University of Hormozgan

International Journal of Industrial Engineering & Management Science

journal homepage: www.ijiems.com

# The Optimal Prioritization of the Replacement of Critical Equipment in Industrial Complexes by Combining LCC and NSGA-II

Milad Ghanbari [a,*], Saeed Ramezani [b], Adolfo Crespo Marquez [c]

[a] Department of Civil Engineering, East Tehran Branch, Islamic Azad University, Tehran, Iran
[b] Department of Industrial Engineering, Iran University of Science and Technology, Tehran, Iran
[c] Department of Industrial Management, School of Engineering, University of Seville, Sevilla, Spain

ARTICLE INFO

*Article history:*
Received: 2021-06-11
Received in revised form: 2021-09-02
Accepted: 2021-09-06

*Keywords:*
Functional competencies
Asset management
Critical equipment
Prioritizing
Replacement of equipment
Reliability

STRACT

The management of capital assets in industrial complexes is very complicated given the large number of existing equipment in them. This becomes even more complicated when several equipment units need to be replaced simultaneously. Since the replacement program is costly and time-consuming, the critical equipment should be identified and prioritized. Thus, the main objective of this research is to develop a decision-making support system (DMSS) for prioritizing the critical equipment. A practical and scientific framework is developed for the optimal prioritization of the replacement of the critical equipment in industrial complexes. This optimization framework is multi-criteria and consists of two mathematical steps. In the first step, life cycle costing (LCC) is used to measure the economic life of the equipment and to identify the critical equipment. In the next step, the optimal time for replacing the equipment and their priorities are determined. An optimization application is designed for this purpose using an NSGA-II method and the Java software. A case study was conducted on Iran's gas transmission operations in Khuzestan province. Out of 595 equipment available in this study, 110 units were identified as critical equipment and were prioritized.

## 1. Introduction

Due to the high sensitivity and large number of equipment in large industrial complexes such as refineries and power plants, capital asset management (CAM) plays an essential role in economic production. Life cycle cost (LCC) assessment has been employed as a typical method for evaluating economic sustainability in capital asset management [1]. As capital assets are essential in the operational processes of the organizations involved, the downtime of the assets needs to be minimized [2].

In industrial factories, in order to replace the depreciated and defective parts, the maintenance department managers use the supply chain management system (SCMS) of spare parts proportional to their demand capacity [2]. In fact, based on the reliability targets and the existing conditions, decision-making support system (DMSS), maintenance plan, and supply chain management can be utilized [3, 4] so that the production line is always ready for service.

Despite the advanced maintenance (corrective, preventive and predictive) measures in large and industrial complexes such as petrochemical and power plants, the equipment replacement program is very sensitive and complicated [5, 6, 7]. In these plants, the spare parts supply chain is a prerequisite for solving this problem [2, 8]. The problem in these plants is that most of them were built more than two decades ago and after many years of operation and maintenance, their equipment must be renovated simultaneously [8]. In these plants, approximately thousands of parts and equipment exist. Therefore, during the replacement time, the maintenance team will face a large number of parts that need to be replaced simultaneously. This is both costly and time-consuming. Hence, a confusion will be created in selecting the equipment that need to be replaced. Some of these pieces of

* Corresponding author.
*E-mail address:*milad.ghanbari@srbiau.ac.ir

equipment have a key role in the production of these plants and neglecting to replace them may reduce production and profitability since months or even years may have passed from their economic life. Thus, identifying these pieces of critical equipment based on some particular criteria is the main challenge of these types of industrial plants. In other words, the research gap here is the development of a practical framework as a replacement decision support system in order to prioritize the critical equipment.

In this research, it is attempted to introduce an optimal model for the prioritization of the replacement of critical equipment in large plants such as petrochemical plants. In this model, LCC assessment is combined with optimization in the form of mathematical equations. Another aim of the current research is to determine some criteria for the identification and evaluation of the critical equipment. Therefore, a model is proposed to prioritize the replacement of the critical equipment. Finally, a case study is conducted to verify the proposed model.

## 2. Literature review

The high importance of LCC assessment becomes clear when deciding on replacing the critical equipment [9, 10, 11, 12, 13]. Life cycle costing applications have been introduced in many papers and fields including: a) the estimation of the useful life of gas turbine engines [14], b) calculating the life cycle cost as a tool for marketing products [15], (c) the evaluation of the sales, repair, and exclusion options [1], and (d) determining the appropriate time for the repair and renovation of the equipment [16]. The combination of life cycle assessment (LCA) method with mathematical and intelligent methods such as multi-criteria optimization [17], fuzzy expert systems [18, 19], and genetic algorithm (GA) [20] has also been considered in previous papers.

Determining the asset priority is a decision that must be taken in conformity with the existing maintenance strategy. When a certain definition of asset priority exists, the strategy that each asset class must follow can be determined [5]. The result of the prioritization process is to determine the equipment criticality for the factory [10]. As mentioned in the previous section, the present study focuses on complex industrial plants such as power plants, refineries, petrochemical plants, and steel, copper, and cement industries. There are few researches in this field focusing on the maintenance management of capital assets.

On the other hand, studies related to prioritizing replacement and maintenance are limited and have been conducted based on questionnaires with a low modeling quality. Decision-making techniques such as analytic hierarchy process (AHP) and multi-criteria decision analysis (MCDA) methods are helpful in solving such problems [5]. However, it should be noted that it is better to use optimization techniques based on mathematical models due to their higher precision. In Table 1, some information of the related investigations has been summarized.

**Table 1.** A summary of previous studies.

| No. | Field | Objective | Methodology | Reference |
|---|---|---|---|---|
| 1 | Industry | Equipment maintenance strategy for critical equipment | Cost-effective maintenance management and scoring | [2] |
| 2 | Pump | I) Maintenance management<br>II) Decision-making support system | A quantitative graphical analysis based on LCC and reliability | [3, 4] |
| 3 | General | Optimal maintenance and replacement policy of the equipment | Discrete non-stationary Markov decision process | [8] |
| 4 | Processing plants | Optimizing the scheduling of preventive maintenance | Ranking based on the genetic algorithm & the Monte Carlo simulation | [21] |
| 5 | Transit | Prioritizing the replacement of capital assets | The LCC approach | [22] |
| 6 | Pump | Selection of equipment for the lowest long-term cost of ownership | LCC and reliability based on the Monte Carlo simulation | [23] |

According to the methodology of previous researches, the critical analysis and prioritization of equipment can be divided into qualitative and quantitative categories. The qualitative analysis depends on the opinion, experience, and insight of individuals, whereas the quantitative method is a bit closer to reality and usually requires more data for analysis. Choosing one of these two methods depends on the maturity of the plant and the managers' preferences to deal with mathematics or opinions [5]. Previous researches showed that multi-criteria models are more comprehensive. However, these models can be more accurate and optimal if they include mathematical operations and artificial intelligence methods.

## 3. The proposed prioritization model

The products of factories and industrial complexes are often divided into the categories of main products and by-products. Each product usually has one or more production stations or production lines. Each production station or production line also comprises a large number of equipment or machinery. The criticality of an industrial complex depends on the criticality of the equipment in its production lines. Therefore, the analysis of the criticality of the whole plant requires a comprehensive framework with a hierarchical viewpoint. The proposed model in the present study for the prioritization of critical equipment is multi-criteria (multi-objective) and has two steps. The first step is the identification of the critical equipment. In the second step, optimal prioritization is done.

The first step in modelling the prioritization of critical equipment for replacement is to define the variables in a mathematical format. All of the data can be shown as matrices based on the historical data for each criterion. The input variables are the criteria for the prioritization of the equipment. Replacement prioritization can be done through finding the optimal times for the replacement of all equipment. By sorting the optimal times for the replacement of the equipment, the priority numbers can be obtained. The equipment with less optimal times have a higher priority. Therefore, the output variables are the priority (P) number and optimal time of replacement (TR). In the following subsections, the proposed model is explained in detail. The conceptual model of this research is schematically shown in Figure 1 and its characteristics are described in the following subsections.

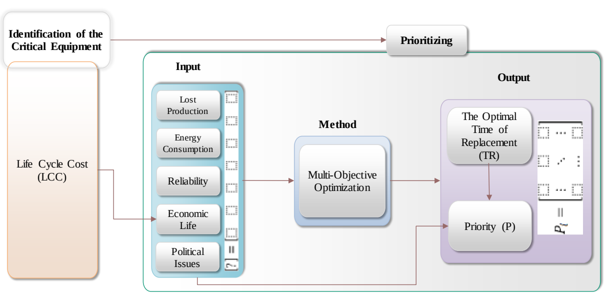


**Fig. 1.** The general schematic of the research methodology.

## 3.1. The first step: life cycle costing

LCC can enter economic competitiveness by reducing the long-term costs of ownership. The objective of the LCC analysis is to choose the most cost-effective approach from a series of alternatives so that the lowest long-term cost of ownership is obtained considering the cost elements including the design, development, production, operation, maintenance, and life cycle support of the equipment [11, 23]. LCC uses the concepts of net present value (NPV) and equivalent annual cost (EAC) [10, 24]. NPV and EAC are important economic techniques for projects or equipment considering such factors as discount rate, cash flow, and time.

In this research, the equipment units whose economic life has passed but are still in service are considered as critical equipment because using them is economically unjustified. The maintenance manager must inspect and list the equipment suspected of being critical in the industrial complex. After the implementation of LCC for all the suspected equipment, the list of the critical equipment can be determined. According to the proposed framework of this research, the equipment whose economic life has passed are considered critical and must go to the second step to be prioritized. To implement LCC for any suspected equipment, the following annual data are required: cost of energy consumption, cost of consuming supplies and spare parts, salaries of human resources, overhaul costs, miscellaneous costs, equipment procurement costs, depreciation costs, taxes, insurance, etc. [10, 24]. The diagram of LCC is shown in Figure 2.

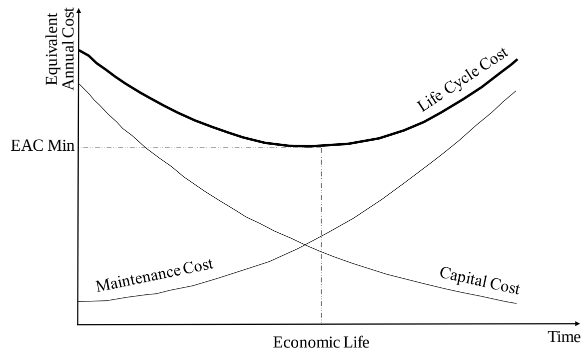


**Fig. 2.** Determining the economic life of an asset by LCC.

## 3.2. The second step: the criteria and prioritizing

After the equipment units whose economic life has passed and whose performance is considered to be economically unjustified are identified, they should be prioritized based on some operating criteria. The equipment units with a lower critical number have a higher priority for replacement. The priority criteria of this research which are key performance indicators (KPIs) in maintenance management [25, 26] are efficiency and effectiveness, energy consumption, reliability (or mean time between failures), financial loss (time passed after economic life), and strategic and political issues. In the following subsections, the mentioned criteria are described in detail.

### 3.3.3. The lost production (effectiveness and efficiency)

Effectiveness is the extent to which the performance of a system fulfills its predetermined and expected goals. In manufacturing and service systems, this concept often refers to the quality of the products or services from the customer's point of view [10, 27]. In terms of maintenance management, effectiveness can show the satisfaction of the organization with using the full capacity of its equipment and assets. Effectiveness can also indicate the reduced overall cost of the organization due to its access to a large number of equipment. Effectiveness, in the general sense, is defined as manufacturing or providing services with the least cost, loss, and effort. The efficiency level can affect the extent of progression [5].

The equipment will naturally be depreciated with the passage of time. One of the effects of this depreciation is the reduction of efficiency and effectiveness which ultimately reduces the production of the industrial complex. Reduced production will lead to lost production which is not desirable. The amount of lost production can also be calculated [28, 29]. Based on the model of this research, the increase in lost production over time indicates the criticality of the equipment which should have been replaced at the optimum time. In order to verify this criterion, the historical data or the performance function of the equipment is required during the baseline period. Based on the present study, the effectiveness of an equipment is equal to the amount of its contribution to total production and its effect on the overall performance of the production line. The performance of the equipment is also defined by comparing its actual performance with its expected nominal performance. Therefore, the equipment whose efficiency and effectiveness in a production line are reduced have a higher priority for replacement.

#### 3.3.4. Energy consumption

Considering energy consumption as a criterion for prioritization means taking environmental considerations into account, because the increased consumption of energy will increase the emission of greenhouse gases (GHG) (especially $CO_2$) [30]. Therefore, by analyzing the historical data or the energy consumption function of the equipment over time, the equipment whose energy consumption is not economically and environmentally justifiable should be replaced at the optimum time. Based on the proposed model of the current research, the performance of the equipment in terms of energy consumption is obtained by comparing its actual energy consumption with its nominal energy consumption. In other words, the equipment units which consume more energy should be replaced as soon as possible to prevent additional costs.

#### 3.3.5. Reliability

Listing and modeling the critical failure of repairable equipment can be an opportunity to improve the reliability (R) of the system [31]. Reliability (probability of system failure) can be depicted by a graphic trend [3, 4] and depends on identifying the root causes of failure. This goal is realized only when a comprehensive database of maintenance records exists [32]. By calculating the function of the mentioned graph, the equipment can be prioritized based on the reliability criterion.

The R criterion depends on the mean time between failures (MTBF) and is used for the evaluation of maintenance [4] so that systems with low MTBF have low R values and high failure rates [10]. The relationship between R and frequency of failures (or the average failure rate) (λ) is shown in Equation (1) [4, 5]. Equation (2) indicates the relationship between MTBF and λ [4, 5]. With the increased depreciation rate or the reduced effectiveness of the maintenance plan over time, the reliability of the equipment is reduced. Therefore, based on the proposed model of the present study, the equipment should be replaced at the optimal time.

$$R = e^{(-\lambda t)} \qquad (1)$$

$$\lambda = \frac{1}{MTBF} \qquad (2)$$

#### 3.3.6. Economic life (financial loss)

One of the goals of maintenance is profitability (i.e. the reduction of *losses* or costs) [10, 25]. According to the results of the first phase of the current study (LCC implementation), there is a point for critical equipment called ‘‘economic life’’. The activity of the equipment after this point is economically unjustified. Therefore, depending on the economic life point of any equipment, early or late replacement will impose extraordinary costs which are considered financial losses. In other words, based on the proposed model of this research, the optimal point for replacing the critical equipment should be the point or time that is closest to the economic life of the equipment. The optimal life of the equipment can be calculated by taking advantage of LCA.

#### 3.3.7. Strategic and political issues (SPI)

In large refinery plants, there are several products and several production stations or production lines. For example, in these plants, several products such as gasoline, ammonia, petrol, and gas are produced. For national strategic reasons (such as sanctions), replacing the equipment (or part of the equipment) in a production line may be given priority even if manufacturing a product in that production line is an economic loss.

## 4. Optimization model

### 4.1. Mathematical modeling

So far, various frameworks and tools such as the Monte Carlo simulation [33] and AHP [34] have entered the field of maintenance management [35]. However, the proposed tool for optimization in the present research is genetic algorithm (GA). As was mentioned in previous sections, identifying the critical equipment is a basic step for planning and prioritizing their replacement. According to the above-mentioned criteria, the critical equipment is characterized by high lost production (Z1), high energy consumption (Z2), low reliability (Z3), and high financial loss (Z4). Therefore, the critical function (FCr) of an equipment can be defined as Equation (3). The description of the used parameters as well as the symbols in the mathematical optimization model are summarized in Table 2.

$$\mathrm{Cr} \propto (Z_1), (Z_2), (Z_3), (Z_4) \qquad (3)$$

The main aim of optimization and prioritization is to reduce the criticality of the industrial plant. Therefore, the optimization function is of the minimizing type as shown in Equation 4. According to the principles of optimization and modeling, assigning relevant constraints could change the boundaries of the feasible region. The first four prioritization criteria introduced in sections 3 and 4 are the objectives. It is wiser to consider the remaining criterion (the strategic and political issues) as a constraint due to the conditions imposed by the government, the owner, and the managers of the industrial plant. In the model of the present research, the multi-objective functions are presented in Equations 5 to 8 and the constraints can be observed in Equations (9) to (15).

**Table 2.** The parameters used in the mathematical optimization model.

| Character | Description | Type (input/output-constant/function) |
|---|---|---|
| K | The number of the products of the plant | Input-constant |
| J | The number of the production stations (production lines) of product k | Input-constant |
| I | The number of the equipment units in the production station (production line) j | Input-constant |
| $Z_1$ | Lost production | Objective |
| $Z_2$ | Energy consumption | Objective |
| $Z_3$ | Reliability | Objective |
| $Z_4$ | Financial loss | Objective |
| $TS_{ijk}$ | The starting operation year of equipment i in production line j of product k | Input-constant |
| $TF_{ijk}$ | The finishing operation year of equipment i in production line j of product k | Input-constant |
| $TR_{ijk}$ | The replacement year of equipment i in production line j of product k | Output-constant |
| $EL_{ijk}$ | The economic life of equipment i in production line j of product k | Input-constant |
| $AP_{ijk}$ | The actual production of equipment i in production line j of product k over time | Input-function |
| $APL_{jk}$ | The total actual production in production line j of product k over time | Input-function |
| $NP_{ijk}$ | The nominal production of equipment i in production line j of product k | Input-constant |
| $EC_{ijk}$ | The energy consumption of equipment i in production line j of product k over time | Input-function |
| $MTBF_{ijk}$ | The mean time between the failures of equipment i in production line j of product k over time | Input-function |
| $EAC_{ijk}$ | The equivalent annual cost of equipment i in production line j of product k over time | Input-function |
| $MinEAC_{ijk}$ | The minimum of the diagram of the equivalent annual cost of equipment i in production line j of product k over time | Intermediate-constant |
| $EAC_{R-ijk}$ | The equivalent annual cost of equipment i in production line j of product k at replacement time | Intermediate-constant |
| $FMPD_{ijk}$ | The maximum production reduction factor of equipment i in production line j of product k | Input-constant |
| $FMED_{ijk}$ | The maximum effectiveness reduction factor of equipment i in production line j of product k | Input-constant |
| $FMEW_{ijk}$ | The maximum energy loss factor of equipment i in production line j of product k | Input-constant |
| $NEC_{ijk}$ | The nominal energy consumption of equipment i in production line j of product k | Input-constant |
| $W_{Z1}$ | The importance weight of objective $Z_1$ | Input-constant |
| $W_{Z2}$ | The importance weight of objective $Z_2$ | Input-constant |
| $W_{Z3}$ | The importance weight of objective $Z_3$ | Input-constant |
| $W_{Z4}$ | The importance weight of objective $Z_4$ | Input-constant |
| SPI | The strategic and political issues | Input-constant |
| $P_i$ | The priority of equipment i | Output-constant |

$$Ob: Min\ \mathrm{Cr} = Min\ Z_1\ , Min\ Z_2\ , \quad Min\ Z_3\ , Min\ Z_4 \tag{4}$$

$$Min\ Z_1 = \sum_{i=1}^{m}\sum_{j=1}^{n}\sum_{k=1}^{v}\left[\frac{\dfrac{\int_{TS_{ijk}}^{TF_{ijk}}(AP_{ijk})\,dt}{\int_{TS_{ijk}}^{TF_{ijk}}(APL_{jk})\,dt}}{\dfrac{\int_{TS_{ijk}}^{TR_{ijk}}(AP_{ijk})\,dt}{\int_{TS_{ijk}}^{TR_{ijk}}(APL_{jk})\,dt}} \times \left[\int_{TS_{ijk}}^{TR_{ijk}}(AP_{ijk})\,dt\right] - \left[(TR_{ijk}-TS_{ijk})\times NP_{ijk}\right]\right] \tag{5}$$

$$Min Z_2 = \sum_{i=1}^{m}\sum_{j=1}^{n}\sum_{k=1}^{v}\left[\frac{\int_{TS_{ijk}}^{TR_{ijk}}(EC_{ijk})\,dt}{\int_{TS_{ijk}}^{TR_{ijk}}(AP_{ijk})\,dt}\right] \tag{6}$$

$$Min Z_3 = \sum_{i=1}^{m}\sum_{j=1}^{n}\sum_{k=1}^{v}\left[\frac{1}{\int_{TS_{ijk}}^{TR_{ijk}}(MTBF_{ijk})\,dt}\right] \tag{7}$$

$$Min\ Z_4 = \sum_{i=1}^{m}\sum_{j=1}^{n}\sum_{k=1}^{v}\left[\frac{EAC_{R-ijk} - MinEAC_{ijk}}{|TR_{ijk} - EL_{ijk}|}\right] \tag{8}$$

*Subject to:*

$$\int_{TS_{ijk}}^{TR_{ijk}}(AP_{ijk})\,dt \geq (1-FMPD_{ijk})\times\left[(TR_{ijk}-TS_{ijk})\times NP_{ijk}\right] \tag{9}$$

$$\frac{\int_{TS_{ijk}}^{TR_{ijk}}(AP_{ijk})\,dt}{\int_{TS_{ijk}}^{TR_{ijk}}(APL_{jk})\,dt} \geq (1-FMED_{ijk})\times\frac{\int_{TS_{ijk}}^{TF_{ijk}}(AP_{ijk})\,dt}{\int_{TS_{ijk}}^{TF_{ijk}}(APL_{jk})\,dt} \tag{10}$$

$$\frac{\int_{TS_{ijk}}^{TR_{ijk}}(EC_{ijk})\,dt}{\int_{TS_{ijk}}^{TR_{ijk}}(AP_{ijk})\,dt} \leq (1+FMEW_{ijk})\times\frac{NEC_{ijk}}{NP_{ijk}} \tag{11}$$

$$TS_{ijk} \leq TR_{ijk} \leq TF_{ijk} \tag{12}$$

$$\{i|i = 1, 2, 3, \dots, m\} \tag{13}$$

$$\{j|j = 1, 2, 3, \dots, n\} \tag{14}$$

$$\{k|k = 1, 2, 3, \dots, v\} \tag{15}$$

## 4.2. The optimization method

In order to optimize the multi-criteria prioritization of critical equipment, the NSGA-II genetic algorithm has been used in this research. The multi-objective optimization with non-dominated sorting genetic algorithm (NSGA) is a well-known algorithm. The abbreviation for the multi-objective genetic algorithm is NSGA-II which is used in multi-objective optimization algorithms because of its unique characteristics. Due to its unique approach in dealing with multi-objective optimization problems, this algorithm has been used by different researchers to create newer multi-objective optimization algorithms. Undoubtedly, this algorithm is one of the most fundamental evolutionary multi-objective optimization algorithms and can be considered as their second generation.

Since there are contradictions between the goals, there is no single solution for multi-objective problems in which all the goals are completely optimal. At the end, a set of dominant solutions will be presented as the optimal solutions which are archived in the Pareto solutions.

In this research, the chromosome length was assumed to be 4 which was equal to the number of the criteria (Figure 3). After the necessary evaluations, the values of the genetic algorithm operators (the number of generations, probability of mutation (pm), and probability of crossover (pc) were selected as follows: max generation number=200, pm=0.15, and pc=0.8. The number of iterations in the algorithm was considered 100.

| Criteria (number) | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| Chromosome length | | | | |

**Fig. 3.** The definition of the chromosome in the current study.

## 4.3. The generated computer program

In order to create a graphical user interface (GUI) for the users, Java software was used since it has good graphics capabilities. Therefore, NSGA-II was coded and run in this software. By receiving inputs from the user and assigning the required settings, the generated program performs the prioritization and optimization steps and presents the expected data outputs and the corresponding diagrams to the user. The picture of the created graphical program is shown in Figure 4.

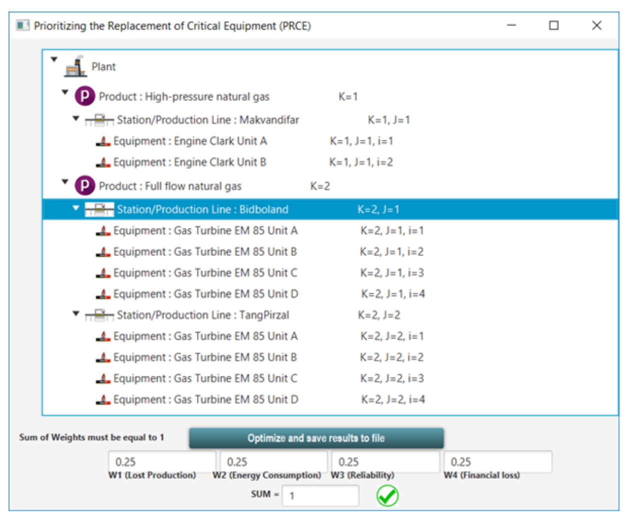


**Fig. 4.** The generated software (via Java) for optimal prioritization.

## 5. Case study

The first region of Iran's gas transmission operations was selected as the industrial complex for the case study due to its comprehensive database. This region is located in Khuzestan province, south of Iran. This plant has 2 products including high pressure gas and full flow gas. The first product has 5 production stations (production lines) and 310 equipment units. The second product has 3 production stations (production lines) and 285 equipment units. Out of a total of 595 existing equipment units, 350 units were suspected of being critical and were selected for LCC analysis according to the maintenance manager's opinion. The implementation of the LCC indicated that 110 equipment units were critical in a way that about 12 to 20 years had passed from their economic life. In the second phase, these 110 units were evaluated for optimal prioritization. The input data were entered into the generated program and optimization was done. Regarding the SPI criterion, the government did not have any limitations to be assigned.

## 6. Analysis of the results

As mentioned in the previous section, with the implementation of the LCC, 110 equipment units were identified as critical. By entering the data of the mentioned 110 equipment units into the program, the critical equipment units were prioritized. By running the program, the final rank or priority for replacing the equipment was determined. Since the number of these equipment units is high and their data are confidential, only the input data and the output results of the equipment units (rated from 1 to 10) are shown in Tables 3 and 4, respectively.

**Table 3.** The input data in the case study.

| Product | Station/production line | Equipment |
|---|---|---|
| K=1 (High pressure natural gas) | j=1 (Makvandifar) | i=1 (Clark Engine Unit A) |
| | | i=2 (Clark Engine Unit B) |
| K=2 (Full flow natural gas) | j=1 (Bidboland) | i=1 (Gas Turbine EM 85 Unit A) |
| | | i=2 (Gas Turbine EM 85 Unit B) |
| | | i=3 (Gas Turbine EM 85 Unit C) |
| | | i=4 (Gas Turbine EM 85 Unit D) |
| | j=2 Tang-e-Pirzal | i=1 (Gas Turbine EM 85 Unit A) |
| | | i=2 (Gas Turbine EM 85 Unit B) |
| | | i=3 (Gas Turbine EM 85 Unit C) |
| | | i=4 (Gas Turbine EM 85 Unit D) |

Table 4 shows that equipment unit number 2 (which is an engine used for producing high-pressure gas) in production line number 1 is the most critical equipment unit in the mentioned complex. Therefore, replacing this engine should be a top priority for the plant managers because it can cause a lot of harm to the complex. According to Table 4, the economic life of this equipment (based on LCC) ended in 2005 which is the same as the optimal time obtained from the output of the multi-criteria prioritization program in the present study. The performance diagrams of this equipment in terms of the prioritization criteria of this research are shown in Figure 5. However, due to the confidentiality of the data, only the historical data ranging from the years 1995 to 2016 have been displayed.

**Table 4.** The output results of optimal prioritization in the case study.

| Product | Station/ production line | Equipment | Economic life (EL) | Optimal time of replacement (TR) | Strategic policy | Final priority |
|---|---|---|---|---|---|---|
| k=1 | j=1 | i=1 | 2005 | 2008 | - | 2 |
| k=1 | j=1 | i=2 | 2005 | 2005 | - | 1 |
| k=2 | j=1 | i=1 | 2005 | 2012.8 | - | 5 |
| k=2 | j=1 | i=2 | 2005 | 2011.5 | - | 4 |
| k=2 | j=1 | i=3 | 2001 | 2014.4 | - | 8 |
| k=2 | j=1 | i=4 | 2002 | 2014 | - | 7 |
| k=2 | j=2 | i=1 | 2005 | 2013 | - | 6 |
| k=2 | j=2 | i=2 | 2005 | 2015.6 | - | 9 |
| k=2 | j=2 | i=3 | 2001 | 2016 | - | 10 |
| k=2 | j=2 | i=4 | 2002 | 2009 | - | 3 |

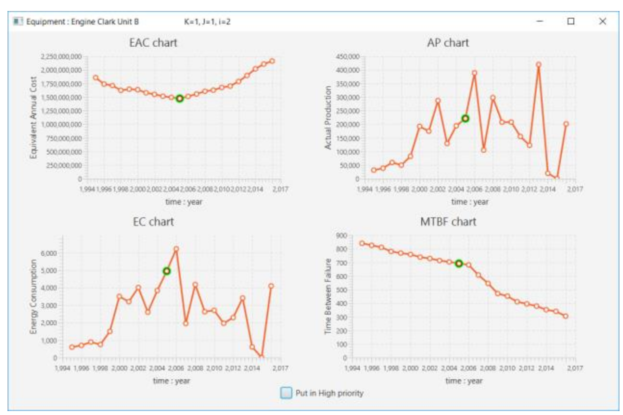


**Fig. 5.** The performance diagrams of the prioritization criteria for the most critical equipment unit

## 7. Conclusion

Industrial complexes are strategically important since there are thousands of equipment units in them. Many of these industrial complexes have been exploited for decades without any equipment upgrades in their production lines. This can lead to severe financial and environmental damage. The depreciated equipment units of these complexes are usually considered as critical equipment. The main concern of the maintenance officials in such complexes should be prioritizing the replacement of the critical equipment since such complexes also have financial and time limitations.

The main goal of this research was to provide a practical and scientific framework for the optimal prioritization of the replacement of critical equipment in industrial complexes. The proposed model of this research had two steps. In the first step, by implementing the theory of LCC, a list of the equipment units whose economic life had passed was determined. These equipment units are called critical equipment. In the next step, these equipment units were prioritized using the optimization program generated in this research based on the NSGA-II method and Java software. The proposed optimization model was a multi-criteria problem with 4 criteria including lost production, energy consumption, reliability, and financial loss. The concepts of effectiveness and efficiency were considered in the criterion of lost production.

The case study of the present research was conducted on Iran's gas transmission operations in the south of the country. Out of a total of 595 equipment units in the complex, 350 equipment units were selected by the maintenance manager as suspected of being critical. The LCC analysis in the first step of the proposed framework showed that among these 350 equipment units, 110 equipment units were critical and their economic life had passed though they were still in operation. The implementation of the second step of the study led to the prioritization of the replacement of these critical equipment units. The replacement of the critical equipment units in this complex based on the proposed optimal prioritization should be on the agenda of the senior managers.

## Acknowledgements

This study was part of a research project conducted by the authors. The authors gratefully acknowledge the National Iranian Gas Company for providing the data required for this study.

## References

[1] Balanay, R., & Halog, A. (2019). Tools for circular economy: Review and some potential applications for the Philippine textile industry. Circular Economy in Textiles and Apparel, 1, 49-75.

[2] Driessen, M., Arts, J., van Houtum, G. J., Rustenburg, J. W., & Huisman, B. (2015). Maintenance spare parts planning and control: a framework for control and agenda for future research. Production Planning & Control, 26(5), 407-426.

[3] Martínez, L. B., Márquez, A. C., Gunckel, P. V., & Andreani, A. A. (2013). The graphical analysis for maintenance management method: a quantitative graphical analysis to support maintenance management decision making. Quality and Reliability Engineering International, 29(1), 77-87.

[4] Barberá, L., Crespo, A., Viveros, P., & Stegmaier, R. (2014). A case study of GAMM (Graphical Analysis for Maintenance Management) applied to water pumps in a sewage treatment plant, Chile. Quality and reliability engineering international, 30(8), 1473-1480.

[5] Márquez, A. C. (2007). The maintenance management framework: models and methods for complex systems maintenance. Springer Science & Business Media.

[6]. Kobbacy, K. A. H., & Murthy, D. P. (Eds.). (2008). Complex system maintenance handbook, Springer Science & Business Media,.

[7]. Ben-Daya, M., Duffuaa, S. O., Raouf, A., Knezevic, J., & Ait-Kadi, D. (Eds.). (2009). Handbook of maintenance management and engineering, Springer London, 7.

[8]. Nguyen, T. K., Yeung, T. G., & Castanier, B. (2013). Optimal maintenance and replacement decisions under technological change with consideration of spare parts inventories. International Journal of Production Economics, 143(2), 472-477.

[9] Mardin, F., & Arai, T. (2012). Capital equipment replacement under technological change. The engineering economist, 57(2), 119-129.

[10] Hartman, J. C., & Tan, C. H. (2014). Equipment replacement analysis: a literature review and directions for future research. The Engineering Economist, 59(2), 136-153.

[11] Al-Chalabi, H., Lundberg, J., Ahmadi, A., & Jonsson, A. (2015). Case study: model for economic lifetime of drilling machines in the Swedish mining industry. The Engineering Economist, 60(2), 138-154.

[12] Sahu, A. K., Narang, H. K., Sahu, A. K., & Sahu, N. K. Machine economic life estimation based on depreciation-replacement model. Cogent Engineering, 2016, 3(1), 1249225.

[13] Van den Boomen, M., van den Berg, P. L., & Wolfert, A. R. M. (2019). A dynamic programming approach for economic optimisation of lifetime-extending maintenance, renovation, and replacement of public infrastructure assets under differential inflation. Structure and infrastructure engineering, 2019, 15(2), 193-205.

[14] Li, Y. G., & Nilkitsaranont, P. (2009). Gas turbine performance prognostic for condition-based maintenance. Applied energy, 86(10), 2152-2161.

[15] Brown, R. J. (1979). A new marketing tool: Life-cycle costing. Industrial Marketing Management, 8(2), 109-113.

[16] Rosenfeld, Y., & Shapira, A. (1998). Automation of existing tower cranes: economic and technological feasibility. Automation in Construction, 7(4), 285-298.

[17] Ahluwalia, P. K., & Nema, A. K. (2007). A life cycle based multi-objective optimization model for the management of computer waste. Resources, Conservation and Recycling, 51(4), 792-826.

[18] Kaminaris, S. D., Tsoutsos, T. D., Agoris, D., & Machias, A. V. (2006). Assessing renewables-to-electricity systems: a fuzzy expert system model. Energy policy, 34(12), 1357-1366.

[19] Sheikhalishahi, M., & Torabi, S. A. (2014). Maintenance supplier selection considering life cycle costs and risks: a fuzzy goal programming approach. International Journal of Production Research, 52(23), 7084-7099.

[20] Monga, A., & Zuo, M. J. (2001). Optimal design of series-parallel systems considering maintenance and salvage value. Computers & industrial engineering, 40(4), 323-337.

[21] Nguyen, D., & Bagajewicz, M. (2008). Optimization of preventive maintenance scheduling in processing plants. In Computer Aided Chemical Engineering, 25, 319-324.

[22] Cohen, H. S., & Barr, J. (2012). State of Good Repair: Prioritizing the Rehabilitation and Replacement of Existing Capital Assets and Evaluating the Implications for Transit, Transportation Research Board, 157.

[23] Eltamaly, A. M., & Mohamed, M. A. (2018). Optimal sizing and designing of hybrid renewable energy systems in smart grid applications. In Advances in Renewable Energies and Power Technologies, 231-313.

[24] Dhillon, B. S. (2009). Life cycle costing for engineers. Crc Press.

[25] Wireman, T. (2005). Developing performance indicators for managing maintenance. Industrial Press Inc: New York,

[26] Mather, D. (2005). The maintenance scorecard: Creating strategic advantage. Industrial Press Inc: New York.

[27] Terminology, M. (2010). CEN (European Committee for Standardization). European Standard EN, 13306.

[28] Nobel, R. D., & Heeden, M. V. D. (2000). A lost-sales production/inventory model with two discrete production modes. Stochastic Models, 16(5), 453-478.

[29] Kaiser, M. J., Dismukes, D. E., & Yu, Y. (2011). Modeling lost production in the Gulf of Mexico—II. Framework and assumptions. Energy Sources, Part B: Economics, Planning, and Policy, 6(4), 378-383.

[30] Ghanbari, M., Abbasi, A. M., & Ravanshadnia, M. (2018). Production of natural and recycled aggregates: the environmental impacts of energy consumption and CO 2 emissions. *Journal of* Material Cycles and Waste Management, 20(2), 810-822.

[31] Marquez, A. C. (2005). Modeling critical failures maintenance: a case study for mining. Journal of Quality in Maintenance Engineering,

[32]. Márquez, A. C., & Herguedas, A. S. (2004). Learning about failure root causes through maintenance records analysis. Journal of Quality in Maintenance Engineering,

[33] Marquez, A. C., & Iung, B. (2007). A structured approach for the assessment of system availability and reliability using Monte Carlo simulation. Journal of Quality in Maintenance Engineering,

[34] Gonzalez Diaz, V., Gomez Fernandez, J., & Márquez, A. C. (2011). Practical application of an Analytic Hierarchy Process for the improvement of the warranty management. Journal of Quality in Maintenance Engineering, 17(2), 163-182.

[35] Márquez, A. C., de León, P. M., Fernández, J. G., Márquez, C. P., & Campos, M. L. (2009). The maintenance management framework: A practical view to maintenance management. Journal of Quality in Maintenance Engineering, 15(2), 167-178.