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Simulation model for the study of maintenance actions in a homogeneous multi-unit system of interchangeable components, with cannibalization

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ABSTRACT

Multi-unit systems pose logistical challenges in maintenance management, as finding a balance between availability and profitability is necessary. Choosing an appropriate maintenance policy can improve the use of available resources. The inclusion of cannibalization policies can offer greater responsiveness to spare part shortages. However, studying the effects of applying these policies in an existing system is only sometimes feasible. In this sense, simulation is presented as a valuable tool to investigate and understand these effects in a way that would not be possible. This article presents a simulation model to analyze different maintenance policies, including cannibalization, applied to a homogeneous multi-unit system of interchangeable components. The results show that even when problems arise in the supply chain of critical spare parts for the units, it is possible to maintain an acceptable availability rate through the implementation of cannibalization policies, which leads to an improvement in the operational availability of the units. Finally, the simulation tool also revealed advantages in describing transients of response to maintenance activities, which provides a complete understanding of how the system behaves in different situations.

1. Introduction

Multi-unit systems have gained importance due to their application in different types of systems such as passenger transport (buses, subways, cabs), cargo transport (trucks, trains), wind farms, industrial robots, similar production lines, etc. [1]. A multi-unit system is a set of independent units that work together to achieve a common objective related to one of the previously mentioned services. Each unit contains modules and components arranged in combination series–parallel. If all units have the same components architecture, it is named a homogeneous system and therefore shares the same failure behavior [2]. Also, if it is possible to exchange components between units for maintenance or production needs, they can be named interchangeable component systems [3]. Maintaining a high availability rate in multi-unit systems represents a challenge regarding reasonable maintenance costs. [4]. Conditions such as limited time for maintenance tasks, identification of the optimal number of critical components in stock, their obsolescence, location, and type of service, optimal replacement of units, and the appropriate selection of a maintenance policy require an optimization of the use of maintenance resources [5].

One of the problems related to optimizing the use of maintenance resources is the management of spare parts. This happens because many components in stock create a high unprofitable cost of capital, and few components create logistical delays on maintenance tasks [6]. Therefore, delays in supply chains, components price fluctuations, changes in the discipline of routes, or the application of an inadequate maintenance policy, etc., can lead to uncertain environments [7] if a shortage of spare components problem affects the system. The literature reports studies on spare parts management systems related to methods to optimize spare parts inventories [8–10]. The selection of an adequate maintenance policy is closely related to optimizing the use of available maintenance resources and, therefore, managing the components involved. [11,12]. Works like [13] propose Markov chains and multi-objective optimization of a maintenance policy in a redundant air system with faults. In [14], preventive, corrective, and inspection are combined to develop an inspection model in a degraded system; the model uses real-time monitoring and defines optimal periods for inspection. Also, in [15], a preventive policy optimization is presented, and spare components and maintenance hours' values are identified in a multi-unit manufacturing system. Other policies are studied in [16], where a proactive maintenance policy is proposed for make-decisions through a dynamic Bayesian network to optimize maintenance periods.

Therefore, the ability of a multi-unit system to carry out its missions is closely related to its maintenance. In [17], maintenance optimization is evaluated from the probability of the system completing a specific

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value mission. Previous works focus on identifying thresholds of remaining useful life (RUL) to optimize the performance of preventive maintenance, assuming an appropriate supply of spare parts. However, it is important to note that a multi-unit system may be required to operate in many uncertain environments that threaten its availability. Unexpected changes in demand, environmental conditions, natural events, trade wars, delays in the supply chain, and pandemics, among others, represent risks for the system's operation and, therefore, the maintenance system. In this aspect, works like [18] present a model that combines maintenance tasks with an inventory policy to generate emergency spare parts ordering if necessary. In [19,20], a quality spare part model is proposed, suppliers of components can be different quality parameters, and it can affect efficiency in maintenance tasks or the total cost of the system [21]. The model in [22] inserts restrictions on some components and divides maintenance tasks between those that need restricted components and those that exist in the inventory or are easy to order. In the related literature, few papers propose component shortage scenarios.

One way to deal with the component shortage in a homogeneous multi-unit system that has maintained a constant interest among researchers is to use cannibalization policies. For example, in [23], a model is proposed to identify the optimal time in which a unit can remain out of service for the replacement of used parts and failed components in other units, Also, in [24,25], an algorithm has been proposed whose objective is to calculate the probability that a unit can complete a mission satisfactorily using the preventive maintenance and spare parts used. Cannibalization is a maintenance policy that consists of the interchange of used components between units for repair purposes to maintain a system's availability as high as possible when other component procurement methods have been exhausted [26].

As can be observed, very few of the works found in the literature have focused on maintenance policies with cannibalization interacting with conventional maintenance policies in homogeneous multi-unit systems; moreover, the evolution of the impact of maintenance tasks completed through cannibalization on the operational availability of the system has not been considered. The models' modularity allows their applications' functionality to be extended. With this, it is possible to study different views of the system, making the model more flexible and thus adapting the parameterization to new study scenarios. Considering that the effects can generate significant demands on the maintenance system, the simulation model will evaluate the feasibility of implementing a cannibalization policy. For this purpose, a comparative study is applied using cannibalization in the presence of preventive maintenance (PM) and corrective maintenance (CM) policies.

Considering the above, this paper presents a modular, flexible, and highly parameterizable simulation model of maintenance policies, including cannibalization in multi-unit systems; That is, the proposed structure allows modeling operation, resources, and maintenance policies independently because the set of units and the system management is decoupled. This structure allows the simulation of flexible system environments to measure the impact of maintenance policies analyzed with different delays and periods in the spare parts supply. It is also possible to apply an imperfect maintenance policy with cannibalization, one, to compare logistic, administrative, and maintenance times with and without cannibalization. Two, to study the system availability and its operational capacity to perform missions, and three, to examine the transient response of parameters such as availability, mean time between failures (MTBF), and mean time to repair (MTTR). Finally, the model analyzes the behavior of the time the parts were exchanged, considering that cannibalization as the reuse of parts should promote an adequate selection of the component.

The paper structure is as follows: first, the document shows aspects of multi-unit systems and the simulation models found. Secondly, it presents the conceptual model and its simulation. And third, it shows the case study of a homogeneous multi-unit system and the scenarios studied. Finally, the results and the conclusions are presented.

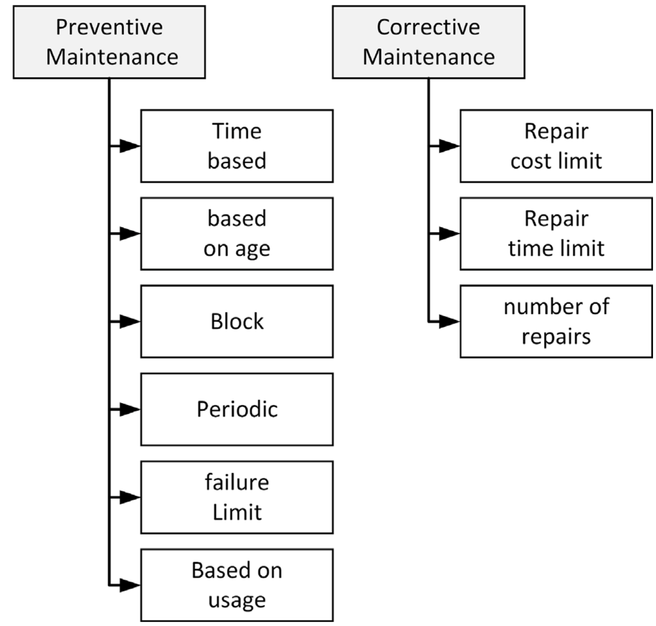

Fig. 1. Maintenance policies applicable to multi-unit systems.

1.1. Multi-unit systems

The literature has focused in recent years on solving the problem of optimizing the maintenance cost of a multi-unit system as a maintenance strategy selection problem (MSS) [27,28]. An MSS problem involves identifying the maintenance policy that optimizes the operational capacity of the system and maximizes its availability [29,30]; Also, it should consider three essential aspects of maintenance related to its components; the dependencies between components, the estimation of the RUL, and the supply of spare parts. Previous research coincides with using the dependencies between modules and components to identify an appropriate maintenance policy. For instance, structural dependence evaluates the critical components that affect the reliability of a unit to prioritize them in maintenance tasks [31]. Stochastic dependence evaluates how the failure of a component affects or degrades the other parts of the system [32,33]. Economic dependence involves identifying the relationship between maintenance costs for a group of components and seeking an optimal grouping to reduce the final cost [34].

Similarly, the RUL is an estimation of the time of life of a component before it fails. An accurate RUL estimate enables optimal component utilization, avoids unscheduled failures, and improves logistical, administrative, and maintenance time [35]. In [36], an RUL estimation method is proposed, compared a centralized and decentralized data sources. In [37], a probabilistic RUL estimation is proposed to improve decisions about components under preventive maintenance policy. It is important to highlight that the estimation of the RUL parameter must align with the possible maintenance policies that can be applied to a multi-unit system. For example, in [38], a selective maintenance policy is proposed that consists of taking advantage of the pause of some of the system units (maintenance time), previously identifying the components that will be intervened (decreased logistical and administrative time). This same policy is applied in [39], along with an imperfect maintenance policy at the component level. Also, in [40], grouping maintenance tasks in a block replacement policy is proposed for catastrophic and non-catastrophic failures. Fig. 1 shows a list of maintenance policies identified in the literature applicable to multi-unit systems.

The above approach does not consider the possibility of delays or shortages in the spare parts supply during maintenance times, which

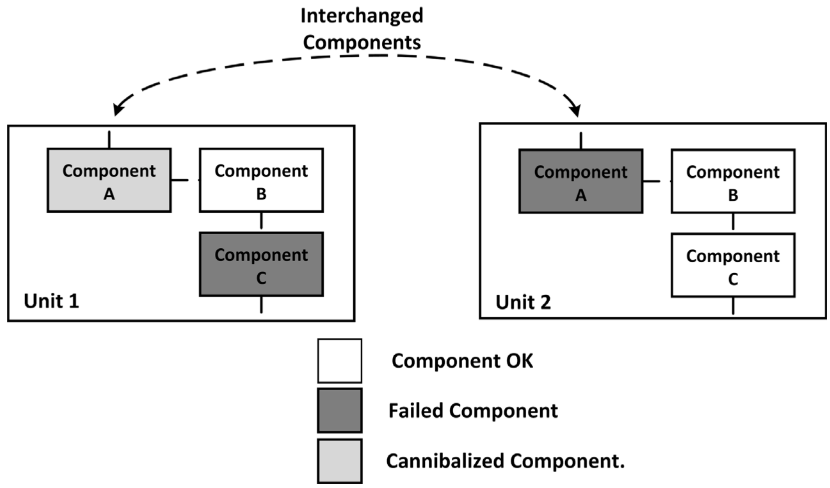

Fig. 2. Example of a cannibalization policy.

can significantly affect system availability. However, multi-unit systems are often immersed in uncertain environments that continually demand changes to component supply policy and maintenance schedules. A special case refers to maintenance logistics times, which can increase disproportionately due to the lack or non-availability of spare parts. The strategies presented in [41,42] can certainly strengthen the supply chain. Still, it is important to note that the specifics of multi-unit systems, such as the number of units, component architecture, and the type of service provided, may present a latent risk that can be addressed by including additional policies that complement those shown in Fig. 1. One way to mitigate spare components shortages in a homogeneous multi-unit system is to apply maintenance cannibalization policies [43]. This is defined as exchanging or reusing modules or parts between units in a failure state or maintenance queue. This exchange is favored when the units have the same component architecture, meaning a homogeneous system. Cannibalization consists of taking a functional used component of a unit named "donor" and replacing it in a unit in failure for the same piece named "receiver". These policies apply when an unforeseen event causes spare parts shortages and the supply time is determined to be longer than the time required to exchange a used part. the objective is to restore the units to service in the shortest possible time and minimize the impact on system availability as much as possible. An example is shown in Fig. 2.

Nonetheless, uncontrolled cannibalization adversely affects maintenance resources [44]. For example, cannibalizing a component multiple times in different units or using components with an RUL near the end of their lifetime decreases the effectiveness of cannibalization. Thus, early works such as [45–47] propose a model to compare different cannibalization policies in an aircraft fleet; Subsequently, the investigation changed to the decisions field, such as in [48,49] where to explore one of the first decision-making models that incorporate cannibalization and also a solution that introduces a simulation model which allows evaluating how cannibalization affects the performance of a multi-unit system. In recent years, other cannibalization policies have been explored. For instance, in [23,26], the Bird cannibalization policy is studied in the presence of preventive maintenance, and the proposed model is represented with hierarchical colored Petri nets. A limitation of the models found is that they do not consider the impact of a maintenance policy with cannibalization on the operational availability of the system, nor do they provide traceability tools for monitoring the lifetime of cannibalized components. This makes it difficult to decide which components to select for cannibalization and how this practice may affect long-term system availability.

1.2. Simulation models

An adequate representation of a multi-unit system and its maintenance manager is complex due to the presence of interdependencies between the units, modules, and components, the operational objectives of the system, the management of maintenance resources, and the corresponding maintenance policies [27]. In contrast, changes and experiments on a real multi-unit system can be done in very few cases. Because of this, some analytical models can become complex when trying to adequately represent the behavior of a system due to the large number of variables that must be considered. Simulation models limit these drawbacks by facilitating analysis and achieving closer interaction with the real system than with analytical models [50,51]. Early simulation multi-unit models with cannibalization policies are shown in [46], where proposed to evaluate the performance of the cannibalization policy through the number of units ready to mission. In [48,49], a simulation model of parallel units is presented to focus on decision-making on cannibalization policies. Finally, in [23], a simulation model described with a colored hierarchical Petri net is proposed to study bird cannibalization.

Therefore, simulation models are valuable tools to study cannibalization in multi-unit systems. However, these models must be highly parameterizable and flexible to adapt to different situations. Also, interdependencies between units, modules, and components join with operational goals, and maintenance policies must be considered. In addition, it is essential that these models become decision-making tools for those responsible for maintenance and thus improve the operational availability of the system.

The following section shows the development of a decoupled simulation model to represent a multi-unit system with a maintenance management system that includes conventional and cannibalization maintenance policies. The simulation model allows inserting parameters to create uncertain environments.

2. Methods

2.1. Definition of homogeneous multi-unit system with interchangeable components

As mentioned in previous sections, a homogeneous multi-unit system of interchangeable components comprises units with a similar component architecture, and it is possible to exchange components between units. A unit is composed of multiple components grouped for functions in modules and sub-modules. Components in a unit can be connected in series, parallel, or series–parallel, creating a structural dependency as a system. The component architecture in a bottom-up mode of a unit proposed is shown in Fig. 3. Each unit comprises n maintainable modules with m components.

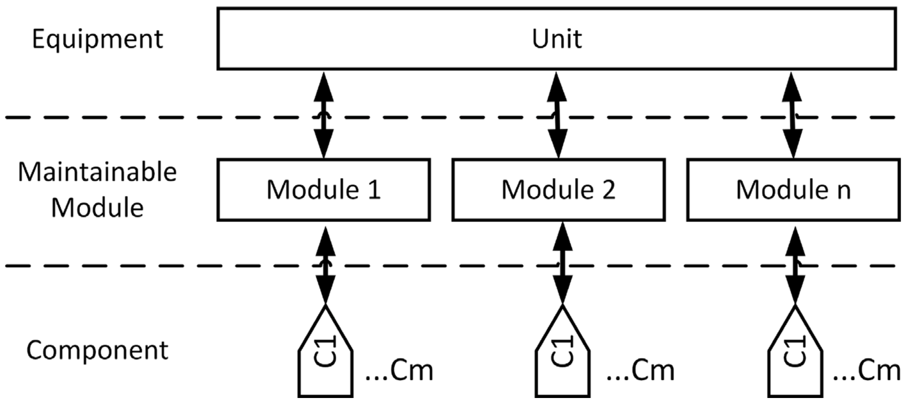

Fig. 3. Components architecture of a unit.

Table 1
States of Petri net model of a component.

States	Observations
Ready	Component is failure-free.
Running	Component participation of a mission.
Failed	Component is in failure.
Replacing	Component is under preventive maintenance policy.
Repairing	Component is under corrective maintenance policy.
Cannibalizing	Component is selected to interchange.

2.2. Modeling of a homogeneous multi-unit system with interchangeable components

Discrete event systems (DES), are an appropriate tool to describe the behavior of systems related to maintenance tasks [50]. This model type uses a set of states that evolve from the occurrence of asynchronous events generated by the system. To describe a DES model, one of the most useful formalisms, because of its versatility and formality, are Petri nets (PN). A generalized PN is a quintuple $PN = (P, T, Pre, Pos, M0)$, where P is the set of m places representing the states, T is the set of n transitions that are associated with the events, $Pre : P * T \rightarrow N(Post : P * T \rightarrow N)$ is the incidence matrix Pre (Post), and $M0$ is the initial marking vector. Pre(p,t)=w (Pos(p,t)=w), which means that there are arcs with weight w from p to t (from t to p); C=Post-Pre is the incidence matrix. An extension of PNs is one in which time is added in the firing of transitions, called timed Petri nets TPN's. A TPN is made up of a pair $\langle \mathrm{N}, \mathrm{Tempo} \rangle$, such that N is the generalized PN and Tempo is a function of time associated with each transition; that is, when a transition is enabled, the firing of that transition occurs when the time of the event tj associated with that transition has been fulfilled. The time tj can be deterministic or stochastically associated with a probability density function, and the PN would be a stochastic Petri net (SPN).

2.2.1. Component model

A component's proposed Petri net model is shown in Fig. 4, with six states explained in Table 1.

The component model categorizes transitions into three types: maintenance system signals, stochastic transitions generated using a random distribution function, and timed transitions activated after a set period. Table 2 summarizes the component model transitions.

The "Time To Be Cannibalized", "Time Preventive Maintenance", and "Time Corrective Maintenance" are timed transitions that are activated after some time has elapsed, and that indicate the duration of a maintenance task. The "Failure" transition is determined by a set of random values generated from the failure function of each component, obtained from a three-parameter Weibull distribution [52], as shown in Eq. (1).t_0 the failure free time or guarantee time, λ the scaling parameter or characteristic life, and β the shape parameter.

$$f_X(x \mid t_0, \lambda, \beta) = \frac{\beta}{\lambda}\left(\frac{x - t_0}{\lambda}\right)^{\beta-1} \exp^{-\left(\frac{x-t_0}{\lambda}\right)^{\beta}} \quad , \quad x \geq t_0 \tag{1}$$

2.2.2. Module model

A module comprises m components with the form of the Petri net of Fig. 4. The module model shown in Fig. 5 has five states, shown in Table 3.

The transitions in a module are logical AND and OR operations of the component states. Table 4 explains transitions in this model.

2.2.3. Unit model

Finally, the unit model shown in Fig. 6 has four significant states, explained in Table 5.

The transitions to the model are AND and OR logical combinations of the module states as shown in Table 6.

2.3. Maintenance and operations management system model

The main function of the maintenance management system is the allocation, analysis, and decision-making of the resources allocated to maintenance tasks. Fig. 7 shows the representation of the maintenance and operations system model modules in the use case diagram. The "SelectMaintenancePolicy" use case represents a module required to select preventive ("SelectPreventivePolicy" use case), corrective ("SelectCorrectivePolicy" use case), and cannibalization policies.

Also "AssignStaff" use case is a module for the management of maintenance hours available. Use case "SelectCannibalizationPolicy" extends functionalities to "SelectMaintenancePolicy" and "ManageInventoryPolicies" cases because it generates components to the inventory but depends on maintenance policy to take them. The "PoliciyComponentsNews" use case is a module that complements the supply of components to the system. Likewise, the "ManagmentMaitenanceOrders" use case is a module needed to manage maintenance preventive and corrective orders generated for the system. Last, the "SelectRouteDiscipline" use case is a module to manage the system's operation, the number of missions, and the units assigned to the mission.

2.3.1. Maintenance order management model

A maintenance order is an administrative act that allocates the necessary maintenance resources to carry out a maintenance activity on a given unit. The maintenance order management was modeled using a colored Petri net (CPN). This is a language for the modeling and analysis of distributed systems, and one of the main features is that they can associate values (colors) to each object (mark). This feature gives CPNs the power to model complex systems because it combines the advantages of PNs with programming capabilities in high-level

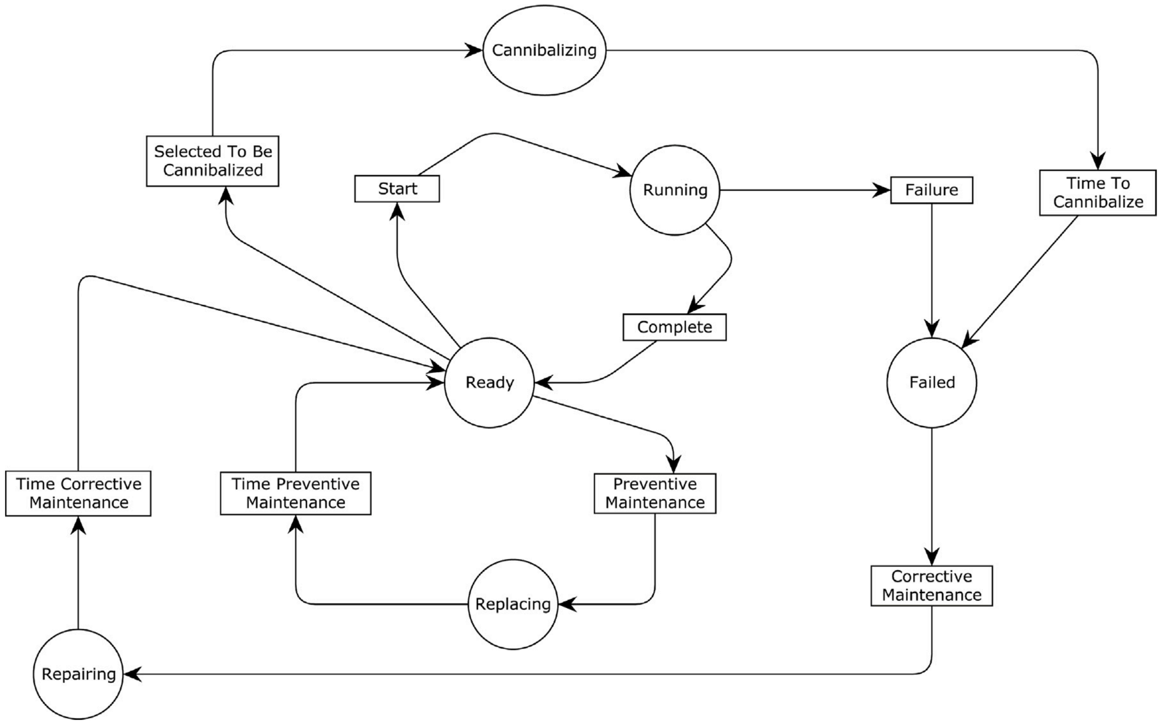

Fig. 4. Petri net behavior model of a component.

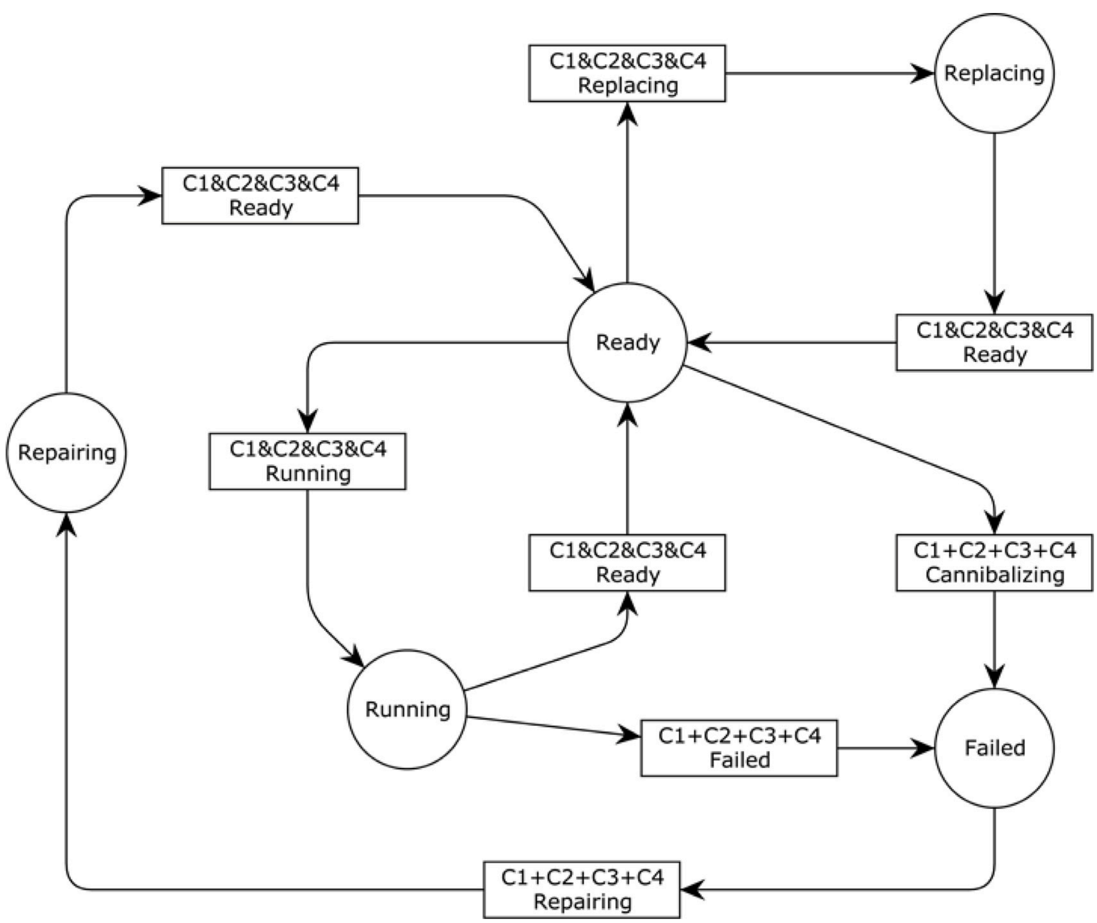

Fig. 5. Petri net behavior model of a Module.

Table 2
Transitions of Petri net model of a component.

Transitions	Type	Observations
Start	Signal	Component is activated (Unit in mission).
Complete	Signal	Component is deactivated.
Failure	Stochastic	Random event generated from a Weibull distribution indicating failure.
Preventive maintenance	Signal	Component will be changed for preventive maintenance.
Corrective maintenance	Signal	Component will be changed for corrective maintenance after failure or cannibalization.
Selected to be cannibalized	Signal	Component is selected to interchange.
Time preventive maintenance	Timed	Represents an operator's time to perform preventive maintenance tasks.
Time corrective maintenance	Timed	Represents the time an operator takes to perform corrective maintenance.
Time to cannibalize	Timed	Represents an operator's time to perform cannibalization (only the time to uninstall the component from the "donor" unit).

Table 3
States of Petri net model of a module.

State	Observations
Ready	Indicates that all components in a module are available.
Running	Indicates that the components of that module are running.
Failed	Indicates the failure of one or more components.
Replacing	Indicates that a preventive maintenance policy replaces at least one component.
Repairing	Indicates that a corrective maintenance policy replaces at least one component.

Table 4
Transitions of Petri net model of a module.

Transition	Type	Observations
Ready	Signal	Operation AND(&) between all Ready states of components.
Running	Signal	Operation AND(&) between all Running states of components.
Failed	Signal	Operation OR(+) between all Failed states of components.
Cannibalizing	Signal	Operation OR(+) between all Cannibalizing states of components.
Repairing	Signal	Operation OR(+) between all Repairing states of components.
Replacing	Signal	Operation AND(&) between all Replacing states of components.

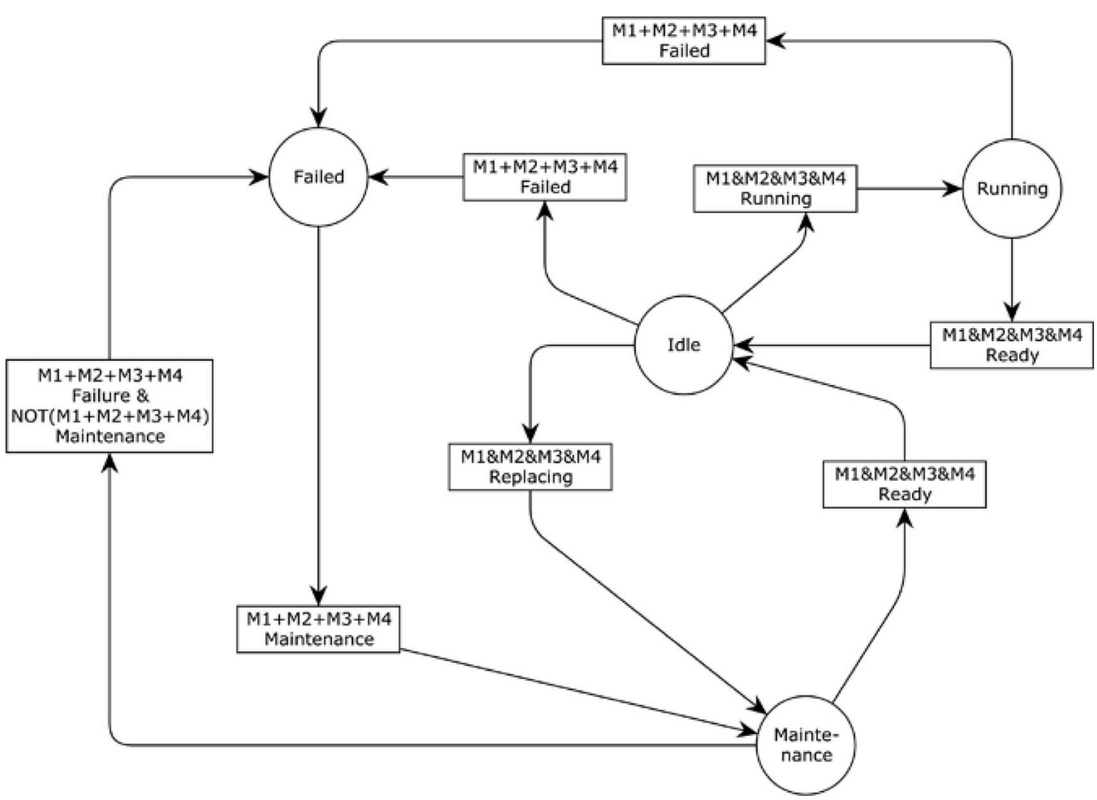

Fig. 6. Petri net behavior model of a unit.

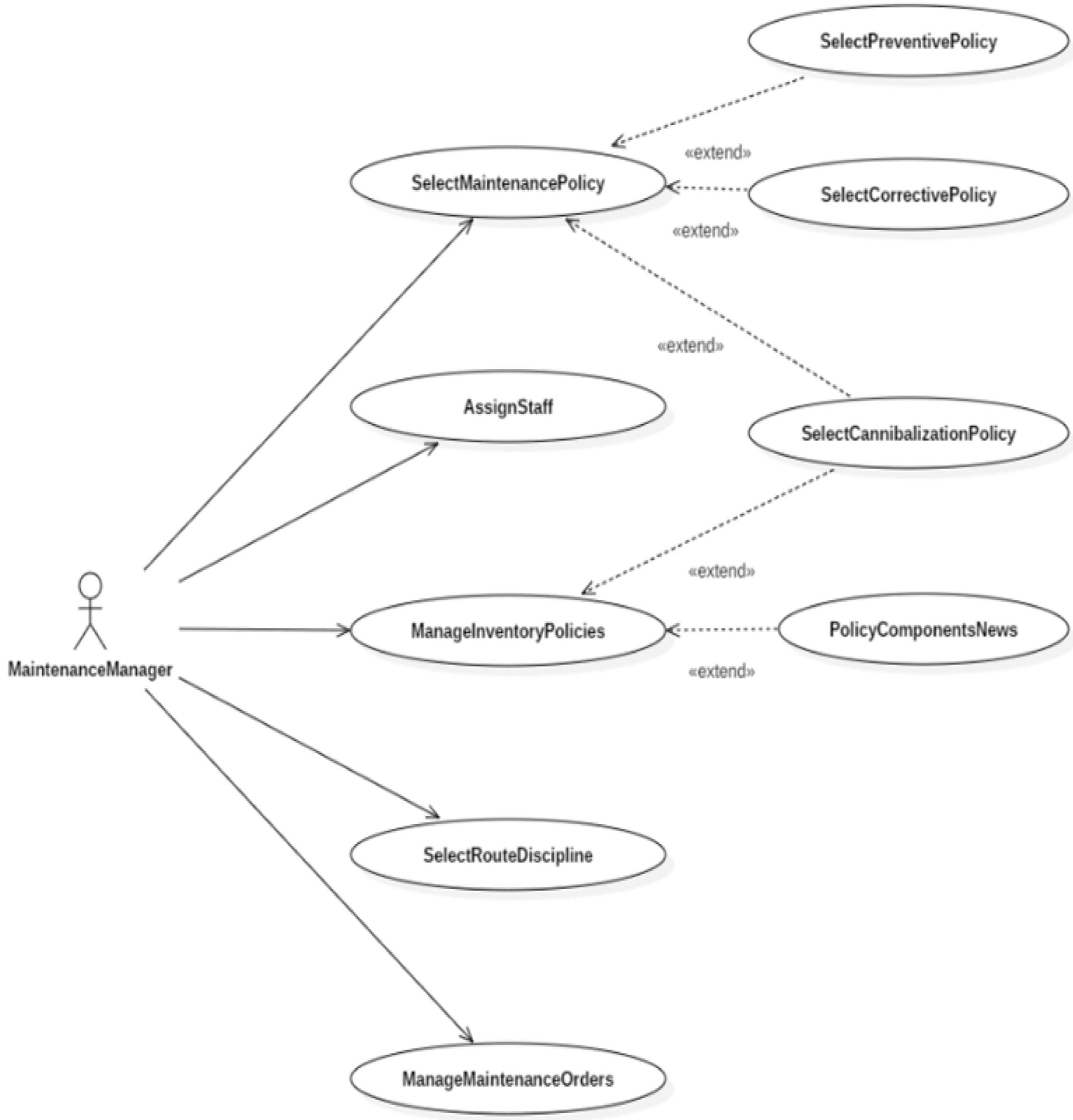

Fig. 7. Use case model of the maintenance management system functionalities.

Table 5
States of Petri net model of a unit.

State	Observations
Idle	Indicates to the manager that the unit is available for a mission.
Running	Indicates that a unit is making a mission.
Failed	Indicates the unavailability of the unit per failure in a component or waiting for a maintenance order.
Maintenance	Indicates that a unit is under preventive or corrective maintenance.

languages. A CPN is defined as $CPN = (PN, C, Cd)$, where PN is a generalized PN defined in Section 2.2, C represents the color sets, and Cd represents the domain color map; thus, $PUT- > C$ [53]. The proposed color sets for the maintenance order management model and the variables used are presented in Table 7.

The color set "Components" represents the parts $G1, G2, G3, \dots, Gn$ that belong to a module or unit (See Fig. 4) . The set "Modules" represents the $HB1, HB2, HB3, \dots, HBn$ modules (See Fig. 5) that are part of the unit. The color set "Units" represents the number of units $M1, M2, M3 \dots Mn$ (See Fig. 6), that are part of the multi-unit system. The maintenance types are identified as $TM1, TM2, TM3 \dots TMn$. The P in the "People" color set represents the maintenance hours. Finally, the maintenance request and the maintenance order are product color sets. These sets are formed from basic color sets. For example, the color set "OrderMaintenance" is the product of color sets like this: (G1 *x* HB1 *x* M1 *x* TM1 *x* P1).

The model presented in Fig. 8 describes processing a maintenance request through a CPN. The management starts in place P1; if a corrective maintenance request arrives, the request is filed in place P2 by activating T1. Then in T2, it is validated that the request parameters have been extracted, identifying the unit and the component in failure (Places P3 and P4). Component availability is verified in (Place P5), but is possible that the component is not available. Therefore, the timed transition T3 represents the delays by logistics that can occur when components are unavailable. If the component is available, a component mark is located in place P6, and resources are allocated for the maintenance request processing through the availability of maintenance hours (Place P10). With the allocated resources, T7 organizes the parameters of the maintenance order that will be triggered at

Table 6
Transitions of Petri net model of a unit.

Transition	Type	Observations
Ready	Signal	Operation AND(&) between all Ready states of modules.
Running	Signal	Operation AND(&) between all Running states of modules.
Failed	Signal	Operation OR(+) between all Failed states of modules.
Maintenance	Signal	Operation OR(+) between all Maintenance states of modules.
Replacing	Signal	Operation AND(&) between all Repairing states of modules.
Failure AND(&) NOT Maintenance	Signal	This transition indicates that a unit in the maintenance queue was selected for cannibalization.

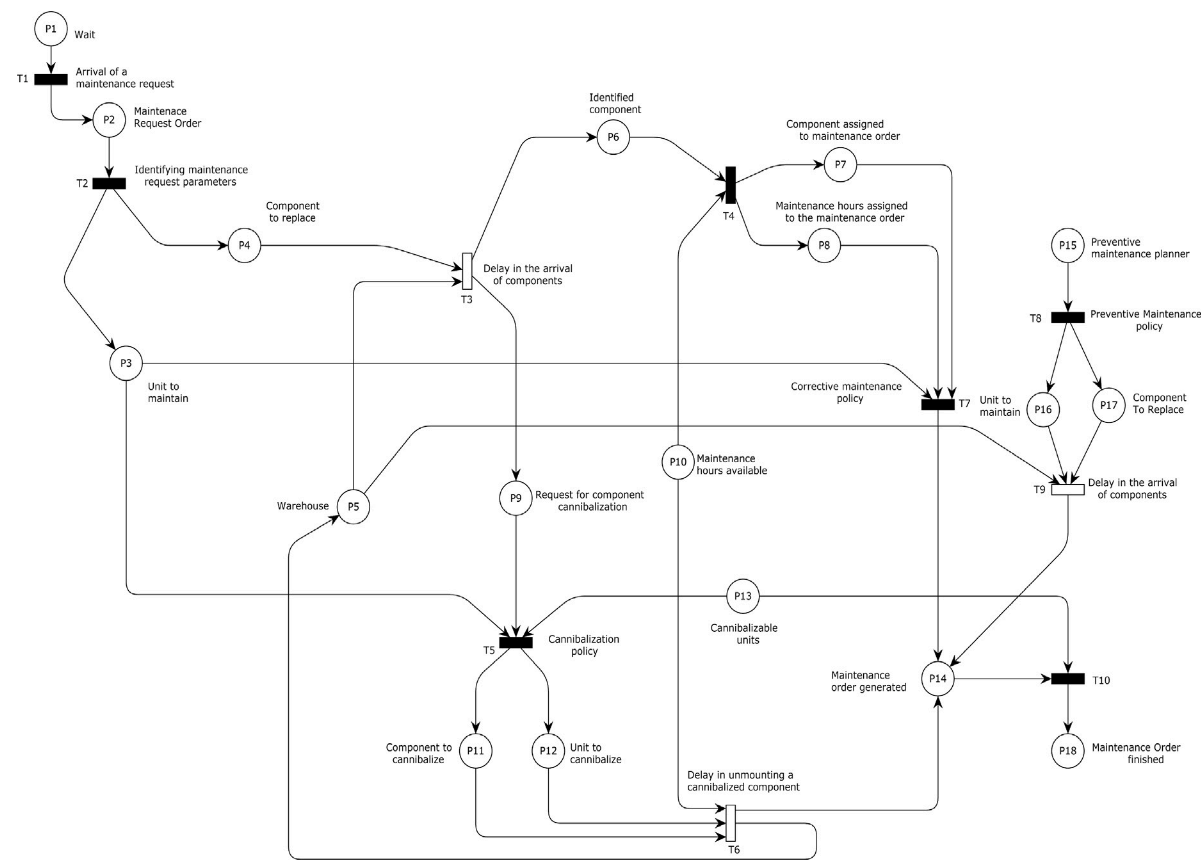

Fig. 8. CPN model of the multi-unit maintenance management system.

Table 7
Color sets and variables used in CPN.

Color set	Items
Components	G1, G2, G3, …Gn
Modules	HB1, HB2, HB3, …HBn
Units	M1, M2, M3, …Mn
Maintenance type	TM1, TM2, TM3, …TMn
People (Maintenance hours)	P1, P2, P3, …Pm
ReleaseResource	R1, R2, R3, …Rm
RequestMaintenance	G x HB x M x TM
OrderMaintenance	G x HB x M x TM x P

location P14. When no component is available in the warehouse, the T3 transition can be conditionally activated to issue a cannibalization request for a component (place P9). The T5 transition validates that the unit requiring the maintenance order differs from the cannibalizable units at P13. If validated as different units, the T5 transition defines the unit and component to cannibalize and issues a maintenance order by cannibalization at location P14 releasing a component administratively assignable to a maintenance order. Finally, if the preventive maintenance planner launches an order through P15, the order is evaluated using the preventive maintenance policy, and it is validated that there are available components. It is possible that the components are not available. Therefore, transition T9 is in charge of evaluating if there are delays in the components. After this time, a preventive maintenance order is added to location P14. The lifetime of the order ends when the unit leaves place P13.

2.4. Implementation

Both homogeneous multi-unit system with interchangeable components and maintenance and operations management system model was implemented in LabVIEW Version 8.6 Patch 2 software through a graphical programming language named G-Code. LabVIEW allows Oriented Object Paradigm (OOP) using *Actor Framework* library, which provides two classes; An *actor class* to create objects or instances and a *Message class* that allows communication between actors. All classes the user creates inherit attributes from one of these two classes.

Fig. 9 shows an overview of the application; on the left side, a homogeneous multi-unit system is implemented. The *Component.vi* is

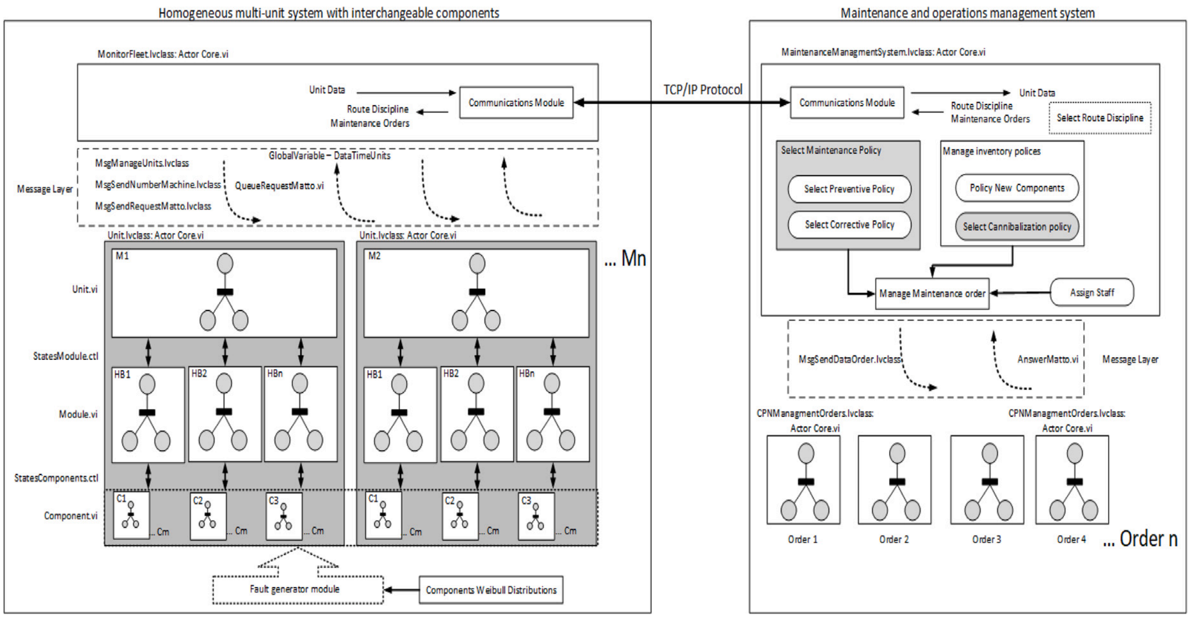

Fig. 9. Block representation of the application in LabVIEW software.

implemented according to the model in Fig. 4. Similarly, the *Module.vi* implemented model presented in Fig. 5 and *Unit.vi* correspond to model presented in Fig. 6. The fault generator module produces a failure event from the Weibull distributions of each unit's components. This model is replicated *n* times by actors from the *actor framework* library according to the size of the multi-unit system. The message layer allows the sending of the routing discipline to each unit by *MsgManageUnits.lvclass* and the maintenance responses *MsgSendRequestMatto.lvclass*. The maintenance requests are sent through a queue *QueueRequestMatto.vi*, and the data is grouped in an array named *DataTimeUnits*. All *units.vi* are managed by the *MonitorFleet.lvclass*, coupled with a connection with TCP/IP protocols with the maintenance and operation management system.

Likewise, on the right side of Fig. 9, the maintenance and operation management system, implements cases explained in Fig. 7. A routing discipline is created in *Select Route Discipline* module. The module *Select Maintenance Policy* contains definitions of corrective and preventive policies. In module *Manage inventory policies*, the cannibalization policies and inventory supply of spare parts rules are defined. On the other hand, the module *Manage Maintenance Order* evaluates request maintenance orders and sends request message *MsgSendDataOrder.lvclass* to create a maintenance order by CPN model of Fig. 8 and assign maintenance resources. Maintenance orders are automatically replicated as new maintenance requests arrive, through actors of *actor framework* library, and remain active until the resources required for their execution are completed. In the end, the maintenance response is sent to a multi-unit system if the order was completed utilizing a queue in *AnswerMatto.vi*.

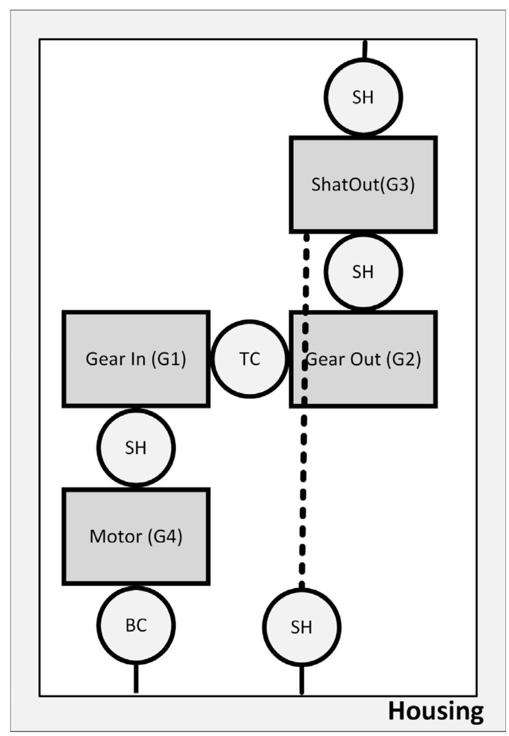

Fig. 10. Function block diagram of a single unit module.

3. Results

3.1. Case study

The case study is a homogeneous multi-unit system with routing (predefined routes) composed of 10 units presented in [54]. The component architecture of a module is shown in Fig. 10.

A unit consists of four maintainable modules like the one in Fig. 10, and each module is a gearbox adapted from [55] composed of 4 components explained in Table 8. Both modules and components are in a serial arrangement, which means that if one component fails, both the module and the entire unit can be affected and fail as well.

3.1.1. Objective and operational discipline route

The operational objective of the system is to cover a route daily. The route time Tr fixed is 360 min; if the value of Tr is divided between the units that belong to the system, it will achieve the dispatch time Td is 36 min by the route [56]. The multi-unit system is available 24 h a day and performs 27 missions. This discipline is shown in Fig. 11.

3.1.2. Spare parts inventory policies

The inventory policy is based on two key parameters proposed in [57]: the moment a new order must be issued and the number of spare parts requested in said order. To determine these parameters, it is

Table 8
System unit failure modes.

Failure mode	Component	Cause
Loss of traction	Input gear (G1)	Lost or chipped gear teeth
Output actuator unbalance	Output gear (G2)	Lost or chipped gear teeth
Excessive engine vibration	Output shaft (G3)	Crack or wear of the tip of the shaft
Engine overheating	Engine (G4)	Shaft unbalance

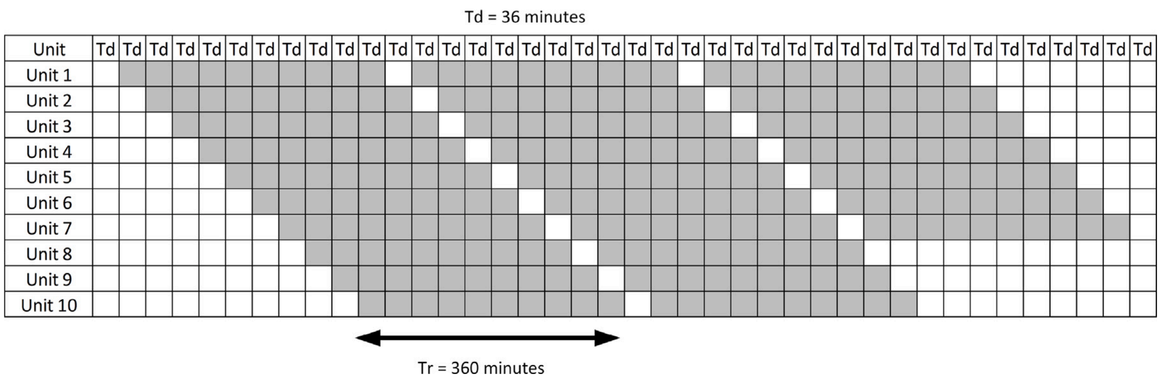

Fig. 11. Case study path discipline.

Table 9
Maintenance policies selected.

Maintenance Strategy	Policy	Observations
Corrective Maintenance	Repair time limit (CM)	The unit is restored by performing minimal maintenance to return it to available before the time limit.
	Repair time limit with Bird cannibalization (CM + Cann)	Bird policy is to select a group of units to act as a component backup in the event of a shortage of spare parts. The designation as a Bird platform is done by a pre-established schedule.
Preventive Maintenance	Time-Based + Block Replacement (PM-Time)	The block replacement policy is applied within a drive when any of the components in a set of the same type have passed a predefined time threshold (Time-based).

considered that the failure-free time of component $G2$ is approximately twice that of component $G1$. In addition, a minimum inventory policy of 1 component per unit of each type is established, except component $G1$, which should have twice the minimum amount of inventory as component $G2$, $G3$, and $G4$. When the inventory level reaches 0, an order must be placed to replace the missing components.

3.1.3. Strategies and maintenance policies selected

Table 9 details the selected maintenance strategies, which include a minimum repair policy, a time-based policy along with a block replacement for like-type components in a unit, and a Bird cannibalization policy. In addition, detailed explanations of each policy are provided.

3.1.4. Evaluation parameters

Indicators are classified into performance, production, costs, and inventory. This has been selected to evaluate the system's performance. Table 10 shows the selected indicators.

3.1.5. Initial parameters of a simulation

Below are some generalities about the initial conditions of the simulation.

- Only units in the "idle" state can be assigned to a mission.
- The failure of a component generates a unit failure.
- Preventive maintenance is performed when the unit is in an "idle" state.
- There is an initial value of spare components in the warehouse.
- There is a parts supply rule through an inventory policy.

Table 10
Parameters evaluated during the simulation.

Group	Indicator
Performance	Mean time between failure (MTBF)
	Mean time to repair (MTTR)
	Operational availability rate (A)
	Mean up time (MUT)
	Mean downtime (MDT)
Production	Mission completed rate (MCR)
	Missions completed
	Daily missions
Cost	Maintenance cost
	Components cost
Inventory	Usage time of a cannibalized component

- All units start in a fully functional "idle" state.

The initial parameters of the simulation are shown in Table 11.

3.2. Results obtained

The use of the model is carried out in various steps. First, the replication of the failure behavior is validated using a known data set. Secondly, failure events are generated from the Weibull distributions of each component to a set of units, and the behavior of the mean failure and repair times is evaluated. Finally, four scenarios are presented that illustrate how the model allows the evaluation of different maintenance policies applied to a multi-unit system

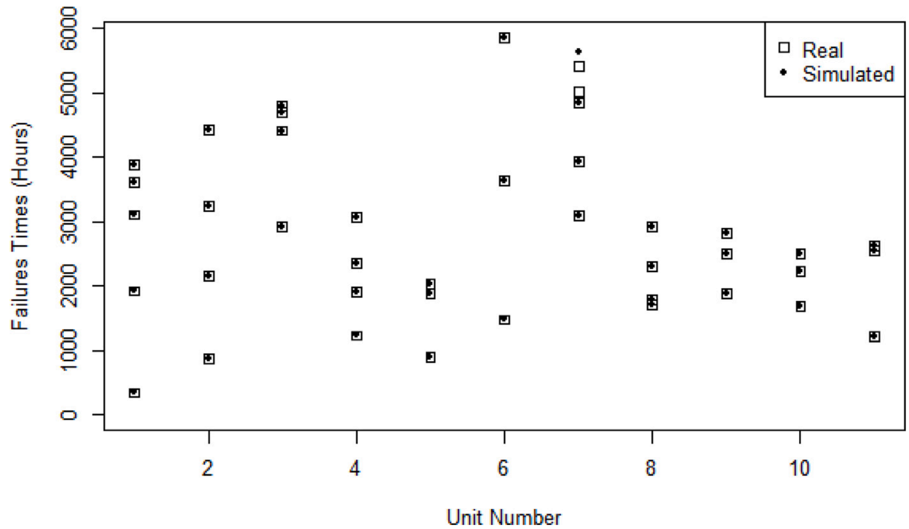

Fig. 12. Comparison of failures generated by the simulated system.

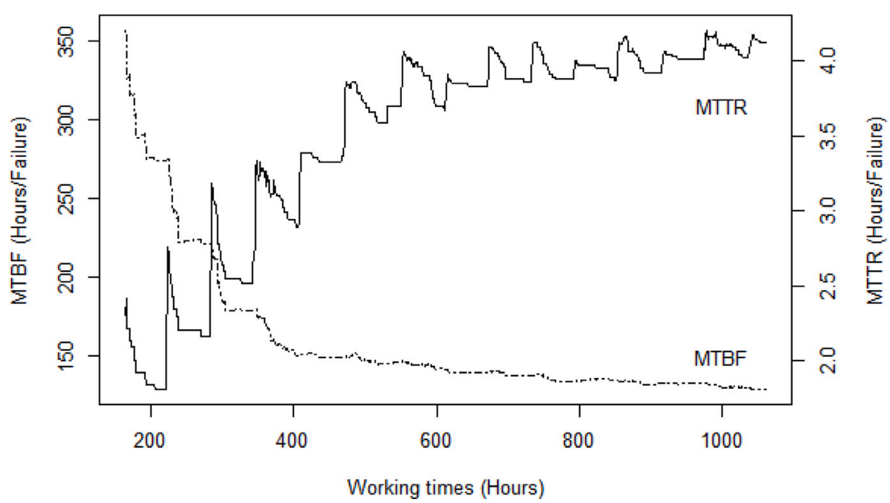

Fig. 13. System response of the MTBF and MTTR indicators.

Table 11
Simulation parameters for the multi-unit system.

Parameter	Values
Units	10
Daily mission	27
Types of components	4 - G1, G2, G3, G4
Modules	4 with 4 components type each one
Initial stock	1 piece per Type component by unit except for G1 with 2 pieces by unit
Component cost	G1 (10$), G2(20$), G3(40$), G4(80$)
Maintenance Cost (Hour)	3$

3.2.1. Verification test

i. *Failure generator module test*

This test evaluates the model's ability to reproduce a set of failures of a known multi-unit system, shown in [58]. The system consists of 11 units, and the dataset contains the failure times of the units for five years. The experiment is repeated 30 times for each simulated unit, and the order of the units is altered in each repetition. A minimum repair maintenance policy is used. The comparison between the input and output data is shown in Fig. 12.

A comparison of the means of the input and output data is used for the analysis. When calculating these averages, it is obtained that the average of the input data is 2857 h, while the average of the output data is 2824 h. The difference between the two means is minimal and lacks significant relevance. To support this result, a paired samples T-test is applied using the Wilcoxon rank method after confirming that the data distribution does not follow a normal distribution. The P value obtained is 0.371. Considering that this P value is greater than 0.05, it can be concluded that there are no significant differences between the input and output data. Therefore, it can be inferred that the model can replicate the failure times of a known multi-unit system.

ii. *Test through performance indicators*

This test validates the behavior of the simulation model through the negative correlation between the MTBF and MTTR indicators. This method is described in [59] and indicates that if the mean time between failures increases, the mean time to repair should decrease and vice versa. If the mean time between

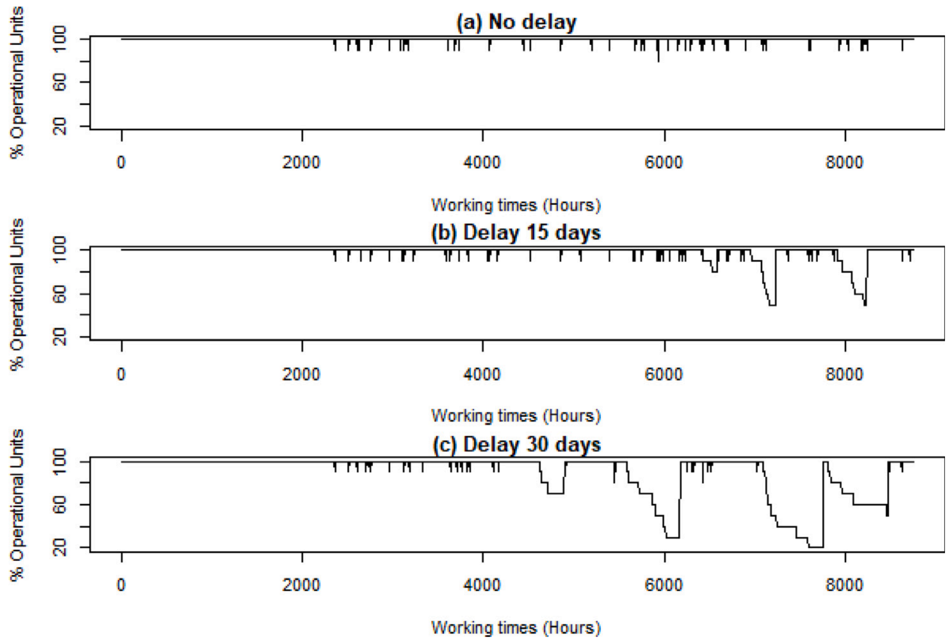

Fig. 14. Percentage of system units capable of carrying out missions applying only Corrective Maintenance (worst scenario).

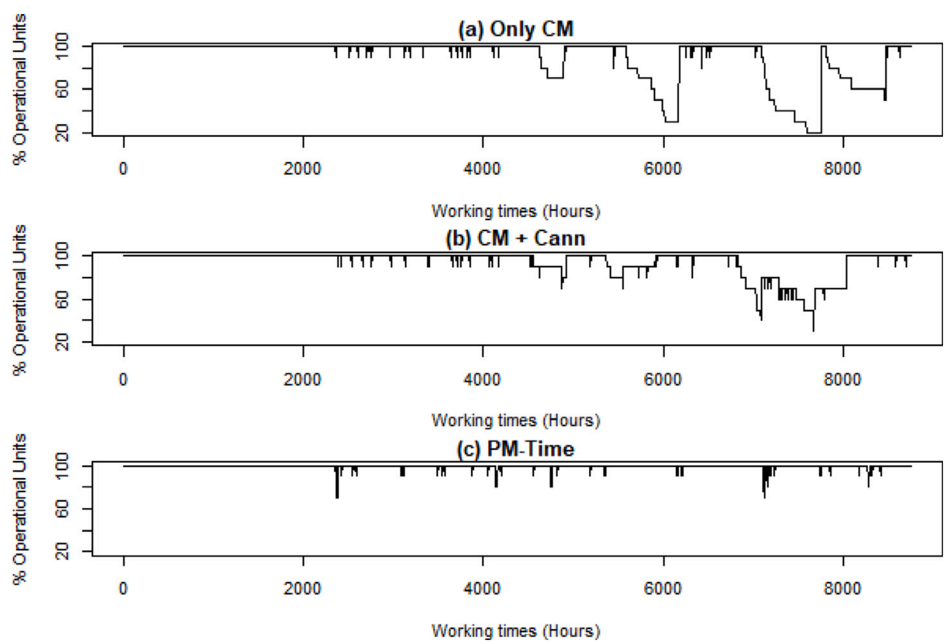

Fig. 15. Percentage of system units capable of carrying out missions.

failures decreases, the mean time to repair should increase. Fig. 13 shows the model's response to the mentioned indicators. The system consists of 10 units, using the initial values shown in Table 11. A total of 30 repetitions were made for each indicator, taking the mean values. Again a minimum repair maintenance policy was used.

The MTBF indicator presents a decreasing trend in the evaluated period. In the same way, the MTTR presents a growing trend for the same period. Operationally, the MTBF shows that the longer the period of use of the units, the time between failures become shorter. Similarly, the mean time to repair increases because the units have more failures. To test the correlation of the indicators, the Pearson correlation coefficient was used, whose value was −0.897, evidencing a strong negative correlation between the indicators.

3.2.2. Scenarios performance

i. *Scenario 1. A multi-unit system with a delay in the supply of spare parts and corrective maintenance (worst scenario)*

This scenario illustrates the percentage change in operating units in a 10-unit system over one year in response to a delay in the spare parts supply. The periods of delay considered are 0, 15, and 30 days respectively. The initial simulation parameters are detailed in Table 11. A minimum repair maintenance policy is implemented.

Fig. 14 shows the behavior of the average percentage of operational units in different scenarios. In the first place, when there is no delay in the supply of spare parts, it is observed that the average percentage of operational units is 99.7%. Although the system shows a high rate of operational units, implementing a minimum repair policy contributes to keeping maintenance times short.

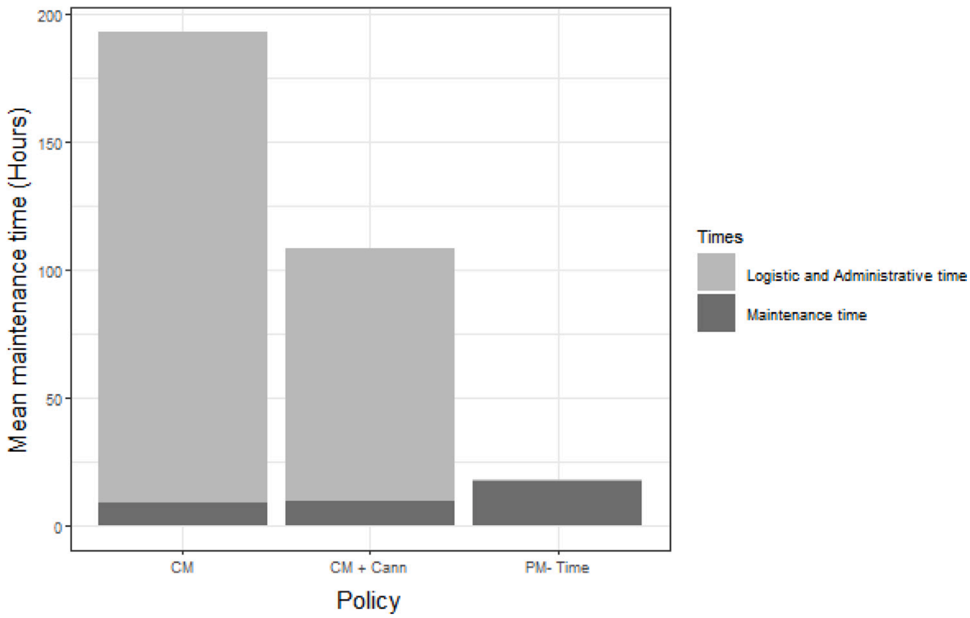

Fig. 16. Comparison of maintenance times for different maintenance strategies.

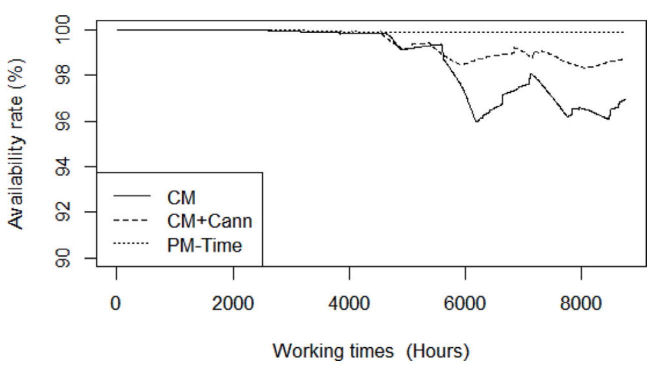

Fig. 17. System operational availability rate for different maintenance strategies.

On the other hand, Fig. 14b shows the average percentage of operational units in the case of a 15-day delay, which reaches a value of 97.5%. However, this average does not reflect the variability in availability during certain periods, specifically between 7,000 and 7,300 h, as well as between 7,900 and 8,200 h, where the percentage of operational units decreased until reaching a value of 50

Finally, Fig. 14c shows the rate of operational units with a delay of 30 days. The average of this rate is 88.9%, which indicates a greater impact on the system's operation. During the periods between 5500 and 6200 h, as well as between 7000 and 7800 h, it is observed that the operating rates range between 20% and 30%. This shows that this scenario presents a significant limitation in its operational capacity in the face of delays in the supply chain of spare components.

ii. *Scenario 2. A multi-unit system with a delay in the supply of spare parts and multiple maintenance strategy*

This scenario builds on scenario 1, where a corrective maintenance policy was found to significantly reduce the operational unit rate when there is a 30-day delay in the spare parts supply chain. In this new scenario, three maintenance policies are implemented: corrective maintenance with cannibalization, corrective maintenance without cannibalization, and preventive maintenance. A bird cannibalization policy determines which units can be cannibalized, and a schedule is established that changes bird units every 15 days. Unlike other studies, it is essential to note that cannibalization in the model is not performed instantaneously. Instead, the simulation reflects the times required to disassemble and manage a cannibalized part. Fig. 15 shows how these different policies act in the presence of a delay in the spare parts supply.

Fig. 15a shows that implementing a corrective maintenance policy presents an average rate of operational units of 88.9%, coinciding with the results obtained in the previous scenario. In contrast, Fig. 15b shows the system's response to applying a maintenance policy with cannibalization, which presents an average rate of operational units of 94.1%. This value reflects a comparative improvement over the policy without cannibalization. However, the average value does not reflect that during the period between 6800 and 8000 h, the system experiences peaks in the rate of operational units, ranging between 30% and 40%. This value indicates a significant decrease in system operability during that period. Using a Wilcoxon rank method, a P-value of 0.001% is obtained, confirming the existence of significant differences between the values of a maintenance policy with and without cannibalization. Finally, Fig. 15c shows how implementing a preventive maintenance policy results in a rate of operational units of 99.5%. By comparison, this result reflects the advantage of this type of policy in terms of system operability.

Comparison of maintenance times. Maintenance time is divided into three categories: logistics, administration, and active maintenance time [35]. Fig. 16 shows the average composition of the maintenance time for each of the policies and parameters used in scenario 2.

For the corrective maintenance policy, it is found that the average maintenance time is 192.4 h, of which 95% corresponds to logistics and administration times. Similarly, using a cannibalization policy, it is observed that approximately 91% of maintenance time is made up of logistics and administration time. However, the mean maintenance time for the policy with cannibalization is 108.6 h, representing a 44% reduction compared to the aforementioned mean times. Finally, the figure allows us to observe that the average maintenance time for a preventive maintenance policy is 18 h, and close to 91% of this time corresponds to effective maintenance time, which indicates a more direct and efficient approach to the maintenance process.

Comparison of operational availability rates. Operational availability is a measure that allows evaluating units' performance as operational elements within a multi-unit system. In this context, availability is not measured individually for each unit but in its performance within the entire system. Thus, availability refers to the time in which a unit can

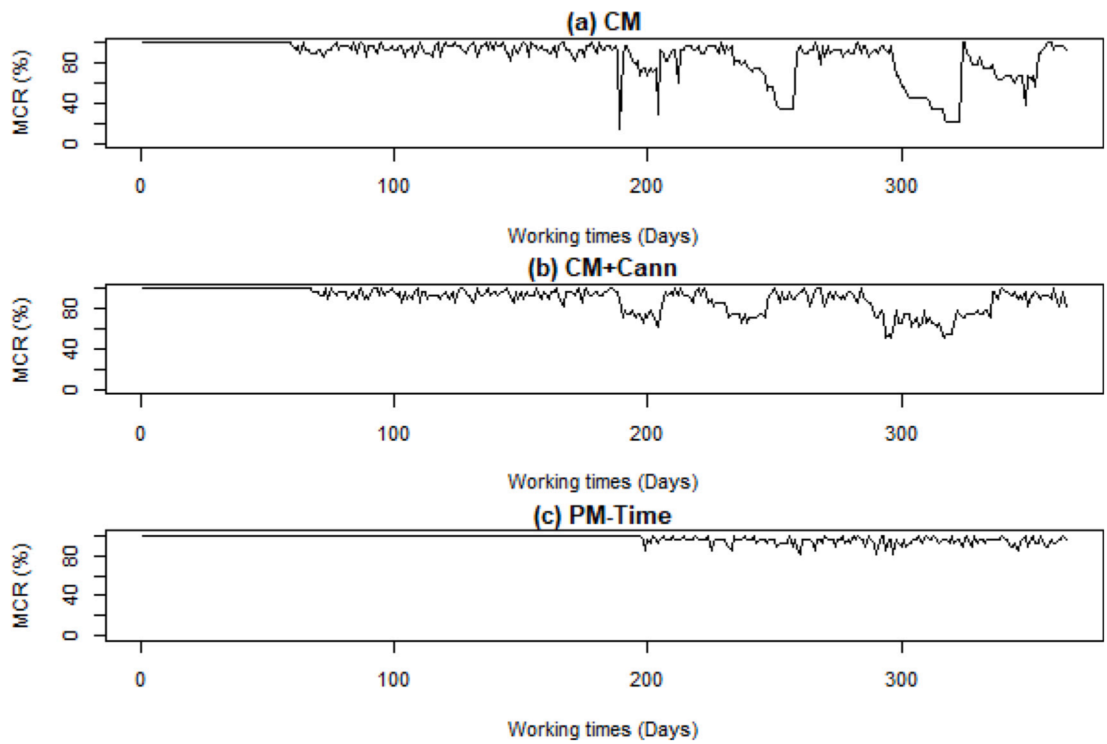

Fig. 18. Comparison of percentage of missions completed with different maintenance strategies.

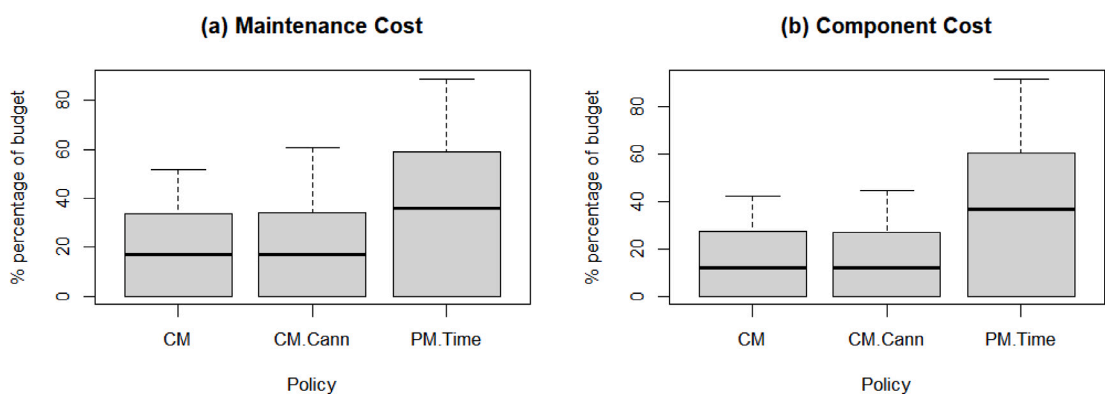

Fig. 19. Boxplot about costs of different maintenance strategies.

carry out its specific function, regardless of whether it is used or not at that moment. The operational availability relates the actives times of the units (MUT) with the unavailable times (MDT) [35]. This definition is shown in Eq. (2).

$$A(\%) = \frac{MUT}{MUT + MDT} * 100 \tag{2}$$

Fig. 17 shows the operational availability of the system for each of the policies implemented in this scenario. A 30-day delay in spare parts supply has been introduced, and the route discipline shown in Fig. 11 has been used. It is observed that the availability rate with the preventive maintenance policy only experiences a decrease of 0.1% in the presence of the delay of spare parts. On the other hand, the operational availability rate decreases by 3.2% with the corrective maintenance policy. In contrast, the corrective maintenance policy with cannibalization results in a 1.3% decrease in operational availability. This value indicates that using a cannibalization policy achieves a 40% improvement in operational availability compared to the corrective maintenance policy in a year.

Comparison of the capacity of system. Meeting the objective in a multi-unit system is essential to guarantee the quality of the service provided. It is through the missions completed by all the units that the required goal is achieved. This section analyzes the fulfillment of the objective in the system multi-unit. Then, the Mission Achievement Rate (MCR) indicator is introduced into Eq. (3), which evaluates the percentage of achievement of the system's daily objective. This indicator relates the number of completed missions to the number of daily missions that must be completed in one year.

$$Mission\ Completed\ Rate\ (MCR)\ (\%) = \frac{Missions\ Completed}{Daily\ Missions} * 100 \tag{3}$$

It is worth mentioning that the system is subject to a 30-day delay in the supply of spare parts. The results of this indicator are presented in Fig. 18. Then, Fig. 18a reveals that due to the limitations in the components, significant decreases in the indicator are observed during the periods of 230 to 260 days and 290 to 330 days, with reductions of between 25% and 30%. These declines indicate a decrease in the quality of service.

On average, the MCR with the corrective maintenance policy reaches 85.3%, which means a significant loss with this policy. On the other

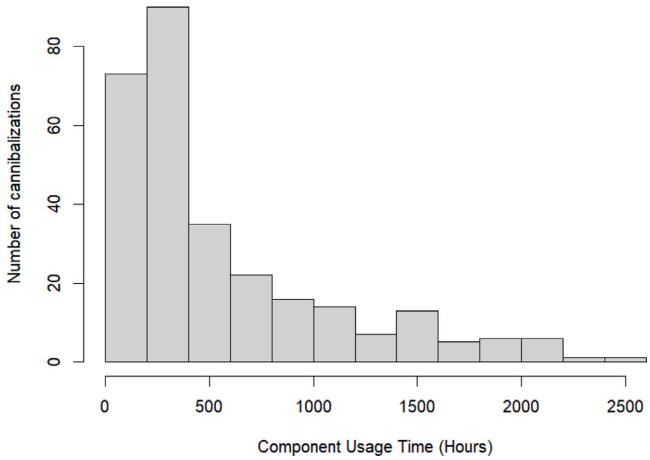

Fig. 20. Distribution of the usage time of the cannibalized "G1" components.

hand, Fig. 18b shows the results obtained when using a cannibalization policy. The average MCR with this policy reaches 89.4%, representing an improvement of 4% compared to the corrective maintenance policy and periods such as 280 and 340 days, where the indicator decreases to 50%. Finally, the preventive maintenance policy shown in Fig. 18c exhibits better compliance with the objective, with an average MCR value of 97.6%. This value demonstrates superior performance compared to the other policies analyzed.

Comparison of costs. Maintenance costs represent a significant part of the operating costs in a multi-unit system. This section analyzes component and maintenance costs for each policy used. Fig. 19 presents a comparative graph of the costs.

The figure shows that the median percentage of budget costs for the corrective maintenance and cannibalization policies are equal in maintenance work (Fig. 19a). However, it is observed that the standard deviation for the maintenance policy with cannibalization in the costs of the maintenance work is 19%, which indicates a greater dispersion compared to the corrective maintenance policy, which has a deviation value standard of 16.1%. This value suggests that a cannibalization maintenance policy, properly managed, does not significantly impact the costs associated with maintenance work. In contrast, Fig. 19b indicates that the median component cost percentages are equal. When analyzing the standard deviations, it is observed that the deviation value for the corrective maintenance policy is 13.3%, while for the cannibalization policy, it is 14.1%, which shows a similar dispersion. This result suggests no significant difference in component costs when using a cannibalization policy.

Usage time of a cannibalized component. Finally, as previously mentioned, using the RUL (Remaining Useful Life) makes it possible to carry out replacements in the components of a unit before a failure occurs. Similarly, identifying a piece with adequate usage time can increase the operational availability of the receiving unit upon receipt of an already-used replacement part.

Fig. 20 presents a histogram showing the relationship between the number of cannibalizations and the usage time when the component was cannibalized. The histogram reveals that most cannibalizations were performed on G1-type components during the 0 to 1000-hour usage period. This information is relevant since it can favor the operational availability of the receiving unit that receives the cannibalized part.

iii. *Scenario 3. Increase in the initial inventory of spare parts, preventing risks of shortages*

In a multi-unit system, maintaining many spare parts poses challenges in management and budget. Having too many components implies unused capital, while having too few pieces can present a risk in case of shortages. This scenario shows the response of a multi-unit system made up of ten units over a year, with a variation of ±50% in the initial components of the system. Fig. 21a shows the operational availability of the system when a corrective maintenance policy is used. If there are few initial components (10-G1, 5-G2, 5-G3, 5-G4), the median has a value of 94.1%, which indicates a significant decrease in system operability.

In contrast, if there are (20-G1, 10-G2, 10-G3, 10-G4) and (40-G1, 20-G2, 20-G3, 20-G4), the medians are 99.8% and 99.9%, respectively, indicating that there is no significant difference in this variation of the initial components. These results can help decide the optimal number of starting components in inventory. On the other hand, when using a cannibalization policy with few spare parts (10-G1, 5-G2, 5-G3, 5-G4), the median value is 98.3%. This value indicates a 4% improvement in the operational availability rate compared to the corrective maintenance policy for the same parameters. However, the other two initial component combinations with a cannibalization policy show little difference concerning the use of a cannibalization policy.

iv. *Scenario 4. Affecting the system with changes in fleet size (system units)*

This scenario presents a context in which there are changes in the available units in a multi-unit system, with a variation of approximately ±50% in the functional units. As in previous scenarios, the system experiences a 30-day delay in the supply of components for a system consisting of 10 units. In this scenario, corrective maintenance and cannibalization policies are contrasted since it has previously been shown that these policies are more sensitive to changes in maintenance logistic times. Fig. 22a shows the operational availability of the system.

Although the availability for a system with five units offers a value of 100%, it is essential to note that the operational availability must be contrasted with the number of missions completed. This value means that the number of missions completed decreases with fewer units. Since the definition of operational availability only considers the times of use and non-availability, the availability rate is raised to the maximum value in this case. On the other hand, Fig. 22b shows a second particularity for a system with five units. The irregular behavior of the

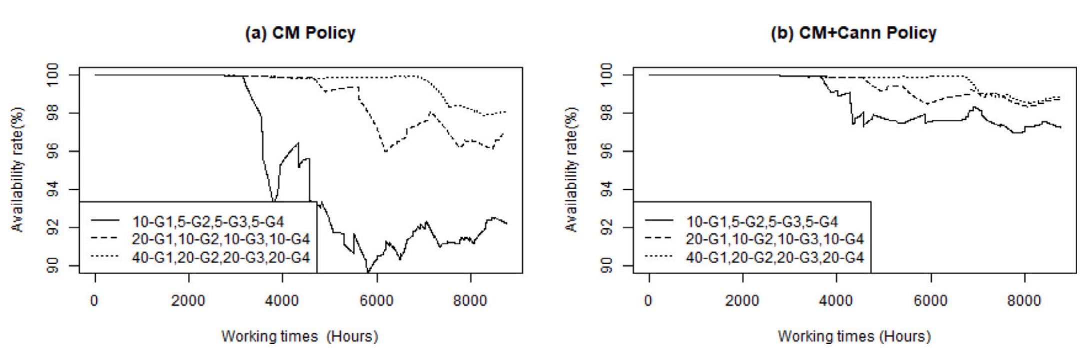

Fig. 21. Operational availability rate for changes in the initial spare parts stock.

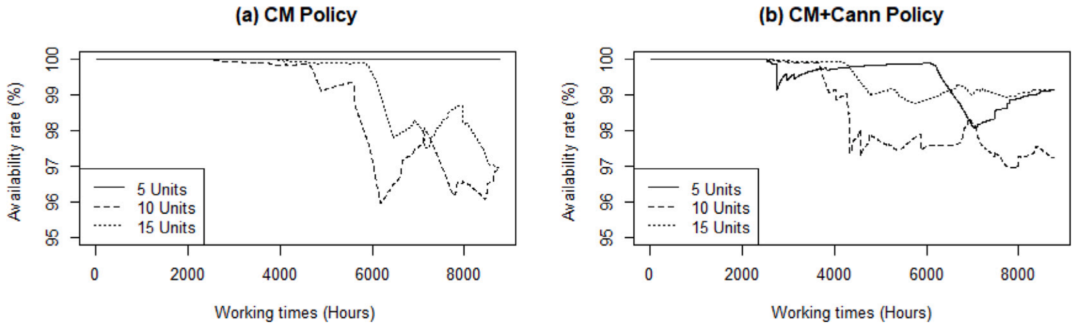

Fig. 22. Operational availability rate for changes in the size of a multi-unit system.

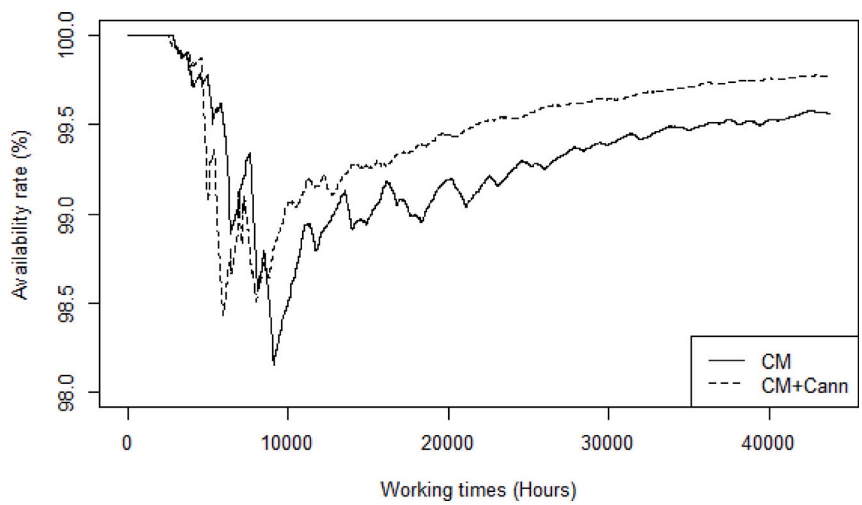

Fig. 23. Operational Availability transient response over 5 years.

availability rate for small systems allows us to infer that cannibalization has lower benefits in systems with a reduced number of units compared to systems with a more significant number of units. The other values of units present a decrease in availability without showing marked differences concerning this parameter.

3.2.3. System transients when maintenance activities are applied.

Applying maintenance policies to a system can cause a transient response, which means that the system reacts and stabilizes again after some time. In multi-unit systems, knowing the transient response can help make decisions on how to adapt the system to the changes that occur in uncertain environments and the actions carried out by the maintenance system.

Fig. 23 shows the transient response of the availability of the case study system for five years when a corrective maintenance policy is applied. It can be seen that the transient has a drop close to 2%, to finally stabilize around 99.5% as the availability value at the end of the period.

In contrast, the corrective maintenance policy with cannibalization shows a drop of approximately 1.5% at the peak of the transient between 2000 and 10000 h but stabilizes at 99.8%, indicating a better system response when using a cannibalization policy. Furthermore, the transitory response of the system with a cannibalization policy is faster than just using a conventional policy.

The MTBF parameter shows the mean time of the drives between failures. Knowing the transient response is also essential for the maintenance manager since it allows them to evaluate the effectiveness of maintenance tasks and manage spare parts inventories. In Fig. 24, it can be seen that using a cannibalization policy during the transient can increase the mean time between failures by 15% compared to a conventional corrective maintenance policy. Furthermore, after the transient between 15000 *y* 20000 h, both policies have similar behavior in the stabilization phase, but the cannibalization policy allows us to observe a better mean time between failures.

On the other hand, the MTTR parameter allows for evaluating the efficiency of the maintenance system during the active maintenance of a unit. In Fig. 25, a difference of approximately 19% less time to repair is observed when only a conventional corrective maintenance policy is used. This is because the cannibalization policy requires more hours of active maintenance.

3.3. Conclusions

The study demonstrated that simulation models help represent maintenance and operation interactions in homogeneous multi-unit systems in the context of supply chain uncertainty.

The results obtained in this study indicate that the proposed simulation model can be an effective tool to support the decision-making of those responsible for maintenance. The model allows the analysis of various aspects of the system in the short and long term. Regarding maintenance policies, the results show that implementing cannibalization positively impacts operational availability, increasing it by approximately 40%. In addition, a 4% improvement is observed in the percentage of missions completed in the short term. In terms of performance indicators, it was found that the application of cannibalization generates a 0.5% reduction in the transient peak of long-term operational availability. Likewise, the mean time between failures (MTBF) improves by 15% when cannibalization is used, although the mean time to repair (MTTR) is higher. This aspect indicates the importance of adequately planning the use of this policy to optimize its effectiveness.

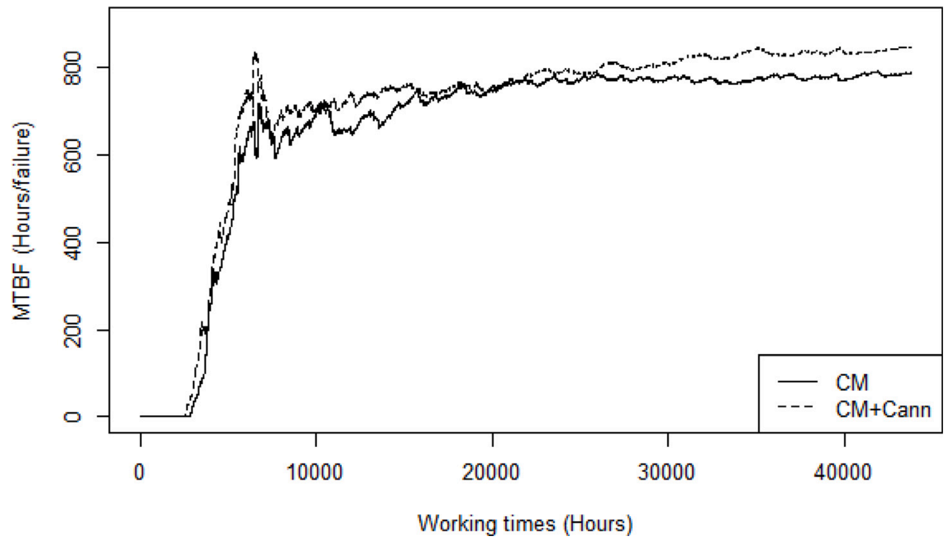

Fig. 24. MTBF transient response over 5 years.

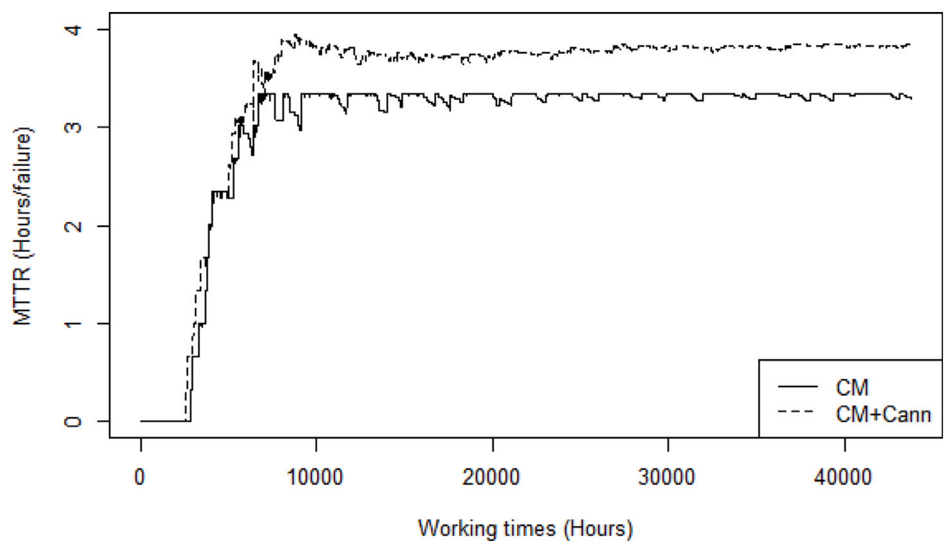

Fig. 25. MTTR transient response over 5 years.

However, there are still limitations in the model that need to be addressed, such as the tracking of cannibalized parts to prevent reuse, the opportunity for cannibalization policies with condition-based maintenance strategies, and operational feasibility in extreme situations such as pandemics and wars that cause limitations on the supply of spare parts for a multi-unit system.

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CRediT authorship contribution statement

Ermilso Diaz: Writing – original draft, Validation, Software, Investigation, Funding acquisition, Conceptualization. **Mariela Muñoz-Añasco:** Writing – review & editing, Supervision, Project administration, Methodology, Conceptualization. **Antonio Correcher Salvador:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization. **Emilio García:** Writing – review & editing, Supervision, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Ermilso Diaz Benachi reports a relationship with Ministry of ScienceTechnology and Innovation of Colombia that includes: funding grants.

Data availability

Data will be made available on request.

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