Simulation-based Modeling for Min/Max Ordering Policy for Repairable Items Inventory Systems

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Abstract

The inventory system of repairable items is a managerial tool used to integrate all information concerning on-hand inventories and movements for new and repaired items. The paper describes developing a simulation model for managing the inventory of repairable items for a manufacturing system where faulty items are sent to a repair shop with uncertain failure rates, lead times, and repair times. The proposed model imitates processing and controlling the on-hand inventory of repaired items and replenishing the inventory of new items using the minimum/maximum ordering policy in a flexible and risk-free environment. We exhibit the appropriateness and effectiveness of the suggested simulation model using a demonstrative case problem. The developed model can be relied on as a tool for estimating healthy on-hand inventories of new and repaired items, downtime, and back-ordered items due to the unavailability of repaired items.

Keywords
Minimum/Maximum Policy; Repairable Items; Inventory System; Simulation; Maintenance

1. Introduction
Production systems are usually concerned with converting inputs such as raw materials, manpower, and processes into products or services that satisfy customer needs. The production systems' primary outputs are finished products or services, and the secondary output is degraded or failed items. This secondary output generates demand for maintenance. (Duffua and Raouf, 2015)

Maintenance systems play a key role in achieving firms' missions, strategic objectives in industries, and profit targets (Saeed Osman, 2016). Maintenance systems are responsible for maintaining, repairing, and overhauling mechanical items for production departments. Maintenance departments are also responsible for keeping a healthy stock of repaired and new spare parts in the inventory. They must conduct timely procurement of new spare parts and timely repair of repairable items. The timely repair that a production system requires is essential for continuing operations and avoiding lost productions. Maintenance systems need to manage their spare items demand and supply effectively and efficiently and manage the on-hand inventory of repaired items.
Additionally, maintenance systems also take care of all faulty repairable items coming from production systems. The repairable items inventory management of a firm can be enhanced by overseeing its inventory level for both new and repaired items, the time required to undergo various processes involved in the procurement of new repairable items, and the repair of faulty repairable items.

Firms face problems of managing repairable items inventory levels and having the correct inventory levels of both repaired and new spare parts at a low cost. Firms also face problems deciding the best ordering policy considering the uncertainty of repairable item failure and repair times. (Saeed Osman, 2022)

This paper's primary focus is to address these problems by describing and developing a general simulation model for imitating the process of generating, processing, and repairing faulty repairable items. The model also mimics the procedures for requesting and procuring new repairable items using minimum/maximum inventory levels (s_{min}-S_{max}) ordering policy and managing both the on-hand inventory of repaired and new repairable items. The s_{min}-S_{max} policy is also a periodic strategy by which the inventory levels of repairable items in maintenance systems are checked every review period, which may also be every T days, weekly, or every T weeks. However, if the inventory level is below a specified value, an order is placed to bring the on-hand inventory to a preferred maximum level.

Nevertheless, as far as the author is aware, no published research has addressed these problems and proposed an approach that models the inventory of repairable items using an in-depth simulation model.

2. Literature Survey

We outline the literature directly related to this spare parts inventory, mainly the inventory simulation approaches adopted by previous research. Marco et al. (2007) adopted simulation for the engineering of spare parts management in multi-site contexts. They developed a simulation model-based decision support system, enabling decisions in spare parts management. Frazzon et al. (2013) proposed a simulation-based conceptual approach to analyze the operational planning of spare parts supply chain effectiveness. Rego and Mesquita (2015) presented results of a large-scale simulation study on automotive spare parts regarding demand forecasting and inventory control to select the best policies. Wakiru et al. (2019) proposed a discrete event simulation model framework for critical repairable subsystems experiencing deterioration, which uses empirical maintenance data to evaluate various maintenance and operational factors interaction effects on system optimization's total repair time.

Further results indicate that spares availability, the time between overhaul (TBO), and reliance on different maintenance strategies significantly impact total repair time. Modeling shared resources like technicians amongst several systems could suggest decision support concerning the same. Another limitation is that the case study considered only PM and CM policies while other maintenance and restorative strategies like condition monitoring, spare reconditioning, and reuse could be incorporated.

Frazzon et al. (2016) developed a simulation-based model to assess the performance improvements that resulted from the integration of intelligent maintenance systems and spare parts supply chain. The simulation-based model allows for preliminary verification of the benefits of hybrid methods in managing the spare parts supply chain. Sharma et al. (2017) presented a simulation-based genetic algorithm optimization approach for anticipating failures in the army equipment, hence for spare parts forecasting and selective maintenance. The methodologies developed will assist the army in increasing the equipment's reliability while keeping the costs associated with spare parts replenishment to the minimum.

Lee et al., (2008) has used a multi-objective simulation-based evolutionary algorithm framework to analyze the aircraft spare parts allocation problems.

Zahedi-Hosseini, Scarf, and Syntetos (2017) developed several joint simulation models for a complex system with multiple identical bearings by integrating simulation with an optimization tool to jointly optimize the planned maintenance inspection interval based on the delay-time concept and the spare parts inventory policy.

Lye and Yuan (2008) developed an exact model, which can be deployed for use in an airline's MRO inventory management. The authors stated that this simulation system allows an MRO operator to predetermine the optimum inventory level and placement.

Very few researchers have developed exact simulation models, which can be deployed for use in repairable items inventory management. (Lye et al., 2008), (Nie and Sheng, 2009), (Kilpi et al., 2008), Lendermann, et al., 2012), (Li et al., 2017).

3. Repairable Items Processing

The maintenance system manages the inventory system of repairable items that are used in production lines (PL). Such systems require repairable items to execute different work orders for preventive and corrective maintenance. Repairable items for preventive maintenance (PM) are replaced by new repairable items taken from the inventory of new repairable items. It is assumed that preventive maintenance must be carried out using only new items, whereas corrective maintenance would be carried out using either a repaired or new repairable items. It is also assumed that preventive maintenance items may be overhauled and reused for corrective maintenance. Therefore, some of the replaced repairable items may be repaired and added to the inventory of repaired items depending on particular operational conditions.

Moreover, repairable items for corrective maintenance (CM) are replaced by either repaired items taken from the inventory of repaired items or new repairable items taken from the inventory of new repairable items. Depending on the repairability of items, faulty CM and PM items can either be repaired or discarded if not repairable. The flow chart given in Figure 1 shows the procedure of processing and managing the inventory of repairable items using maximum/minimum reordering policy.

Figure 1 shows that the repairable items arriving from production lines are inspected and sorted into PM and CM items based on whether the work order requires the repairable item for preventive maintenance or corrective maintenance. For PM, a new item is taken from the inventory of new repairable items. Concurrently, the faulty repairable item is checked for overhauling; if the faulty item is unoverhaulable, it will be discarded; otherwise, it is repaired and added to the inventory of repaired items.

As for CM, the faulty repairable item is checked to decide on its reparability. If the faulty item is unrepairable, it would be discarded and then either replaced by an item from the repaired item inventory (*if any available*), or a new repairable item would be requested and ordered. If the faulty item is repairable, one of the following three actions would be taken (1) replaced by an item from the inventory of repaired items and then repaired and added to the inventory of repaired items. (2) repaired and reused if there is no on-hand inventory of the repaired items, and its repair time is shorter than the lead time. (3) replaced by a new repairable item and then repaired and added to the inventory of repaired items if there is no on-hand inventory of the repaired items, and its repair time is longer than the lead time.

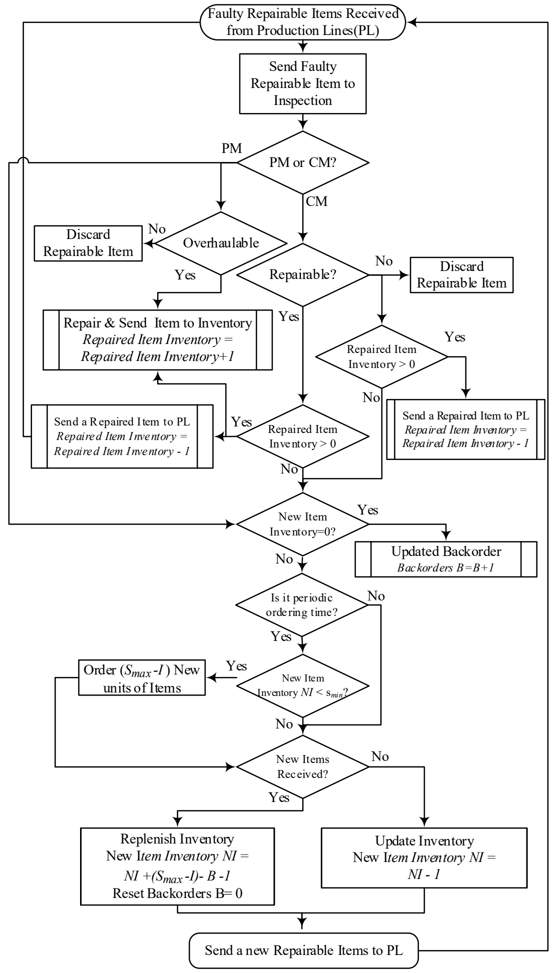

Figure 1. Flowchart of Processing Repairable Item

Moreover, orders are placed based on the minimum/maximum (s_{min}-S_{max}) ordering policy. The lot sizes are determined to bring the inventory of new repairable items, when it falls below the minimum inventory level s_{min}, up to maximum inventory level S_{max} by the end of a fixed review interval.

4. Proposed Approach – Heuristic-Based Simulation Model

We developed a simulation model to imitate the inventory of repairable items with the s_{min}-S_{max} ordering policy. The model consists of seven submodels: (1) production lines as input source; (2) sorting and processing repairable items; (3) repair shop and inventory of repaired items; (4) inventory of repaired items; (5) discarding unoverhaulable and unrepairable items. (6) processing of the requests for new repairable items; (7) backordering repairable items; (8) s_{min}-S_{max} ordering of new repairable items; and (9) inventory of new repairable items. We introduce the key parameters that are required for modeling the repairable items inventory system in Table 1, while the pseudo-code of the proposed model is given in Figure 2.

The first submodel is developed to mimic the production lines from which faulty repairable items arrive. This submodel represents the model input source that randomly creates CM faulty items based on a given probability distribution; it also generates PM faulty items based on a predetermined maintenance plan. A set of attributes such as operating hours, number of repairs, max operating hours, max number of repairs, repair time, lead time, arrive time, etc. is assigned to individual PM and CM faulty repairable items using given probability distributions.

Table 1. Model Key Parameters

Symbol	Description	Type
IAT	Inter-arrival Time	Constant
NOHI	On–hand inventory of new Repairable items	Variable
ROHI	On-hand inventory of repaired Repairable items	Variable
BOI	No of backordered repairable items at time t	Variable
LT	Lead time	Attribute
RT	Repair time	Attribute
MT	Maintenance type	Attribute
RIT	Repairable item type	Attribute

Symbol	Description	Type
OV	Overhaul-ability	Attribute
RE	Repair-ability	Attribute
DT	Downtime/Backordering Time	Variable
AT	Arrive Time	Attribute
TNOW	Current Time	Variable
NOC	Number of Clones	Attribute
NDI	No of Discarded Items	Variable

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- SUBMODEL I
    CREATE PM faulty repairable items    IAT=……;
        ASSIGN
        MT=1; RIT=1; OV=0or1; RT=……; LT=…
        END ASSIGN
    GO TO LABEL: Processing PM faulty Items

    CREATE CM faulty repairable      IAT=………;
        ASSIGN
        MT=1; RIT=1; OV=0or1; RT=……; LT=….
        END ASSIGN
    GO TO LABEL: Processing CM faulty Items
- SUBMODEL II
    LABEL: Processing PM faulty Items
    SIGNAL: Signal Value =1 //to send items to PL
        DECIDE
         IF OV=1 THEN
          GO TO LABEL: Repair
         ELSE
          GO TO LABEL: Discard
         END IF
    END DECIDE
    LABEL: Processing CM faulty Items
     DECIDE
         IF RE=1 THEN
           DECIDE
              IF NQ(ROHI.Queue) > 0  THEN
                SIGNAL Signal Value =1
           ELSE
              CLONE NOC = 1 Send clone to
             LABEL: Request New Item
           END CLONE
                   END IF
       END DECIDE
                   GO TO LABEL: Repair
          ELSE
                   GO TO LABEL: Discard
          END IF
- SUBMODEL III
    LABEL: Repair
    PROCESS Delay Value = RT
        GO TO LABEL: Repaired Items Inventory

- SUBMODEL IV
    LABEL: Repaired Items Inventory
     DECIDE
      IF RIT = i THEN
       HOLD Repaired Item queue:
          wait for   signal value = 2
            IF signal value = 2
          Then release one repaired item
        END HOLD
       END IF
     END DECIDE
    DISPOSE: Send Repaired Item to PL

- SUBMODEL V
    LABEL: Discard
      RECORD NDI = NDI + 1
    DISPOSE
- SUBMODEL VI
    LABEL: Request New Items
     DECIDE
      IF NOHI=0 THEN
            GO TO LABEL:
                   Backordered Items
      ELSE IF NOHI_i< s_i AND T=PRT
        CLONE NOC=1 Release Item
        END CLONE
        GO TO LABEL:
                  Ordering New Item
      ELSE
            GO TO LABEL:
                   Release New Item
- SUBMODEL VII
    LABEL: Backordered Items
     RECORD BOI = BOI + 1
      ASSIGN
      NBI = NBI + 1
      AT = TNOW
      END ASSIGN
    DECIDE
      IF RIT = i THEN
       HOLD Backordered PM Item queue
            IF NOHI > 0 Then
        satisfy PM item requests from queue
       END HOLD

        ELSE
      HOLD Backordered CM Item queue:
           IF NOHI > 0 OR ROHI > 0 Then
       satisfy CM item requests from queue
      END HOLD
     END IF
    END DECIDE
     RECORD DT = TNOW - AT
      DECIDE
       IF NOHI > 0 THEN
        CLONE NOC = 1 Send clone to
         LABEL: Release New Item
        END CLONE
       ELSE
        SIGNAL signal value = 2
      END DECIDE
       DISPOSE close backorder request
- SUBMODEL VIII
    CREATE Periodic Review of  Inventory
     LABEL: Ordering New Repairable Items
      RECORD NO = NO + 1
       DELAY Place a new order Delay value = OPT
       DELAY Lead Time Delay
           Delay value = LT
       CLONE # of Clones = S_max-NOHI
          Clone destination
              LABEL: Receiving New Items
       END CLONE
     DISPOSE: Order is received and processed

- SUBMODEL IX
    CREATE Initiate Inventory of items
       IAT = M;  RIT = ......;
    GO TO LABEL: Receiving New Items
    LABEL: Receiving New Item Requests
       SIGNAL : Signal Value = #
    DISPOSE: Close New Item Requests
    LABEL: Receiving New Items
       HOLD New Items queue:
          wait for signal value = #
              IF signal value = #
          Then release one new item
       END HOLD
    DISPOSE: Send New Repairable Item to PL
```

Figure 2. Simulation Model Pseudo-Code

The second submodel is used for sorting and processing PM and CM faculty repairable items. PM faulty items are processed by sending a new repairable item to production lines, and then the faulty item is sent to the repair shop if it can be overhauled. Otherwise, it is sent to discard. The submodel also imitates the procedure of processing CM faulty items, as shown in Exhibits 1. Depending on the CM faulty items' repairability, it is routed to the repair shop or discard station. Also, depending on the availability of repaired items and the faulty item's repair time, a repaired or new repairable item is sent to production lines.

The repair shop and inventory of repaired items submodel given in Exhibit I imitates the process of repairing or overhauling the faulty items based on the repair time attribute assigned to individual items in the first submodel. Those repaired items are either sent back to the production lines or added to the inventory of repaired items if the production line has already received a replacement. Moreover, the fifth submodel is used to record the discarded repairable items.

The sixth submodel is for processing the requests for ordering new repairable items if a faculty item is not repairable or the repair time is taking longer than the lead time. The seventh submodel mimics the backorders of repairable items accumulated and held in a queue to be fulfilled upon the arrival of replenishment orders. This submodel also counts the backordered items and records the unavailability or downtime of individual items.

The order size is developed in the eighth submodel, where a single order is placed periodically by the end of a given time interval. Using the s_{min}-S_{max} ordering policy, the on-hand inventory of new repairable items must be checked against the minimum on-hand inventory s_{min}. Suppose the on-hand inventory falls below a specified minimum level smin at a periodic review time. In that case, a requisition for a new replenishment order is processed to bring the on-hand inventory up to a specified maximum level S_{max}. This submodel mimics the lead time required to receive the new repairable items in new items' inventory. The last submodel is developed for imitating the events of receiving and processing the requests for new repairable items.

5. Illustrative Example

For illustrating the proposed simulation model, production lines with one type of faulty repairable items is considered. The input parameters used for this example are given in Table 2.

Table 2. Simulation Mode Attributes and Parameters

Attributes and Parameter	**CM**	**PM**
Interarrival Time (*hours*)	*Exponential*(3)	8 (*2 item*)
Probability of Repair/overhaul	60%	10%
Repair/Overhaul Time (*days*)	*Uniform*(1,4)	*Uniform*(2,6)

The lead time to receive an order is assumed to be triangularly distributed with 5, 7, and 10 working days as min, mode, and max, respectively. It is assumed that the repair shop operates two 8-hour shifts a day, 5 days a week, with one technician.

As initiation stage, we run the proposed submodel for 7 working days for estimating the demand over the average lead-time for the repairable items, which is found to be 76 faulty items. We set the maximum in inventory level S_{max} at 429. We ran the model for the whole year (261 working days). For the periodic reviews of the on-hand inventory using the s_{min}-S_{max} ordering policy, we conducted scenario-based experiments using the proposed model with on-hand inventory reviews that are performed every 1, 3, 5, 7, 10, 12, 15, and 20 days. The maximum on-hand inventory, number of orders, number of backordered items, and unavailability are given in Table 3, and the sensitivity graph for these measures of performance with respect to changing the review periods is shown in Figure 2. The unavailability of a repairable item is measured from the time a backordered item is created to the time a repaired or new item is sent to the production line.

Table 3. Summaries of Simulation Model Outputs

Review Period	Max on-hand Inventory		Max No. of Orders	Max No. of Backordered Items	Max Unavailability (*hours*)
	New	Repaired			
1 day	189.44	0.12	7	62	16.26
3 days	185.85	0.13	7	90	22.81
5 days	180.98	0.14	7	149	37.20
7 days	177.30	0.13	6	219	41.28
10 days	178.40	0.13	7	313	64.63
12 days	167.56	0.12	6	428	77.92
15 days	166.47	0.10	6	346	55.74
20 days	175.45	0.11	7	569	106.73

The proposed model is implemented in Arena simulation software. The system used to solve the Arena simulation models for the illustrative case is HP laptop using Windows 10 and MAD Ryzen 5 with 2.1 GHz processor, 8 GB of RAM. The number of replications in the Arena simulation software is set at ten replications.

In this graph shown in Figure 3 we can see that changes in the review period have a major effect on the number of backordered items and unavailability/downtime and a minor effect on the on-hand inventories and number of placed orders.

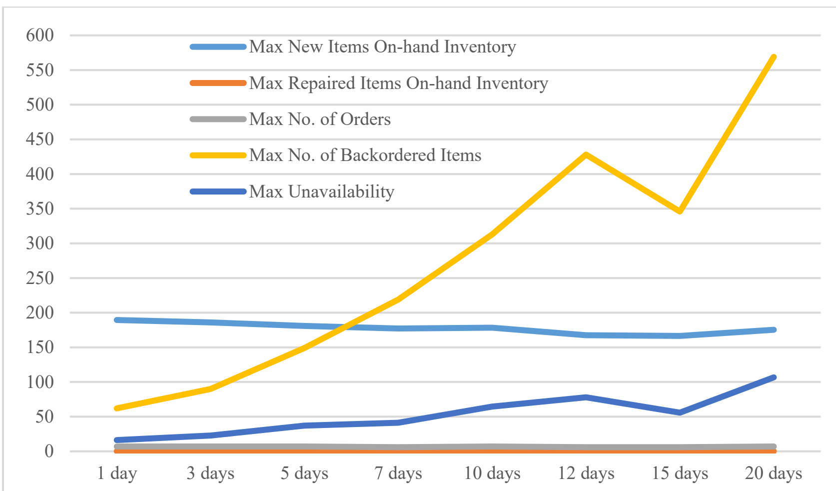

Figure 3. Sensitivity Graph – Illustrative Example

The results given in Table 3 and graphed in Figure 3 are valuable managerial insights provided into the complex inventory system of repairable items. These managerial insights are extremely important for achieving maintenance, repair, and overhaul organization's objectives, such as minimizing unavailability and backordered items, minimizing inventory costs, and maximizing service levels.

6. Conclusions

Simulation modeling has become a promising method for investigating real-world processes. This paper described the development of a simulation model. The proposed model's objective is to investigate the utilization of the maximum/minimum inventory level strategy for ordering new repairable items in a flexible and risk-free manner.

We presented a case problem of inventory of repairable items to exemplify the proposed simulation model's applicability and suitability. The key outcomes are the valuable model for maximum/minimum ordering policy, as just building a simulation model into the complex inventory system of repairable items is instructive regardless of results. The proposed model provided promising managerial insights about maximum/minimum ordering policy that would further be compared with other ordering strategies as a future study. These managerial insights are vital for achieving organizations' objectives, such as minimizing inventory costs and maximizing service levels.

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