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Article

Blockchain Design with Optimal Maintenance Planning

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Abstract: Rapid advancement of data management and sharing technology has urged organizations to develop effective maintenance management systems. This research, therefore, proposes and implements an Electronic Repair Records (ERR) system for the blockchain of maintenance planning and management. In ERR, this research develops two optimization models for scheduling and sequencing failure repairs from different types over multiple periods. Each failure repair is treated as a block, for which the data, current hash, and previous hash are obtained from failure repair parameters, resources availability information, and the optimal values of the start and finish times of the assigned failure repairs. The scheduling model assigns failure repairs to technicians and in maintenance shops on each scheduling period at a minimal total cost of delay, undertime, and overtime costs, while the sequencing model sequences the assigned failure repairs at minimal total overtime costs and minimum total repair start times. Once the blocks are confirmed, the blockchain is then shared through an electronic network among all maintenance departments. The developed ERR system was implemented to manage the repairs of 36 failures from different failures in six maintenance shops over a period of three days. The results showed that this system is found to be effective in managing optimal repairs and efficient in improving the utilization of available resources in maintenance shops. These advantages may result in significant savings in maintenance costs and better utilization of resources. In conclusion, the developed ERR system including the optimization models can provide in real-time assistance and de-centralized technology to planning engineers when managing maintenance activities over multiple periods in a wide range of business applications.

Keywords: maintenance; blockchain; failure repairs; electronic repair record; scheduling; sequencing

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1. Introduction

Effective data management and sharing are vital elements for the efficient running of business applications and to provide analytical information that helps drive operational decision-making and strategic planning by business managers and other end users. An effective technology for this purpose is the adoption of the blockchain, which might result in profound tangible impacts on planning business operations. The blockchain is defined as the decentralized technology that is applied to register, confirm, allocate, and transfer all manner of data [1,2]. It gives the opportunity for a traceability aid, records management, and other business applications [3]. In technology circles, it is used as a permanent distributed directory to record all value activities. Each node participating in the activity would have access to the ledger from multiple devices. Participants can initially review all activities connected to the blockchain [4]. On any distributed database, each element is called a block [5–7]. The structure of the block, as shown in Figure 1, is mainly composed of five components: the data maintained in the distributed database blocks; the current hash which is functions and values that meet the demands needed to solve for the current block computations; the previous hash which is values that are used to chain the blocks; Timestamp which is all time events for each block starting from when the block is added to the chain; and finally, other information that consists of the used tools and software with the complexity level. The blocks are then connected as shown in Figure 2 to ensure synchronization between blocks and avoid separating any individual block from the other blocks [8–11].

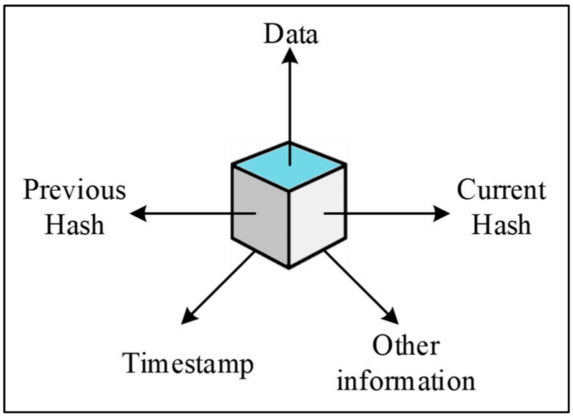

Figure 1. Individual block with its main components.

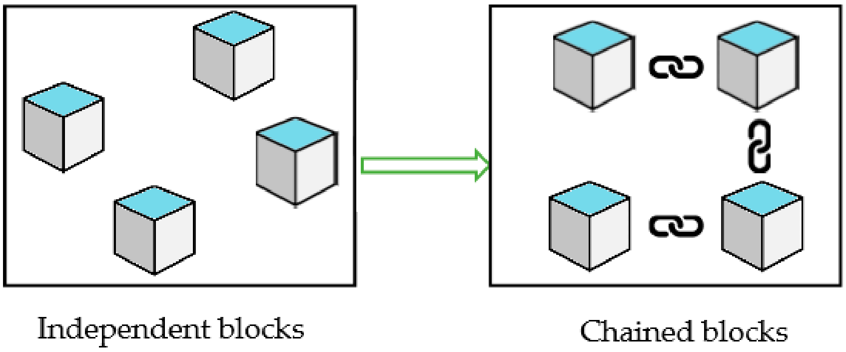

Figure 2. Chaining blocks.

The adoption of the blockchain has been implemented in many business applications, including: banking industry [12], technology in transportation in Industry 4.0 strategy [13], supply chain traceability [14], agri-food value chain management [15], electronic healthcare [16], the Australian carbon market [17], and construction projects [18–21].

Further, the vast development of data management and sharing technology has urged a real need to develop an effective approach for managing maintenance activities. In addition, maintenance activities play a critical role in increasing productivity but through consuming costly and limited resources, including repair time, skilled staff, equipment, and spare parts. Moreover, the increasing complexity of maintenance activities challenges maintenance engineers to constantly strive for cutting incurred maintenance costs through effective activities planning [22–25]. An emerging challenge to maintenance engineers is to schedule and sequence maintenance activities at minimum maintenance costs while maximizing resource utilization. Significant research efforts, therefore, have been devoted to developing optimization models or heuristics for scheduling and sequencing activities of interest in a wide range of applications [26–30]. For example, El-Sharkh and El-Keib [31] formulated a fuzzy model for integrated generation and transmission maintenance scheduling problems under uncertainties. The model was tested on the IEEE 118-bus system with 33 generating units and 179 transmission lines. Ruiz et al. [32] proposed a simple criterion to schedule preventive maintenance operations into the production sequence. The objective function of the optimization criterion is minimizing the makespan of the sequence using six adaptations of existing heuristic and metaheuristic methods to a set of 7200 instances. The results revealed that the modern Ant Colony and Genetic Algorithms provide very effective solutions for dealing with the scheduling and sequencing of maintenance operations. Squires and Hoffman [33] considered an operating military optimization problem by formulating and implementing complementary models to full-sized instances using the sliding windows formulation. The objective was minimizing the cost of assigning all items to a set of facilities and maximizing the number of scheduled jobs considering their tardiness budget. Xiao et al. [34] developed an optimization model connecting preventive maintenance with production scheduling using a genetic algorithm. The objective to minimize the total cost, which consisted of production cost, preventive maintenance cost, minimal repair cost, and tardiness cost was the main target. Irawan et al. [35] developed a mixed-integer linear optimization model based on the Dantzig–Wolfe decomposition method for maintenance scheduling in offshore wind farms. The objective functions were to minimize maintenance costs, including travel, technician, and penalty cost. Then, the model determines the optimal schedule for maintaining the turbines and the optimal routes for the crew transfer vessels to service the turbines along with the number of technicians required for each vessel. Liao et al. [36] developed a single-machine-based integration model based on a genetic algorithm to meet the requirements of production scheduling and preventive maintenance in group production. Minimizing total completion time and maintenance costs were the main objective functions. Gholami and Hafezalkotob [37] used a combination of data mining techniques and time series models to schedule maintenance activities. A real database was considered that included failures and values of factors degrading the pump at the time of failure. A clustering algorithm was used to categorize failures based on the similarity in the types of maintenance activities. Then, rules were extracted for characterizing the clusters. Finally, time series models were used to predict the time period for each factor. Kiefer et al. [38] presented a strategic mixed-integer programming model for scheduling maintenance measures for the infrastructure of transportation systems. Minimization of the sum of maintenance costs, cost of extra trams, cost of busses, and penalty cost was the main objective function. Alayo and Paucar [39] developed a mixed-integer linear optimization model for maintenance scheduling in a transmission company. The objective function included minimizing equipment unavailability due to maintenance activities. Finally, the model was applied to the Peruvian system. Su and Schutter [40] determined an optimal time schedule for the maintenance activities and optimal routes for the maintenance crew for the railway in the Dutch regional network. The objective function was to minimize the total setup costs and the travel costs over the whole planning horizon. The track maintenance scheduling problem with three variants of the Capacitated Arc Routing Problem with a fixed cost was solved by transforming them into three node routing problems. Samadi et al. [41] proposed an Inspection-Based Maintenance model for yearlong transmission equipment maintenance scheduling. The probability distribution of the deterioration condition was estimated using the transition probability matrix of the Markov process. The optimal inspection time of equipment was obtained by minimizing the total cost, including inspection, maintenance, and failure costs. Maintenance of transformers and transmission lines in IEEE-RTS and IEEE 57-bus test systems were used for illustration of the proposed model. Chansombat et al. [42] developed a mixed-integer linear model for simultaneously optimizing the integrated production and preventive maintenance scheduling in the capital goods industry. The objective function was to minimize total costs involving the following: penalty and holding costs; preventive maintenance costs; and production idle time costs. Yeardley et al. [43] utilized machine learning to predict both machine faults and repair time and used their data to underpin the scheduling of maintenance activities. The proposed methodology was used to plan maintenance and optimize the schedule with a cost objective within the constraints of labor availability and plant layout. A dataset was obtained using a simulated Fischertechnik (FT) model. Results showed that the overall plant maintenance costs were reduced by decreasing unplanned downtimes and increasing maintenance efficiency. Hu et al. [44] proposed a linear programming-enhanced rollout model for constrained deterministic and stochastic maintenance scheduling with an infinite horizon. The maintenance optimization under uncertainties was treated as a Markov Decision Process problem and then solved by a modified Reinforcement Learning method. Chou and Yu [45] developed a mathematical model to determine the optimal individual maintenance schedule and group maintenance schedule for various components. The optimal maintenance schedule was designed to maximize cost-effectiveness while minimizing environmental and safety risks. Fuzzy probabilities were employed to assess the environmental and safety risks. Urbani et al. [46] formulated mathematical scheduling and sequencing models for maintenance repairs for bi-objective maintenance scheduling on a networked system with limited availability of maintenance personnel. Also, they proposed an algorithm that is a good approximation of the Pareto front in terms of costs and productivity was adopted to determine a set of maintenance schedules. Consequently, this research aims at developing mathematical models for scheduling and sequencing maintenance activities including failure repairs from different types over multiple periods that minimize the total cost of delay, undertime and overtime costs, and minimum total repair start times. However, little research has been reported on blockchain adoption with information that is obtained by optimal scheduling and sequencing of maintenance activities and employed to define the components of the blocks.

In practice, the increasing complexity and variety of maintenance activities have challenged decision-makers to adopt effective management systems that enable them to manage maintenance plans effectively at minimal maintenance costs and maximal utilization of maintenance resources. In these regards, this research contributes to ongoing research by developing a framework for the adoption of an Electronic Repair Record (ERR) for maintenance management and planning. The blockchain framework involves the development of mathematical models that aim at optimal scheduling and sequencing of maintenance activities from different categories over multiple periods. The ERR system allows effective and secure information management and sharing directly to maintenance engineers and relevant participants. The proposed blockchain framework can be applied to obtain optimal maintenance plans in various business applications. The remainder of this paper, including the introduction, is outlined in the following sequence. Section 2 develops the ERR system. Section 3 illustrates the ERR in a real case study. Section 4 presents the research results. Section 5 summarizes the conclusions.

2. Development of the ERR System

The proposed ERR system for maintenance planning is depicted in Figure 3 and described as follows:

Step 1: Assume several orders of failure repairs from different categories (mechanical, electrical, and others) are received via an electronic system or a cloud-based system, where each failure repair has been assigned a specific due date for repair. These failures are analyzed and then summarized in a maintenance management system (MMS). In this research, each failure is treated as a block. Based on the existing database in MMS and technical knowledge, the following data are filled in regarding each block, including the sending department, failure type, repair due date, repair duration, repair dependency, failure severity, required technician skills, and key resources of the time horizon. The blocks are accessed by the maintenance planning engineers to determine the current block and previous hashes through scheduling and sequencing modelling. Hence, two mathematical models are formulated under stochastic repair durations.

Step 2: The scheduling model aims to assign suitable available resources to failure repairs at minimum maintenance costs via cloud computing. The results of this step include the assigned repair technician, maintenance shop, and day of repair. Assume that a maintenance shop consists of W technician crew ($w = 1, \ldots, W$), E equipment ($e = 1, \ldots, E$), F failures ($f = 1, \ldots, F$), and S shops ($s = 1, \ldots, S$), as illustrated in Figure 4. Let y_{fst} be a binary decision variable that determines which shop s will be assigned to the repair failure f on which day t; where y_{fst} equals 1 if failure f is assigned to shop s on day t; otherwise, y_{fst} equals 0. The scheduling model determines the optimal y_{fst} values, total cost along with overtime hours, O_{st}, and idle time hours, I_{st}, for shop s on day t. The objective function of the scheduling model is to minimize the total of associated costs in all repair shops; delay costs, in which the waiting time for the failure repair is calculated as the time between the arriving date, DA_f, and scheduled repair time t.

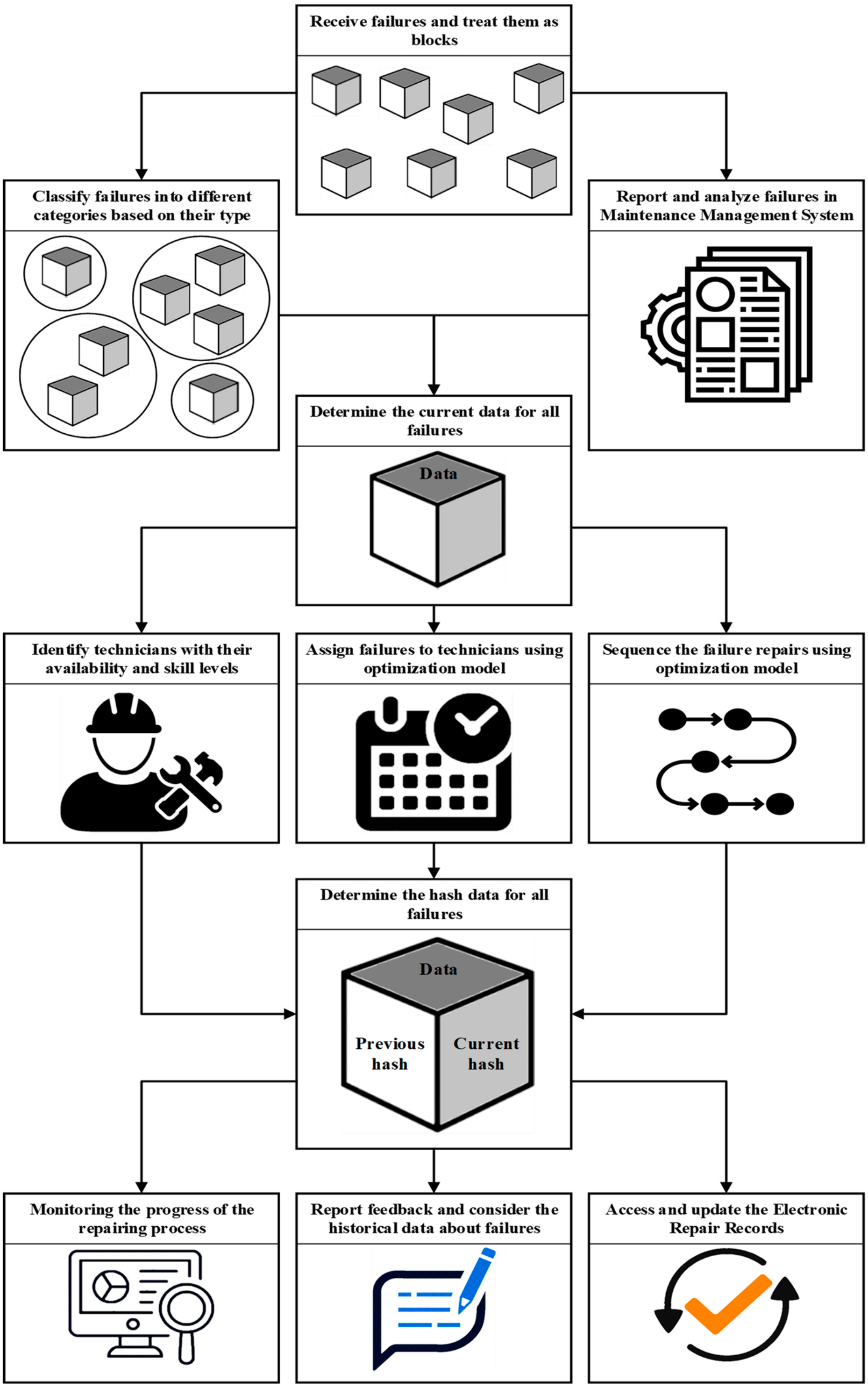

Figure 3. The life cycle of the ERR system.

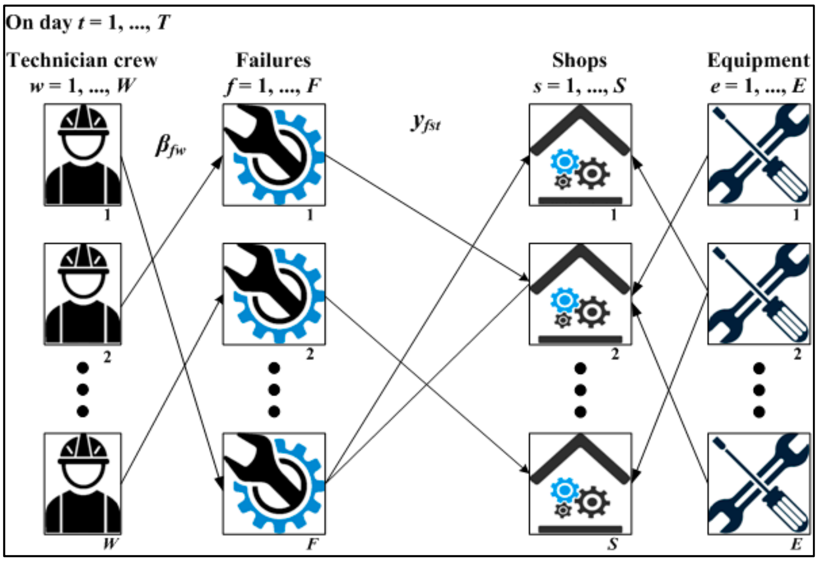

Figure 4. Illustration of shops scheduling for multiple periods.

Let Cd and DA_f denote the total delay cost per day and the arriving date of failure f, respectively. When a failure repair is assigned (y_{fst} = 1) within the scheduling period T, the total of delay costs, $Cdtot^{(1)}$, for F scheduled failure repairs in S shops over T period is then expressed mathematically as:

$$Cdtot^{(1)} = \sum_{t=1}^{T}\sum_{s=1}^{S}\sum_{f=1}^{F} y_{fst}\left(t - DA_f\right) \cdot Cd,\ \forall y_{fst} = 1 \tag{1}$$

However, when the repair of failure f is not scheduled (y_{fst} = 0) during the scheduling period T, the waiting or delay time of the failure repair in this period is calculated as the time between the failure arriving date, DA_f, and its repair due date, $Ddue_f$, as also illustrated in Figure 5.

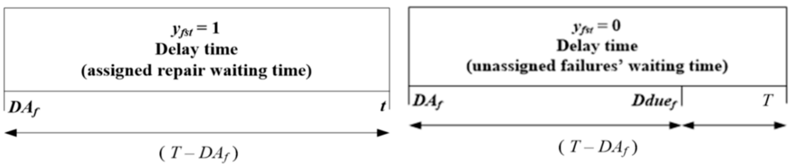

Figure 5. Illustration of delay time calculation.

Then, the total of delay cost for all unscheduled failure repairs, $Cdtot^{(2)}$, is formulated as:

$$Cdtot^{(2)} = \sum_{f=1}^{F}\left(1 - \sum_{t=1}^{T}\sum_{s=1}^{S} y_{fst}\right) \cdot \left(T - DA_f\right) \cdot Cd,\ \forall y_{fst} = 0 \tag{2}$$

Let Ci denote the idle time cost per hour and I_{st} denote the idle time of shop s on day t (in hours). Idle time cost represents the cost of unutilized time of the regular hours in all MD shops. Then, the total idle time cost, $Citot$, for S shops over T period is expressed mathematically as follows:

$$Citot = \sum_{t=1}^{T}\sum_{s=1}^{S}\left(I_{st} \cdot Ci\right), \tag{3}$$

Let Co denote the overtime cost per hour and O_{st} denote the overtime of shops on day t. Overtime costs represent the cost of work performed after regular hours of all MD shops. Then, the total overtime cost, $Cotot$, in S shops over T period, is expressed in Equation (4).

$$Cotot = \sum_{t=1}^{T}\sum_{s=1}^{S}(O_{st} \cdot Co), \tag{4}$$

Finally, the objective function of Model I is written as:

$$\begin{aligned}
&Min \sum_{t=1}^{T}\sum_{s=1}^{S}\sum_{f=1}^{F} y_{fst}\left(t - DA_f\right) \cdot Cd + [\text{Total of delay cost for all scheduled failures}]\\
&\sum_{f=1}^{F}\left(1 - \sum_{t=1}^{T}\sum_{s=1}^{S} y_{fst}\right) \cdot \left(T - DA_f\right) \cdot Cd + [\text{Total of delay cost for all unscheduled failure}]\\
&\sum_{t=1}^{T}\sum_{s=1}^{S}(I_{st} \cdot Ci) + \sum_{t=1}^{T}\sum_{s=1}^{S}(O_{st} \cdot Co),\ [\text{Total idle time and overtime cost for shops}]
\end{aligned} \tag{5}$$

where

$$I_{st} = \alpha_{st}\left(N_{st} - \sum_{f=1}^{F} y_{fst} \cdot Dtot_f\right), \quad \forall s, t \tag{6}$$

$$I_{st} \geq 0, \quad \forall s, t \tag{7}$$

Further, the objective function is subjected to the following constraints:

1. For shop s on day t, the idle time, I_{st}, t is always positive and equal to the difference between regular time hours and the summation of the duration of all performed repairs. Let N_{st} denote the regular time of shop s on day t (hours) and α_{st} specifies whether shop s is working on day t or not. The total duration of repair, $Dtot_f$, is the time reserved for a given repair procedure, including the time required for setup, $dset_f$, repairing, $dreps_f$, and changeover, dch_f.
2. Then, the overtime, O_{st}, for shop s on day t is always positive and equal to the summation of the duration of repairs of F failures performed outside regular hours of that shop, or mathematically:

$$O_{st} = \alpha_{st}\left(\sum_{f=1}^{F} y_{fst} \cdot Dtot_f - N_{st}\right), \quad \forall s, t \tag{8}$$

$$O_{st} \geq 0, \quad \forall s, t \tag{9}$$

3. The total of repair durations of F failures on day t in shop s can exceed regular hours by the maximum allowed overtime for this shop on day t. Let Z_{st} denote the maximum overtime allowed in shop s on day t. Then, the overtime repair duration must not exceed Z_{st}, as expressed in Equation (10).

$$\sum_{f=1}^{F}\left(y_{fst} \cdot Dtot_f\right) - N_{st} \leq Z_{st}, \quad \forall s, t \tag{10}$$

4. Let λ_{wt} and β_{fw} be binary variables that identify whether technician crew w is available on day t and the repair assignment of failure f to technician crew w, respectively. It should be emphasized that the repair assignment of failure f to technician crew w depends on this failure's category and skill level of this crew. In addition, the total repair duration of F failures in S shops by the technician crew w on day t should not exceed the maximum working time, G_{wt}, on this day. Mathematically,

$$\sum_{f=1}^{F}\sum_{s=1}^{S} y_{fst} \cdot Dtot_f \cdot \beta_{fw} \cdot \lambda_{wt} \leq G_{wt}, \quad \forall w, t \tag{11}$$

5. Let the binary variable, τ_{fst}, denote the availability of the needed equipment to repair failure f in shop s on day t. To assign a failure repair to shop s on day t, shop s, skilled crew w, and equipment should be available, and their assignment should be applicable as expressed in Equation (12):

$$y_{fst} \leq \alpha_{st} \cdot \tau_{fst} \cdot \sum_{w=1}^{W} \left(\beta_{fw} \cdot \lambda_{wt} \right), \quad \forall s,\ f,\ t \tag{12}$$

6. The failure's repair due date, $Ddue_f$, should be respected and a failure repair should be assigned at most once in S shops, or

$$\sum_{t=1}^{T} \sum_{s=1}^{S} y_{fst} \leq 1, \ \ \forall f | t \geq DA_f \tag{13}$$

$$\sum_{t=1}^{T} \sum_{s=1}^{S} y_{fst} = 0, \quad \forall f | t < DA_f \tag{14}$$

7. Integrality of the variables should be assured by introducing Equation (15):

$$y_{fst}, \tau_{fst}, \lambda_{wt}, \beta_{fw}, \alpha_{st} \in \{0, 1\} \tag{15}$$

8. Failure repairs are assigned based on the duration of a failure's repair as well as a failure's severity and seriousness. A failure that requires a repair duration of less than or equal to a half hour will be assigned first in shop s, as given by Equation (16).

$$\sum_{t=1}^{T} \sum_{s=1}^{S} y_{fst} = 1, \quad \forall f \in [1, \ldots, F] | Dtot_f \leq 0.5 \ \& \ t \geq DA_f \tag{16}$$

9. Let RPN_f denote the risk priority number of failure f, which indicates the failure's severity and seriousness. Then, the repair of a failure with RPN_f is equal to or greater than the selected criteria of the failure severity and seriousness, CRT, shall be assigned only once in shop s, as stated in Equations (17) and (18).

$$\sum_{t=1}^{T} \sum_{s=1}^{S} y_{fst} = 1, \quad \forall f \in [1, \ldots, F] | RPN_f > CRT \ \& \ t \geq DA_f \tag{17}$$

$$\sum_{t=1}^{T} \sum_{s=1}^{S} y_{fst} = 0, \quad \forall f \in [1, \ldots, F] | RPN_f > CRT \ \& \ t < DA_f \tag{18}$$

10. However, if the risk priority number of failure f, RPN_f, is less than CRT, then it should be postponed to the next scheduling period, T_2, and assigned once at most in shop s, as expressed in Equations (19) and (20).

$$\sum_{t=1}^{T} \sum_{s=1}^{S} y_{fst} \leq 1, \quad \forall f \in [1, \ldots, F] | RPN_f \leq CRT \ \& \ t \geq DA_f \tag{19}$$

$$\sum_{t=1}^{T} \sum_{s=1}^{S} y_{fst} \leq 0, \quad \forall f \in [1, \ldots, F] | RPN_f \leq CRT \ \& \ t < DA_f \tag{20}$$

The obtained optimal scheduling results are finally attached to blocks, as depicted in Figure 6.

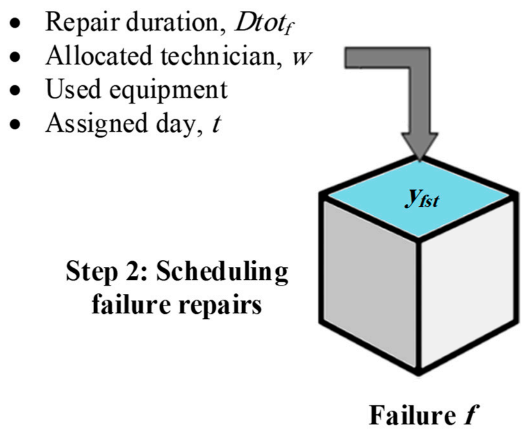

Figure 6. The stored data in each block after step 2.

Step 3: The sequencing optimization model is formulated to obtain the start times of failure repairs and then the optimal results are stored in their corresponding blocks. The sequencing model aims to minimize the sum of the total overtime, O_{st}, in all S shops over the scheduling period T and the total of repairs' start times, sts_f, of all F failures. That is,

$$Min \sum_{t=1}^{T} \sum_{s=1}^{S} O_{st} + \sum_{f=1}^{F} sts_f \text{ [Total overtime of all shops]} \tag{21}$$

The objective function is subject to the following constraints:

1. The closing time, L_{st}, for shop s on day t cannot be before the completion of regular hours, N_{st}, and the maximum allowed overtime is Z_{st}, as illustrated in Figure 7, where the closing time, L_{st}, constraints are expressed mathematically as follows:

$$\begin{aligned} L_{st} \cdot y_{fst} &= 9y_{fst} \mid \max\left\{sts_f + Dtot_f\right\} \cdot y_{fst} > 8; \quad \forall f,\ s,\ t \\ L_{st} \cdot y_{fst} &= 8y_{fst} \mid \max\left\{sts_f + Dtot_f\right\} \cdot y_{fst} \le 8; \quad \forall f,\ s,\ t \end{aligned} \tag{22}$$

$$L_{st} \ge N_{st}, \quad \forall s,\ t \tag{23}$$

$$L_{st} - N_{st} \le Z_{st}, \quad \forall s,\ t \tag{24}$$

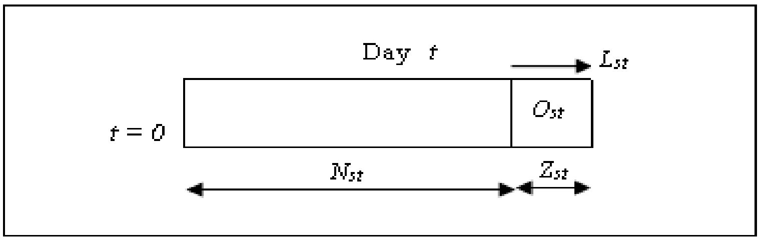

Figure 7. Illustration of closing time for shop s.

The completion time of failure repair, tcs_f, should be equal to the summation of the repair start time, sts_f, setup time, $dset_f$, repair duration, $dreps_f$, and changeover time, dch_f, for each failure repair in shop s on day t, as illustrated in Figure 8. Consequently, the tcs_f is expressed mathematically as follows:

$$tcs_f = sts_f + Dtot_f, \quad \forall f$$

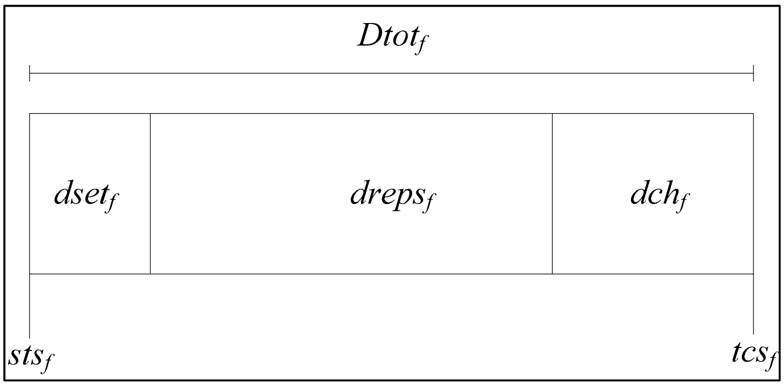

Figure 8. Illustration of related times of failure f.

2. Let OP_t denote the time of the shop opening on day t. Then, the overtime, O_{st}, of shop s on day t is the difference between the closing time, Ls_t, and regular hours, N_{st}, as illustrated in Figure 9 and expressed in Equation (25).

$$O_{st} \geq L_{st} - (N_{st} + OP_t), \quad \forall s,\ t \tag{25}$$

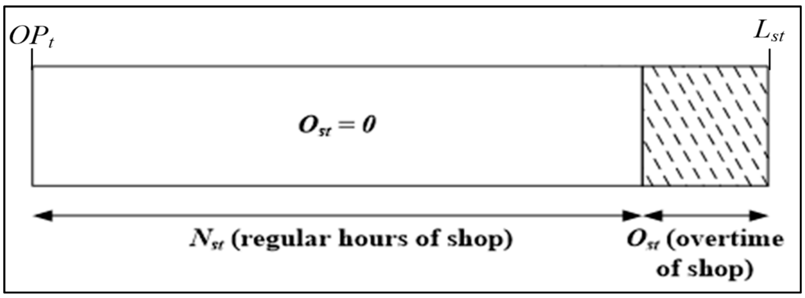

Figure 9. Illustration of overtime in shop s.

Furthermore, the overtime of each shop on each day t, O_{st}, should always be positive, as formulated in Equation (26).

$$O_{st} \geq 0, \quad \forall s,\ t \tag{26}$$

3. The overtime, O_{st}, for shop s on day t should not exceed the maximum overtime of that shop, Z_{st}. That is,

$$O_{st} \leq Z_{st}, \quad \forall s,\ t \tag{27}$$

4. All repairs should be performed after the opening of the shop, OP_t. Then, all failure repairs start times, sts_f, should begin after shop opening, as stated in Equation (28).

$$sts_f \geq OP_t, \quad \forall f,\ t \tag{28}$$

5. The technician crew should operate during the interval of regular hours, N_{st}. Let B_{wt} denote the start of the working time of crew w on day t and G_{wt} denote the corresponding maximum working time of crew w on day t. The repair of failure f performed by crew w on day t should be completed before G_{wt}, as given in Equation (29).

$$sts_f + Dtot_f - M\left(2 - \beta_{fw} - \sum_{s=1}^{S} y_{fst}\right) \leq G_{wt}, \quad \forall f,\ w,\ t \tag{29}$$

6. If the repairs of distinct failures f and j are assigned to the same crew w ($\beta_{fw} = \beta_{jw} = 1$) in the same shop s on the same day t, the sts_f of failure j is scheduled after the repair of failure j is completed, as expressed by Equation (31).

$$sts_j \geq \left(sts_f + Dtot_f\right) - M\left(5 - \chi_{fjt} - \beta_{fw} - \beta_{jw} - \sum_{s=1}^{S} y_{fst} - \sum_{s=1}^{S} y_{jst}\right), \quad \forall w, t, f, j \in [1, \ldots, F] | f \neq j \tag{30}$$

7. If failures f and j are assigned to the same shop ($y_{fst} = y_{jst} = 1$) and failure f will be repaired before failure j, $\chi_{fjt} = 1$, on the same day, as shown in Figure 10, then the start time of failure j, sts_j, should be equal to or greater than the entire time required in shop s for the repair of failure f. That is,

$$sts_j \geq sts_f + Dtot_f - M\left(3 - \chi_{fjt} - y_{fst} - y_{jst}\right), \forall s, t, f, j \in [1, \ldots, F] | f \neq j \tag{31}$$

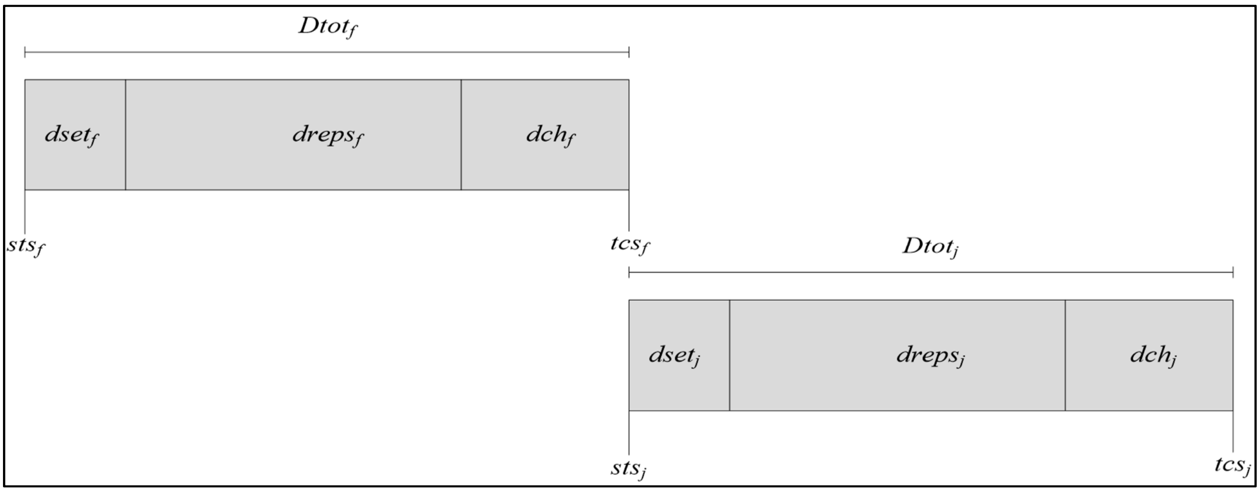

Figure 10. The sequence of failure f assigned to shop s.

The dependency of failure repairs should be respected. That is, if the repair of failure f in any shop is to be started before the repair of failure j, then the start time of failure f should be earlier than the start time of failure j, as expressed in Equation (32).

$$sts_j \geq sts_f - M\left(1 - \chi_{fjt}\right), \ \forall t, \ f, \ j \in [1, \ldots, F] | f \neq j \tag{32}$$

Moreover, the repair precedence is established for failures f and j on the same day in shop s, as presented in Equation (33).

$$\chi_{fjt} + \chi_{jft} = \sum_{s=1}^{S} y_{fst} \cdot \sum_{s=1}^{S} y_{jst}, \ \forall t, f, j \in [1, \ldots, F] | f > j \tag{33}$$

8. The failure with RPN_f greater than the selected criteria of failure severity and seriousness, CRT, shall be repaired first. That is,

$$\begin{matrix} sts_f \cdot y_{fst} = 0 | \max\left\{RPN_f > CRT\right\}; \\ sts_f \cdot y_{fst} = sts_f \cdot y_{fst} | \max\left\{RPN_f \leq CRT\right\} \end{matrix} \quad \forall f, \ s, \ t \tag{34}$$

9. If the *RPN* for failures *f* and *j* are equal on the same day in shop *s*, the failure with an earlier arrival time, *DA*, shall be assigned first, as expressed by Equation (35).

$$\begin{gathered} sts_j \cdot y_{fst} \cdot y_{jst} \geq sts_f | \left\{ RPN_f = RPN_j \ \& \ DA_f < DA_j \right\} \cdot y_{fst} \cdot y_{jst}; \\ sts_j \cdot y_{fst} \cdot y_{jst} \geq sts_j | \left\{ RPN_f = RPN_j \ \& \ DA_f \geq DA_j \right\} \cdot y_{fst} \cdot y_{jst}; \\ \forall t, s, f, j \in [1, \ldots, F] | f \neq j \end{gathered} \tag{35}$$

10. The binary decision variables are written as:

$$y_{fst} \in \{0,1\}, \quad \beta_{fw} \in \{0,1\}, \quad \chi_{fjt} \in \{0,1\} \tag{36}$$

The sequencing model is finally solved, and the additional information will be added to blocks, as depicted in Figure 11.

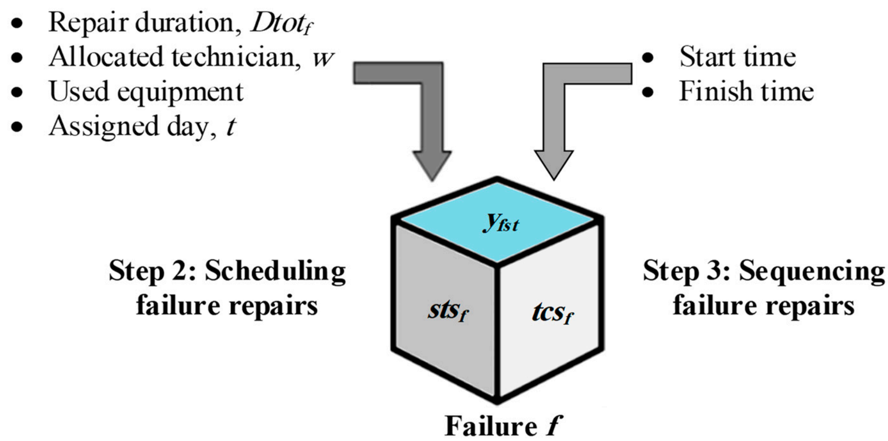

Figure 11. The stored data in each block after step 3.

Step 4: Each completed block is next assigned a hash to avoid access to the block information by unauthorized individuals. In this research, the block hash includes the failure category, assigned technician, maintenance shop, and the day in which the failure will be repaired with its start and finish times, while considering blocks dependency. For example, suppose block 2 shall be repaired after block 1. If the repair of block 1 has a start time at time 0 (previous hash of block 1) and its finish time at time 2 (hash of block 1) on day 1, then the repair of block 2 should have a start time at time 2 (=previous hash of block 1) and finish time on the same day 1 (hash of block 2), as depicted in Figure 12.

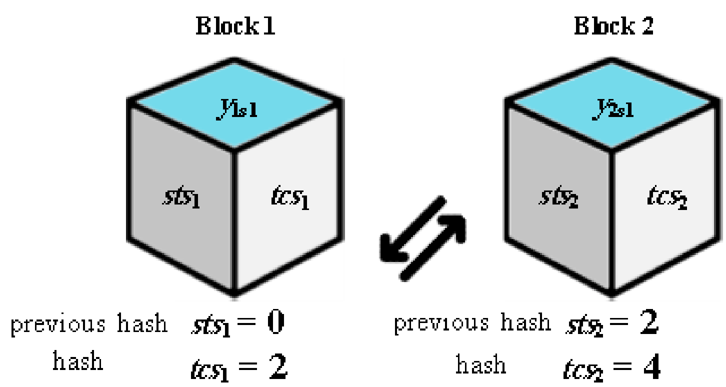

Figure 12. The linkage between blocks.

Step 5: Blocks are finally transferred via computer networks for consensus of the maintenance and relevant departments, as shown in Figure 13. The implementation of IoT and smart contracts can be employed to facilitate this process of blockchain approval and validation. Accessibility to the ERR to amend, remove, and approve is permitted by the planning section in the maintenance department. The maintenance manager can monitor the execution of maintenance activities through the number of executed blocks compared to the scheduled number of failure repairs and evaluate the efficiency of repair activities. The ERR system can provide online daily, weekly, or monthly repair progress reports, efficiency evaluations, and shops utilization of resources in the maintenance department to enable maintenance managers as well as the relevant department take in real-time decisions, as shown in Figure 14.

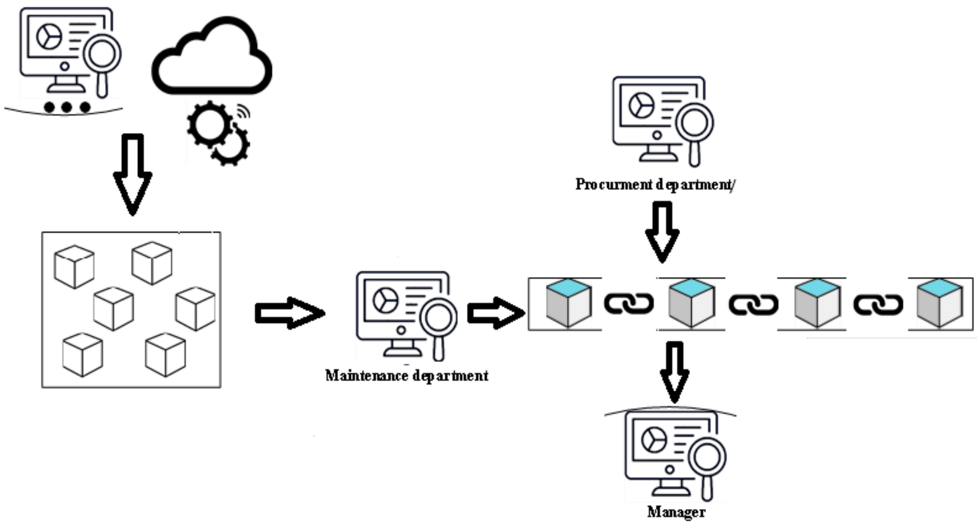

Figure 13. Blockchain technology for failure repairs.

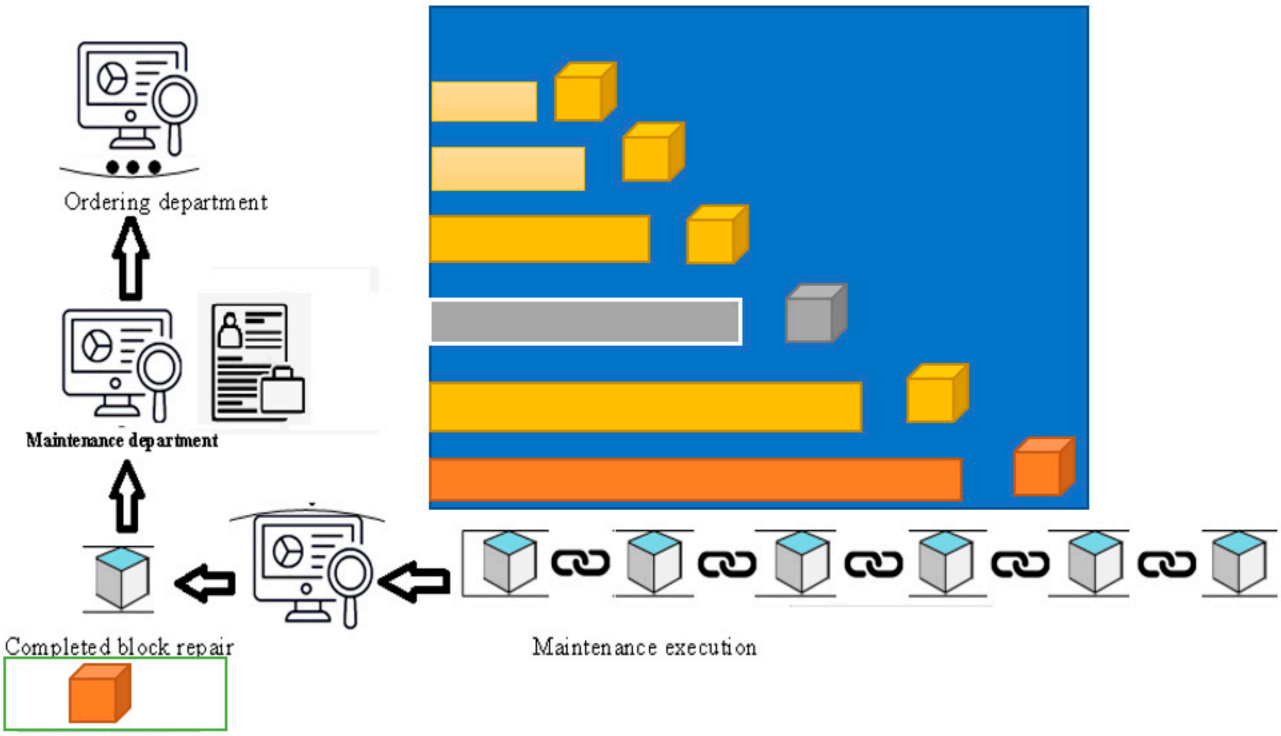

Figure 14. ERR output.

3. Application of Electronic Repair Records

The following case study was employed to illustrate the developed ERR system in a maintenance department and is presented as follows:

Step 1: Receiving failure repairs

A maintenance department performs failure repair services in its six shops, as shown in Table 1.

Table 1. Maintenance shops.

Maintenance Shop, *s*	Maintenance Category
1, 3, 5	General failures
2	Electrical failures
4	Mechanical failures
6	Welding processes

A total of 36 regular failures (F = 36) were received via smart contract to be repaired over a period of three days (T = 3). Failure-related variables are presented in Table 2. The availability matrix for the shop (α_{st}-matrix) and technician crew are presented in Tables 3 and 4, respectively.

Table 2. Failure-related variables.

f	Failure-Related Variables							f	Failure-Related Variables						
	DA_f	$dset_f$	$dreps_f$	dch_f	$Dtot_f$	$Ddue_f$	RPN_f		DA_f	$dset_f$	$dreps_f$	dch_f	$Dtot_f$	$Ddue_f$	RPN_f
1	2	1	2	1	4	2	0.9	19	1	0.2	0.8	0.5	1.5	1	0.1
2	1	0.5	1.5	1	3	1	0.75	20	1	0.2	0.5	0.3	2	2	0.1
3	−1	0.25	0.75	0.5	1.5	1	0.95	21	1	1	1	1	3	1	0.4
4	−2	1	1.5	1	3.5	1	0.1	22	2	0.2	0.8	1	2	2	0.3
5	1	0.5	1	0.5	2	1	0.5	23	2	1	1.5	1	3.5	3	0.5
6	1	0.25	0.5	0.25	1	3	0.3	24	1	1	1.3	0.7	3	1	0.05
7	2	0.5	2	1	3.5	2	0.02	25	1	0.3	0.3	0.4	1	1	0.01
8	2	0.25	1.25	0.5	2	3	0.05	26	0	0.5	1	1	2.5	2	0.3
9	1	0.25	1	0.25	1.5	1	0.3	27	3	0.25	1	0.25	1.5	3	0.5
10	3	1	1	1	3	3	0.08	28	2	0.5	1	0.5	2	2	0.2
11	3	1.25	1.5	0.25	3	3	0.2	29	1	0.25	0.5	0.25	1	1	0.1
12	1	1	1	0	2	2	0.09	30	1	0.75	1.5	0.75	3	1	0.09
13	2	1	2	1	4	2	0.3	31	2	0.5	1.25	0.25	2	2	0.02
14	1	1	1	1	3	1	0.2	32	1	1	2	1	4	3	0.01
15	1	0.5	0.5	1	2	2	0.01	33	3	0.25	1.75	1	3	3	0.3
16	1	0.5	1	1	2.5	2	0.7	34	1	1.5	2	0.5	4	1	0.06
17	3	0.5	0.5	0.5	1.5	3	0.4	35	1	1	1.5	1.5	4	2	0.24
18	3	0.5	1	1.5	3	3	0.3	36	2	1	1	1	3	2	0.35

Table 3. Technicians' availability (λ_{wt}-matrix).

Technician Crew (w)	Day (t)			Technician Crew (w)	Day (t)		
	1	2	3		1	2	3
1	0	0	1	7	1	1	1
2	0	0	0	8	1	1	1
3	1	1	1	9	1	1	1
4	1	1	1	10	1	1	1
5	1	1	1	11	1	1	1
6	1	1	1	12	0	1	0

Table 4. Shops' availability (α_{st}-Matrix).

Shop (s)	Day (t)		
	1	**2**	**3**
1	1	1	0
2	1	1	1
3	1	0	0
4	1	1	0
5	1	0	1
6	1	1	1

In step 2, the optimal failure assignment is presented in Figure 15. However, it is noted that there were no failures scheduled at shop 1 on day three, shop 3 on days two and three, shop 4 on day three, and shop 5 on day two, due to the shops' unavailability. Although shop 6 was available on day one, the equipment to perform the repair in this shop on day 1 was not available. The results also showed that 33 failures were scheduled; however, the repairs of the three failures 10, 17, and 18 are unscheduled due to workers' unavailability on day 3. Thus, their repairs can be scheduled on day 4 or subcontracted.

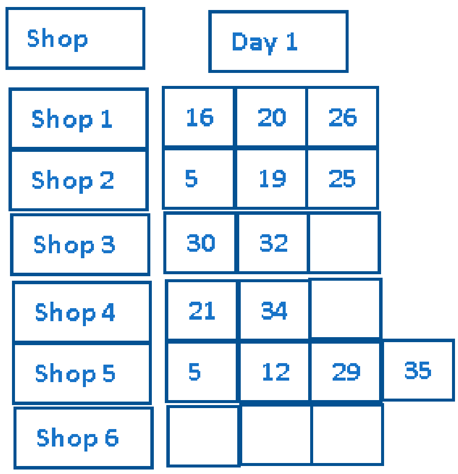

Figure 15. The failure assignment optimal results.

Step 3 utilizes the optimal scheduling results to obtain the optimal sequence of blocks by solving the proposed sequencing model. Figure 16 displays the obtained results. The optimal results from scheduling and sequencing models will be stored in each block.

In Step 4, a hash is assigned to each block. Practically, the linkage between blocks (failure repairs) that will be repaired on the same day can be referenced by the start and finish repair times. As noted previously, failure 30 should be repaired on day 1 at time 0 (should be repaired first on that day) at maintenance shop 3. In addition, failure 32 should be repaired on day 1 at time 3 at the same maintenance shop 3. Then, the linkage between these two failure repairs is developed, as depicted in Figure 17.

In step 5, all assigned blocks are shared with relevant stations through computer networks. Finally, the blockchain is created among private networks for access without the possibility to make changes. Once a block has been completely repaired, feedback is sent to the maintenance department and the maintenance engineers make necessary changes to update the block hash.

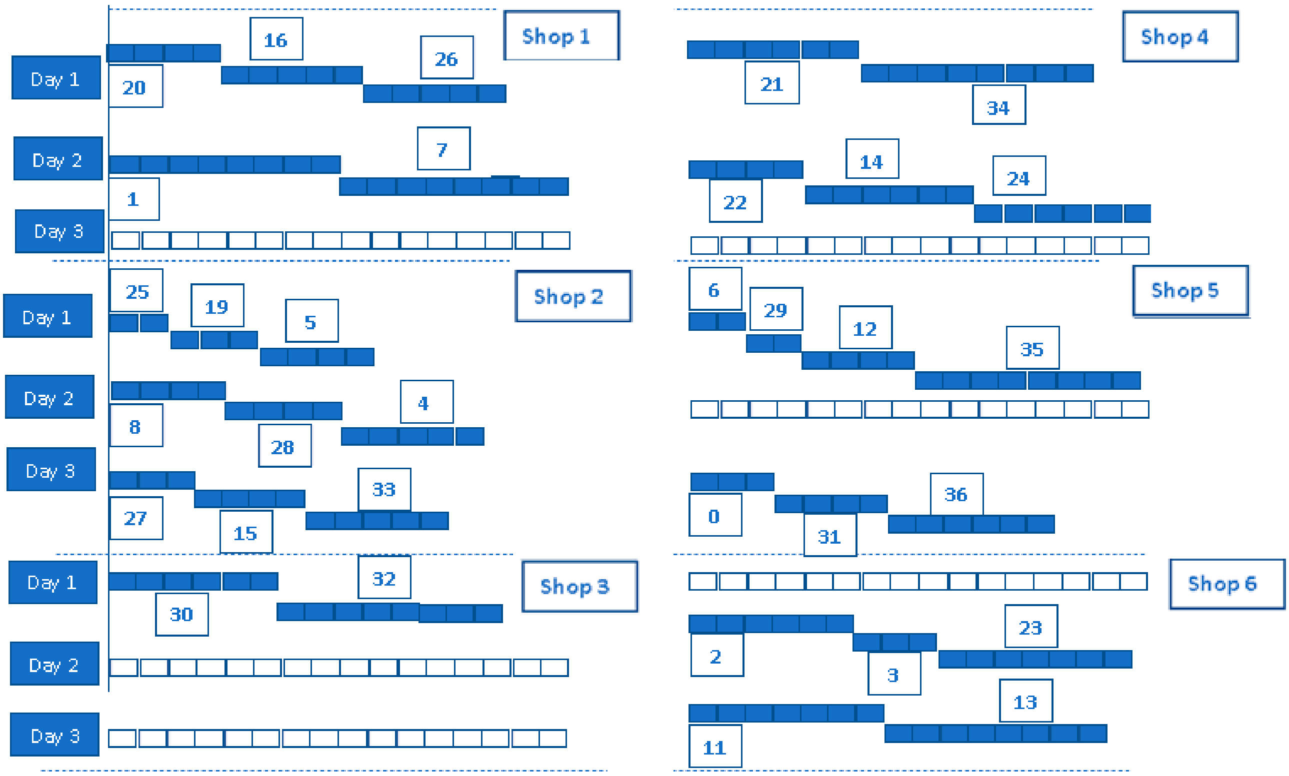

Figure 16. The sequencing repairs for the scheduled failures.

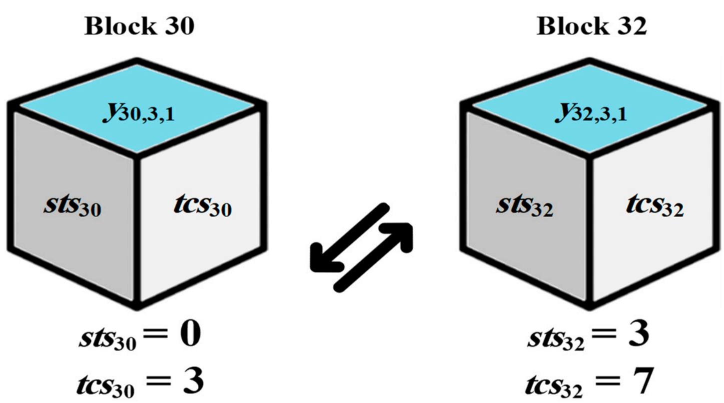

Figure 17. The linkage between blocks 30 and 32.

4. Research Results

The developed ERR system enables effective management and monitoring of the progress of maintenance activities. Further, using the optimization models can provide efficient utilization of maintenance resources and reduce high maintenance costs. Finally, progress reports and statistical analysis for the performance of the maintenance department are obtained in real time, which enables managers to take on time corrective actions. For illustration, the calculated overtime and idle time (hours) are listed in Figure 18, where the total overtime and idle time are zero and 12 h, respectively. Noticeably, the largest idle time (=5.5 h) is incurred in shop 2. The total costs of idle and delay times are 30 and 540 JOD. Such a report enables maintenance engineers to take the proper actions to reduce such costs, enhance the skills of repairmen, and increase utilization of maintenance shops by applying a preventive maintenance policy.

Overtime | Idle time

Shop	Day 1		Day 2		Day 3		Total	
Shop 1	0	1.5	0	0.5	-	0	0	2
Shop 2	0	3.5	0	0.5	0	1.5	-	5.5
Shop 3	0	1	0	-	0	-	-	1
Shop 4	0	1	0	0	0	-	-	1
Shop 5	0	0	0	-	0	1.5	-	1.5
Shop 6	0	-	0	0	0	1	0	1
Total	0	7	0	1	0	4	0	12

Figure 18. The calculated overtime and idle time in maintenance shops.

Moreover, the shops' utilization equals the total repairing time divided by the normal working hours. Figure 19 displays the calculated shop utilization. The smallest utilization is 77%, which corresponds to shop 2. Nevertheless, such utilization values are acceptable. As a result, it can be concluded that the developed ERR system including the optimization models is found effective in the scheduling and sequencing of failure repairs, managing maintenance activities, and controlling maintenance resources.

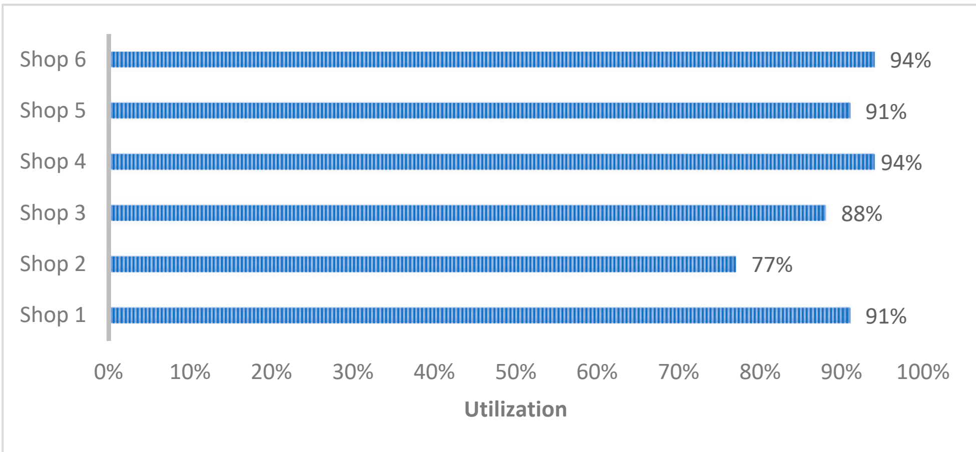

Figure 19. Estimated shops' utilization.

Most of the previous work focused on developing a framework for the adoption of the blockchain in data management and sharing. However, this research contributes to literature and practice by: (1) developing optimal information for blocks by formulating and solving optimization models for scheduling and sequencing maintenance activities; (2) generating effective planning of maintenance activities that optimizes resources utilization and minimizes maintenance costs; (3) developing an effective framework for blockchain adoption that can be customized to other applications, such as project management, healthcare, and production; (4) providing real-time information on the progress of business operations, deliveries, and other important information and providing analytical/statistical reports that help decision-makers and end users to track the current status.

5. Conclusions

This research developed an ERR system with two optimization models used for scheduling and sequencing failure repairs in the blockchain under minimal costs. Each failure was treated as a block. Then, the optimization models were used to assign daily resources and shops to failure repairs and sequence repair activities in each maintenance shop. A real case was employed for illustrating the developed ERR system. Thirty-six failures from different categories were received for repair in six maintenance shops over a three-day period. The models were found effective in managing 33 failure repairs in this period, while the remaining three failures were delayed due to the unavailability of repair technicians. Besides, the utilization of maintenance shops was acceptable. Still, maintenance managers can enhance the utilization of shops by implementing preventive maintenance, adding new multifunctional equipment, and multiskilled technicians. In conclusion, the developed ERR system including the developed optimization models is found effective in managing and controlling the blockchain of failure repairs at minimal costs and can help in: (i) analyzing the various cost elements associated with scheduling and sequencing of failure repairs and determining the necessary actions to minimize costs and improve utilization and (ii) reducing failure waiting time and delay costs. Future research considers developing an electronic patient recording system.

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