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INCREASING AVAILABILITY THROUGH TECHNICAL CANNIBALISATION BASED ON SCENARIOS: A CASE STUDY OF TRANSPORT FLEET MAINTENANCE

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***Abstract**:*

This paper presents a formal decision-making model supporting the management of technical renewal processes in transport fleets under conditions of limited spare parts availability and supply uncertainty. The study addresses prolonged vehicle downtime caused by delays in spare parts delivery and proposes technical cannibalisation as an admissible maintenance strategy alongside renewal based on the supply system. Unlike approaches in which cannibalisation is treated only as an emergency action, the proposed framework formalises it as an independent renewal path incorporated into availability management. The model defines the relevant sets of vehicles, component states, spare parts resources, donor and recipient vehicles, and decision rules for selecting the renewal option. The decision-making algorithm considers spare parts availability, acceptable delivery time, component eligibility for cannibalisation and the expected renewal time of potential donor vehicles. The applicability of the model is demonstrated using empirical operational data from a military transport system comprising 50 Iveco Stralis vehicles observed over a three-year period. Three scenarios are analysed: renewal without cannibalisation, partial cannibalisation limited to low-risk components, and total cannibalisation treated as a counterfactual upper-bound scenario. The results show that technical cannibalisation improves fleet availability compared with renewal based only on the supply system. Average fleet availability ranged from 91.81% to 92.72% in the no-cannibalisation variants, depending on the assumed spare parts delivery time. Partial cannibalisation increased availability to 93.05%, while total cannibalisation achieved the highest value of 95.50%. The analysis also indicates that extending the admissible scope of cannibalisation reduces the operational consequences of long downtime intervals and improves fleet readiness stability. The proposed model may serve as a decision-support tool for maintenance planning in transport systems operating under limited spare parts availability, supply uncertainty or crisis conditions. It enables quantitative assessment of alternative renewal strategies and supports selection of maintenance actions aimed at increasing operational availability.

Keywords: *modelling of transport systems, technical cannibalisation, availability, decision-making process*

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1. Introduction

Modern transport systems are characterised by complex structures integrating technical, organisational, and information components into a unified operational framework. The functioning of these systems is based on the coordinated interaction of fleet elements, service and maintenance support, logistical resources, and management processes. Within this framework, each vehicle operates as a component of a larger system, while the overall efficiency and reliability depend on the proper coordination of activities and the effective flow of information (Carvalho et al., 2025; Migawa et al., 2021).

Availability is one of the key parameters characterising the operational efficiency of transport systems (Ziółkowski et al., 2024). It describes the ability of a means of transport to perform assigned tasks at a given moment, in accordance with its intended purpose and operational requirements. Availability is commonly defined as the ratio of the time during which a system remains operational and available for use to the total observation period (Birolini, 2017; Pham, 2003). The literature emphasises that availability results from the interaction of two principal factors: reliability and the effectiveness of maintenance processes. Their appropriate combination minimises downtime and ensures the continuity of system operation (Pham, 2003; Wang & Miao, 2021). Maintaining a high level of availability is a prerequisite for the uninterrupted execution of transport processes, the stability of supply chains, and the safety of traffic participants (Alaei et al., 2024). At the same time, it supports the achievement of organisational objectives, such as timely service delivery and customer satisfaction. Conversely, a low level of availability leads to increased downtime, delays, and financial losses (Mendes et al., 2023).

The failure of a single means of transport may result in a reduction in the availability of the entire fleet. This, in turn, leads to disruptions in operational schedules and increased maintenance costs. This situation may generate a cascade effect, whereby the loss of serviceability of one vehicle increases the operational load on the remaining fleet elements. In the long term, such conditions contribute to uneven resource wear and an increased failure rate (Oszczypała et al., 2023). For this reason, the analysis of the availability of an individual means of transport should always account for its impact on the availability of the entire fleet (Rudyk et al., 2019; Siergiejczyk et al., 2017). It should also be noted that high reliability of individual vehicles does not necessarily guarantee a high level of system availability. If repair, maintenance, or spare parts supply processes are inefficient, overall readiness is reduced (Jacyna & Semenov, 2020; Wang & Miao, 2021). Therefore, availability should be regarded not only as a measure of technical condition, but also as an indicator of management effectiveness and the quality of operational processes in transport systems.

One of the main factors affecting the availability of transport systems and complex operational systems is the timely delivery of spare parts (Koçağa & Şen, 2007; Ullah et al., 2022). Delays in deliveries lead to extended downtimes, which directly reduce availability and operational efficiency indicators (Oszczypała et al., 2022; Rymarz et al., 2022). As emphasised by Semenov and Jacyna (2022), logistical resilience constitutes a key element in ensuring the continuity of technical renewal processes. The authors indicate that, under conditions of increasing uncertainty, supply chains should be designed to withstand operational and economic disruptions (Wróblewski & Niekurzak, 2022). Sherbrooke (2004) notes that delays in the delivery of spare parts lead to an increase in the number of inoperable devices and require higher levels of safety stock to be maintained in order to maintain the required level of operational availability. Furthermore, Alomar and Diallo (2025) presented that, in aviation systems, reducing spare parts delivery times and applying predictive planning methods (ARIMA, Holt–Winters, logistic regression) enabled a reduction in AOG (Aircraft On Ground) downtime by up to 49% between 2020 and 2024. A case study conducted at SmartLynx Airlines demonstrated that reducing the average delivery time from 25 to 12 days and improving coordination with suppliers resulted in a 57% decrease in AOG incidents and reduced total aircraft downtime from 630 to 320 hours per year.

In transport systems, reducing repair times directly reduces costs associated with lost availability, reliability and uncompleted tasks. Shorter spare parts delivery times allow for a reduction in safety stock levels, which translates into lower inventory holding costs. However, reducing waiting times for spare parts is typically associated with increased operating expenditures and requires the implementation of advanced information systems, real-time inventory

monitoring, and close integration with suppliers. In addition, it also necessitates a denser distribution network, faster transport channels, or larger local inventories, thereby increasing both operating and investment costs.

A high level of transport system availability can be achieved through the implementation of maintenance strategies that enhance reliability and reduce the time required to restore technical objects to an operational state. Under conditions of limited spare parts availability and disruptions in global supply chains, technical cannibalisation has become an increasingly common practice in transport fleet maintenance. This strategy involves the deliberate removal of serviceable components from one unit and their use in repairing another unit. Such actions are intended to maintain the required level of system availability in the presence of spare parts shortages, random delivery delays, or urgent operational demands (Babu, 2018; Diaz, Muñoz-Añasco, Salvador, et al., 2023; Fisher, 1990b). Figure 1 presents a simplified concept of the technical cannibalisation process between two similar means of transport. A faulty vehicle (the cannibalised vehicle) contains an operable component (the cannibalised part), while another vehicle (the recipient vehicle) has experienced a failure of the same component (the failed part), which prevents it from performing transport tasks. The process of replacing the damaged component with a technically operable one is referred to as technical cannibalisation.

In practice, technical cannibalisation primarily involves mechanical components that do not require calibration, such as elements of the drive system, cooling system, or auxiliary equipment (Investigation into Equipment Cannibalisation in the Royal Navy, 2017). Research conducted by Salman et al. (2007) confirms that these components are most frequently classified as operable, and their reuse does not require specialised diagnostic procedures. These observations indicate that the applicability of technical cannibalisation depends on the type of component considered. Mechanical and easily replaceable components may be reused with relatively limited additional procedures, whereas electronic and safety-related components require a higher level of technical control, including diagnostic checks, software configuration, calibration and validation. In the present study, this distinction is treated as an admissibility and interpretation constraint rather than as a separate risk variable in the quantitative model.

In transport-related studies, technical cannibalisation has been analysed in various domains, including aircraft maintenance (Babu, 2018; Diaz, Muñoz-Añasco, & Correcher-Salvador, 2023; Fisher & Brennan, 1986; Sheng & Prescott, 2017, 2019), helicopters (Ziółkowski et al., 2022), rolling stock (Sheng & Prescott, 2019), marine vessels (Diaz, Muñoz-Añasco, & Correcher-Salvador, 2023; Gordova & Tverdynin, 2024) and land vehicles (Diaz, Muñoz-Añasco, & Correcher-Salvador, 2023; Dreyfuss & Stulman, 2019; Sheng & Prescott, 2019). This issue is described both as a temporary measure for restoring operational availability and as a method of technical resource management under conditions of spare parts shortages and logistical constraints. Several authors (Diaz, Muñoz-Añasco, & Correcher-Salvador, 2023; Fisher, 1990b; Salman et al., 2007; Sheng & Prescott, 2017) emphasise that technical cannibalisation is a multidimensional phenomenon, and its impact on the functioning of transport systems should be analysed across three main dimensions: operational, economic, and organisational.

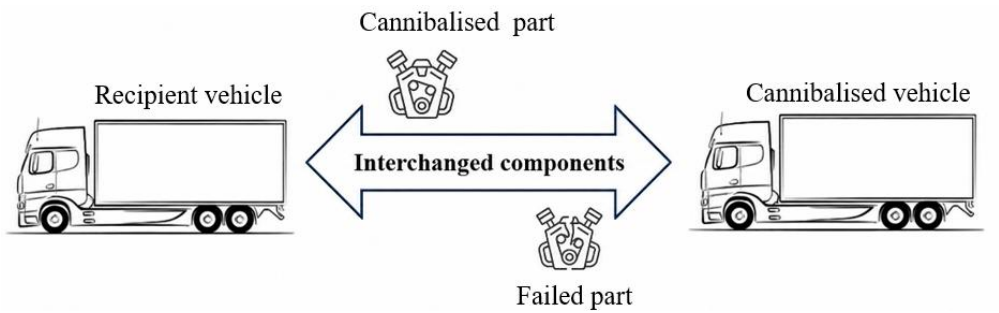


Fig. 1. Technical cannibalisation process.

Technical cannibalisation is widely applied in military equipment maintenance systems. Between 1996 and 2001, the United States Air Force recorded approximately 850,000 documented cases of its use in aircraft maintenance processes (Salman et al., 2007). Similar trends were observed in naval forces, as reported by the National Audit Office (Investigation into Equipment Cannibalisation in the Royal Navy, 2017) in relation to the Royal Navy of the United Kingdom. Between 2012 and 2017, more than 3,200 cases of cannibalisation of naval equipment were recorded. The primary causes identified included spare parts shortages, delivery delays, and budgetary constraints.

The long-standing practice of technical cannibalisation in military systems, observed well before its quantitative scale was formally documented, provided the impetus for the first attempts to assess its impact on operational availability using quantitative methods. One of the pioneering contributions in this field is the work of Fisher and Fisher with Brennan, which focuses on the stochastic modelling of fleet maintenance systems incorporating cannibalisation (W. W. Fisher, 1990; W.W. Fisher, 1990; Fisher & Brennan, 1986).

In the initial stage of the research, Fisher and Brennan (1986) demonstrated that the effectiveness of cannibalisation as a maintenance strategy strongly depends on operating conditions, particularly on the relationship between cannibalisation times and repair times, as well as on the utilisation level of maintenance resources. Subsequently, W.W. Fisher (1990) proposed an analytical formulation of the problem based on a continuous-time Markov process, assuming exponential distributions for failure times, repair times, and cannibalisation activities. The modelling framework was further extended by W. W. Fisher (1990), where definitions of technical cannibalisation, availability measures, and the key factors determining the applicability of this strategy in military systems were systematized.

Technical cannibalisation allows the continuity of operational activities and may significantly reduce repair times and improve availability indicators. At the same time, however, it leads to increased costs, extended secondary repair times, and reduced availability of other fleet units (Dreyfuss & Stulman, 2019; Sheng & Prescott, 2019). Diaz, Muñoz-Añasco, Salvador, et al. (2023) demonstrated that, when appropriately modelled and supervised, cannibalisation may constitute an element of a coherent asset maintenance policy, particularly in environments characterised by high supply uncertainty. The results presented by the authors are based on simulation studies using hierarchical temporal Petri nets, without providing an analytical model of system states. The analysis is limited to observing the evolution of availability and reliability indicators in scenarios involving cannibalisation. Similarly, Sheng and Prescott (2017) modelled system states through the labelling of hierarchical coloured Petri nets, which allows for detailed simulation of maintenance and service processes. However, this approach does not yield an explicit analytical description of the state space or a formal characterisation of the underlying stochastic process. While the models proposed by Sheng & Prescott (2017) focus on optimising multi-stage decision-making and integrating cannibalisation with maintenance policies under conditions of high uncertainty, and the work by Diaz, Muñoz-Añasco, Salvador, et al. (2023) highlights the importance of monitoring and modelling in resource-constrained environments, the present study provides an empirical, quantitative assessment of the effects of different technical cannibalisation scenarios (partial and total) on the availability factor. Previous simulation studies (Salman et al., 2007; Sheng & Prescott, 2017, 2019) indicate that the application of cannibalisation can significantly increase fleet availability, particularly under conditions of limited spare parts. At the same time, (Sheng & Prescott, 2016, 2017) showed that the effectiveness of this strategy strongly depends on its implementation, as it may lead to the accumulation of inefficiencies in selected fleet units serving as component donors (so-called cannibalisation birds).

The aim of this article is to develop a decision-making model for maintenance operation, taking into account the process of technical cannibalisation. The formalisation of variables and decision sets forming the basis of the proposed decision-making algorithm is presented. Unlike previous studies, in which cannibalisation has been treated primarily as a temporary solution, in this study it is treated as an independent path of technical renewal. This approach enables a quantitative assessment of its impact on system availability under conditions of limited spare parts resources. In addition, the proposed model may serve as a decision-support tool for repair planning and availability management in transport fleets. Its

structure and parameter definitions ensure a high degree of generality, allowing the model to be adapted to various types of technical systems that require the optimisation of maintenance processes under conditions of uncertainty and limited resource availability.

On this basis, the empirical part of the study verifies the research thesis that the controlled inclusion of technical cannibalisation as an admissible renewal path improves fleet availability compared with a renewal policy based only on the supply system. More specifically, the analysis examines whether extending the set of components eligible for cannibalisation increases the mean fleet availability coefficient and reduces inter-vehicle dispersion of availability by limiting the effect of long downtime intervals. This thesis is evaluated by applying the no-cannibalisation, partial cannibalisation and total-cannibalisation scenarios to the same chronological sequence of recorded failures.

The main contributions of the paper are as follows:

– the development of a mathematical decision-making model for the application of technical cannibalisation within a transport system maintenance strategy;
– the integration of availability aspects with the technical maintenance strategy, enabling an assessment of the impact of decision-making on fleet availability;
– a quantitative comparison of different levels and scenarios of technical cannibalisation (none, partial, and total) under various decision-making conditions;
– the verification of the proposed methodology through a real-world case study of a land transport system.

The paper is divided into four sections. Section 1 introduces the research problem, defines technical cannibalisation, and reviews the relevant literature concerning its application in transport systems. Section 2 presents the research methodology and the mathematical model, including the definition of sets and decision variables, based on the adopted assumptions. The assumptions of the analysed case study are discussed in detail and include the fleet structure, component classification, delivery time variants, and cannibalisation scenarios. In addition, the decision-making algorithm for selecting the technical renewal path is described. Section 3 presents the results of the analysis of three technical cannibalisation scenarios, obtained using data from an actual transport system. The following scenarios are compared: no cannibalisation, partial cannibalisation, and total cannibalisation, with respect to their impact on vehicle availability. Section 4 provides a summary and final conclusions. The practical implications of applying technical cannibalisation as a strategy to support fleet availability management are highlighted, and directions for further research are proposed.

2. Methodology

2.1. Assumptions

This section presents a mathematical model of the technical cannibalisation process in transport systems under conditions of limited availability of spare parts. The model takes into account the collective structure of the vehicle fleet, the state of the supply system's resources, as well as the time constraints and decision-making functions related to the selection of parts donors. The symbols and decision variables used in the mathematical formulation are specified. The model has been formulated in such a way as to enable the analysis of three alternative scenarios for the technical renewal process: without cannibalisation, with partial cannibalisation, and with total cannibalisation.

The following assumptions have been made:

1. The transport system consists of homogeneous vehicles, which means that all structural and operational components are identical. This ensures full interchangeability of parts among vehicles.
2. The times spent in operable and inoperable states follow arbitrary distributions.
3. A cannibalised vehicle is defined as a vehicle that contains a functional component required for renewal and is characterised by the longest expected technical renewal time.

The notation, variables and acronyms used in the mathematical formulation of the proposed decision-making model are summarised in Table 1.

2.2. Technical renewal implementation scenarios

In transport systems operating under conditions of limited spare parts availability, the technical renewal process of vehicles may follow different decision paths. The selection of an appropriate strategy depends on the tasks performed, the current state of logistical resources, technical parameters of the fleet

and procedural conditions related to the procurement of components.

In accordance with the adopted supply model, the repair of a damaged vehicle can be carried out using the supply system (SS) or through technical cannibalisation. In order to analyse the impact of the decisions made on technical renewal time and overall system availability, three representative scenarios were developed: no cannibalisation, partial cannibalisation and total cannibalisation. These are illustrated in Fig. 2.

To ensure comparability, all three scenarios were applied to the same chronological sequence of failures recorded for the fleet between 2019 and 2021. Thus, the no-cannibalisation and total-cannibalisation scenarios should be interpreted as counterfactual maintenance policies: the empirical failure history was kept unchanged, while only the renewal path and the resulting downtime were modified.

Scenario 1 (no cannibalisation) assumes that the renewal process relies entirely on available logistical resources, whereas Scenarios 2 and 3 involve various forms of technical cannibalisation, which can significantly reduce the renewal time of a single vehicle and thus improve fleet readiness. Each of these is discussed in subsections 2.2.1–2.2.3.

Table 1. Notation, variables and acronyms

Notification	Details
$\boldsymbol{V}$	Set of all objects (vehicles) in the fleet
$\boldsymbol{SS}$	Supply system set
$\boldsymbol{N}$	Number of vehicles in the set $\boldsymbol{V}$
$\boldsymbol{\Psi}$	Set of attributes
$\boldsymbol{v_i}$	$\boldsymbol{i}$-th vehicle in the fleet, $\boldsymbol{i = 1, \ldots, N}$
$\boldsymbol{m}$	Number of parts in the vehicle
$\boldsymbol{vp}$	Vehicle parts
$\boldsymbol{s_{ij}(t)}$	Technical condition of the part $\boldsymbol{vp_j}$ in the vehicle $\boldsymbol{v_i}$ at time $\boldsymbol{t}$: $\boldsymbol{s_{ij}(t) \in \{0, 1\}}$
$\boldsymbol{s_{rj}(t)}$	Technical condition of the part $\boldsymbol{vp_j}$ in the vehicle $\boldsymbol{v_r}$ at time $\boldsymbol{t}$
$\boldsymbol{s_{cj}(t)}$	Technical condition of the part $\boldsymbol{vp_j}$ in the vehicle $\boldsymbol{v_c}$ at time $\boldsymbol{t}$
$\boldsymbol{V_A(t)}$	Set of technically operable vehicles at time $\boldsymbol{t}$
$\boldsymbol{V_B(t)}$	Set of technically inoperable vehicles at time $\boldsymbol{t}$
$\boldsymbol{R_S}$	Renewal process with Supply System
$\boldsymbol{R_C}$	Renewal process with technical cannibalisation $\boldsymbol{v_C \in V_B(t)}$
$\boldsymbol{C}$	Set of parts subject to cannibalisation
$\boldsymbol{C_P}$	Set of parts subject to partial cannibalisation, $\boldsymbol{C_P = \{c_{baterry}, c_{tyre}\}}$
$\boldsymbol{C_T}$	Set of parts subject to total cannibalisation
$\boldsymbol{c_{battery}}$	Spare parts - batteries
$\boldsymbol{c_{tyre}}$	Spare parts - tyres
$\boldsymbol{v_c}$	Cannibalised vehicle (donor)
$\boldsymbol{v_r}$	Recipient vehicle
$\boldsymbol{T(j)}$	Waiting time for parts delivery for part *j*
$\boldsymbol{\tau}$	Acceptable part delivery time
$\boldsymbol{\tau_i}$	Acceptable part delivery time for scenario $\boldsymbol{i}$
$\boldsymbol{T_R\,(v_j)}$	Expected vehicle renewal time $\boldsymbol{v_i}$
$\boldsymbol{A}$	Mean fleet availability coefficient
$\boldsymbol{A_i}$	Availability coefficient of vehicle $\boldsymbol{v_i}$
$\boldsymbol{D_i}$	Total calendar downtime of vehicle $\boldsymbol{v_i}$ during $\boldsymbol{T_i}$
$\boldsymbol{T_i}$	Observation horizon of vehicle $\boldsymbol{v_i}$

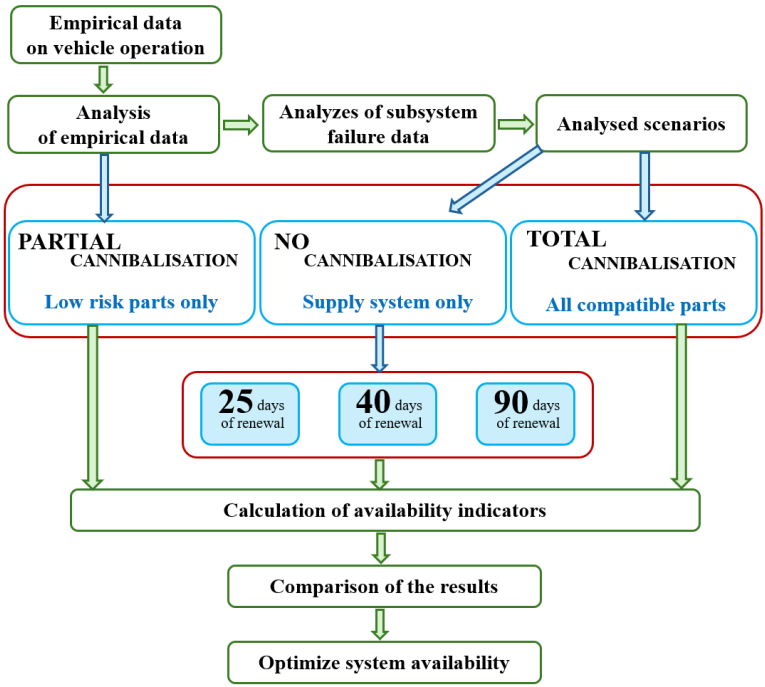


Fig. 2. Cannibalisation-based renewal scenarios: total cannibalisation, partial cannibalisation, and no cannibalisation

2.2.1. Scenario 1. No cannibalisation

In Scenario 1, all components required to restore a vehicle to an operable state are obtained exclusively from the supply system (SS), without sourcing parts from other vehicles in the fleet. The repair process is fully dependent on available stocks and the capability of the supply system to replenish them. For each recipient vehicle v_r, the set of spare parts C subject to cannibalisation is empty, which can be expressed as:

$$C = \emptyset. \tag{1}$$

Depending on the procedure used to obtain parts (the procurement procedure), three variants of the waiting time for order fulfilment were adopted (Table 2). The presented procurement modes $R_{S\text{-}25}$, $R_{S\text{-}40}$ and $R_{S\text{-}90}$ represent three characteristic waiting times for spare parts in a situation where the technical renewal of a vehicle is carried out exclusively through the traditional supply system (SS). The variation in the accepted values of acceptable delivery times for parts τ_i corresponds to the actual differences in the duration of procurement procedures in Poland, conducted in accordance with the *Public Procurement Law* (PPL) and the internal regulations of military institutions as contracting authorities.

Differences in the acceptable spare parts delivery times τ_i are a key factor influencing the availability level of the vehicle fleet available in the transport system. Variant $R_{S\text{-}25}$ represents priority delivery, in which the required parts are available from stock and can be delivered within 25 days. Variant $R_{S\text{-}40}$ reflects the standard parts procurement cycle (up to 40 days). The most time-consuming variant, $R_{S\text{-}90}$, corresponds to a full tender procedure lasting up to 90 days.

In the present implementation, spare parts delivery times were treated deterministically according to the adopted delivery-time variants of 25, 40 and 90 days. The model does not separately parameterise removal and installation time or the probability of secondary damage associated with cannibalisation; these aspects are therefore treated as limitations of the present scenario-based implementation.

Table 2. Procurement procedures taking into account the waiting time for the delivery of spare parts

Designation	Procurement procedure	Description of the procedure	Logistical conditions	Waiting time [days]
$R_{S\text{-}25}$	Accelerated	Tender procedure below EU thresholds conducted in accordance with PPL procedures and internal regulations, using abbreviated procedures.	Available stock within the SS or priority delivery under an accelerated procedure.	25
$R_{S\text{-}40}$	Standard	Tender procedure below EU thresholds conducted in accordance with PPL procedures and internal regulations, without the use of shortened procedures.	No spare parts are available within the SS, and standard delivery procedures apply without the possibility of acceleration.	40
$R_{S\text{-}90}$	Full, statutory duration	Tender procedure above EU thresholds conducted in accordance with the PPL and internal regulations, without the application of shortened procedures.	No spare parts are available within the SS, requiring a full PPL procurement cycle, including non-standard, complex, or foreign deliveries, with no possibility of acceleration.	90

2.2.2. Scenario 2. Partial cannibalisation

Partial cannibalisation represents a technical renewal scenario in which only selected components are removed from inoperable vehicles while access to the supply system (SS) is maintained for the remaining components. In this scenario, the vehicle renewal process is based on the assumption that only specific components may be obtained from donor vehicles. All other parts required for full renewal must come from the supply system. In the analysed model, based on empirical data, it is assumed that only batteries and tyres are subject to technical cannibalisation. The scope of this scenario was deliberately limited to low-risk replaceable components. Batteries and tyres were selected because they were identifiable in the empirical maintenance records and their replacement does not require software configuration, calibration of electronic control units, or validation of safety-critical systems. Therefore, Scenario 2 should be interpreted as a controlled low-risk cannibalisation policy applied to selected consumable or easily replaceable components, rather than as a general rule applicable to all vehicle subsystems. Accordingly, the set of parts subject to partial cannibalisation C_P is defined as:

$$C_P \in \{p_{battery}, p_{tyre}\}. \tag{2}$$

2.2.3. Scenario 3. Total cannibalisation

In the case of total cannibalisation, a damaged vehicle is restored to an operable state exclusively using components removed from a donor vehicle, provided that these components are structurally and functionally compatible and can be installed directly without modification:

$$C_T = \{p_j : j = 1,2,\dots,m\}. \tag{3}$$

Although this scenario is referred to as total cannibalisation, it should not be interpreted as unrestricted reuse of every possible subsystem. It represents a counterfactual upper-bound scenario in which the scope of potentially removable components is wider than in Scenario 2, provided that technical compatibility and direct installation are possible. Electronic or safety-critical components requiring additional software configuration, calibration or formal validation are not explicitly modelled as a separate component class.

In contrast to partial cannibalisation, where only selected components are taken, total technical cannibalisation involves the possibility of obtaining any parts from a vehicle that has been taken out of service and temporarily designated as a donor. In practice, this approach provides the quickest means to restore the readiness of recipient vehicles in conditions of limited spare parts.

2.3. Mathematical model of cannibalisation

Let $V = \{v_1, v_2, \dots, v_N\}$ denote the set of N vehicles forming the fleet under study. Each vehicle v_i is characterised by a set of features Ψ, including, among others, technical condition, type of parts, mileage, and repair history. Each vehicle $v_i \in V$ can be represented as a set of m parts:

$$v_i = \{vp_j : j = 1,2,\dots,m\}. \quad (4)$$

The technical condition of each part is described by the binary state variable $s_{ij}(t)$:

$$s_{ij}(t) \in \{0,1\}, \quad (5)$$

where:

$$s_{ij}(t) = \begin{cases} 1, & \text{if part } vp_j \text{ in vehicle } v_i \\ & \text{is operable at time } t, \\ 0, & otherwise. \end{cases} \quad (6)$$

The state of vehicle v_i can equivalently be represented as a vector of binary component states:

$$v_i = (vp_1, vp_2, \dots, vp_m),\ vp_j \in \{0,1\}, \quad (7)$$

where:

$$vp_j = \begin{cases} 0, & \text{if part } vp_j \text{ is inoperable} \\ 1, & \text{if part } vp_j \text{ is operable} \end{cases}. \quad (8)$$

The fleet set V can be divided into two disjoint subsets of technically operable vehicles $V_A(t)$ and technically inoperable vehicles $V_B(t)$:

$$V_A(t) = \{v_i \in V : \forall_j\ s_{ij}(t) = 1\} \quad (9)$$

$$V_B(t) = \{v_i \in V : \exists_j\ s_{ij}(t) = 0\} \quad (10)$$

Therefore, the following relation applies:

$$V = V_A(t) \cup V_B(t),\ V_A(t) \cap V_B(t) = \emptyset. \quad (11)$$

After an event occurs at time t, consisting of a change in the state of at least one part vp_j of the vehicle v_i from state 1 to state 0:

$$\exists_{j=1,2,\dots,m} \left[s_{ij}(t^-) = 1 \wedge s_{ij}(t) = 0\right], vp_j \in v_i, \quad (12)$$

a technical renewal process is initiated. The procedure for selecting the appropriate technical renewal path, illustrated in Fig. 3, is formulated in the form of a decision diagram.

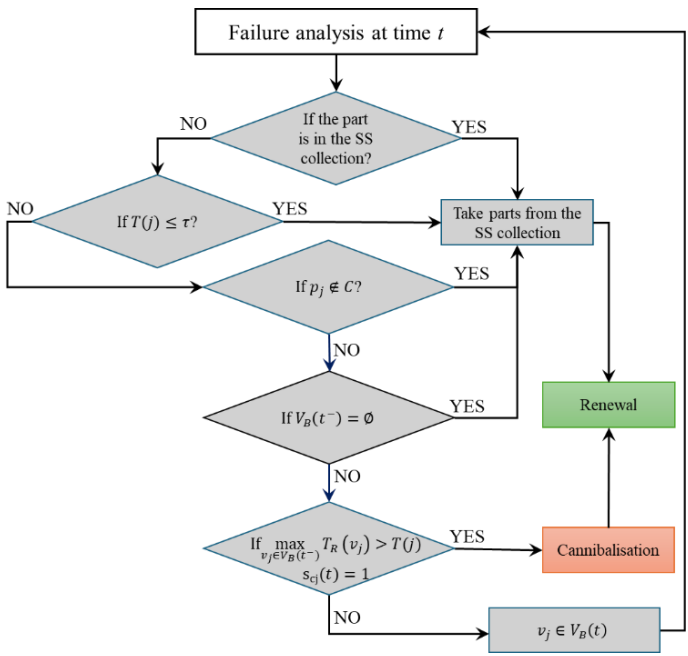


Fig. 3. Flowchart of the proposed method

In the case of damage to a part p_j at time t, the process of verifying the availability of this part in the warehouse SS is initiated. The notation $p_j \in SS$ means replacement of the damaged component from the warehouse SS. Otherwise, the following condition is analysed:

$$T(j) \leq \tau. \tag{13}$$

If condition (13) is fulfilled, it is checked whether part p_j belongs to the set of parts subject to cannibalisation C. In a case where:

$$p_j \notin C, \tag{14}$$

repairs are carried out based on deliveries from the system SS.
Mathematically, the process of repairing a damaged vehicle using parts from SS can be described by the following equation:

$$s_{ij}(t) = \begin{cases} 1, & if\ vp_j \notin C\ \vee (vp_j \in SS \vee T(j) \leq \\ & \leq \tau) \vee V_B(t^-) = \emptyset, \\ 0, & otherwise. \end{cases} \tag{15}$$

If $p_j \in C$ and the fleet system contains at least one faulty unit $VB(t^-) \neq \emptyset$, a vehicle $v_c \in V_B(t^-)$ is searched for which satisfies the condition:

$$v_C \in V_B(t) \wedge T_R(v_C) = \max_{v_j \in V_B(t^-)} T_R\left(v_j\right) > T(j) \wedge s_{cj}(t) = 1, \tag{16}$$

The fulfilment of both conditions is the basis for choosing the repair option based on technical cannibalisation. Otherwise, the decision-making procedure is restarted for the next iteration. Mathematically, this can be expressed by the following equation:

$$R_C\left(v_r, v_C, p_j\right) = \begin{cases} 1, & if\ R_S\left(v_r, SS, vp_j\right) = 0 \wedge vp_j \in C \wedge \\ & V_B(t^-) \neq \emptyset \wedge \max_{v_j \in V_B(t^-)} T_R\left(v_j\right) > T(j) \\ 0, & otherwise. \end{cases} \tag{17}$$

$$R_C\left(v_r, v_C, vp_j\right) = 1 \Longrightarrow \Longrightarrow s_{rj}(t) = 1 \wedge s_{cj}(t) = 0. \tag{18}$$

The Equations (17–18) indicate that the donor vehicle is selected as the unit for which the expected technical renewal time is the longest. This corresponds to the rational use of fleet resources, since the vehicle with the longest restoration time is the least operationally critical and its components can therefore be used first. The process of technical cannibalisation between the donor vehicle v_C and the recipient vehicle v_r implies that the cannibalised part vp_j in the vehicle v_r reaches an operable condition $s_{rj}(t) = 1$, while in the donor vehicle v_C it reaches an inoperable condition $s_{cj}(t) = 0$.

2.4. Calculation of vehicle and fleet availability coefficients

The availability coefficient was expressed in its standard time-based form, commonly used in reliability and availability analysis of technical objects and transport systems (Birolini, 2017; Pham, 2003). For vehicle v_i, the coefficient was calculated as:

$$A_i = \frac{(T_i - D_i)}{T_i} = 1 - \frac{D_i}{T_i} \tag{19}$$

where: T_i is the observation horizon of vehicle v_i, and D_i denotes the total calendar downtime this period.
In this study, downtime was not decomposed into separate diagnosis, spare-parts waiting, repair or cannibalisation-operation components. Instead, D_i represents the complete period from vehicle withdrawal from service to restoration to an operable state. Such an interpretation is consistent with availability-oriented analyses in which downtime is treated as the total period during which a technical object remains unavailable for operation, regardless of the internal structure of the maintenance process (Birolini, 2017; Pham, 2003).
Since the analysed transport system is composed of a set of vehicles whose individual availability affects the availability of the fleet as a whole, the mean fleet availability coefficient was calculated as the arithmetic mean of the vehicle-level coefficients (Oszczypała et al., 2022; Rudyk et al., 2019):

$$A = \frac{1}{N} \cdot \sum_{i=1}^{N} A_i \tag{20}$$

In the analysed dataset, all vehicles were observed over the same calendar period. Therefore, T_i was identical for all vehicles.

3. Results and discussion

3.1. Description of case study

The case study analysed in this paper focuses on Iveco Stralis AT 260 S35Y/P heavy goods vehicles operated within the military transport system. These vehicles are designed for the long-distance transport of bulk, palletised, and containerised loads, while ensuring high performance and structural durability. The vehicles have been in service since 2003 and have been used to perform military road transport tasks in Poland. The analysis was based on operational data collected from 50 tractor units of this type, operated between 1 January 2019 and 31 December 2021.

The impact of technical cannibalisation on the fleet availability index was examined under three decision-making scenarios:

- Scenario 1. No cannibalisation, using spare parts exclusively from the *SS* warehouse, assuming three variants of waiting time for parts: 25 days, 40 days and 90 days;
- Scenario 2. Partial cannibalisation, vehicle renewal using only selected parts (batteries and tyres) from donor vehicles;
- Scenario 3. Total cannibalisation, using all parts available at the time from donor vehicles.

In all cases, the scenario calculations were based on the same empirical failure sequence. Differences between scenarios therefore result from the assumed renewal policy applied after each failure, rather than from different failure histories.

The study provides a quantitative comparison of different levels of technical cannibalisation depending on the adopted scenario. Analysis of the data presented in Table 3 allows an assessment of the availability level of the analysed vehicle fleet over a three-year operational period. As shown in the table, 41 out of 50 vehicles, representing 82% of the total fleet, experienced at least one failure during the observation period. In contrast, the remaining 9 vehicles (18%) recorded no failures, indicating a high level of overall fleet availability. A total of 177 failures were recorded over the three-year period, corresponding to an average failure rate of 3.54 incidents per vehicle during the analysed timeframe. Additionally, 46% of the fleet experienced between zero and two failures, which does not significantly limit operational capability and suggests that the analysed transport system is appropriately organised and managed.

Table 3 reports all recorded failures, regardless of their duration. By contrast, Figures 4-8 are filtered visualisations of downtime intervals and include only periods of vehicle unavailability exceeding one week. The one-week threshold was adopted solely for graphical readability and operational interpretation, because the charts use a weekly time scale and focus on downtimes relevant to fleet-availability planning. Failures removed within less than one week were retained in the failure count reported in Table 3, but were not displayed as separate downtime intervals in Figures 4-8. Consequently, the number of failures in Table 2 should not be directly compared with the number of downtime intervals shown in the figures.

Table 3. Summary of vehicle failures over a three-year period of operation

Vehicle ID	No. of failures	Vehicle ID	No. of failures	Vehicle ID	No. of failures	Vehicle ID	No. of failures	Vehicle ID	No. of failures
1.	6	**11.**	**0**	21.	7	**31.**	**0**	41.	2
2.	5	12.	3	22.	6	**32.**	**0**	42.	5
3.	7	**13.**	**0**	23.	2	33.	8	43.	3
4.	10	14.	5	24.	4	**34.**	**0**	44.	3
5.	8	15.	5	25.	5	35.	1	45.	4
6.	8	16.	1	26.	2	**36.**	**0**	**46.**	**0**
7.	8	17.	12	27.	2	37.	2	47.	2
8.	10	18.	3	28.	4	38.	1	48.	2
9.	3	19.	2	29.	1	**39.**	**0**	49.	4
10.	1	**20.**	**0**	30.	5	40.	4	50.	1

3.2. Comparison of cannibalisation scenario results

Table 4 and Figures 4–8 present a comparison of the impact of the analysed technical renewal scenarios on transport fleet availability. The analysis includes three reference variants in which technical renewal is performed exclusively through the supply system and differentiated by spare parts delivery time, as well as two alternative scenarios involving technical cannibalisation: partial and total. The availability values reported in Table 4 were obtained using Eqs. (19)–(20), with each scenario applied to the same chronological failure sequence. Therefore, the differences between the scenarios result from the adopted renewal policy and the resulting downtime, rather than from different failure histories. The partial cannibalisation scenario reflects the empirical data from the analysed real transport system, in which this operational strategy was implemented. The remaining scenarios were treated as counterfactual variants and compared with the implemented partial cannibalisation policy.

To illustrate the operational benefits of the implemented partial cannibalisation policy, the no-cannibalisation scenario was analysed using three delivery-time variants, as shown in Figures 5–7. These charts present the potential additional downtime that would have occurred for the seven recipient vehicles if the same failure sequence had been handled exclusively through the supply system. As the assumed spare parts delivery time increases, the potential downtime of these vehicles also increases.

The subsequent analysis estimated the potential benefits of extending the implemented partial cannibalisation policy to total cannibalisation. The cannibalisation window is defined as the time interval during which a donor vehicle transfers operable components to restore inoperable recipient vehicles. Expanding the range of components eligible for cannibalisation produced 35 potential cannibalisation uses involving 15 recipient vehicles, not 35 separate recipient vehicles. Figure 8 presents these time savings as potential renewal time reduction. The maximum reduction in vehicle downtime, amounting to 46 weeks, was observed for vehicle no. 41. This value refers to the time-based reduction of the long downtime interval under the total-cannibalisation scenario, whereas the second failure recorded for this vehicle in Table 3 was resolved within less than one week and is therefore not shown in Figure 8.

In the partial cannibalisation scenario, 7 donor vehicles and 7 separate recipient vehicles participated in component exchanges. A total of 11 cannibalisation operations were performed, limited exclusively to low-risk components such as tyres and batteries. This strategy resulted in a high fleet availability coefficient of 93.05%, a level that could not have been achieved under any scenario without cannibalization.

It should also be emphasised that the empirical data did not identify electronic or safety-critical components as a separate cannibalisation category. The real-data partial cannibalisation scenario was limited to tyres and batteries, while the total cannibalisation scenario was used as a counterfactual availability benchmark rather than as evidence of unrestricted cannibalisation of all component types. Consequently, the model does not estimate additional risk coefficients for electronic or safety-critical components. The results should therefore be interpreted as availability effects under defined component admissibility assumptions. In practical maintenance decision-making, cannibalisation of electronic or safety-related systems should require additional diagnostic, validation and formal technical approval procedures.

Table 4. Technical cannibalisation scenarios – comparative data

Type of cannibalisation	Number of cannibalised vehicles	Number of Recipient vehicles	Number of cannibalisation uses	Average availability values [%]	Median of availability values	Interquartile Range (IQR) Q3-Q1
No cannibalisation - 25 days	—	—	—	92.72	96.82	0.0959
No cannibalisation - 40 days	—	—	—	92.49	96.64	0.0912
No cannibalisation - 90 days	—	—	—	91.81	96.64	0.0469
Partial cannibalisation	7	7	11	93.05	96.92	0.1051
Total cannibalisation	2	15	35	95.50	98.04	0.1098

In the total cannibalisation scenario, two vehicles served as donors of components for the other units in the fleet. In total, 15 vehicles acted as recipients, and the number of cannibalisation operations performed was 35. This means that individual donors supported more than one recipient. The fleet availability coefficient obtained was 95.50%, which was the highest among all the scenarios analysed. Compared with the no-cannibalisation variants, the availability gain depends on the adopted delivery-time baseline: it amounts to 2.78% relative to $R_{S\text{-}25}$ (from 92.72% to 95.50%), 3.01% relative to $R_{S\text{-}40}$ (from 92.49% to 95.50%), and 3.69% relative to $R_{S\text{-}90}$ (from 91.81% to 95.50%). Compared with partial cannibalisation, total cannibalisation increased mean availability by 2.45%. Partial cannibalisation increased mean availability by 0.33% relative to $R_{S\text{-}25}$ and by 1.24% relative to $R_{S\text{-}90}$. Consequently, relative to the 90-day no-cannibalisation baseline, partial cannibalisation accounts for approximately 34% of the availability gain achieved by total cannibalisation, calculated as (93.05–91.81)/(95.50–91.81). If the 25-day baseline is adopted, the corresponding share is approximately 12%. This indicates that partial cannibalisation provides a measurable availability improvement, although the full availability gain is achieved only when the admissible scope of cannibalisation is extended. The availability coefficient values obtained in the analysed scenarios confirm the positive impact of technical cannibalisation on the operational availability of the transport fleet.

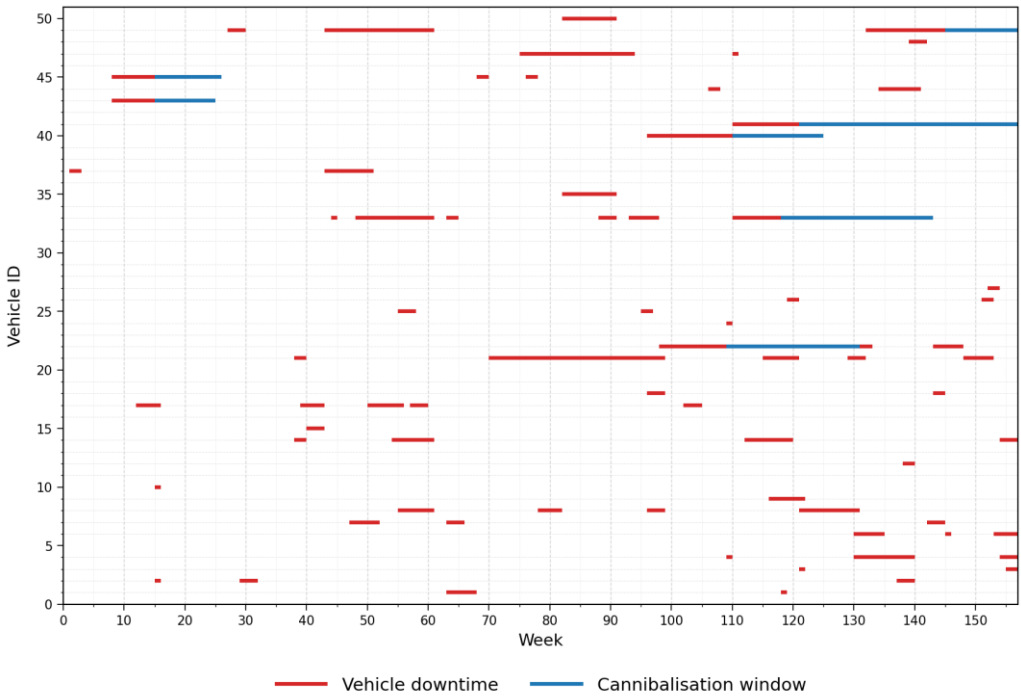


Fig. 4. Partial cannibalisation – empirical data of the real transport system

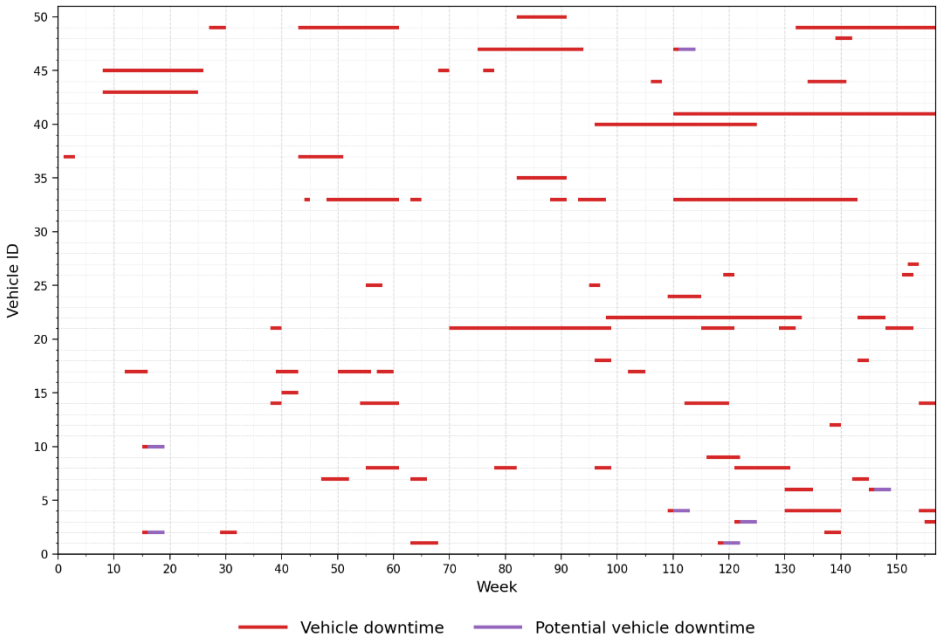


Fig. 5. No cannibalisation - 25 days

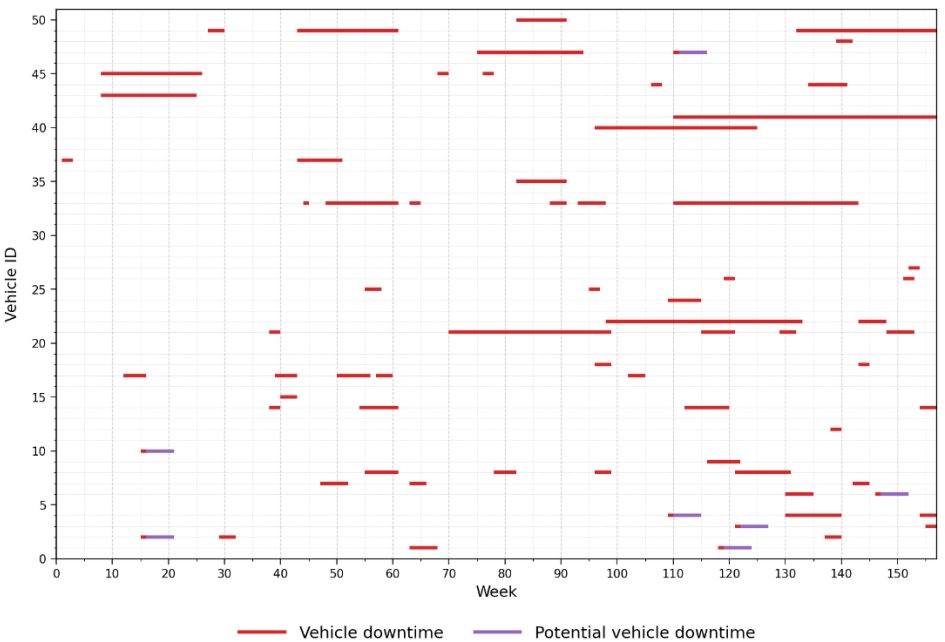


Fig. 6. No cannibalisation - 40 days

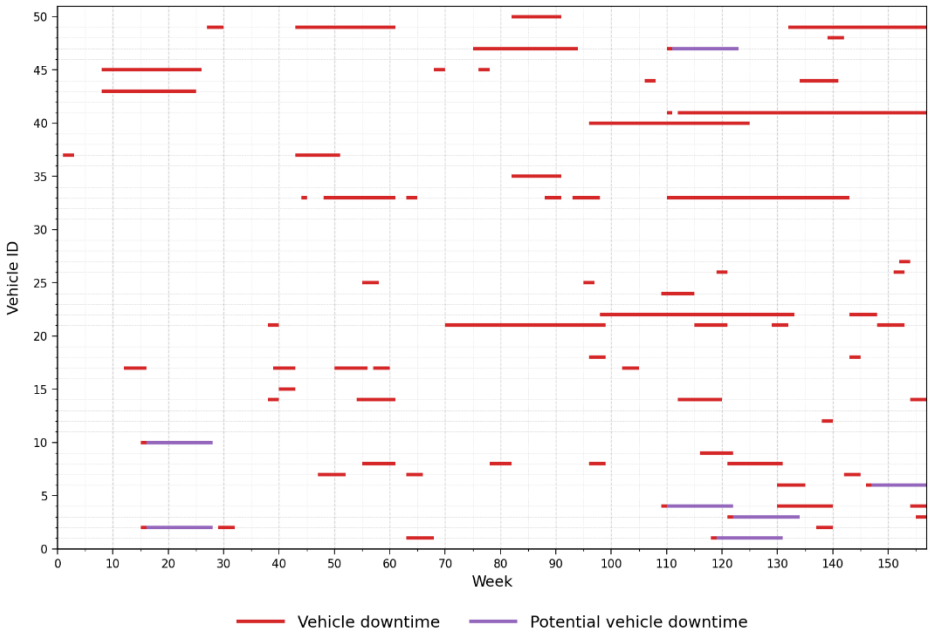


Fig. 7. No cannibalisation - 90 days

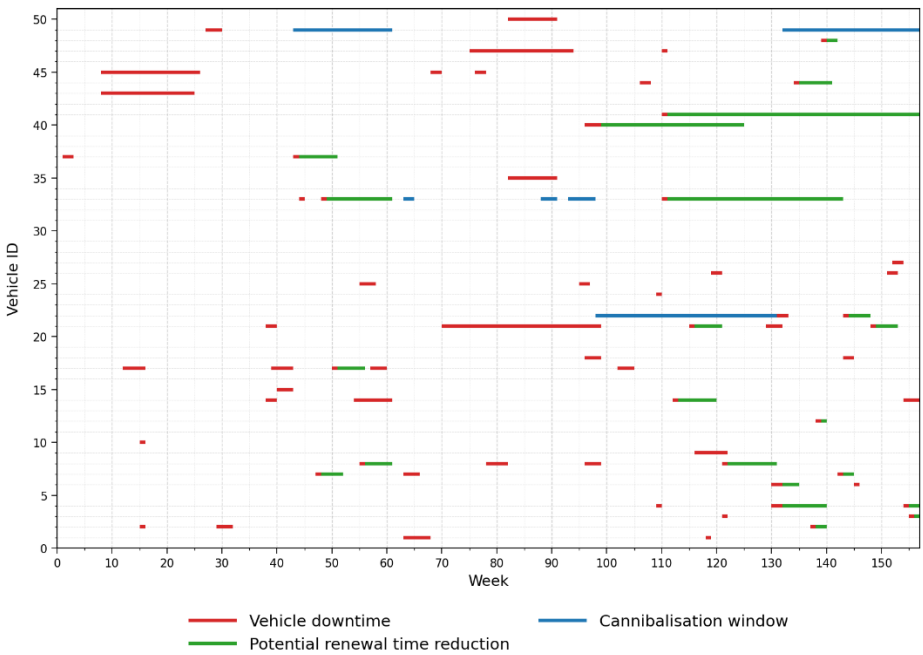


Fig. 8. Total cannibalisation

Note: Figures 4-8 should be interpreted as visualisations of selected downtime intervals rather than as event-by-event plots of all failures reported in Table 3.

A graphical comparison of the availability coefficient distributions for the analysed scenarios is presented using Fig. 9. Presented box plots enable the assessment of distribution location measures, interquartile ranges, and the presence of outliers. In addition, the histograms of the availability coefficient shown in Fig. 9 allow for an analysis of the shapes of the empirical distributions, particularly with respect to skewness, value concentration, and the occurrence of extreme cases depending on the adopted technical renewal strategy.

Scenarios involving cannibalisation are characterised by higher median values (0.9692–0.9804) than the variants without cannibalisation (0.9664–0.9682). Their IQR values (0.1051–0.1098) are comparable to or slightly higher than those observed in the no-cannibalisation variants (0.0469–0.0959).

Scenario variants without cannibalisation are characterised by greater dispersion of availability coefficient values. Depending on the adopted spare parts delivery time variant (25, 40 or 90 days), the median availability values range from 0.9664 to 0.9682. The availability coefficient distributions show the presence of four outliers in the lower range below 0.8000, which confirms the system's greater susceptibility to organisational downtime associated with waiting for spare parts and component shortages.

The availability coefficient distribution for variant $R_{S\text{-}25}$ (25-day spare parts delivery time) is irregular, with observations predominantly concentrated in the upper range of values. A high level of availability ($A > 95\%$) is achieved by 60% of the fleet vehicles (30 out of 50), while the availability of 16 vehicles (32%) was in the range of 80.00–95.00%. At the same time, 4 vehicles (8%) achieved availability levels below 80.00% (including two cases below 70.00%), confirming the presence of lower-range outliers.

For longer spare parts delivery times (Variant 2 and Variant 3), a decrease in mean fleet availability is observed (Fig. 9). The mean availability decreased from 92.72% for $R_{S\text{-}25}$ to 92.49% for $R_{S\text{-}40}$ and 91.81% for $R_{S\text{-}90}$, while the median values remained relatively stable, ranging from 96.82% for RS-25 to 96.64% for RS-40 and RS-90. This indicates that longer logistical delays did not shift the entire distribution uniformly, but mainly affected vehicles exposed to longer renewal periods.

A comparison of variants RS-25 and RS-40 indicates that extending the delivery time of parts did not lead to major changes in the number of vehicles in individual availability ranges.

However, the differences between these variants are revealed in the shape of the distribution on the histogram, and in particular in the shift of observation concentration within the 80.00–95.00% from the 90.00–95.00% interval towards 80.00–90.00%, as well as in the increased dispersion of values below 80.00%. Although the number of low-availability observations remains unchanged, their distribution becomes more heterogeneous. A further extension of the delivery time to 90 days (variant $R_{S\text{-}90}$) intensifies this trend, resulting in an expanded lower tail of the distribution and reduced concentration of values in the upper availability range. This phenomenon confirms the increasing sensitivity of the system to logistical delays as spare parts delivery times increase. Consistently, extending delivery times from 25 to 90 days resulted in a systematic increase in the standard deviation of the analysed sample ($R_{S\text{-}25}$: $\sigma = 0.0991$, $R_{S\text{-}40}$: $\sigma = 0.0994$, $R_{S\text{-}90}$: $\sigma = 0.1029$), which also indicates increasing variability and greater heterogeneity of the readiness coefficient distribution in scenario variants without cannibalisation. In the partial cannibalisation scenario, the distribution of the availability coefficient is characterised by limited variability, as evidenced by an interquartile range of $IQR = 0.1051$.

In the partial cannibalisation scenario, the median (Me) of the distribution was $Me = 0.9692$ (96.92%) and was comparable to the scenarios without cannibalisation, while the standard deviation ($\sigma = 0.091$) was lower than that observed in the no-cannibalisation scenario variants. The lower quartile $Q_1 \approx 0.8949$ indicates that 75% of the vehicles achieved an availability level of at least 89.5%. The distribution histogram shows right-skewed asymmetry with a clear concentration of observations in the upper range of values, with 66% *of the fleet* (33 out of 50 vehicles) attaining availability levels exceeding 95%. The lowest recorded availability coefficient was 52.57%, which is analogous to the minimum value observed in the no-cannibalisation scenario.

Within the analysed sample, 43 cases were identified in which the application of the partial

cannibalisation scenario did not result in an improvement in availability relative to the scenario without cannibalisation. This concerned vehicles with damaged parts not included in the replacement strategies. The observed distribution structure reflects the limitation of dividing the fleet into fully operable and long-term inoperable vehicles and is a direct result of the selective nature of maintenance interventions. Available components are preferentially allocated to vehicles with shorter expected recovery times and higher operational potential. As a result, part of the fleet achieves readiness levels above 95%, while vehicles requiring the replacement of components excluded from the cannibalisation strategy remain in the lower tail of the distribution. This mechanism leads to a smoothing of the distribution and eliminates the pronounced bimodality characteristic of the scenarios without technical cannibalisation.

The total cannibalisation scenario is characterised by the highest central tendency of the availability coefficient distribution $Me = 0.9804$ (98.04%) and the lowest level of dispersion in terms of standard deviation. This is reflected in the lower quartile value $Q_1 \approx 0.8902$, the concentration of 72% of the sample (36 out of 50 observations) above the 95% availability threshold, and the presence of only two observations with availability values below 80%. As a result, 50% of the vehicles are located within the interquartile range defined by $Q_1 - Q_3$ (0.890212–1.0000), which indicates a strong concentration of the distribution in the upper part of the scale and a high degree of homogeneity in fleet availability.
The lowest standard deviation value ($\sigma = 0.0610$) observed across all scenarios results from the limitation of extremely low availability values and the concentration of observations in the upper range of the distribution. This mechanism leads to a reduction in average deviations from the mean, confirming that total cannibalisation not only increases the overall availability level but also stabilises its distribution. These results suggest that, under severe spare-parts shortages, broader cannibalisation may help maintain a higher and more uniform level of fleet availability. However, because the empirical data used in this study were collected under peacetime operating conditions, the applicability of this conclusion to armed-conflict conditions should be treated as a hypothesis requiring further verification.

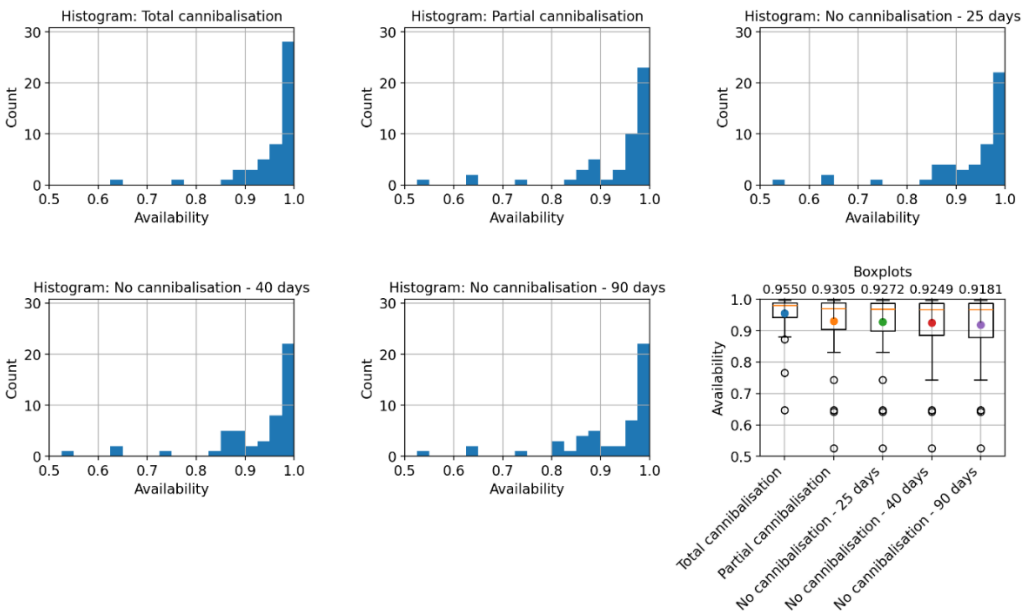


Fig. 9. Distributions of the availability coefficient for individual scenarios

4. Conclusions

This paper proposes a method for assessing the impact of different technical cannibalisation scenarios on the availability of a transport fleet operating under conditions of limited spare parts availability. The application of the proposed analytical framework enabled a quantitative comparison of three technical maintenance scenarios.

The analysis included both fleet-level availability indicators and unit-level availability distributions. This made it possible to identify differences in operational stability and susceptibility to logistical and organisational downtime associated with spare parts delivery delays. Previous studies addressing this research problem have not focused on a quantitative comparison of different cannibalisation scenarios. The evaluation of all analysed scenarios indicates that increasing the scope of cannibalisation interventions results not only in an increase in the average fleet availability level (from 91.81% for $R_{S\text{-}90}$ to 95.50% for the total cannibalisation scenario), but also in a reduction in variability of the availability coefficient among individual vehicles. This effect is reflected in lower distribution dispersion and a stronger concentration of observations in the upper range of values. Consequently, higher fleet availability and a more uniform distribution of availability levels across vehicles are achieved.

The no cannibalisation scenario proved to be the least effective under the longest spare-parts delivery time. In this group of variants, mean fleet availability decreased from 92.72% for $R_{S\text{-}25}$ to 92.49% for $R_{S\text{-}40}$ and 91.81% for $R_{S\text{-}90}$. Although most vehicles still operated with relatively high availability, failures requiring spare parts introduced downtime dependent on the adopted delivery-time variant. The analysis demonstrates that the implementation of controlled technical cannibalisation leads to a measurable improvement in transport system availability under conditions of limited spare parts supply. In the partial cannibalisation scenario, the mean availability coefficient increased to 93.05%, while in the total cannibalisation scenario it increased to 95.50%. At the same time, a larger share of vehicles was concentrated in the upper availability range, which indicates that technical cannibalisation reduced the operational impact of long downtime intervals affecting selected vehicles.

Total cannibalisation, although requiring the designation of a portion of the fleet as component donors, provides the highest operational availability potential. The achieved average fleet availability of 95.50% was the highest among all analysed scenarios. This scenario effectively reduces long-term downtime caused by a lack of spare parts, particularly improving the performance of the vehicles most affected by long downtime. Furthermore, the reduction in standard deviation to $\sigma = 0.0610$ confirms a substantial decrease in variability of availability levels across the fleet.

The application of technical cannibalisation resulted in an increase in the share of vehicles with very high availability ($A > 95\%$) from 60% in scenario variants without cannibalisation to 66% in the partial cannibalisation scenario and to 72% in the total cannibalisation scenario. These results confirm that technical cannibalisation increases average fleet availability and improves the distribution of availability by shifting a larger part of the fleet into the high-availability range. Consequently, it represents an effective tool for improving transport system availability in environments characterised by limited spare parts access.

Technical cannibalisation allows for the immediate acquisition of a required component from another vehicle, reducing repair time and thus increasing fleet operational availability (Salman et al., 2007; Sherbrooke, 1971, 2004). However, its application requires increased workload for maintenance personnel and involves a risk of secondary damage during component dismantling (Diaz, Muñoz-Añasco, & Correcher-Salvador, 2023; Dreyfuss & Stulman, 2019; Fisher, 1990a). Moreover, excessive reliance on cannibalisation may result in the permanent withdrawal of certain vehicles as donors, complicating their future restoration to full operational capability (Diaz, Muñoz-Añasco, Salvador, et al., 2023; Salman et al., 2007; Sheng & Prescott, 2016). Therefore, the selection of an appropriate cannibalisation scenario should account for operational priorities and acceptable risk levels. If maximising availability is the primary objective, total cannibalisation yields the most favourable results. However, if the key objective is to reduce costs and keep the maximum number of vehicles in service, partial cannibalisation is a compromise that improves availability with less structural disruption to the fleet.

Future research may extend the proposed model by incorporating cost-based and predictive analyses of different cannibalisation levels and logistical delay scenarios. Such an extension may build on multi-echelon spare-parts inventory models, including METRIC-type approaches, to jointly assess spare-parts allocation, cannibalisation intensity and the cost of maintaining operational availability. This would allow for a more comprehensive evaluation of the economic viability of technical cannibalisation as an alternative or complement to traditional spare-parts procurement. In particular, future studies should identify the threshold of cannibalisation intensity at which operational gains, such as increased fleet availability and reduced downtime, outweigh the additional costs of maintenance work, time consumption, donor-vehicle restoration and the risk of secondary damage.

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