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Improving the Allocation of Resources to Different Strategies of Medical Equipment Maintenance and Repair with System Dynamics Approach Case study: Razavi Hospital of Mashhad

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ABSTRACT

Appropriate maintenance strategies reduce the overall operating cost of medical equipment and its depreciation, leading to increased equipment availability. This study is looking for an optimal strategy to increase access to medical equipment and reduce maintenance costs. It generally aims to increase the net value of the equipment maintenance system. The present study has designed a simulation model of dynamic systems in order to investigate the contribution of preventive and corrective maintenance measures and strategies to improve the overall performance of medical equipment. In this regard, first, the key variables in the maintenance and repair system of medical equipment have been identified, and their relationships have been compiled in the form of causal loops; then, the primary model has been completed in the form of stock and flow charts which have been simulated in Vansim software. The results show that increasing preventive maintenance by reducing the need for corrective measures leads to increased access to equipment and reduced maintenance costs. The ratio of change of resources and the amount of its allocation to each of the corrective and preventive maintenance measures have been obtained through simulation and according to the amount of primary and secondary variables in the case of the study (Razavi Hospital). The simulated model can be implemented for other hospitals considering their internal conditions.

Keywords

Maintenance strategies, Medical equipment, System dynamics, Optimization, Simulation.

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1. Introduction

Modern medical devices and equipment have become complex and sophisticated and are expected to operate under stringent environments. Hospitals must ensure that their critical medical devices are safe, accurate, reliable and operating at the required level of performance. The most significant problem for many developing countries is not the lack of equipment but rather the fact that 50% and sometimes up to 75% of the supplied equipment is not operative (Gómez-Chaparro et al. 2020). The maintenance of medical equipment is as essential as its design and development. The cost of maintaining a medical device during its lifetime is usually higher than purchasing it (Darzi et al., 2019). Medical equipment technologies require planned and unplanned maintenance, and in recent decades, their maintenance cost has increased dramatically due to the increasing costs of medical equipment (Ahmed, 2016). Due to the high cost of purchasing medical equipment, it is vital to maintain this equipment in order to control hospital costs efficiently. On the other hand, one of the most critical problems faced by medical staff in hospitals is the unavailability of medical equipment when needed due to the malfunctioning of the medical equipment repair and maintenance system. An appropriate maintenance system is required for almost all equipment in order to guarantee performance and accessibility (Almakrami, 2021).

Incidentally, the medical maintenance of large-investment resources, which was once thought to be a necessary evil, is currently essential in creating additional value. The first challenge for medical departments is to define which maintenance strategy should be deployed for each piece of equipment (Mahfoud et al. 2017). Now, strategies mainly implemented for most hospital equipment include corrective and periodic preventive maintenance.

Corrective Maintenance (CM) is carried out after a fault has been recognized; it is intended to put the failed item back into a state where it can perform its required function. PM is carried out at predetermined intervals or according to prescribed criteria and is intended to reduce the probability of failure or the degradation of items (European Committee for Standardization, 2010). The selection of a maintenance strategy depends on a number of factors, including the cost of downtime, redundancy and the item's reliability characteristics. Consequently, this issue varies among organisations and assets despite the importance of establishing a balance between PM and CM in minimizing costs (Stenström, 2015).

The present study, by reviewing the available resources regarding the selection of medical equipment maintenance strategies, seeks to provide a comprehensive approach by considering the interaction between effective factors affecting the selection of maintenance strategies. It tries to determine the optimal number of resources allocated to each corrective and preventive maintenance action by establishing a reasonable balance between corrective and preventive maintenance costs. Research regarding the determination of maintenance strategies of medical equipment as well as the application of the system dynamics in the field of maintenance and repair are as follows:

Medical technology management plays a crucial role in health care. Effective medical device management is required to ensure high-quality patient care. Efficient and accurate equipment provides a high degree of patient safety. Accomplished medical device management will significantly assist in reducing adverse incidents and medical device-related accidents. For medical technology management, hospitals must have activities for maintaining, inspecting, and examining all medical equipment in the inventory (Sezdi, 2016). Preventive maintenance is a core function of clinical engineering, and it is essential to guarantee the correct functioning of the equipment. As the variety of medical equipment increases, the size of maintenance activities increases, and the need for better management and control becomes essential (Dejaco et al., 2019). According to Jamshidi et al. (2014) preventive maintenance will reduce major repairs and prevent inappropriate performance of medical equipment. Preventative maintenance exists in many industries and was previously used in health centers only for heating and air conditioning systems, but recently it has been used for medical equipment too. A preventive maintenance strategy is the essential maintenance activity of medical devices. Other factors, such as the "medical equipment control program" and "appropriate medical equipment selection", will help implement the optimal maintenance program. Generally, the preventive maintenance process prevents device wear-out or improper functioning of medical devices and prolongs the life of medical equipment; thus, medical devices are kept in a desirable condition and do not quickly deteriorate (Zamzam et al., 2021). Bahreini et al. (2018), emphasizing the importance of medical equipment repair and maintenance strategies and the impact of medical equipment on the mortality rate of patients, have presented a model for prioritizing the repair and maintenance of medical equipment in Jordanian hospitals. The results of their study show that the application of this model has a significant impact on minimizing equipment malfunctioning, increasing its reliability, cost savings and improving the safety of the equipment. Mekki et al. (2012) developed a model for enhancing medical equipment repair and maintenance programs in developing countries using a system dynamics approach. They have proposed their model in 3 hospitals in Sudan and 12 hospitals in Egypt. Their results revealed that the failure rate, the rate of disabled machines and maintenance costs are the most critical factors affecting a system of maintenance and repair of medical equipment. In 2015, Jamshidi et al. proposed a risk-based priority framework for choosing the best maintenance strategy. This framework consists of three main stages: the first phase is the fuzzy analysis of failure factors and their effects (FFMEA). In the second stage, all aspects of risk are considered in prioritizing medical equipment. Finally, in the third stage, each piece of equipment's most appropriate maintenance strategy is proposed according to its rating. The results of their study show that managers can use this framework to classify medical equipment according to the obtained ratings and required maintenance activities and increase access to high-risk equipment. In 2015, Abdo et al. used a system dynamics approach to assess medical equipment repair and maintenance systems in developing countries. In their study, they designed a model for determining the contribution of corrective and preventive maintenance strategies in order to improve the overall performance of medical devices. Indeed, their study has provided a desirable maintenance strategy to increase the operational accessibility of medical devices and reduce their deterioration.

Compared to the previous studies, the innovation of this paper is that the model presented in this research is more complete than the previous research by considering different subsystems, including cost, availability and number of defects. A more comprehensive model than past studies has been designed to show a more accurate picture of the dynamic behavior of the medical maintenance and repair system using the concept of a system dynamics. This paper aims to create a dynamic system model to increase the effectiveness of medical equipment over its lifespan by monitoring the performance of medical equipment and developing appropriate maintenance strategies. This paper presents a dynamic hypothesis, and then the model's critical variables are identified. To illustrate the relationship between variables, the Causal loop diagrams have been developed. In the next step, the stock and flow diagram of the medical equipment maintenance system is mapped, and finally, the model is simulated in the form of three different policies.

2. Methodology

In this study, a questionnaire consisting of 18 questions was used to collect data on the variables identified in the model. It should be noted that this paper focuses on maintenance strategies of the equipment in the ultrasound section of Razavi Hospital. The relevant questionnaires were completed through face-to-face communication. Aggregated data is only used to determine the initial position of the system, to set the range of variables and to present real policies. Also, the hospital records of previous years have been used to provide reference modes. Vensim software was used in this research, a visual modeling tool that allows the conceptualization, documentation, simulation, analysis and optimization of dynamic system models. Generally, Vensim is a simple, flexible way to simulate dynamic systems models using a Causal loop and stock and flow diagrams (Vensim, 2007). There have been several tests to validate the model; in this study, the extreme conditions test is performed to check whether or not the equations make sense when subjected to extreme conditions (Ahmad et al. 2015). Extreme condition analysis analyzes if the parameters in the model behave appropriately under extreme conditions. To assess this response, surfaces were compiled for each endogenous variable (Nazareth et al. 2015).

3. System dynamics model

This section reviews a systemic view of maintenance by establishing a system dynamics model. This model considers the relationships between corrective and preventive maintenance actions, equipment breakdowns, equipment availability and process quality. The model uses the causal loop diagram and flow diagram to depict processes, concepts and interdependencies used in system dynamics.

3.1. Dynamic hypothesis

The allocation of available resources for corrective and preventive maintenance actions through dedicating a larger budget and human resources will reduce the average time required for each equipment repair. As a result, the repair rate increases and their defect rates decrease. By lowering the defect, the average time between the two breakdowns has increased; in fact, the number of hours that the device is out of service decreases, increasing the accessibility to devices. Also, reducing equipment deficiencies by reducing the number of hours that devices operate despite the defects will improve the functionality of the equipment and thus increase access to them. On the other hand, with the increase in preventive maintenance actions, the

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number of devices that operate without defects will increase the equipment's functionality and, consequently, its access. With an increase in the availability of devices, if there is a demand for them, the number of operating hours of the devices increases, which will result in equipment wear and tear and, consequently, an increase in the rate of the defect and the number of breakdowns. Ultimately, it reduces access to the device. In general, the balanced allocation of maintenance resources to preventive and corrective maintenance actions will increase access to equipment and reduce maintenance costs, including maintenance and repair costs, and finally, the net worth of the maintenance strategy increases.

3.2 Causal loop diagram

Following the dynamic hypothesis, the causal loop diagram is created. In Figure 1, the causal loop diagram of the medical equipment maintenance system is presented. This diagram is used to display the feedback structure of the system, and it contains two or more causal relationships that link various variables to the model. Feedback is a key concept in the dynamic system showing the interactions between variables. In general, there are two feedback loops: positive or self-reinforcing loops and negative or self-equilibrium loops. Positive loops increase the growth effect exponentially, while negative loops, according to the equilibrium approach, reduce the gap between the existing system and the equilibrium state. The causal diagram shown in Figure 1 can be divided into two subsystems, a maintenance subsystem and a preventive or periodic maintenance subsystem. These two subsystems are connected by the variables of availability and maintenance costs. Failure and function have a negative and positive effect on availability; however, the impact of device availability on the two variables of failure and function is positive. Therefore, there are two loops: the loop between the function and availability, which is positive and the loop between the failure and availability, which is negative.

Since allocating more resources and personnel for maintenance will lead to increased costs and thus reduce the effectiveness of maintenance strategies, the cost variable is also presented in the causal diagram. In this paper, the increase in resources and personnel allocated for repairs leads to a doubling of the cost of corrective maintenance; there is a positive and exponential relationship between preventative maintenance actions and related costs.

The model output and basis for subsequent decision-making are the net maintenance value. The net maintenance value is affected by two variables: the availability of the device and the cost of maintenance which can be used to analyze maintenance actions and strategies.

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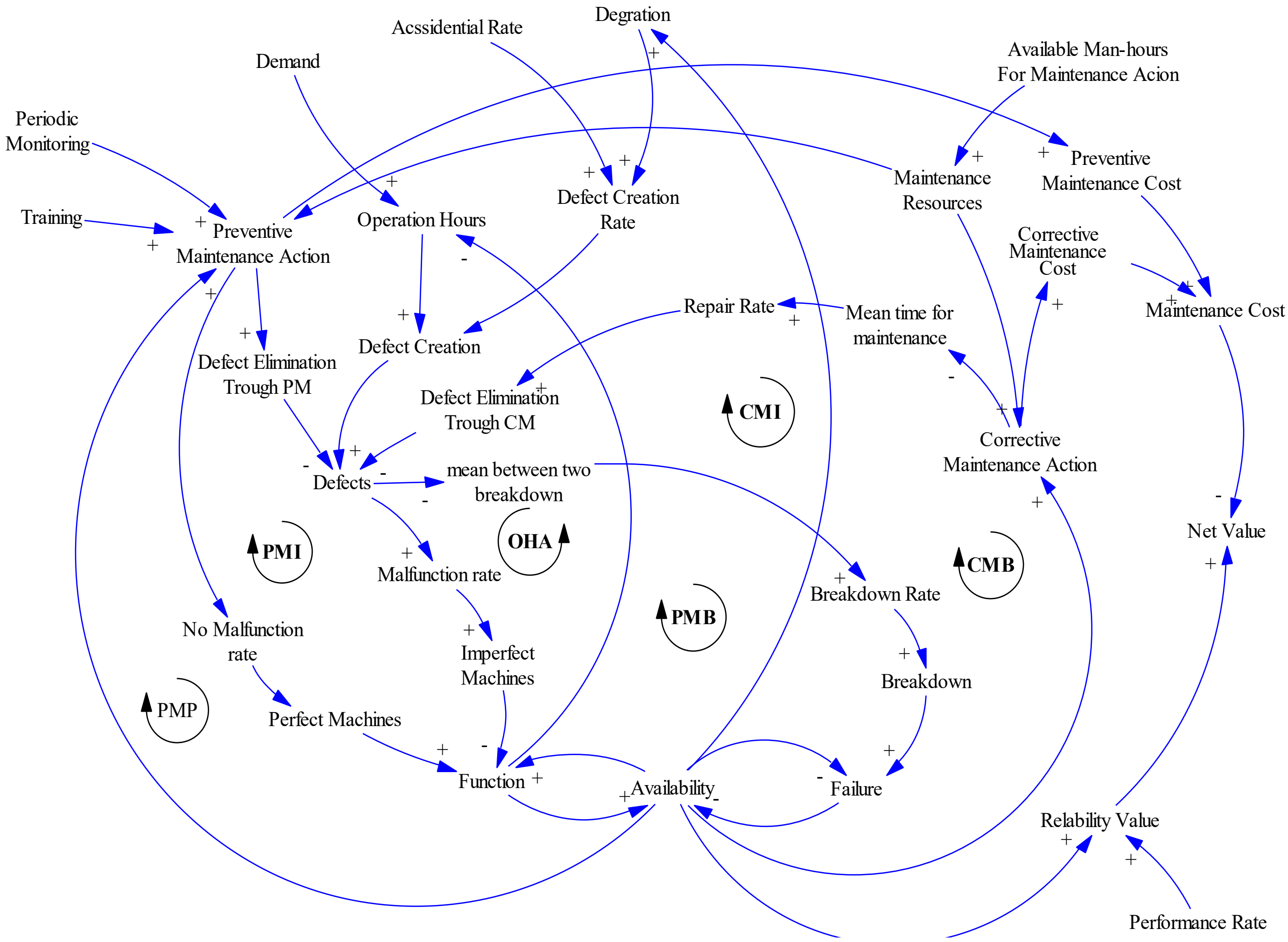

Figure 1. The causal loop diagram of the medical equipment maintenance system

3.3. Stock and flow diagram

In Table 1, the characteristics of the identified variables are presented. According to engineers and maintenance managers of the hospital, the set of variables presented is the starting point for modeling the system.

One of the most critical limitations of the causal loop diagrams is their inability to display the stock and flow structure of the system. Stocks and flows, along with feedback, are two key concepts in dynamic systems. Generally, stocks occur in a system due to the difference between the rates of input and output flows during a process in the system. Stocks lead to the creation of memory in the system as the basis for actions and decisions in the system. Stocks also cause delays and imbalances in the system.

Based on the research question and the causal loop diagram, since the purpose of the research is to improve the outcomes of the medical equipment maintenance system, the variables of the number of defects along with the total cost of maintenance and availability are considered as the stock variables, and the net value variable is the output variable as the ultimate goal of the research. For better understanding, each of the subsystems of the stock and flow diagram is examined separately.

Table 1. The key variables' definition and formulation

Variable	Unit of measurement	Kind of variable	Definition	Formulation
Availability	Hours	Stock	The number of hours the device is available to be used and perform task operations	$\int (function - failure)dt$
Function	Hours per month	Flow	The number of hours that the device is in the functional state each month (including correct operation and acceptable operation)	$perfect + 0.5 * imperfect$
Corrective Maintenance Cost	Currency in month	Flow	The monthly costs for corrective maintenance actions are shown	$\text{MIN}(\text{CM resource rate} * \text{maintenance resource}, 4 * \text{break down} + \text{imperfect})$
Defect	Number	Stock	The total number of defects that result in poor performance of the device or its disability.	$\int defect\ creation - (defect\ elimination\ by\ PM + defect\ elimination\ by\ CM)dt$
Preventive maintenance cost	Currency in month	Flow	The monthly costs for preventive maintenance actions are shown	$maintenance\ resource * PM\ resource\ rate$
Total maintenance cost	Currency	Stock	The total amount of money allocated to corrective and preventive maintenance actions.	$\int (CM\ cost + PM\ cost)dt$
Device failure	Hours per month	Flow	The number of hours the device is out of service in the month.	$break\ down\ rate * Defects$
Defect creation	Number per month	Flow	The number of defects created in the month	$defect\ rate * operational\ hours$
Elimination of defects through CM actions	Number per month	Flow	The number of defects that are resolved in the month through corrective maintenance actions	$PM\ action * PM\ rate$
Elimination of defects through PM actions	Number per month	Flow	The number of defects that are resolved in the month through preventive maintenance actions	$DELAY1(CM\ action, 25)$

As shown in Figure 2, failure and function negatively and positively affect availability in the availability subsystem. In contrast, the effect of device availability on these two variables (failure and function) is positive. The degree of disruption and defect in the device, as well as the perfect device, has a direct impact on availability.

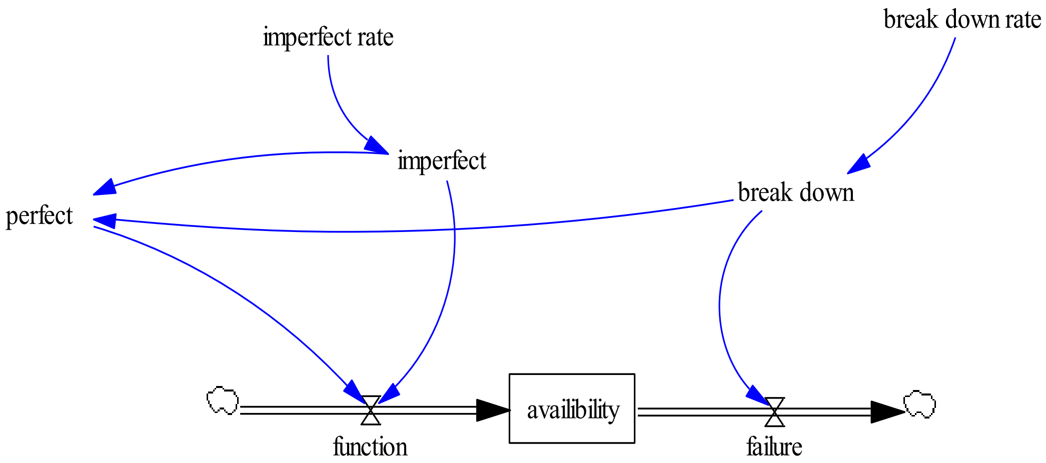

Figure 2. The stock and flow diagram of the availability variable

Figure 3 below shows the system failure. This subsystem examines the relationship between preventive and corrective maintenance strategies and the degree of defect in the device. Increasing available resources for maintenance will lead to an increase in corrective maintenance actions through more resource and manpower allocation. Thus the average repair time is reduced, which means that the repair rate has increased and the amount of defect (flow and stock) decreases. As a result of reducing the defect, the number of hours the device is out of service is reduced and eventually, the device's failure rate is reduced too. On the other hand, increased maintenance resources will increase preventive maintenance actions, including replacement policies and technical actions. Therefore, the number of hours the device is defective decreases, and the average time between failures increases, which results in a decrease in the failure rate and the number of hours the device is out of service, and ultimately the failure rate of the device decreases.

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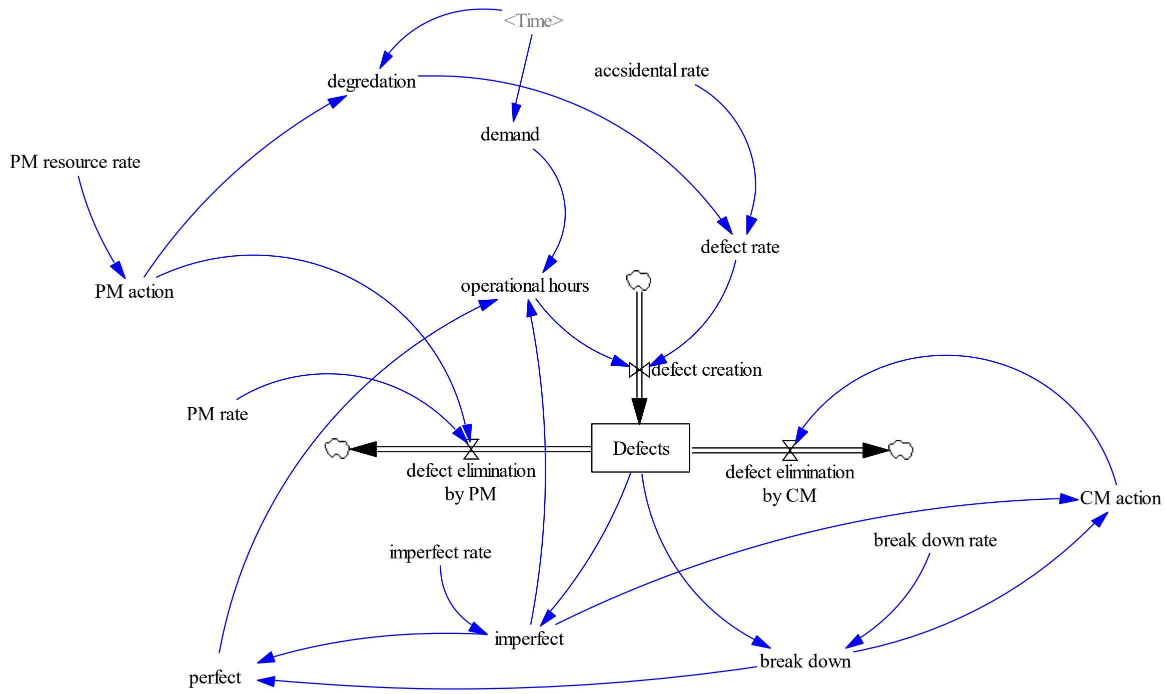

Figure 3. The stock and flow diagram of the defect's variable

As shown in Figure 4, the maintenance subsystem reflects the level of the actions of each corrective and preventive maintenance strategy and the total maintenance cost. The amount of corrective maintenance strategy actions depends on the percentage of the allocated resources and the degree of breakdown and disruption of the device; on the other hand, the amount of preventive maintenance strategy actions depends on the allocated resources.

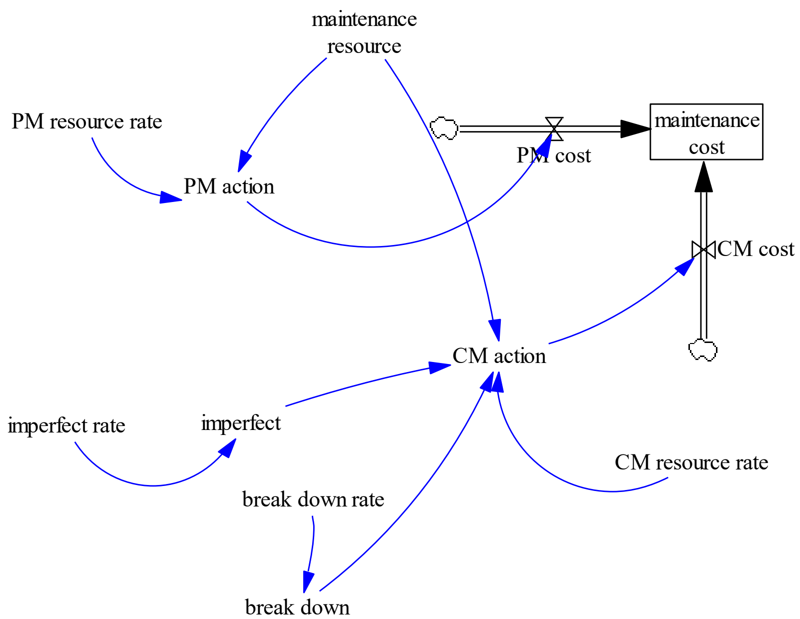

Figure 4. The stock and flow diagram of the maintenance cost variable

An integrated stock and flow diagram is presented in Figure 5, and it is the result of the integration of three subsystems of defects, availability of the device and maintenance costs.

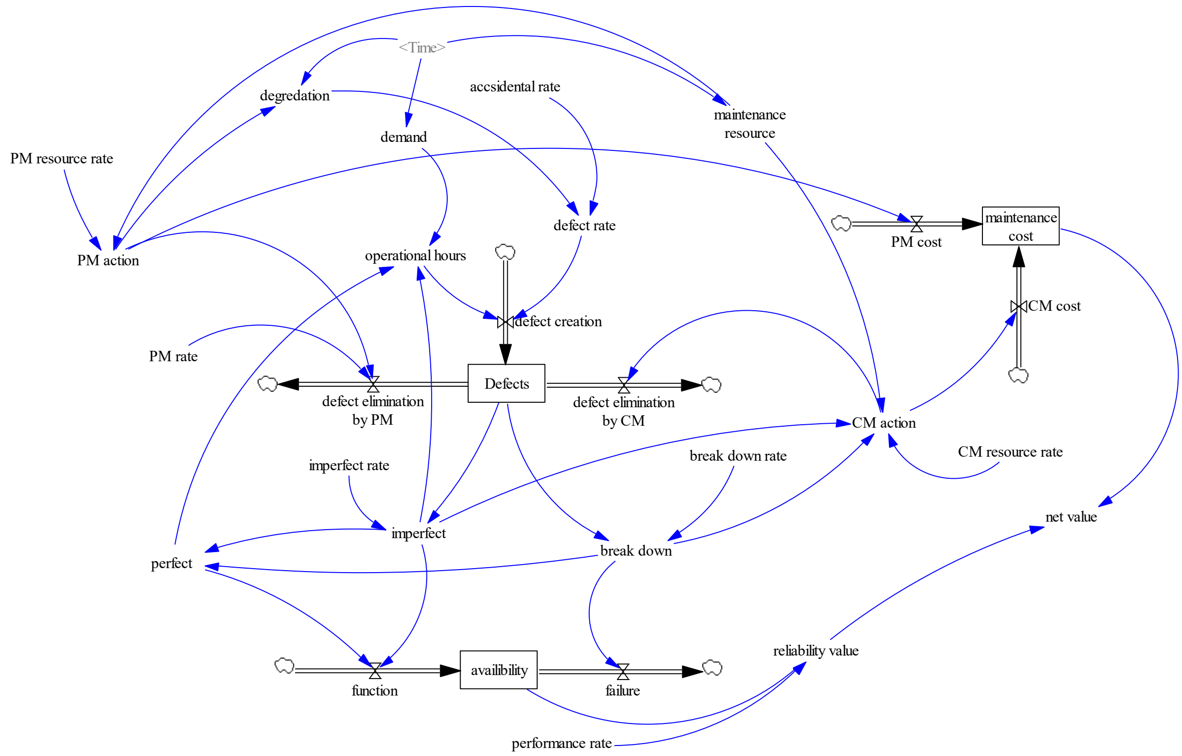

Figure 5. The stock and flow diagram of the system of medical equipment maintenance

3.4. The model validity

System dynamics models' validity is divided into structural and behavioral validity. Structural validity means creating relationships in the model that represent the relationships of the real world (taking into account the purpose of the study) expressively and adequately (Oliva, 2003). Behavioral validity means that the model's behaviour sufficiently represents the phenomenon's behaviour in the real world. The structural validity of the model has priority over its behavioral validity, and only when the structure of the model is valid can the validity of its behavior be investigated (Khan, 2009). Therefore, in the present study, an extreme conditions test has been used to assess the validity of the model. Considering the main parameter in the minimum and maximum mode and the output test of the model is the method of this type of validation to check its sensitivity to these changes. Although the graphs from extreme points may never be observed in real terms, the logical behavior of the model is expected. For this purpose, on one side of the spectrum, the percentage assigned to the corrective maintenance strategy is zero, and the preventive maintenance strategy is 100. On the other side, the percentage considered for the corrective maintenance strategy is 100, and for the preventive maintenance, strategy is zero. In reality, in matters relating to the repair and maintenance of medical equipment, the above conditions will not occur due to repairs needed in emergency conditions, and this is only for validating the behavior of the endogenous variables.

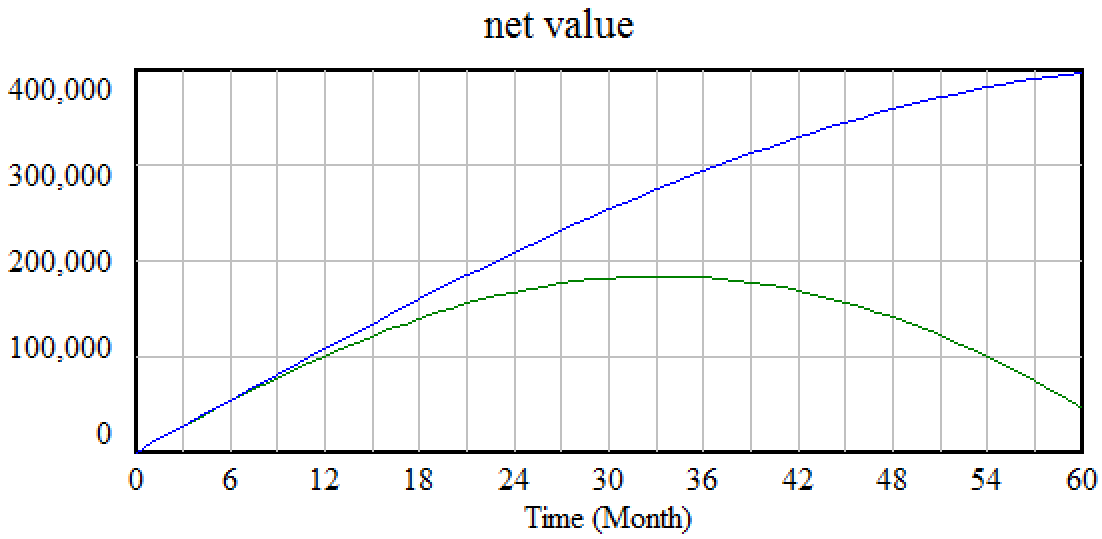

Figure 6. The extreme conditions test of the net value variable

As shown in the Figure 6, by allocating the total budget to preventive maintenance, the net value of the system will be an uptrend. On the other hand, by allocating the total budget to corrective maintenance, the net value of the system after some time will be downtrend towards zero. Observing these logical behaviors of the system at extreme points will verify the model's validity.

4. Results and discussion

This section examines various policies regarding allocating maintenance resources to preventive and corrective maintenance strategies. The first policy is to review the process of maintenance strategies in the current situation, meaning that no changes to the current corrective and preventive maintenance policies are applied. In fact, in the present condition of the hospital, the resources available for maintenance are allocated equally to the corrective maintenance and preventive maintenance strategies. In the second policy, the ratio of resources and personnel allocated to corrective maintenance increased from 50% to 70%, and the resources and personnel allocated to preventive maintenance decreased from 50% to 30%.In the third policy, the percentage of resources allocated to preventive maintenance increased to 70%, and it was reduced to 30% for the corrective maintenance strategy. The flow and a stock diagram for the three variables of availability, net value and maintenance costs for the above policies are presented in Figures 7, 8 and 9, respectively.

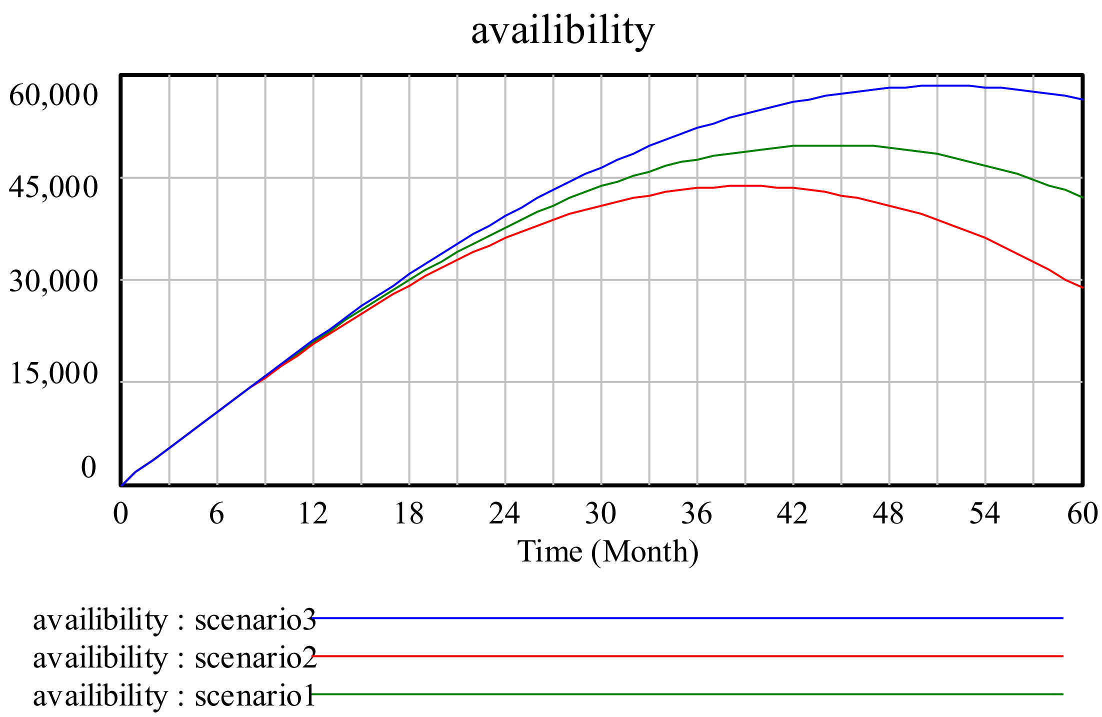

Figure 7. The stock and flow diagram of the availability of equipment for various policies

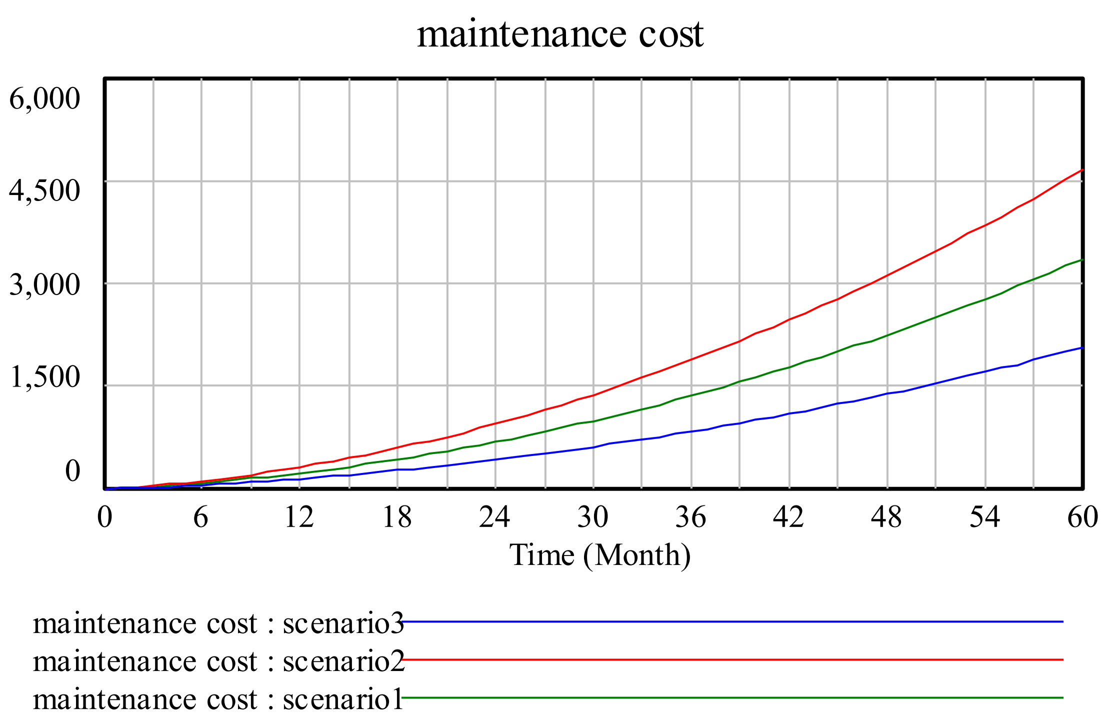

Figure 8. The stock and flow diagram of maintenance cost for various policies

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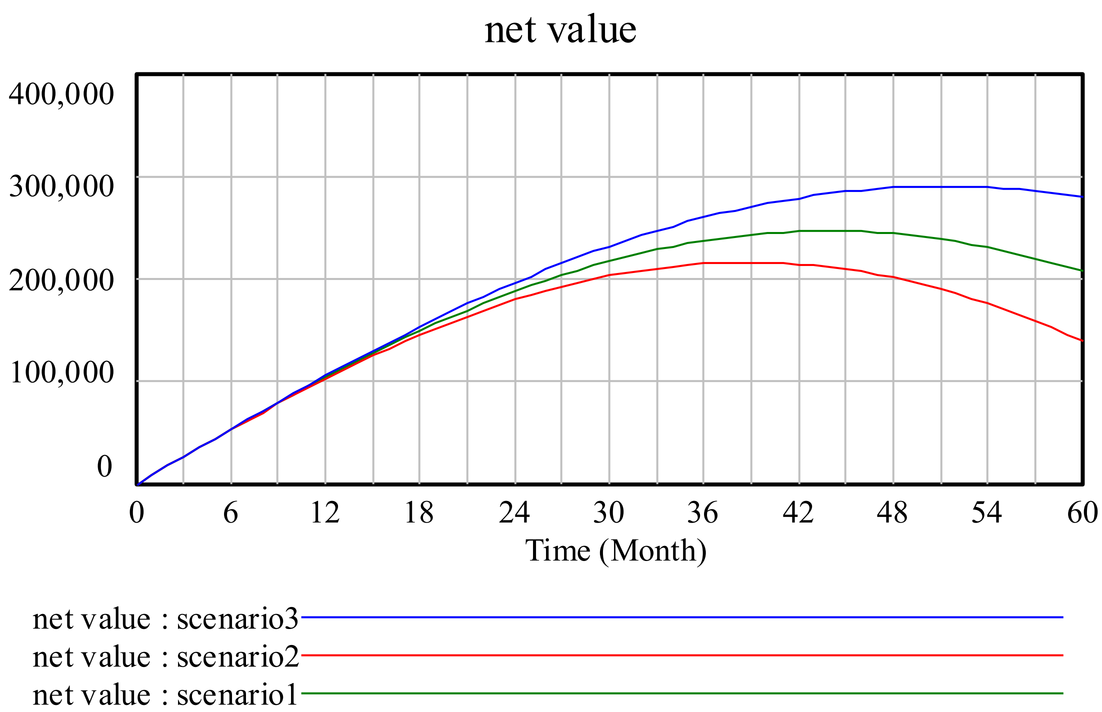

Figure 9. The stock and flow diagram of net value for various policies

As shown in the above diagrams, the changes made in the above policies lead to changes in the level of availability, net value and maintenance costs of maintenance strategies.

The area under the curve for each policy identifies the best maintenance strategy to be chosen by decision-makers. In fact, the policy that has the highest area under the curve, according to formula (1) is the best policy. In fact, the policy that has the highest area under the curve is the best policy.

$$Area = \int Net\ valu(t)dt = \sum Net\ value(t)dt\ \times \Delta t \quad (1)$$

The area under the curve for availability and net value diagrams is the highest for policy 3 and is the lowest for policy 2, and the area under the curve for policy 1 is between these two policies. As seen in the diagrams above, there are no significant differences in the policies in the early months. Still, over time, policy 3, which allocates a greater share of resources to the preventive maintenance strategy, has the highest area for availability and net value and the lowest area for maintenance costs. Therefore, based on the values of net worth, availability and maintenance cost, policies 3, 1 and 2, respectively, are proposed to develop maintenance strategies for Razavi Hospital equipment.

5. Conclusion

This paper uses a dynamic system approach for modeling hospital maintenance programs (ultrasound section of Razavi Hospital) and resource sharing between various equipment maintenance strategies. According to this approach, a causal loop diagram has been used to provide causal relationships among identified key variables. Also, the stock and flow structure was used to simulate the proposed system. The model presented in this study is more complete about the cost and availability of defects subsystems than previous research. The advantage of this article over previous papers is that the net worth variable, which is the result of two cost and availability variables, is added to the model and allows a more accurate decision-making policy. In previous articles, maintenance or machine disruption variables were considered the final variables of the models. Due to the interaction between the variables and the effects of factors such as functionality, reliability and availability, those models lacked comprehensiveness. At the same time, this paper attempts to present a comprehensive model that illustrates a more accurate picture of the dynamic behavior of the medical maintenance system using the concept of a dynamic system.

In this paper, various maintenance strategies were considered regarding the proposed model and then, based on the net value of each strategy, the contribution of each strategy was determined from resources. In fact, the strategy that has the highest net worth is considered the best strategy. Based on the simulation results and the examination of different policies, we conclude that investing in different maintenance strategies in the early years does not make any significant changes in the outputs of the model; in other words, different strategies do not differ significantly. But investing more in the preventive maintenance strategy and allocating more resources to this strategy will lead, in the long run, to higher levels of equipment availability and net worth in comparison with the other two strategies proposed in this paper.

Considering the huge investment in the medical equipment sector of the country's hospitals, the importance of having a precise system for repairs and maintenance is clear. Detailed planning can increase the system's useful life and reduce costs. Due to the lack of accuracy and attention to proper maintenance, and lack of timely system repairs, the devices are depreciated and retired before they reach the end of their useful life, and the high costs incurred for their early replacement. Using the right maintenance strategy and allocating the required budget can lead to better functioning of the devices and significant cost savings. This research showed that the simulation approach based on system dynamics in the health field could analyze the future and examine the facts and the impact of policies more precisely. In this study, it has been shown that investing in different maintenance strategies in the early years does not create noticeable changes in the model outputs, but investing more in preventive maintenance strategies. In the long term, it will lead to positive and significant changes in the outputs of the model compared to the other two strategies. Increasing the awareness of medical equipment specialists, empowering them and supporting senior managers from the achievements of this research can have increasing effects in reducing repair costs and maintaining and extending the life of medical equipment.

Adding other subsystems can improve and adapt the current model to every hospital's internal conditions. Hospital internal policies, the effectiveness of maintenance personnel, training and development of human resources, and how to deal with competitors (in private hospitals) are also the components that make the model presented in this research more complete.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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