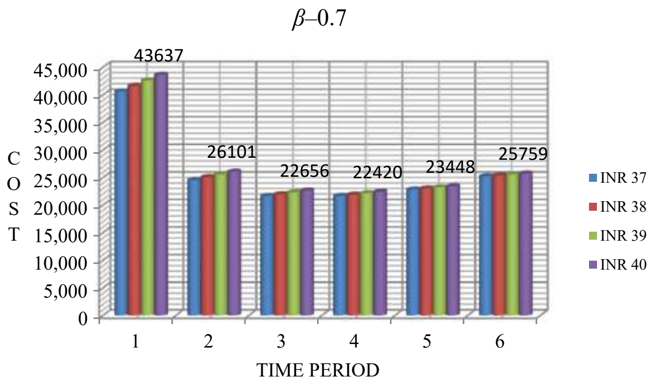

Figure 8. Cost illustrations during different periods for β-0.7

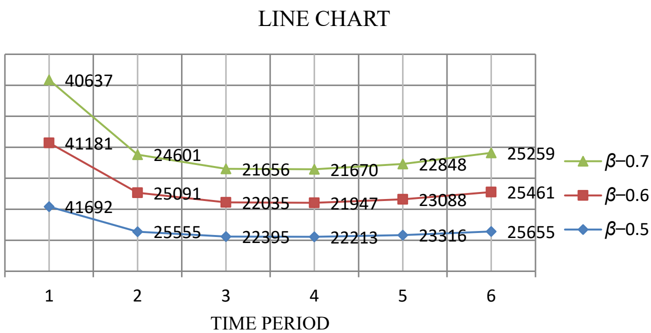

Figure 9. Chart indicating trend of operational cost over time for INR 37

that, if the street lights are operated for more than fourth period, then the operational cost will be high. The extra cost which have to be spent in case of not determining the best operational time, can be easily identify by the line charts depicted by Figures 9–12. Therefore, the devised approach can help in recognizing the cost benefits that can be gain by utilizing the optimum replacement policy, which can be easily determined by the presented work. The operational costs overtime revealed in the charts are derived from group replacement in the initial first period followed by individual replacement in the subsequent periods. The study shows that the optimality in operational costs can be achieved by linking individual cum group replacement policy.

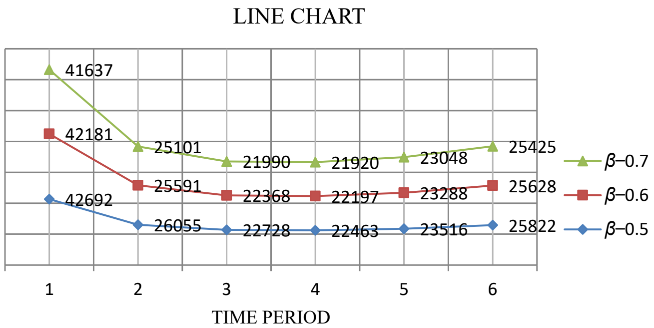

Figure 10.
Chart indicating trend of operational cost over time for INR 38

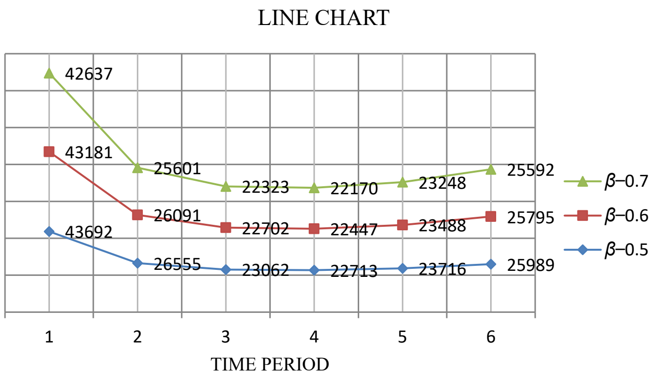

Figure 11.
Chart indicating trend of operational cost over time for INR 39

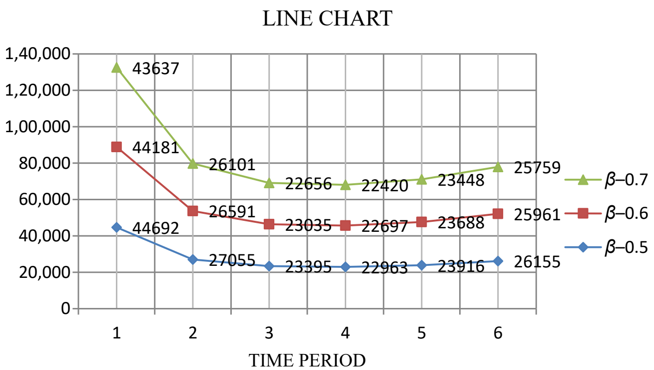

Figure 12.
Chart indicating trend of operational cost over time for INR 40

5. Conclusions

In this study, a technique has been developed for replacement, which can account imprecise, inexact and uncertain information. In the presented work, the authors developed a grey-reliability approach for approving a policy of replacing street lights, which can be further implement to those assets, whose failures cannot be corrected by repair actions; but can only be set by replacement. Sensitivity analysis suggests that the minimum operational cost can be achieved by supporting replacement of lights at the end of fourth period. The operational cost charts over time in sensitivity analysis indicates a pattern, which warns that, if the street light are operated for more than fourth period, then the operational cost will be high.

The work suggested the group replacement of street lights at the end of fourth period followed by repetitions of group replacement actions on every fourth period for operating street lights with minimum cost. The present study integrates the concept of quality control circle, supply chain management and replacement theory under one shadow. Sensitivity analysis charts depicts the extra cost, which have to be spent, if the proposed approach is not utilized in framing a policy decision by the concerns. Results of the study revealed that the optimality in operational costs can be achieved by linking individual cum group replacement policies. Cost benefits as well as maintenance efforts can be effectively planned with the help of this study.

This study provides an important approach to deal with the real-time information for crafting a replacement model using grey set theory. By conceptualizing the present study following few calculation steps, it will be possible by the firms to manage their operational assets with lowest cost by shaping the economic replacement instant.

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Appendix
Nomenclatures

QCC	Quality Control Circle
SCM	Supply Chain Management
GST	Grey Set Theory
$\otimes$	Grey set

$\underline{a}$	Lower limit of Grey set
$\overline{a}$	Upper limit of Grey set
β	Whitening coefficient
$\widehat{\otimes}_{jk}$	Aggregated grey set
$R^{index}_{\otimes_{jk}}$	Grey Reliability Index
δ_i	i^{th} duration of operational time
ξ_k	k^{th} decision maker
$f_{initial}$	Initial replacement of units
$f^{i^{th}}_{end}$	Individual replacement at the end of δ_i period (Number of failures)
γ^{i}_{fp}	Failure probability for i^{th} time period

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