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# Reliability and Maintenance Optimization at a Saudi Glass Production Plant

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## Abstract

The increase in automation due to the changing market and the expansion of product diversity has led to an increase in the demand for more sophisticated equipment. As a result, the dependability and maintainability of equipment have become critical in managing the quantity and quality of the products produced. Therefore, preventive maintenance (PM) should be performed during the manufacturing process in order to ensure the stipulated reliability and dependability of the production process specifications. Unscheduled PM, on the other hand, can have detrimental financial implications for the company, as well as a reduction in the overall production line reliability. This work considers a realistic multi-objective PM scheduling problem in a production line at a local Saudi glass plant. The reliability of the production line, maintenance costs, and system downtime are measured as multiple objectives, and different thresholds are applied for the available budget and maintenance periods. The aim is to apply a mathematical model to maximize the system's reliability and minimize overall costs. The results of the multi-objective model have shown a significant decrease in cost of about 12%.

## Keywords
Reliability, Maintainability, Optimization, Production, Preventive Maintenance.

## 1. Introduction
The role of maintenance and reliability in today's manufacturing environment is critical for most firms. Constant and reliable maintenance planning can ensure a steady-state manufacturing process. The complexity of automated systems has recently grown as a result of rapid changes in technology. Proper maintenance planning and control strategies are vital, particularly in the manufacturing industry, which uses expensive and specialized equipment and has stringent environmental requirements. With the loss of profits due to the neglect of the importance of maintenance and reliability in such industries, there is a need for better maintenance planning and scheduling.

Traditional factory management rules are different from current tactics used to control production and maintenance. Due to the wide range of variables that affect the performance of production and control activities, these techniques are more predictable and adaptable. Production scheduling plays a key role in production management. Production scheduling may need to consider the state of the manufacturing system and the operating circumstances in the production environment. Decision support systems are widespread in industrial engineering because they enable managers to control their resources based on various production limitations on a more general level. Due to complicated manufacturing systems, decision support systems resolve to integrate several technologies with human resources, eventually resulting in a high-efficiency production process.

Local production plants in Saudi Arabia with substantial capital investments tend to spend money to improve quality, safety, maintainability, and reliability, resulting in a declining profit margin for the company. When the production process is evaluated and the unwanted faults in production are determined, a high percentage of efficiency and productivity can be achieved. Additionally, performing a reliability evaluation by predicting the failure pattern in the plant will also help with maintenance planning and scheduling, resulting in less downtime in production and will help the company save money. One of the common maintenance planning strategies to improve the overall reliability and quality of systems is preventive maintenance (PM).

In summary, the contribution of this work is threefold. (1) It presents an integrated quality-reliability-maintainability approach to reduce associated costs; (2) it applies the proposed methodology to a glass production plant; and finally, (3) it suggests a multi-objective optimization model that reduces costs and improves reliability. The remainder of this paper is structured as follows. Section 2 presents the theoretical background of the current work. Section 3 presents an overview of related works in the literature on preventive maintenance scheduling. Section 4 showcases the methodology pertinent to the developed model. Sections 5 and 6 present the results and conclude the work, respectively.

## 2. Background

### 2.1 Maintenance Importance

"Maintenance is a set of organized activities that are carried out in order to keep an item in its best operational condition with minimum cost acquire" (Ebeling, 1997). It can also be defined as "the combination of all technical and administrative actions, including supervision actions, intended to retain an item in, or restore it to, a state in which it can perform a required function" (Ebeling, 1997). The importance of the maintenance function and, therefore, the importance of maintenance management have increased over the years as technology has advanced. The expansion of the use of mechanization and automation has resulted in a reduction in the number of production workers while simultaneously increasing the amount of capital invested in manufacturing equipment and civil infrastructure. As a result, the proportion of personnel employed in the maintenance area has increased, as has the proportion of maintenance expenditures allocated to total operating expenses (Dekker, 1996).

Maintenance operations and maintenance management have become more important in all sectors of manufacturing and service organizations. The main reason is that capital inventory continues to grow, as does the need for outsourcing system operation and maintenance. Maintenance management is becoming increasingly important and will need scientific support to develop. Maintenance management may theoretically have profited from the emergence of a substantial subfield of operations research called maintenance optimization. Maintenance optimization is one of the most important issues in production, as a failure of a system while being used can be expensive and dangerous. When a machine in a system does not work, it takes longer not only to finish the tasks that were assigned to it but also to affect all the other planned tasks in the system. Because of this, jobs cannot be done on time, which will cost the company money and might hurt its reputation. During this optimization process, different methods can be used. It can be done by making the maintenance policy more realistic by adding features and conditions.

### 2.2 Maintenance History and Strategies

In the maintenance history, maintenance of a factory was seen before World War II as an unnecessary expense that did not contribute to the value of the final product. Repairing a broken device was the cheapest option for maintenance during this time. Preventive maintenance, which was established during and after World War II when engineering and scientific technologies progressed, was significantly less expensive. Preventive maintenance was repair and upkeep took on increased importance throughout the industrial revolution (El-Ferik and Ben-Daya, 2006). The most difficult challenge was that the steam engine boilers often exploded, injuring or killing everyone around them. Due to this, a variety of technical evaluations were performed to ensure that the boiler was in good operating order. Similarly, the German TÜV was founded in 1865 following a massive boiler disaster. To avoid the loss of lives, it was decided to carry out routine maintenance. Although machines were normally only mended when they broke if no one was hurt (Ebeling, 1997). Currently, there are different types and/or classifications of maintenance strategies, which are mainly divided into planned and unplanned maintenance. Common types in the industry are corrective maintenance, preventive maintenance (which is our focus in this article), risk-based maintenance, and condition-based maintenance (Ebeling, 1997). Figure 1 summarizes the maintenance history before and after World War II.

### 2.3 Preventive Maintenance

Preventive maintenance is defined as a series of activities carried out on equipment, machines and/or systems before failure for protection and prevention of degradation in performance. PM is either time-based or condition-based, intending to minimize the likelihood and impact of failures, especially in critical production systems (Levitin and Lisnianski, 2000). The aim of preventive maintenance is to maintain machines and facilities in such a way that breakdowns and emergency repairs are minimized. Preventive maintenance activities include replacements, adjustments, major overhauls, inspections, and lubrications (Ebeling, 1997).

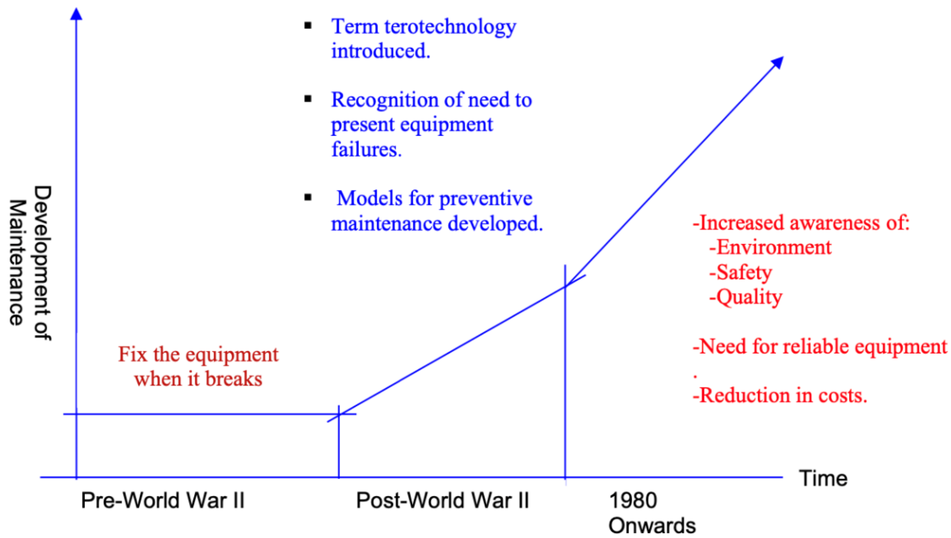


Figure 1. Maintenance History (Ebeling, 1997)

## 2.4 Types of Preventive Maintenance

There are mainly two types of maintenance actions: scheduled and unscheduled. Scheduled maintenance is the class that includes preventive maintenance. PM is based on the idea that it is more cost-effective to prevent problems from occurring in the first place than it is to fix them after they have happened. There are several types of PM that are known in the literature:

- Routine Maintenance: This includes the types of maintenance tasks that are repeated in nature and occur at regular intervals, such as lubrication, cleaning, and minor adjustments.
- Running Maintenance: This includes maintenance tasks that are performed while the machine or equipment is running. These tasks are performed prior to actual preventive maintenance tasks.
- Opportunity Maintenance: This is a set of maintenance tasks that are performed on a machine or building when an unplanned opportunity arises while other machines or buildings are getting their planned maintenance.
- Window Maintenance: This is a set of maintenance actions that are performed when a machine or piece of equipment is not needed for a certain amount of time.
- Shutdown Preventive Maintenance: This is a set of preventive maintenance activities that are carried out when the production line is in a total stoppage situation (Ebeling, 1997).

Maintenance planning can be thought of as an end-to-end process that looks for and solves problems before they occur (Levitin and Lisnianski, 2000). This means figuring out what parts and tools are needed for the different tasks and making sure they are available and set up in the right places. Often it involves a planner writing out instructions for how to do a job, figuring out, and gathering the necessary parts and/or tools before a job is given. Maintenance planning also includes maintenance tasks related to parts such as the handling of reserve parts, the ordering of non-stock parts, the installation of parts, the illustration of parts, the management of breakdowns and supplier lists, and quality assurance (QA) and quality control (QC) (Duffuaa and Raouf, 2015). Figure 2 shows the integration between all departments on the shop floor, which are quality control, maintenance planning and scheduling, and production planning and scheduling.

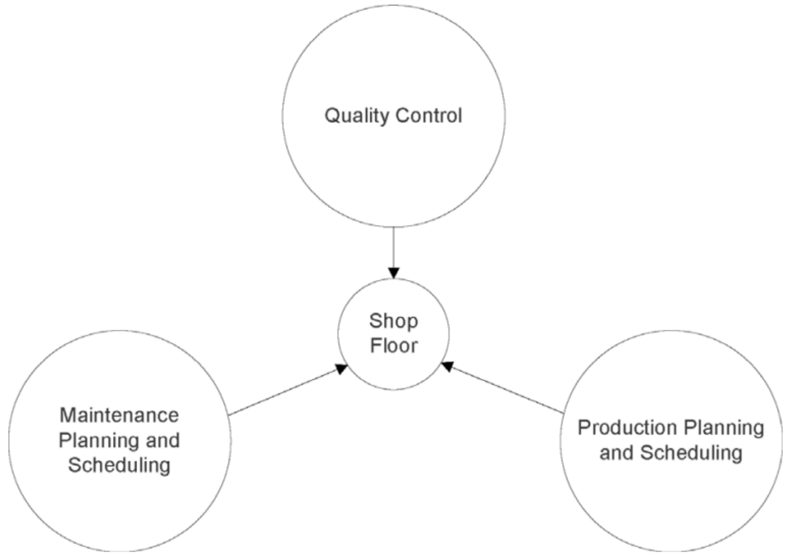


Figure 2. Shop floor departments (Duffuaa and Raouf, 2015)

### 2.5 Relationship between Maintenance Planning and Quality Control

Modern production systems rely on optimal and effective planning and scheduling for each of their constituent parts to operate effectively. It is common practice to prepare for one element in isolation from the others, completely disregarding the possibility of their interdependence. Furthermore, this autonomous planning is carried out by functional teams that are distinct from each other. The plans for a single function coming from this process may interfere with the plans for other functions. When the maintenance function assigns a scheduled shutdown, for example, a notification will be sent to the production unit when this shutdown is scheduled. Recommended maintenance can increase machine availability, but will have a negative impact on production planning. In a similar vein, production schedulers may tend to push machines beyond their maximum capacity to keep up with demand. Under these conditions, productivity can increase, but the number of machine breakdowns can cause machine availability to decrease (Ben-Daya et al., 2016).

Independent planning may lead to optimal performance at the level of a single function. A typical management approach is to consider the overall production system, however, different ideal solutions may not provide the optimal solution for the entire system. In most cases, there is a global optimal that encompasses all the primary functions of the production system. Achieving this global optimal can only be accomplished by integrating models for all the various functions involved. Integrated production models are expected to deal with a variety of objectives, some of which conflict with each other. As a result, disjoint arrangement of these pieces will result in conflicts between their respective functions. When two or more aspects of the production system work together to minimize disturbance, the overall effect is less disruptive. An example of coordination in a real-world setting is shown in Figure 3, where production planning is completed before the plan is transferred to the factory floor for implementation. During this time, the maintenance planning and scheduling department will produce its own plans and schedules, which will be applied on the production floor.

Due to the multi-objective structure of integrated models, they are typically difficult to solve on a first pass. As a result, the degree of integration in planning between functions is kept to a minimum. Planners can assign higher priority to a specific function and design a plan specifically for that function. The output plan will be used as an input to the second priority function, which will be implemented as follows: As a constraint, a plan will be constructed for that function using the input from the other function as input. In the case of a machine that is out of service for an extended period of time, production schedules might be developed to account for this situation. Coordination, rather than true integration, might be viewed as the result of this circumstance. The interconnected model is a term used to describe these types of model (Gerbert et al., 2014).

A production system needs more than coordination to increase productivity and reduce costs. This work is motivated by this need and provides a state-of-the-art model for the integration between production planning, scheduling, maintenance, and quality. Integrated models are expected to offer savings in operating costs in addition to better utilization of resources.

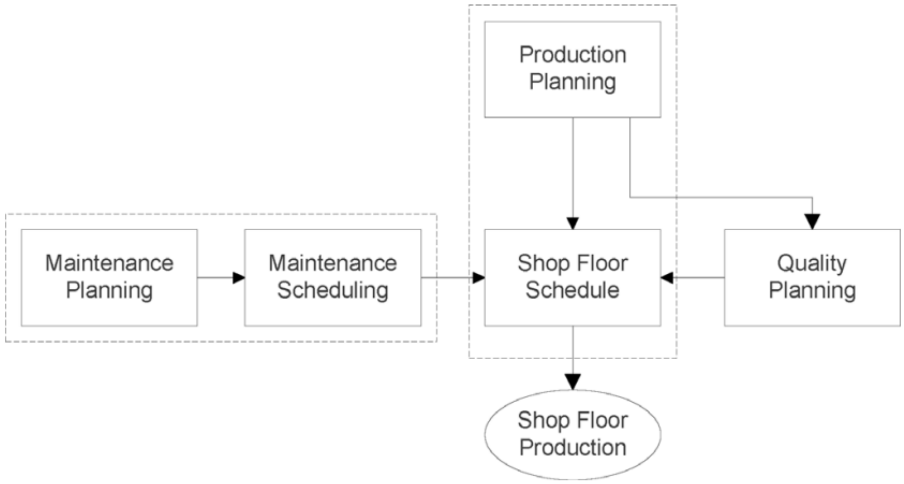


Figure 3. Sequence of procedures related to production planning (Ben-Daya et al., 2016)

## 3. Related Work

The literature shows that many scholars have worked on preventive maintenance scheduling challenges and solved them using evolutionary algorithms and simulation methodologies. Furthermore, the different research studies that are relevant to this work used several optimization methodologies to improve preventive maintenance scheduling, such as linear programming (LP), multi-objective programming, and genetic algorithms (GA) (Alardhi et al., 2007; Levitin and Lisnianski, 2000; Lisnianski et al., 2010; Quan et al., 2007; Taboada et al., 2008). Several related studies are reviewed below.

Pereira et al. (2009) developed a particle swarm optimization (PSO) strategy to optimize preventive maintenance scheduling. They prioritized dependability and affordability and allowed for adjustable intervals between maintenance. They used the strategy to create a system composed of seven main components: four valves and three pumps. Tian et al. (2009) came up with a physical programming-based way to solve the multi-objective condition-based maintenance (CBM) optimization problem for a single unit using the proportional hazards model. The decision maker can make a good trade-off between cost and reliability with the proposed method. They used an example of CBM to show this. Tian and Liao (2011) carried out similar studies on multi-component systems. Harrou et al. (2010) conducted a novel research study for systems with a series-parallel transmission topology. They identified the issue of poor maintenance optimization. A significant part of their effort was to determine how often preventive maintenance should be performed to maximize uptime. To come up with a solution, they used harmony search and genetic algorithms. Lin and Wang (2012) proposed a hybrid GA in order to optimize preventive maintenance recuring actions in series-parallel systems. Properties such as the structure of reliability block diagrams, maintenance priority to individual components, and maintenance periods, are considered in the developed model utilizing component importance measures. Based on that, the total maintenance cost was minimized by determining optimal maintenance periods for these important components. Ebrahimipour et al. (2015) Proposed a multi-objective PM scheduling model in a serial-parallel multiple production line that accounts for the reliability of production lines, costs of maintaining, failure, and downtime of system with different thresholds for available manpower, spare part inventory, and periods under maintenance is applied.

Li et al. (2021) proposed a novel approach for integrating preventive maintenance into production planning of a complex manufacturing system based on availability and cost. The proposed approach predicts the required capacity of each machine through an extreme learning machine algorithm and calculates the opportunistic periods to implement PM tasks to have less impact on production; it also provides scheduling planning with the least number of maintenance personnel through an ant colony optimization algorithm. Gholizadeh et al. (2022) proposed an optimization model considering PM covering flexible flow-shop system scheduling in a series–parallel production system of disposable appliances. The mathematical model considers both the operation times and the availability of the whole production system to minimize delays. Since uncertainty exists in real industrial systems, the processing times are uncertain here. To handle the uncertainty of processing times, robust optimization has been applied to solve the problem, and a scenario-based genetic algorithm (SBGA) and a particle swarm optimization (PSO) algorithm have been developed to solve the proposed model.

## 4. Methodology

### 4.1 Plant Layout Description

For the current plant, the first step of the production process is to choose raw materials from the inventory department, which are the main materials in glass manufacturing such as silica, sand, sodium carbonate, and feldspar. When raw materials are selected, they are sent to the batch house; here, raw materials are weighted, mixed, and transferred to the hopper (a melting furnace) where the melting process takes place. After that, the materials that have been batched will be introduced into the furnace during the melting process, where they will undergo heating and melting. The raw materials will be subjected to high temperatures, reaching up to 1200 °C. Inside the furnace, the raw materials will transform, transitioning into a state of liquid glass. In the next process, the feeding will be carried out by glassblowers (need to be done at an optimum chosen temperature to avoid defects in the product). Subsequently, the formation occurs, which involves applying the liquid glass into molds and blowing air into the glass to help the shaping process. As soon as the glass is removed from the machine, it must be annealed. To relieve tension, phase separation, or crystallization that has formed within the glass, annealing is necessary. The structural condition of the glass will change in this step. Eventually, after the product cools, it undergoes an initial inspection, where the machinery checks the product to find any defects or deformations. Any defective product will go to the recycling center for the recycling process, and all transferring operations are performed by conveyors. Figure 4 shows the entire production line process.

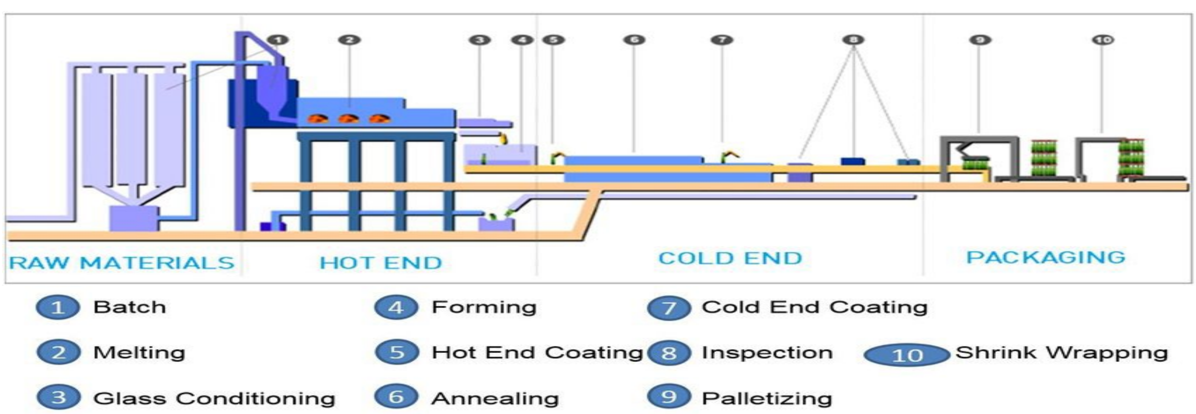


Figure 4. Production line processes for the current plant

### 4.2 Cause and Effect Diagram

The plant reported that the manufacturing process is out of control due to the presence of assignable and common causes. The assignable causes were defects in the raw material supplied and/or poor maintenance of the machinery. However, the common cause was high temperature in the factory that affects the productivity of the staff that monitors the process. Based on that, a cause-and-effect diagram (as shown in Figure 5) to organize possible causes for a specific problem or effect by graphically displaying them in increasing detail, suggesting causal relationships among theories. It was found that the breakdowns were random and can most likely be improved by suggesting an improved maintenance plan. It should be noted that quality characteristics tools were used to evaluate the overall quality of the products, that is, control charts were provided by the plant but cannot be presented due to the confidentiality of information.

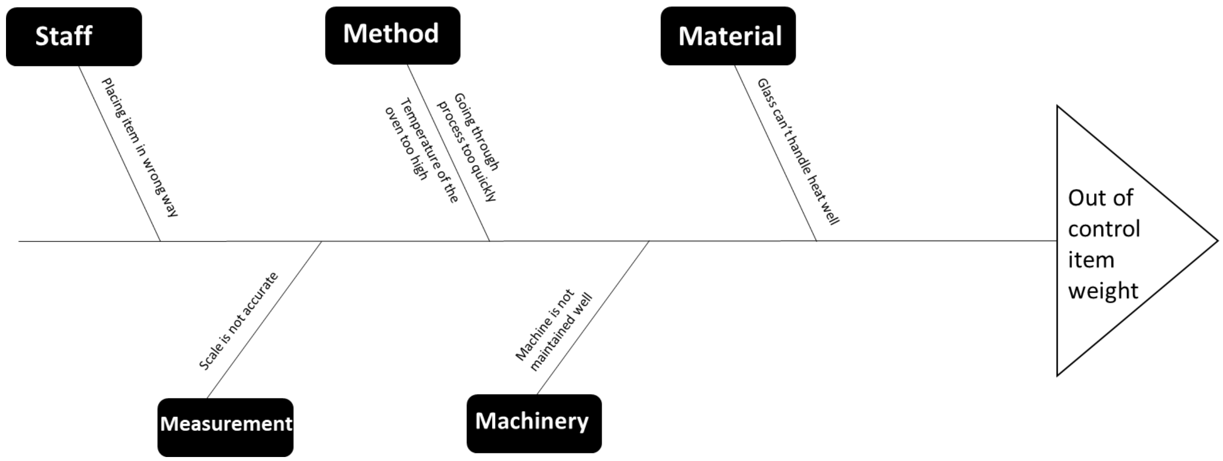


Figure 5. Cause and effect diagram

### 4.3 Problem Definition

The current Factory does not take into consideration scientific approaches on how to optimize maintenance and reliability, which eventually add unnecessary cost and low reliability. The plant suffers from sudden breakdown of production lines due to poor planning and scheduling of maintenance and reliability. In this work, we need to determine the failure rate of the components depending on the data collected. Maintenance activities are assumed to be adjustment and replacement. We will assume an interval of time (0, T). The possible maintenance actions for system components are adjustment, replacement, or no taken action. If a component is adjusted, we assume that the component's "effective age" will be reduced with a coefficient α ranging between zero and one affecting the failure rate of the component. However, if a component is replaced, the component will be assumed as if it is in its initial state, that is "as good as new", where its failure rate following the maintenance action is similar to the failure rate at time equal zero. Moreover, the effective age of the component will not change if no action is taken at the end of the period. Furthermore, a single adjustment or replacement action requires a discrete uniform period of time between a lower and upper limit, where decreasing the failure rate will eventually increase reliability. After determining the distribution of failure rate, we will apply a mathematical model with the multi-objective of minimizing cost and maximizing reliability. Ultimately, the mixed integer nonlinear program model developed will determine the best possible maintenance schedule. A preventive maintenance plan was constructed according to the data collected from the plant, including the effective age of each component classified according to the historical failure rates observed. It is assumed that preventive maintenance should be carried out one day before expected breakdown (n-1) to ensure minimal downtime for the production line and minimize maintenance costs as much as possible. Furthermore, we assumed that if the component is working, then its performance will not be affected.

### 4.4 Model Development

The production line on which we are conducting our reliability and maintainability optimization study is a series system with 35 components. For the developed model, a few assumptions need to be stated first:

1. The model is applied for one month (T=30 days) since our data is for March 2022.
2. Breakdown of the production line occurs whenever any component fails.
3. Each component has a unique effective age since the components are supplied by different suppliers.
4. The constant age reduction factor is assumed to be 15% per year.
5. The mathematical model is nonlinear since it has a multiplication of multiple decision variables.

**Notations**

$UA_i$: Unit cost of adjustment of component i
$UR_i$: Unit cost of replacement for component i
$FC_i$: Fixed cost of system downtime for component i
$MaxB$: Maximum budget for maintenance
$T$: Total period (30 days)
α: Age reduction factor of adjustment activities

$DA_i$: Duration time of adjustment of component i
$DR_i$: Duration of replacement time of component i
$\lambda_i$ : Lambda value for i
$t_{i,j}$: Effective age of component i at the start of period j
$t'_{i,j}$: Effective age of component i at the end of period j
$x_{i,j}$: Number of replacements of component i in period j
$y_{i,j}$: Number of adjustments of component i in period j
$a_{i,j}$: Binary decision variable equals 1 if component i in period j is adjusted, 0 otherwise
$r_{i,j}$: Binary decision variable equals 1 if component i in period j is replaced, 0 otherwise

**Multi-Objective Function**

$$Min\ Cost = \sum_{i=1}^{N} \sum_{j=1}^{T} \left(UA_i\, y_{i,j} + UR_i\, x_{i,j}\right) + \sum_{i=1}^{N} \sum_{j=1}^{T} \left(DA_i\, y_{i,j}\, FC_i + DR_i\, x_{i,j}\, FC_i\right) \quad (1)$$

$$Max\ Reliability = \sum_{j=1}^{T} \prod_{i=1}^{N} e^{-\int_{t_{i,j}}^{t'_{i,j}} \lambda_i(t)dt} \quad (2)$$

s.t.

$$\sum_{j=D}^{D+\max\{DRi,DAi\}} a_{i,j} + r_{i,j} \le 1 \ ;\ i = 1, \dots, N\ ;\ D = 1, \dots, (T - \max\{DR_i, DA_i\}) \quad (3)$$

$$t_{i,1} = 0 \quad i = 1, \dots, N \quad (4)$$

$$t_{i,j} = \left(1 - a_{i,j-DAi}\right)\left(1 - r_{i,j-DRi}\right)t'_{i,j-1} + a_{i,j-DAi}(\alpha\, t'_{i,j-DAi})$$
$$i = 1, \dots, N \quad j = 1, \dots, T \quad (5)$$

$$t'_{i,j} = t_{i,j} + \frac{T}{j} \qquad i = 1, \dots, N \quad j = 1, \dots, T \quad (6)$$

$$\sum_{i=1}^{N} \sum_{j=1}^{T} (DA_i\, a_{i,j} + DR_i\, r_{i,j}) \le T \quad (7)$$

$$\sum_{i=1}^{N} \sum_{j=1}^{T} \left(UA_i\, a_{i,j} + UR_i\, r_{i,j}\right) \le MaxB \quad (8)$$

$$DA_i \in Z \quad (9)$$

$$DR_i \in Z \quad (10)$$

$$a_{i,j}, r_{i,j} \in (1,0) \quad (11)$$

$$FC_i, UA_i, UR_i, DA_i, DR_i \ge 0 \quad (12)$$

Equation (1) represents the cost function to be minimized, which is the cost of replacements and adjustments of components. Equation (2) shows the reliability function to be maximized for the series production line system. Constraint (3) ensures that neither adjustment nor replacement can be performed on a component in each period until the previous maintenance actions have been completed. Constraint (4) ensures that the initial age of each component at the start of the first period is zero. Constraint (5) determines the effective age of component *i* at the start of period j concerning previous adjustment or replacement activities performed on it. Note that maintenance activities are assumed to be performed on components only at the end of any given period. Constraint (6) determines the effective age of component *i* at the end of the period. Constraint (7) determines a threshold for the system's downtime due to maintenance activities. Constraint (8) specifies that performing replacement and adjustment activities is limited by the maximum available budget. Constraints (9)-(11) ensure that both replacement and adjustment durations are integers and that the decision variables for adjustments and replacement are binary. Finally, Constraint (12) determines the nature and range of the remaining decision variables.

## 5. Results

In this section, we share the results found and discuss their implications. To solve the multi-objective model, LINGO software (Lindo, 1998) has been used. The model was run using a goal programming approach where we let the cost objective function run, get the results, and then fit the results into the reliability objective function. After 23 hours and 34 minutes of running the code and performing more than 3000 solver iterations, the optimum solution could not be reached. Figure 6 shows the LINGO screen for the current iteration.

```
Local optimal solution found.
Objective value:                              0.1549502E-34.
Objective bound:                             -0.1549502E-34
Infeasibilities:                              0.1421085E-13.
Extended solver steps:                                   110
Total solver iterations:                                3251
```

Figure 6. LINGO software screen results for goal programming

Since LINGO does not comply with multiple objective functions, the team applied the cost objective function for the second iteration with the reliability objective added as a constraint with a threshold. After running the model, the results showed a reduction in the objective value, which is the total maintenance cost for the 35 components, compared to the maximum budget allocated by the factory of 2,917,095 SAR. Figure 7 shows the terminating screen of the iteration. Based on the output, the expected maintenance saving costs for the suggested plan are 2,567,043 SAR which is approximately a 12% reduction from its maximum maintenance budget.

```
Local optimal solution found.
Objective value:                              2567043.
Objective bound:                              2567043.
Infeasibilities:                              350052.2
Extended solver steps:                             301
Total solver iterations:                          3164
```

Figure 7. LINGO software screen results for final results

Note that the current solution is not considered an optimal solution, but rather near-optimal; in fact, we terminated the solver after more than 20 hours of no objective value improvement. It seems that the problem being non-convex and nonlinear has caused the software to face several computational difficulties. Nonetheless, the current near-optimal solution is found to be better than the current factory maintenance plan. The graph below (Figure 8) illustrates the difference in the maintenance budget before and after optimization.

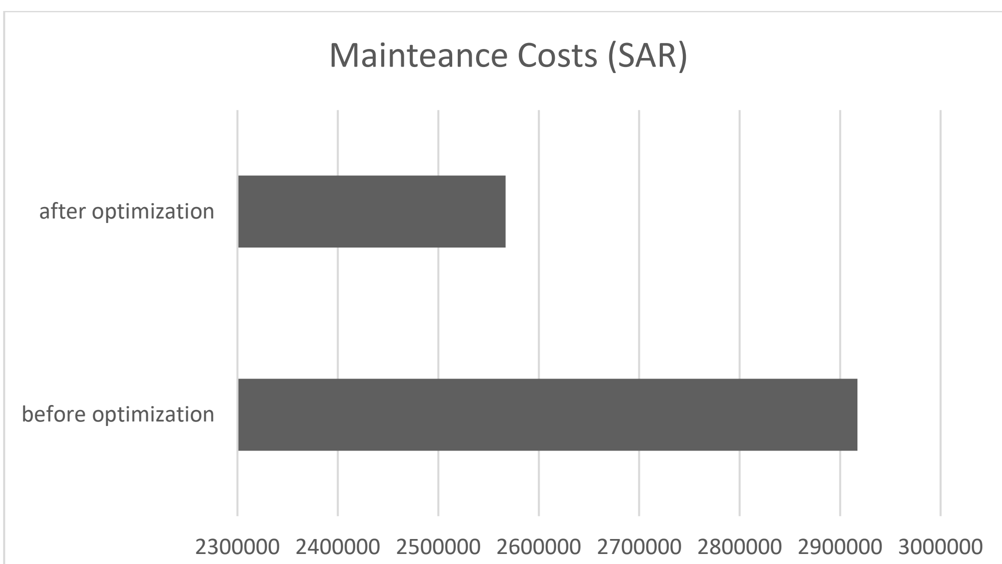


Figure 8. Maintenance costs before and after the optimization model

## 6. Conclusions and Future Work

In this article, we study production line systems and how to improve reliability and maintenance activities while decreasing maintenance costs. The reliability of the system in a production company is an essential factor in measuring the performance of any company. Therefore, in this work, quality improvement and reliability optimization approaches have been used to find the best maintenance policy for the given problem. The current work focused on a segment of a production line with a total number of 35 components in a local glass plant to implement our approach; in fact, we tried to cover different components with divergent quality and reliability characteristics to gain a better understanding of the reliability of the whole system.

Mathematical optimization is the most common approach to designing the best possible outcome for industrial problems; indeed, that was the case for the current problem. In this work, a multi-objective PM scheduling problem is considered in a production line at a local Saudi glass plant. Reliability of the production line, maintenance costs, and system downtime are measured as multiple objectives, and different thresholds are applied for available budget and maintenance periods. It is found that applying a near-optimal preventive maintenance plan to the factory can reduce downtime and reduce unnecessary costs by at least 12%, resulting in about 400,000 SAR savings.

For future work, genetic algorithms could be used to overcome the computational obstacles faced due to the size of the problem, especially if the problem grows in size by adding a higher number of components. Moreover, applying machine learning approaches, such as clustering techniques, is among future directions that would help overcome the computational burden of reliability optimization and maintenance scheduling problems. In addition, developing a stochastic nonlinear model with random adjustment and replacement times can also be one of the future directions of the current work.

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