UNIVERSIDADE FEDERAL DO PARANÁ

ISLAN DE CASTRO GOMES

OPTIMIZATION OF SPARE PARTS INVENTORY MANAGEMENT FOR CAPITAL GOODS MAINTENANCE

CURITIBA
2023

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OPTIMIZATION OF SPARE PARTS INVENTORY MANAGEMENT FOR CAPITAL GOODS MAINTENANCE

Projeto de dissertação apresentado para obtenção do grau de Mestre em Engenharia de Produção. Curso de Pós-Graduação em Engenharia de Manufatura, Setor de Tecnologia, Universidade Federal do Paraná.

Orientador: Prof. Dr. Fernando Deschamps
Coorientador: Prof. Dr. Pablo David Valle

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No dia vinte de novembro de dois mil e vinte e tres às 08:30 horas, na sala Teams, Sala Virtual, foram instaladas as atividades pertinentes ao rito de defesa de dissertação do mestrando **ISLAN DE CASTRO GOMES**, intitulada: **Optimization of spare parts inventory management for capital goods maintenance**, sob orientação do Prof. Dr. FERNANDO DESCHAMPS. A Banca Examinadora, designada pelo Colegiado do Programa de Pós-Graduação ENGENHARIA DE MANUFATURA da Universidade Federal do Paraná, foi constituída pelos seguintes Membros: FERNANDO DESCHAMPS (UNIVERSIDADE FEDERAL DO PARANÁ), GONZALO ENRIQUE MEJIA DELGADILLO (UNIVERSIDAD DE LA SABANA), DAGMAR PIOTR TOMANEK (INTERNATIONAL SCHOOL OF MANAGEMENT), MARCIO FONTANA CATAPAN (UNIVERSIDADE FEDERAL DO PARANÁ). A presidência iniciou os ritos definidos pelo Colegiado do Programa e, após exarados os pareceres dos membros do comitê examinador e da respectiva contra argumentação, ocorreu a leitura do parecer final da banca examinadora, que decidiu pela APROVAÇÃO. Este resultado deverá ser homologado pelo Colegiado do programa, mediante o atendimento de todas as indicações e correções solicitadas pela banca dentro dos prazos regimentais definidos pelo programa. A outorga de título de mestre está condicionada ao atendimento de todos os requisitos e prazos determinados no regimento do Programa de Pós-Graduação. Nada mais havendo a tratar a presidência deu por encerrada a sessão, da qual eu, FERNANDO DESCHAMPS, lavrei a presente ata, que vai assinada por mim e pelos demais membros da Comissão Examinadora.

Curitiba, 20 de Novembro de 2023.

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TERMO DE APROVAÇÃO

Os membros da Banca Examinadora designada pelo Colegiado do Programa de Pós-Graduação ENGENHARIA DE MANUFATURA da Universidade Federal do Paraná foram convocados para realizar a arguição da Dissertação de Mestrado de **ISLAN DE CASTRO GOMES** intitulada: **Optimization of spare parts inventory management for capital goods maintenance**, sob orientação do Prof. Dr. FERNANDO DESCHAMPS, que após terem inquirido o aluno e realizada a avaliação do trabalho, são de parecer pela sua APROVAÇÃO no rito de defesa.

A outorga do título de mestre está sujeita à homologação pelo colegiado, ao atendimento de todas as indicações e correções solicitadas pela banca e ao pleno atendimento das demandas regimentais do Programa de Pós-Graduação.

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RESUMO

Peças de reposição desempenham um papel importante no apoio à manutenção de bens de capital, contribuindo para a redução do tempo de inatividade e para o prolongamento d de sua vida útil. Porém, à medida que os sistemas se tornam mais avançados e sua confiabilidade também aumenta ao longo do tempo, ambas as tendências ampliam a quantidade de componentes com baixa demanda e, por conta disso, o gerenciamento de peças de reposição se torna mais complicado. Consequentemente, dada a preocupação relacionada com os gastos globais em serviços pós-venda, clientes exigindo altos níveis de disponibilidade, juntamente com a redução do TCO (Custo Total de Propriedade) na compra de novos sistemas, tem emergido a busca por métodos mais eficientes para se gerenciar o estoque de peças de reposição. Com base na utilização de técnicas da indústria 4.0, o objetivo deste estudo é propor uma estrutura para o fornecimento de peças de reposição, reduzindo os custos de manutenção e de tempo de inatividade. Como resultados parciais de um piloto no Brasil, o estoque morto foi reduzido em mais de 50%, a taxa de rotatividade aumentou em 30% e os pedidos de emergência foram reduzidos em 25%. Outro piloto no Chile comprovou a possibilidade de reduzir 10% do estoque total de uma determinada região, escolhendo um local específico para centralizar peças de baixo giro, servindo também como armazém de apoio.

Palavras-chave: Indústria 4.0, Big Data, Peças de Reposição, Gestão de Estoques, Manutenção, Supply Chain.

ABSTRACT

Spare parts play an important role in supporting capital goods maintenance, contributing to downtime reduction and lifetime extension. However, once systems are becoming more advanced, and their reliability has also increased over time, both trends enlarged the amount of components with low demand, and, due to that, spare parts management has become more complicated. Consequently, given the concern related to global spending in after-sales services and customers demanding high uptime levels, together with TCO (Total Cost of Ownership) reduction when buying new systems, the search for more efficient methods to manage spare parts inventory has emerged. Based on the use of industry 4.0 techniques, the aim of this study is to propose a framework for spare parts provisioning, reducing both maintenance and downtime costs. As partial results for a pilot in Brazil, dead stock has been reduced over 50%, turn over rate increased by 30% and emergency orders reduced by 25%. Another pilot in Chile proved the possibility to reduce 10% of the overall stock of a certain region, choosing a specific location to centralize low runner parts, operating also as a support warehouse.

Keywords: Industry 4.0, Big Data, Spare Parts, Inventory Management, Maintenance, Supply Chain.

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LIST OF ACRONYMS

DC – Distribution Center

DO – Day Order

DSI – Dealer Service Index

HA-HCLDS - High Availability, High Cost and Low Demand Systems)

JIT – Just-in-Time

LSPs – Logistics Service Providers

LTB – Last Time Buy

MCIC – Multi Criteria Inventory Classification

MTO – Make to Order

MTS – Make to Stock

OEM – Original Equipment Manufacturer

SC – Supply Chain

SO - Stock Order

TCO – Total Cost of Ownership

TOC - Theory of Constraints

TOR – Turn Over Rate (inventory turns per year)

TPS – Toyota Production System

VOR - Vehicle Off Road

CONTENTS

1. INTRODUCTION

Spare parts management is essential for the capital goods segment. As definition, a capital good is a machine used by manufacturers to produce goods or deliver services to customers (Olivotti D et. al 2018). Examples of capital goods are medical equipments used by hospitals to diagnose and cure patients, and buses, used by a service company to transport people. Due to a technical issue, connected to the wear influence caused by different types of factors, capital goods, like any other good, fail. And, once they fail, maintenance is required, which means to retain an item in, or restore it to, a state in which it can perform its required function. A failure of capital good may interrupt a factory completely, or, when mentioning public transportation for example, severely impact a large amount of people.

Bake et al. (2018) reinforce that what matters for capital goods users are the costs during their entire life cycle, known as the Total Cost of Ownership (TCO). The first TCO is the acquisition cost, which is high in most cases. Later, after start of usage, other costs arise, being maintenance and downtime the other main parts of the TCO. Maintenance cost is related to all resources needed for maintenance, and may be executed by the user, by the OEM or by a third company. In any case it includes spare parts, service and infrastructure costs. And Downtime cost involves not only direct costs, connected to the output reduction of the capital good, but also indirect costs, that cause loss of reputation and result, unfortunately, in future sales decrease.

For capital goods, it is mandatory to be prepared for both preventive and corrective maintenances. In both cases spare parts are required, either due to prior scheduling, preventive, or in case of a failure, corrective, having the part available for exchange (repair by replacement). It avoids too long and costly downtime. And, due to the uncertainty of spare parts demand, companies that provide after sales service normally keep inventory.

Boone et al. (2018) claim that the primary means for reducing costs is to simply reduce the amount of on-hand inventory. However, the authors warned that efforts to “lean” service parts inventory must be entered into cautiously. Unlike most manufacturing inventories, the lack of service parts inventory can mean the complete shutdown of an operation. Whether through the cost reductions, parts availability, or disruptions mitigation, the main goal of service parts management is customer satisfaction. So, extremely vital to downtime reduction is parts availability, which means having available parts waiting for the customer demand. The author demonstrated that inventory control policy, particularly for items with low and uncertain demand, has a significant role in parts availability, and that the perfect set-up is having parts available when required only, with short lead times and, as an effect, providing customer service without increasing operational costs. However, an increase in availability typically requires an increase in inventory on-hand and, consequently, also increasing the overall logistics cost. The costs can be drastically affected also when, due to a back-order occurrence, an expedited freight to satisfy customer demands is required. This critical relationship between availability and premium freight cost indicates that the primary goal is the search for a balance between both KPIs (Key Performance Indicators). The main challenge is to correlate the cost of having the part available with the cost associated with a back-order.

Extensive research has been conducted across industry segments in this area, including studies related to machine availability (Ghodrati et al. 2013), preventive maintenance (Jiang et al. 2015), and repair level (Chang et al. 2005) with OEMs (Original Equipment Manufacturers) or a third-party provider (BEHFARD et al. 2015).

In addition, Boone et al. (2016) also mention that it is expected that Big Data will revolutionize Supply Chain in the next years, holding, therefore, great potential for improving spare parts management. Thus, investigations focused on Big Data to improve spare parts management are needed. Connecting these and other sub-areas and considering the importance of more efficient methods to manage spare parts inventory, the aim of this study is, based on the use of industry 4.0 techniques, to propose a framework for spare parts provisioning, reducing both maintenance and downtime costs. The fact is that, even if information is not obtained from the field, or not even from social networks connected to end customers, companies usually have a lot of data available, which is not used, or is, at most, underutilized. And, at least, through some of them, an adaptive approach to inventory management can be created, in order to reach a better decision-making for a quite known problem: better define the spare parts inventory strategy.

In other words, for taking the decision to no longer keep a certain item in stock at a certain location, or to have its stock coverage reduced, it is relevant to make use of as much information as possible, to guarantee that the reduction was achieved without negative impact to end customers. Also, once it is a binary decision (Yes or No), it may like being simple, but it involves taking significant risks. And only with the drastic reduction of uncertainties it will be possible to advance significantly in this direction.

1.1. PROBLEM FORMULATION

Large amounts of money are invested in spare parts inventory, which results in a great interest in more efficient methods to improve spare parts management. Better strategies for spare parts provisioning will reduce both maintenance and downtime costs.

In addition, nowadays customers explicitly look at the TCO when buying a new capital good, looking not only for a high equipment availability but also for low costs. Since a characteristic of the spare parts market is low or very low demand, even statistical analysis is uncertain and relying on past data may not help significantly. To deal with above trends it is imperative to come with technological and/or business models innovations. In this last area, OEMs have been offering their customers service contracts to convince them to outsource maintenance activities (Cohen et al. 2007). So, OEMs can increase parts penetration, adding volume to the spare parts market, getting data from different sources and, consequently, better applying statistical analysis.

Being the OEM responsible for the full service, the customer simply pays a fixed cost per year, becoming the OEM’s task to manage everything, being fully responsible for all maintenances. Also, as a tendency in the last few years, the user does not even have to buy the equipment, but just its function. In addition, with the application of Industry 4.0 features, like Big Data and IoT, nowadays it is possible to measure critical components parameters that will reveal its degradation behavior (JONGE et al. 2017).

Therefore, considering the pressure for cost reduction, as well as the advent of new technologies and the use of still unexplored data, any mean to downsize spare parts stock, without decreasing customer service, would be more than welcome in all capital goods industry. And, based on that, it is possible to formulate a problem question, which can be stated as: “How may a capital goods industry use data already available in its supply chain/inventory processes to improve its stock decisions?”

1.2. GENERAL OBJECTIVE

The general objective of this work is to develop an adaptive framework based on data-driven procedures to support decision-making for capital goods spare parts inventory management and apply it in a real case.

1.3. SPECIFIC OBJECTIVES

- Identify inventory management procedures that may incorporate a data-driven approach to help the decision-making.
- Propose an adaptive framework that incorporates data-driven procedures for capital goods spare parts inventory management.
- Apply the proposed framework in at least one real case.

1.4. CONTEXT ANALYSIS

Although facing a general problem, once the spare parts management for capital goods is quite similar between companies, even from different segments, it is necessary to choose one to apply the proposed framework. A single truck dealership in Brazil was chosen, which belongs to a network with more than a hundred members, separated into different groups, with different beliefs and cultures. Even with this sample restriction, mainly chosen due to fund and support constrains, replicating the findings is something believed to be fully possible, which can also help in validating and building confidence in the results. More recently, in the third quarter of 2023, the study has been expanded to other two dealers in south of Chile.

1.5. TECHNOLOGICAL PRODUCT

Proposing an adaptive and data-driven approach framework to spare parts inventory management, with the usage of quantitative parameters and industrial practices, in the aftermarket area of a chosen company, which is still poorly adopting such a type of methods. The framework consists of a flowchart that, through positive or negative responses to certain types of control, leads the items to the best possible decision, on whether or not stock them close to the end customer. At first the results have been shown through an Excel file, but a Power BI has been developed to expose the potential of the tool, once the implementation can be disseminated to other dealers besides the one chosen as a pilot. And, despite not being part of the current work, which will be finalized in 2023, this study intends to change the current decision-making algorithm of the chosen company, therefore automating the framework and providing scale benefits, inside and outside Brazil.

1.6. WORK CONTRIBUTIONS

As mentioned by Boone, et al. (2017), service parts management is especially challenging, due to several factors, such as: demand uncertainty, limited sourcing options, risk of obsolescence, inefficient ordering processes, poor inventory management, part proliferation, ageing systems and parts, and system configuration changes. Due to these points described, such work can contribute not only to academy, but mainly to industry, which has aimed to become increasingly productive.

1.6.1. Contributions to Academy

The background of this study is related to explore the literature connected to spare parts inventory management system development. As first contribution it is important to differentiate spare parts from other typical inventory types, such as raw materials, work in progress and finished goods. This understanding helps to explain why some of the tools and techniques widely used in most supply chain management situations cannot be applied to spare parts inventories (Slater P., 2016). The author also mentions that, related to maintenance, it is important to understand spare parts in the context of the end users, which is most often the maintenance and reliability function. Another contextual issue is understanding the financial considerations of spare parts inventory management, due to its impact in opportunity cost. Stablished the foundation, studies should focus on establishing reasonable frameworks to manage spare parts inventory. It includes understanding the minimum requirements for a workable system, establishing an identification system and management policies, and finally understanding the afore mentioned best practice.

1.6.2. Contributions to Industry

Independent on what part of the business is under analysis at a certain moment, there will always be a system for addressing the key things that need to be done. In production planning there will be a way that capacity and demand are identified, prioritized, and scheduled; in procurement a way that purchase orders are assessed, vendors selected, and invoices matched; in spare parts management, in the other hand, a way that decisions are made on what or not to stock, and how many, when decided to. What is less certain is whether the system in use is the most effective and efficient way to get the job done. As stated by Slater (2106) the reason is that the systems that are in place today either are deliberately designed or have evolved randomly. And he mentions that, not all “designed systems” are perfect or even fully effective, but there is a reasonably good chance that a designed system will perform better than a random system.

As affirmed also by the author, too many companies allow themselves to have a system that has evolved randomly. In his research, almost 50% of the companies score their development of spare parts management policies as either “not defined, formal inventory policies” or “broad based corporate level policy”. Those companies are saying that they do not have a specific set of policies designed for day-to-day application, helping them on spare parts inventory management challenges. He also studied about the development and implementation of a specific spare parts stocking policy, defining parameters to guide the primary decisions on whether or not to stock an item and then how many to stock. The number of respondents with nothing in place reached 75%. It results in a large number of companies massively overstocked with some parts, while facing, at the same time, low levels of trust, due to the fact that they are not holding or delivering fast enough the really critical parts.

Another limitation mentioned is that, while it is seen as an important criterion for the spare parts classification, stock out cost is estimated with difficulties. This leads to think to the need for specific methods to help industrial people in effectively using the criterion for driving part classification.

The author also mentions that, by nature, all forecasts are based on assumptions, which, in effect, make any forecast a guess. Even worse, many people do not even try to determine the likely basis of future demand for an item; they merely extrapolate the past into the future without necessarily questioning if that is an appropriate approach to take. This is the basis of most software packages. The author still declares that the use of software makes it easy to abdicate responsibility for decision making.

Due to such facts, this work has the potential to propose a new framework that can be used to react more quickly to facts, instead of trying to guess what may happen or not in the future.

2. THEORETICAL FOUNDATION

This chapter aims to provide concepts for a good understanding of the research, introducing the key concepts (and their specific breakdowns). It is divided in two main subjects: Inventory Management, where spare parts, capital goods and aftermarket area will be discussed, and Data Driven Procedure, exploring data analytics, database systems and big data. At the end of each sub-topic, when understood as necessary, a paragraph will be added with the author's comments about why it has been included and its importance for the current study.

2.1. Inventory Management

2.1.1. Spare Parts Management

As stated by Bacchetti and Saccani (2011), a major problem talking about spare parts stands in the absence of research with an integrated management perspective. They argue that an approach integrating spare parts classification, demand management, forecasting, inventory management models and performance measurement is hardly present in the traditional literature. They conclude that the adoption of an integrated view is one of the main aspects affecting the overall effectiveness of spare parts management within companies. Every organization should then establish an integrated spare parts management system.

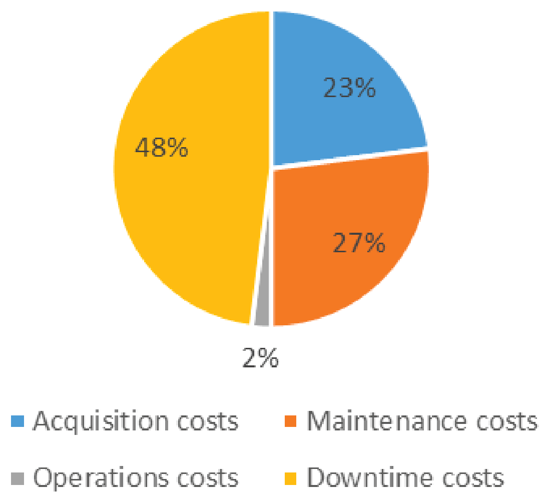
They also argue that for some items customer orders are placed very sporadically, just once or twice over several years. And that, in these cases, a time series forecasting method cannot be used and only a reactive approach is possible.

Basten and Houtum (2014), when discussing system-oriented inventory models for spare parts, focused on two types of spare parts networks, single-location and multi-echelons models, which are discussed various extensions, including the use of lateral and emergency shipments. Other extensions discussed by the authors are: 1) Part condemnation. If it is a repairable part the assumption that such repair will be successful is common. In practice, however, components fail due to many reasons. Some of the resulting defects are repairable, while others are not. Besides, many parts can only be repaired for a limited number of times, due to the fact that their performance slowly decreases after each repair. 2) Batching. Generally, one-for-one replenishments will make sense for expensive parts, which have high inventory holding costs and/or low demand rates. For cheap components, however, it may be appropriate to use a fixed batch size. Also, failed parts sometimes are sent into repair or orders are placed at external suppliers: then some form of batching may be desired. 3) Multiple demand classes. In many OEM networks it is common to find different service levels for customers, like bronze, silver and gold contracts, for example, that are increasingly higher priced. One way the authors comment as possible to differentiate between customer is propose, in case of a stock out, emergency shipments for priority customers only, or also by using for them a dedicated stock. 4) Criticality. It is related to the consequences for the system if that part is not replaced immediately. It is important once not necessarily the entire system fails when some component fails. And it is relevant to consider mainly for users that maintain their own systems, different that those when the OEM has a service contract with. 5) Advanced demand information. Inventory control may benefit from using information on the condition of the installed base and from other forms of advance demand, like monitoring the degradation state of components in the installed base, for example. 6) Repair shop capacity planning. Decisions about the shop floor should strongly influence spare parts inventory. Enabling faster repairs should require less quantity of spare parts to achieve the same service level. In some cases, repairs can be optimized by, for example, automating part of the process; and, when delays are occurring due to internal restrictions, bottlenecks can be identified and reduced by installing more equipment or hiring more people. Preferentially, decisions on the shop floor and inventory control should be integrated, which can contribute to lower costs than when inventory control strategy is determined without considering shop floor decisions. 7) Facility location problem. Mainly for OEMs that perform maintenance on their installed base should expand their vision of point of stock beyond their facilities. Companies such as IBM depend on logistics service providers (LSPs) to stock their spare parts close to their customers. In other words, LSPs are responsible for the stocking locations. As a result, it is relatively inexpensive to change the stocking locations and the decision on where to locate these stock points becomes a tactical, instead of a strategic problem. 8) Level of repair analysis. Level of repair analysis is used to decide on which are the components to repair and which to discard, where in the repair network to execute the repairs, and where to install the capabilities required to perform them, such as manpower and equipment.

2.1.2. Downtime and Total Cost of Ownership (TCO)

About systems downtimes Bake et al. (2018) declares that it starts when there is a failure during the operational time and ends when the system starts operating again. Different causes have been attributed to downtime in the literature. Lack of timely or incomplete support, such as spare parts as well as the operating environment, which may cause significant losses. The author argues also that maintenance and service logistics are key activities that influences systems downtimes and reliability. They mention that downtime can be caused also by the design of the equipment, but mainly by parts failures. They reinforce that there are two performance measurements related to downtimes in industrial equipment, logistics delay and repair time. Logistics delay can be best addressed by design of service logistics and maintenance concepts. Meanwhile, repair time can be influenced also by early design decisions of the equipment. Increasing the uptime of service systems can also be influenced by exploiting the capabilities of the tools in industry 4.0. Some of these capabilities include connectivity of devices, like sensors, communication, cyber physical systems, internet of things (IoT) as well as the data analytics using big data techniques. The author argues that downtime can result in lost revenue, customer dissatisfaction and possible associated claims. And once capital goods systems are high value equipment, downtimes and their related costs are very significant. The Figure 1 shows the impact of every cost for capital goods segment, called TCO (Total Cost of Ownership).

Figure 1 – Total Cost of Ownership distribution



Source: Bake et al. (2018)

Due to that, product availability is crucial for capital goods, once these types of systems are subject to high requirement of productivity. Therefore, further reduction of unscheduled downtimes has received great importance in this industry, mainly due to the fact that the value of the item is high and the economic impact of failures during the used life cycle phase is severe. This value driven business model of systems requires that the relationship between the customer and the provider is enhanced by effective communication. It occurs since effective communication provides feedback that can be used by the provider to quickly address maintenance issues and improve equipment uptimes. The capabilities of Industry 4.0 tools with their communication and connectivity skills can improve spare parts inventory planning, contributing to decrease logistical delay and improving maintenance decisions.

It is important to mention that, in addition to logistics delay, another performance measurement of relevant importance is delivery time, once speed is one of the main variables to be considered. As affirmed by Frei F. (2018), delivery on the promised date, but do not meet customer expectations, cannot be considered as excellence. And, another performance management, as important as the first one, is repair time, once in many cases it is possible to wait for the delivery time of the item, especially when the geographic condition is favorable.

2.1.3. Lean and Agile Integration

The Just-in-Time (JIT) management is usually associated with the Toyota Production System (TPS) and Taiichi Ohno's work (Ohno, 1988) with a clear emphasis on waste elimination in the supply chain. More recently lean thinking (Womack and Jones, 1996) has demonstrated the broad potential of the waste elimination in improving business performance. The emphasis is closely associated with inventory reduction, and one of the key concepts is providing problem solving insights, which is very effectively demonstrated by the ship and rocks analogy. In this analogy once the inventory (water level) is lowered, the sources of waste (the rocks) are exposed. The rocks are named with potential problems, such as supplier delays, rejects, long set-ups, downtime, insufficient capacity, machine breakdowns, late deliveries, etc. The elimination of those sources of waste enables the inventory to be lowered without impacting material flow (the ship) (Martichenko, 2010). The JIT management system was created to simultaneously improve customer service and efficiency, by focusing on reduce variation in the system and enable flow. Through set-up time reduction, statistical process control, supplier development, total productive maintenance, etc., sources of internal variation to the supply chain were progressively reduced, reducing consequently the need for inventory. However, it is more easily achieved with standard products and stable demand. Agility, in the other hand, is related to special products and volatile demand. So, in order to have the proposed system working well, it is also necessary to stabilize the overall output rate and decouple the effect of market demand variation (STRATTON et. al. 2003).

Consequently, Agile supply is more pragmatically defined and closely associated with quick response. Table 1 indicates some distinguishing attributes of the associated supply chains.

Table 1 - Lean versus Agile supply

Distinguishing attributes	**Lean supply**	**Agile supply**
Market placed demand	Stable	Unstable
Product variety	Low	High
Product life cycle	Long	Short
Manufacturing task	Low cost	Delivery speed
Purchasing policy	Product specific	Assign capacity
Information enrichment	Desirable	Important

Source: Stratton et al. (2003) modified

From Table 1, and creating a parallel with the spare parts area, it is perceived that, different than manufacturing flow, there are higher demand instability, as well as variety of products and high delivery speed expectation, especially when talking about low-runner parts. Also, another important attribute from the previous table concerns to the importance of having available information for decision making.

Also, the traditional attitude is placing inventory between each process, effectively decoupling the impact of the fluctuations. However, for Agile supply an alternative to investing in inventory to protect the flow under these conditions is investing in additional capacity. The use of protective capacity, rather than protective inventory to enable flow, is also the norm in the service industry, where people otherwise form inventory queues.

Goldratt (1990), a management consultant and one of the proponents of the TOC (Theory of Constraints) affirms that, in any operating system, there exists the phenomena of dependency and fluctuation and, when combined in a delivery system, they define the fundamental characteristics of production flow, which may be viewed at the factory or supply chain level.

Stratton et al. (2003) exposed that with the growth in product innovation and demand uncertainty, supply chains need to strategically locate inventory and capacity to enable flow. It requires a holistic perspective, and investment in capacity to protect the flow rather than inventory is central to the agile supply paradigm, and the use of separation principles provides a practical approach to exploring innovative perspectives to mitigate the impact of the conflict. The authors argue that, although the Agile/Lean supply conflict is generic, it is important to define specific business trade-offs through data analysis and dialogue.

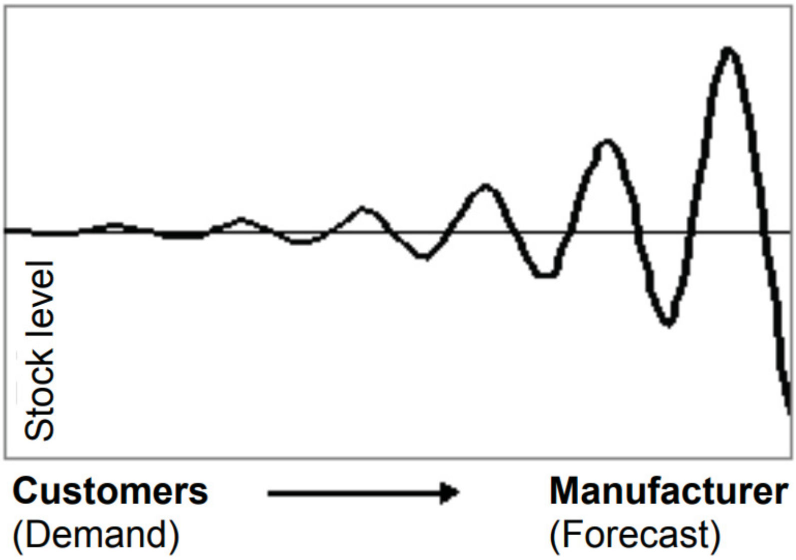
An important thing to note about this section is that, in the aftermarket area, once many of its attributes are more connected to the agile supply, keeping an item in stock at the point of use may not be the best decision. And this decision needs to consider the delivery speed, that is, the lead time between order placed and item delivered.

2.1.4. Bullwhip Effect

Bullwhip Effect is an observed phenomenon in forecast driven distribution flows. It indicates a lack of synchronization among members of the same supply chain. Even a slightly change in customer demand ripples upstream and with amplified oscillation, similar to the result of a whiplash movement. Due to the fact that the supply patterns do not match the demand patterns, inventory accumulates over several stages, as explained by the Fig. 2. Once customer demand is rarely perfectly stable, businesses must forecast demand to properly position inventory. Variability, coupled with delays in placing orders through the supply chain, frozen periods and long lead times for manufacturing and shipping goods, create this effect. Forecasts are also based on statistic figures, that are rarely perfectly accurate, and, due to that, companies often carry an inventory buffer as safety stock. Moving upstream the supply chain (from end consumer to raw materials supplier), each participant has greater observed variation in demand and, consequently, greater need for safety stock. In periods of rising demand, downstream participants will increase their orders. In periods of falling demand, orders will fall or completely stop to reduce inventory. Bullwhip Effect is also attributed to the separate ownership from different members of the supply chain. Each member tries to amplify its profit, thereby decreasing the overall profitability of the total chain (BUCHMEISTER, et al., 2018).

Buchmeister et al. (2018) states also that every supply chain analysis must consider Bullwhip Effect. It shows how small changes in demand are progressively amplified as far as the supply chain member is from the final customer, as shown in the Figure 2. It is also understood that forecast variance contributes drastically to that effect in the chain.

Figure 2 – Stock variability amplification in a SC due to Bullwhip Effect



Source: Buchmeister et al. (2018)

Bullwhip effect has been identified as contributing to increased uncertainty in the supply chain and, consequently, poor performance in costs, long lead times and low service levels for end customers (NAIM et al., 2002).

Metters R (1997) identified the magnitude of the problem by establishing an empirical lower limit on the profitability impact, as a result of the bullwhip effect. His studies indicate that the importance of the bullwhip effect to a company differs greatly depending on the specific business environment. He argues that, given appropriate conditions, however, eliminating the bullwhip effect can increase product profitability by 10 to 30%.

One of the possible benefits of this work, once eliminated the stock of some SKUs in the last member of the supply chain, is to reduce consequently the stock of the previous member of it. It is possible by the mitigation of the bullwhip effect, once orders will be placed based on the final customer demand, and not on assumptions about future needs.

2.2. Data Driven Procedure

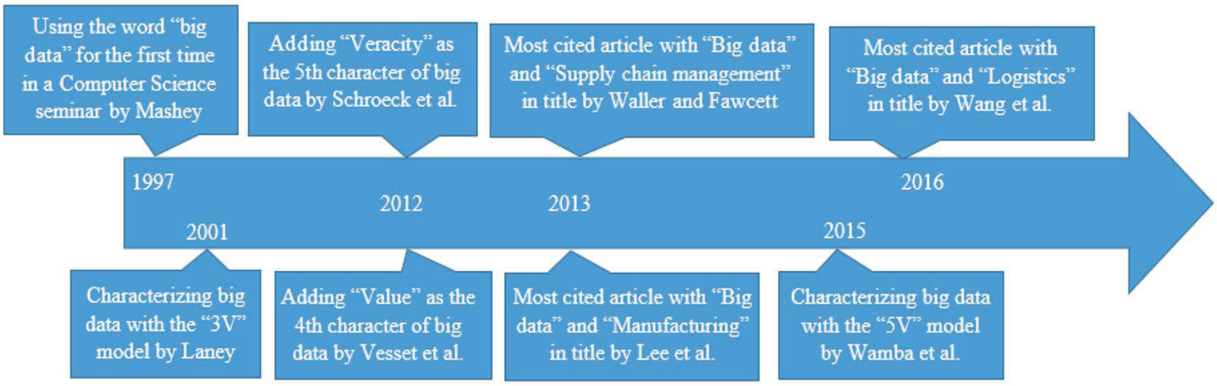
Ghalehkhondabi et al. (2020) affirms that according to information technology development trends and data availability, more companies are using big data analytics in their supply chains. About 60% of the research on big data applications in supply chain management were published after 2017, that have increasingly focused on big data applications in predictive analysis, rather than in the other types of data analysis.

Big data includes data sets that cannot be analyzed by the common traditional data analysis tools, once refers to a high volume of data, with high velocity and variety. These properties require more efficient methods than those used in conventional database systems (VAN DER AALST, 2012).

The author explains that big data entered the field of practical research in the XXI century, once there was no noteworthy research applying big data analysis before 2000. The main characteristic of big data is simply its huge volume of data, but some other characteristics have been added to this definition over the years. The first time that Big Data was defined by the 3V model (Volume, Velocity, and Variety) was in a study by Laney (2001). Volume refers to the amount of available data; Velocity to the timeliness of the data; and Variety to the diversity of the data types, including unstructured, semi-structured, and also structured data sets.

Two other important Vs have been added to the definition of big data in the most recent decade. The economic Value refers to the importance of profit gained by analyzing those data, and Veracity refers to the probability of having some uncertainty or imprecision in big data. Wamba et al. (2015) integrated all the Vs in one place and introduced the 5V big data framework for the first time. Figure 3 represents the evolutionary timeline of the big data concept, as well as the most-cited articles using big data in manufacturing, logistics, and supply chain management.

Figure 3 – Big data framework evolution during the time



Source: Ghalehkhondabi et al. (2020)

The authors attest that big data analysis is a process that transforms terabytes of low-value data into a small amount of high-value data and also that a big data system can be separated into four consecutive phases: data generation, data acquisition, data storage and data analytics.

IoT and Industry 4.0 revolutions can change the paradigms in logistics and operations management. The main contributions to logistics are in transportation, warehousing and inventory. It can increase efficiency, safety and operations security by real-time monitoring and controlling of the process, traceability of items through the Supply Chain, reducing downtime risks and providing collaboration among suppliers due to bullwhip effect impact reduction (KEIVANPOUR et al., 2019).

The authors also mention that the application of IoT in maintenance can optimize predictive maintenance by real-time monitoring of the operation condition and wear level of components, estimating its remaining lifetime. The sensors, sending real-time information to a data analysis module, can not only update the estimation of the remaining lifetime of components but also send required notifications to the maintenance department, in order to take the necessary actions. Hence, the contribution of IoT in inventory management, maintenance and transportation could enhance the spare parts management operations.

Once the use of data is increasing year after year, it is possible to move from a reactive to a proactive approach or, at least, react quickly, keeping all members informed about order traceability.

3. METHODOLOGICAL APPROACH

In order to achieve the objectives of this study, such as, propose an access the applicability of an adaptive framework that incorporates data-driven procedures for spare parts inventory management, a protocol was elaborated. Design Research Protocol was chosen due to a necessity to design and evaluate an information system, being considered a valuable framework for organizing and conducting the research.

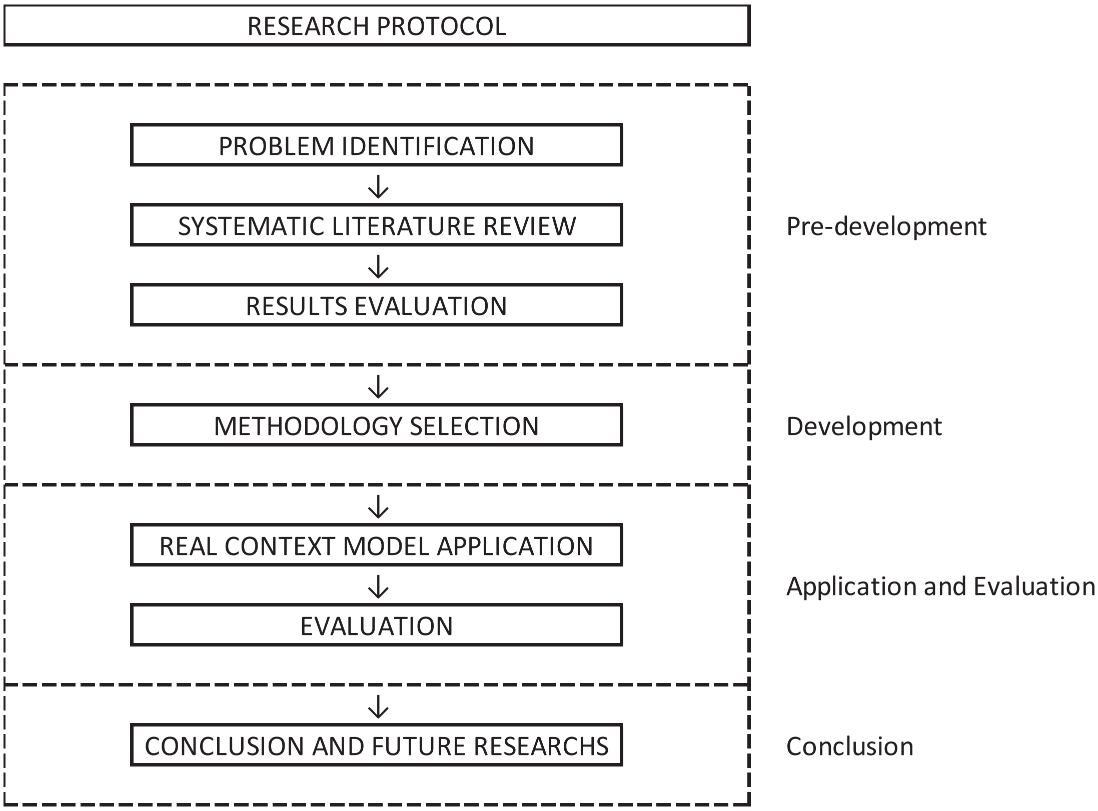
The main reasons for using a DSR here is that it provides a structured approach to the research process, which can help to ensure that all important aspects were considered and addressed. Also, to ensure that the research is relevant and useful. By engaging with stakeholders and involving them in the design and evaluation process, ensuring that the resulting system or application meets their needs and is likely to be adopted and used in practice. It enables also to increase the impact of the research and make it more significant to both academic and industry domains.

In this section it will be presented procedures and parameters used for the research development, aiming to reach the proposed objectives.

3.1. Research Protocol

In order to achieve the research objectives, a protocol was elaborated. The base model was extracted and adapted from Dresch (2013). The sequence and methods adopted are shown in Figure 4.

Figure 4: Design research protocol base model



Source: Adapted from Dresch (2013)

The first action is "problem identification", being necessary to justify why it is important to study this issue. From the justification, the problem must be understood in a clear and objective way. Then it starts the Systematic Literature Review (SLR), that aims to provide support in the process of exploring problems, like those being addressed. It contributes to identification, evaluation and interpretation of all available and relevant research, in order to answer a specific research question, topic or phenomenon.

According to Ensslin et al. (2010), to carry out a systematic literature review, the PROKNOW-C (Knowledge Development Process – Constructivist) method is recommended. It helps the researcher in the selection of Bibliographic Portfolio, aligned with the research study, and also with a structured and gradual bibliometric analysis. The researcher has a crucial role in this process during the parameterization phase, defining the search premises, selecting research bases that will be used as a source of available knowledge, delimitating the search axes and time restrictions, selecting the year of origin of the material to be used, optimizing filters or criteria that will be applied systemically across the entire available material base, in order to include or exclude publications from the analyzable material base.

The use of the PROKNOW-C method encourages the construction of knowledge and fundamentally supports the development of exploratory or descriptive research in the choice or selection of publications considering the relevant impact factor in the scientific community. Ensslin et al. (2010) describe the method consisting of the following steps:

a) bibliographic portfolio selection;

b) portfolio bibliometric analysis;

c) review of the bibliographic reference and conclusions on the research topic.

The method will provide the researcher with a useful base of articles to be studied, with subjects aligned with the proposed research theme. The choice of the PROKNOW-C method is based on the inherent difficulty presented in the process of obtaining material aligned with the research theme within the wide universe of academic material available for bibliographical reference. Thus, the use of the PROKNOW-C method is an important tool in structuring a solid base of material useful to the researcher, and an important partner in the construction of new studies knowledge. Then it starts the definition of the search axles for scientific articles, followed by some procedures until reaching the stage of filtering and selection of the relevant bibliographic portfolio related to the subject (Ensslin et al., 2010). With the research axes defined, the next step is establishing the keywords to be used. Later, the selected words adherence is verified, ensuring that they are able to discriminate the scientific articles referred to the research area.

Dresch A. (2013) mentions also that it is possible that the researcher finds a ready and ideal artifact which fully meets his needs to solve the problem. And that, in these cases, the research should not be continued, considering that the artifact is properly developed and can be directly applied. And that, in this case, the study could not be considered a DSR, due to its lack of relevance. However, considering that cases like these are exceptions, the researcher should proceed directly to the next step, proposing an artifact to solve the specific problem. The objective of identifying artifacts already developed, addressed to similar problems, is to allow the researcher to make use of good practices and lessons learned, obtained from other authors. Furthermore, identifying existing artifacts can help the researcher to be assertive in his proposals. It is also at this moment that the researcher begins to understand and define the solutions that may be considered satisfactory. From this moment the researcher should start the next stage of the DSR, which is the proposition of artifacts to solve his specific problem, considering essentially its reality, context, viability, etc. In addition, it is in this stage that the current situation is analyzed, and possible solutions are presented. The author mentions that the process of proposing artifacts is essentially creative, an that the researcher should make use of his knowledge, with the aim of proposing a robust solution. Then there are the project and, in sequence, the development of the proposed artifact, that corresponds to the process of building the artifact itself. It is at this time that the researcher will build the internal environment of the artifact. The construction of it may make use of different approaches, such as computational algorithms, graphical representations, prototypes, mock-ups, etc. And the next and last stages of the DSR to be considered in this study are the evaluation of the artifact, formalization of learnings and conclusions.

Based on the content above, it is believed that the DSR model is an adequate approach to be used in this work, and the next chapters will detail all steps of the chosen protocol.

4. PRE-DEVELOPMENT

This section is related to the three first steps of the protocol, in which the problem is identifyed, validating the subject to be studied, a Systematic Literature Review (SLR) is presented, and, finally, an exploratory review of the selected articles is exposed, which will be categorized and its contribution to the topic discussed.

4.1. Problem Identification

In the problem identification section it is possible to establish a connection with what has been described in the introduction, once the investment in spare parts inventory increase operational costs drastically, and improvements in spare parts management can help to reduce not only maintenance but also downtime costs. As mentioned by Protopappa et al. (2017), it is mandatory to provide differentiated approaches, in order to reduce complexity in supply chain management and to enable companies to respond to varied customer needs in a timely and profitable manner. The authors reinforce that despite the benefits of supply chain segmentation, many companies still struggle to identify the main drivers that define the correct segments. And it is the first step to propose an inventory strategy that can match customer value proposition and design an end-to-end segmentation framework, in order to meet business needs.

4.2. Systematic Literature Review

4.2.1. Selection of articles already published about the researched topic

For this study, the SCOPUS Elsevier, Science Direct and Web of Science databases were used, accessed through the Portal of CAPES. The search period extended from October 26th to November 03rd, 2022.

In this study, two axels were defined, as presented in the table 2. They are aligned with the objective of reviewing the literature on different applications of data in spare parts inventory management. The first axel is connected to logistics area, aiming to maximize the return of potential articles in different areas that can add to the knowledge creation, using the words Aftermarket, Spare Parts and Inventory Management. The second axel, focused on the technology side, the words used were Industry 4.0, Machine Learning and Big Data. Table 2 shows each of the search axel and their respective keywords.

Table 2: Definition of research axel and keywords:

Axel 1: Logistics	Axel 2: Big Data
Aftermarket	Industry 4.0
Spare Parts	Machine Learning
Inventory Management	Big Data

SOURCE: The author (2023)

Considering each terms isolatated, the following references were identified as shown in Table 3.

Table 3: Number of bibliographic references by search term

Term	Publications Qty
Machine Learning	641,908
Big Data	281,973
Industry 4.0	35,749
Inventory Management	23,385
Spare Parts	21,858
Aftermarket	4,866

SOURCE: The author (2023)

Considering the combination of terms, the following references were identified as shown in Table 4.

Table 4: Number of bibliographic references with the combination of terms

Term	Publications Qty
Big Data & Inventory Management	2,823
Big Data & Spare Parts	2,008
Industry 4.0 & Inventory Management	1,372
Industry 4.0 & Spare Parts	1,339
Big Data & Spare Parts & Inventory Management	649

SOURCE: The author (2023)

Once the objective of the research is to verify the use of a significant amount of data to manage inventory for spare parts, it was chosen the results obtained by the combination of the three search terms, as shown in the last line of the Table 4. Thus, the total number of bibliographic references that will initially compose the database of articles/bibliographic portfolio has a total of 649 results.

To this initial amount, inclusion and exclusion criteria were applied, as follows.

i. Inclusion criteria:

a) type of publication: scientific articles, theses and dissertations;

b) time frame: documents published from 2012;

c) language of publication: English.

ii. Exclusion criteria:

a) Duplicated articles: Some material eliminated, even with different titles or some other information (abstract, keywords, authors, DOI, etc). In this study, out of the 649 articles, a total of 87 duplicates articles were found into different article databases.

b) Titles consistency: exclusion of articles not aligned with the research topic. For this study, only 113 articles with titles consistency were found.

c) Abstracts alignment: with the research theme, at this stage, all 113 abstracts articles were analyzed and, as a result, 39 were selected.

d) Scientific recognition: out of these 39 articles, it was verifyed the scientific recognition of the journals in which they were published. Except for 2 articles, whose content was fully conected to the research theme, all the others with less than 5 citations were eliminated. As a result, a total of 22 articles were selected to compose the continuity of the research, as presented in the Table 5.

Table 5 - Base of selected articles per publication year

N	Author	Title	Year	Citations
1	W Romeijnders, R Teunter, W Van Jaarsveld	A two-step method for forecasting spare parts demand using information on component repairs	2012	145
2	S Torabi, S Hatefi, B Pay	ABC inventory classification in the presence of both quantitative and qualitative criteria	2012	140
3	I Roda, M Macchi, L Fumagalli, P Viveros	On the classification of spare parts with a multi-criteria perspective	2012	17
4	A Bacchetti, N Saccani	Empirically driven hierarchical classification of stock keeping units	2013	75
5	B Kader, D Sofiene, R Nidhal, E Walid	Jointly optimal preventive maintenance under spare parts order strategy	2013	9
6	RJI Basten, GJ van Houtum	System-oriented inventory models for spare parts	2014	205
7	S Kumar, A Chakravarty	ABC and VED analysis of expendable medical stores at a tertiary care hospital	2015	111
8	C Boone, J Skipper, B Hazen	A framework for investigating the role of big data in service parts management	2017	49
9	Poppe, J., Basten, R., Boute, R.	Numerical study of inventory management under various maintenance policies	2017	52
10	F Lolli, A Ishizaka, R Gamberini, E Balugani	Decision trees for supervised multi-criteria inventory classification	2017	24
11	J. Bake, M. Pessôa, J. Becker	Service Chain Logistics Management for Increasing Equipment Uptime	2018	6
12	D. Olivotti, S. Dreyer, P. Kölsch, C. Herder, M. Breitner	Realizing availability-oriented business models in the capital goods industry	2018	12
13	S Behfard, A Al Hanbali, MC van der Heijden	Last Time Buy and repair decisions for fast moving parts	2018	11
14	Q Hu, JE Boylan, H Chen, A Labib	OR in spare parts management: A review	2018	183
15	F Costantino, G Di Gravio, R Patriarca, L Petrella	Spare parts management for irregular demand items	2018	70
16	S Keivanpour, DA Kadi	The Effect of “Internet of Things” on Aircraft Spare Parts Inventory Management	2019	30
17	Sarah Van der Auweraer, Robert N. Boute, Aris A. Syntetos	Forecasting spare part demand with installed base information: A review	2019	72

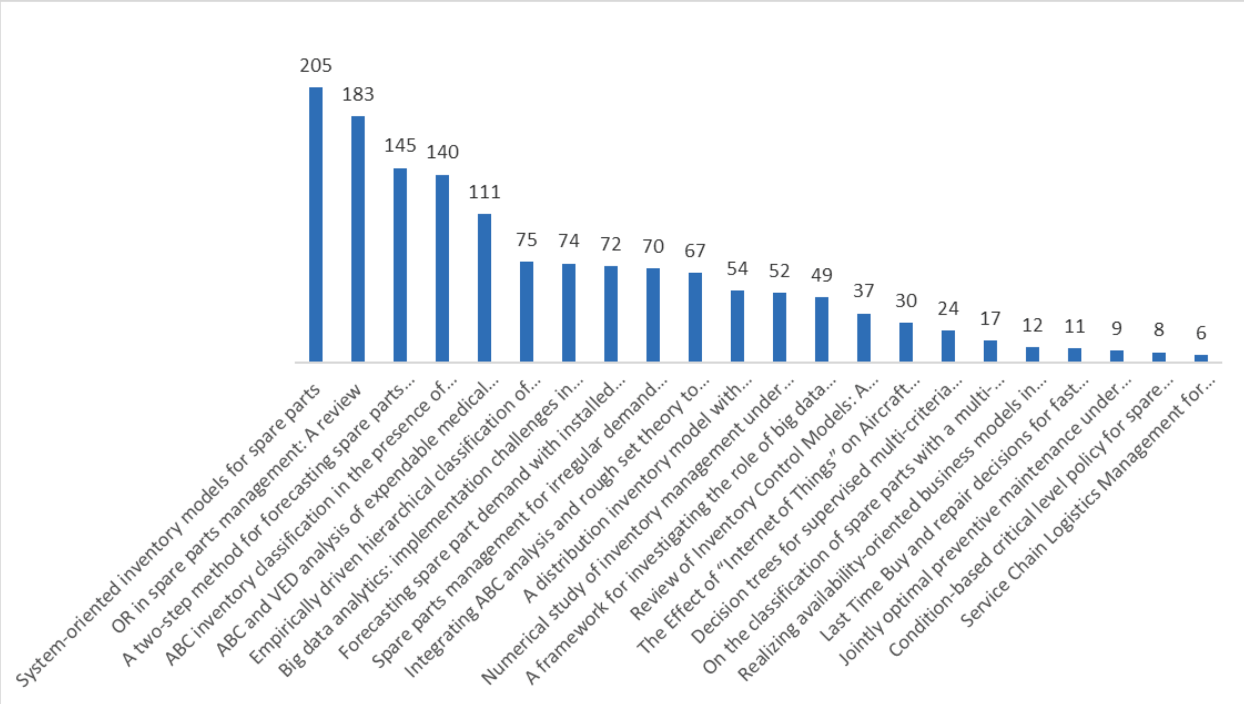
18	I Jackson, J Tolujevs, Z Kegenbekov	Review of Inventory Control Models: A Classification Based on Methods of Obtaining Optimal Control Parameters	2020	37
19	R Raut, V Yadav, N Cheikhrouhou, V Narwane…	Big data analytics: implementation challenges in Indian manufacturing supply chains	2021	74
20	P Dendauw, T Goeman, D Claeys, K De Turck	Condition-based critical level policy for spare parts inventory management	2021	8
21	M Mehdizadeh	Integrating ABC analysis and rough set theory to control the inventories of distributor in the supply chain of auto spare parts	2020	67
22	C Howard, S Axsater, J Maklund	A distribution inventory model with transshipments from a support warehouse	2011	54

SOURCE: The author (2023)

4.2.2. Relevance Estimation

The scientific recognition consists of checking the number of times that the article was cited. The article with the highest number of citations was: "System-oriented inventory models for spare parts", with 205 citations, as shown in the Graph 1. It is important to notice that recent publications may have a low number of citations, however chosen due to their relevance to the research topic.

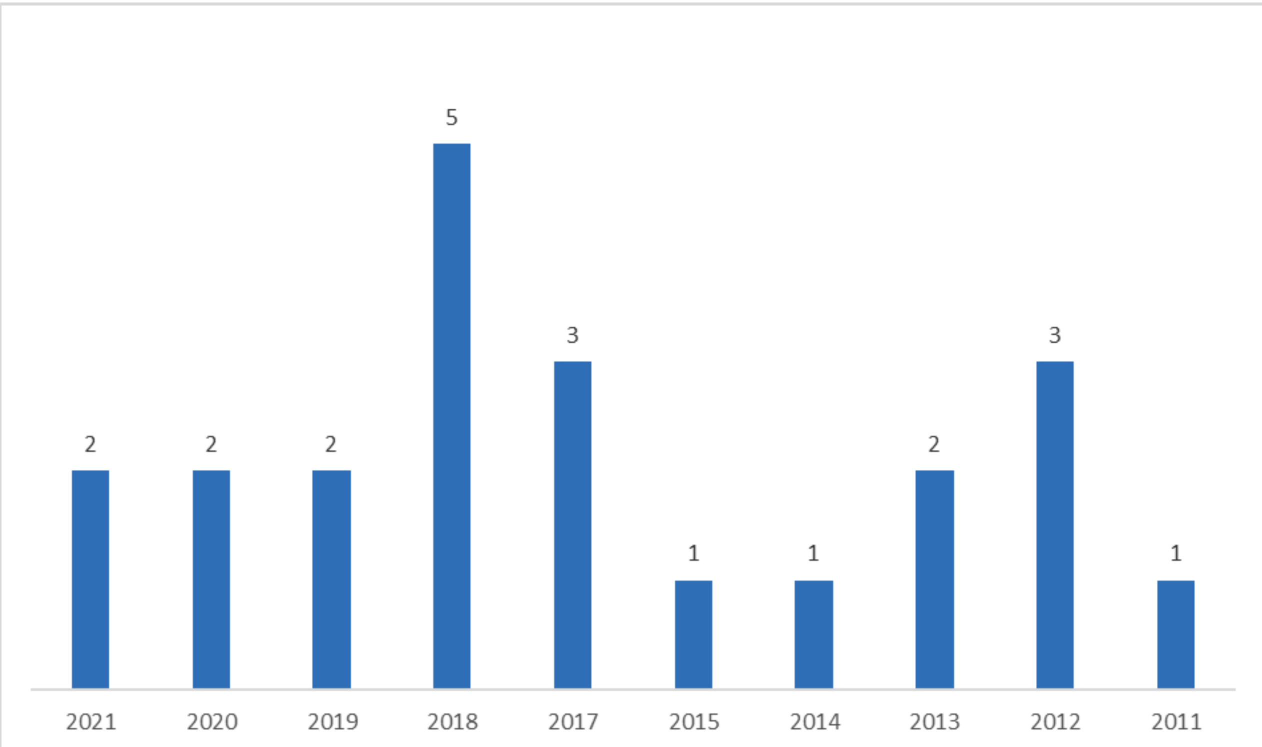
Graph 1 - Number of citations received by selected articles



SOURCE: The author (2023)

The number of articles chosen by publication year is shown in the Graph 2.

Graph 2 - Number of articles selected per publication year



SOURCE: The author (2023)

It is pertinent to mention that the oldest one is from 2011 and 50% (11 out of 22) of those were published from 2018, demonstrating that the basis used for this research is relatively recent, in addition to its relevance for the study.

4.2.3. Results Evaluation

This section presents an exploratory review of the selected articles to find out how they are addressing the issue spare parts inventory management and its different related areas.

As the first step of evaluation phase the 22 selected articles have been classified in 6 different groups, as showed in the Table 6, numbered according to the order shown in the Table 5.

Table 6 - Selected articles classification

Uptime / Availability	Capital Goods Maintenance	Inventory Management	Spare Parts Forecasting	Spare Parts Classification	Industry 4.0
6; 11; 12	5; 9	13; 14; 15; 20; 22	1; 17	2; 3; 4; 7;10; 18; 21	8; 16; 19

SOURCE: The author (2023)

In the next paragraphs the content of the articles will be discussed based on the classification proposed by Table 6, created properly to categorize the articles to contribute to the understanding of the chosen elements, to be studied and, if decided to, inserted into the proposed framework.

When discussing Uptime / Availability and Inventory Management groups, they teach us that spare parts sourcing becomes an even greater challenge the longer is the service period of the capital good. The reported problem is due to the fact that the production of the spare part will cease at some point, while the remaining service period is still long. For those cases its mandatory to develop an accurate policy to find the near optimum Last Time Buy (LTB) quantity (BEHFARD, et al. 2018) [13].

Also, related to condition-based maintenance, Dendauw et al. (2021) [20] mention that a proactive maintenance strategy occurs when the machinery condition is monitored and, consequently, preventively maintained when it shows signs of degradation, in which case the necessary spare parts are provided from stock. However, machines may occasionally suffer from sudden shocks, or may fail before showing any signs of deterioration. Due to that the authors propose a condition-based critical level policy for spare parts, to avoid downtimes costs. Poppe et al. (2017) [9] studied the use of advanced demand information in managing spare parts inventory. The increase in inventory requirements of preventive maintenance policies can be compensated for condition-based maintenance. They found that inventories can even be lower compared to corrective maintenance, considering the correct use of advanced demand information. Their study clarifies the behavior of the inventory related costs under various maintenance policies.

Inventory optimization of high-value spare parts may generate a significant reduction of cost to allow a better allocation of resources in maintenance management. However, the Sherbrooke’s METRIC (Multi Echelon Technique for Recoverable Item Control), the most common method used to define an overall optimization process, cannot be applied properly to HA-HCLDS items (High Availability, High Cost and Low Demand Systems), once they often follow irregular demand patterns, with very frequent zero-demand values. Due to that it is necessary to develop a new model, and studies confirmed that those methods outperform the traditional Poisson-based approach (COSTANTINO et al. 2018) [15].

About system-oriented inventory models, Basten et al. (2014) [6] explain that a single location model for inventory should occur if all items can be supplied fast enough from one stock point, what normally occurs when covering a relatively small region. However, for larger networks the model may be useful where lateral transshipments are seldomly used, and it is appropriate also to determine the base stock levels of each local warehouse, considering a certain average delay for the replenishments at the central depot. It is also recommended when the local warehouses are divided into groups, with lateral transshipments being applied within each group only. Such a network may be modeled considering that for each group a multi-location model with lateral transshipments is used. For the central warehouse, a single-location model is used, with demand flows resulting from each group.

When discussing spare parts forecasting Van der Auweraer et al. (2019) [17] mention that the classical literature about spare part demand forecasting studies methods for intermittent demand mainly. However, most of those methods do not consider the demand generating factor, which originated from parts replacement. This information from service operations, considered as installed base one, can be used to forecast the future demand for spare parts. In their study the authors focus on (1) what type of installed base information can be useful; (2) how this information can be used to provide forecast; and (3) the value of using installed base information to improve forecasting.

On the other hand, Romeijnders et al. (2012) [1] affirms that forecasting spare parts demand is clearly difficult, once the demand is typically intermittent or lumpy, and that some methods for forecasting cannot be properly applied, once they are not based on the repair operations that cause the intermittency and lumpiness of demand. Due to that they propose a method that, in addition to spare parts demand, considers the type of component repaired. They prove that the two-step method is one of the most accurate methods, and that it performs better than others, using information on planned maintenance and repair operations, in order to reduce forecasts errors by up to 20%.

On the classification of spare parts, Torabi et al. (2012) [2] mention that organizations classically apply ABC analysis, but unfortunately most of them are satisfied with just one classification type. And, even with several methods being developed recently, almost all of them assume that all criteria are quantitative type, and hence cannot handle the qualitative criteria which are not stated numerically. The authors presented a model that can handle both quantitative and qualitative criteria in an efficient way, by applying a common weight approach. Although, most of the existing methods just take quantitative criteria, the modified model accounts for both quantitative and qualitative ones simultaneously.

Kumar et al. (2015) [7] used ABC and VED (classification by criticality, being V: Vital, E: Essential and D: Desirable parts) analysis to identify categories of parts to focus, improving the management control of what really matters. They concluded that scientific inventory management tools need to be routinely applied in parts management, as it contributes to a rational use of resources and consequent improvement in uptime.

Roda et al. (2012) [3] also discussed the spare parts classification for manufacturing equipment, focusing on classification methods and adoption of a multi-criteria perspective, in order to find a proper criticality analysis of spare parts. Remarks are also provided for what concern the implementation of spare parts classification with a multi-criteria perspective in a real industrial environment.

Bacchetti et al. (2013) [4] proposed a hierarchical multi-criteria classification method for inventory management and applied in a case study. The classification method was built based on 6 different dimensions, resulting in 12 different classes of parts, for which differentiated forecasting and inventory policies were proposed and tested. The results of their simulation study demonstrated the reduction of the total logistics costs by 20%, and still achieving the specified service level targets for each class. They mentioned also that even more importantly is that the proposed approach was simple enough to be understood and applied by company managers, increasing the probability of its adoption in the real world.

When mentioning IoT, Keivanpour et al. (2019) [16] explore the application of it by optimizing predictive and scheduled maintenance, monitoring operation conditions in real-time. The focus is verifying the components level of stresses, estimating their remaining lifetime. Sensors can send real time information to a data analysis, that will estimate the remaining lifetime and send notifications to the maintenance department, who will take the necessary actions. Consequently, the contribution of IoT can enhance spare parts management operations.

5. DEVELOPMENT

5.1. Methodology Selection

The next phase is proposing a framework for spare parts inventory management. It ends with a pilot chosen, helping to evaluate the adequacy, effectiveness and feasibility of it, revealing issues with its solution and enabling regional characteristics identification.

Based on the articles evaluated from the literature review, presented in the section 4.2.3, it is possible to conclude that the major challenge for spare parts inventory management is connected to low runner parts, mainly due to its demand characteristics. As explored before, even with modern statistical modeling, predict the future based on past data is an arduous task when there is a great demand unpredictability.

And, also considering the integration between Lean and Agile, the proposal is to develop a framework that allows postponing as much as possible the decision to stock in the last member of the supply chain, keeping the item as MTO (Make to Order) for as long as possible, and using the previous member to provide parts availability.

This postponement alternative will not only contribute to reduce stock, and its consequent obsolescence risk mainly, but also mitigate the impact of the bullwhip effect, once the demand will not be amplified between the last two members of the supply chain. And this solution is only possible due to the fact that the final customer demand will be the unique parameter for placing orders.

Based on this assumption, and considering a multi-criteria approach, possible variables to be included in the framework were studied, presented in the Table 7 (KRISHNA et al., 2017).

Table 7. Selective Control for Inventory Management.

Type of control	Description	Main Use
ABC (always better control/Pareto's law)	Consumption value of items	To control raw material components and WIP of business.
HML (High, Medium, Low)	Unit price of material	To control purchases.
XYZ	Value of items in storage	To review the inventory, their uses, etc., at scheduled interval.
VED (Vital, Essential, Desirable)	**Criticality of items**	**To determine the stocking levels of spare parts.**
FSN (Fast, Slow and Non moving)	Consumption pattern of the items	To control obsolescence.
SDE (Scarce, Difficult and Easy to obtain)	**Problems faced in procurement**	**Lead time analysis and purchase strategies.**
GOLF (Govt, Ordinary, Local, Foreign sources)	Source of supply	Procurement storages.
SOS (Seasonal and Off seasonal)	Nature of supplies	Procurement and holding strategies for seasonal items.
PRQ	Shelf life of items	To have control over items based on their expiration dates.

SOURCE: Krishna, et al (2017)

It was decided to include from the Table 7 some classification types. SDE classification, in order to clarify whose items are easy to obtain, and VED, once the criticality of the item must be a fundamental parameter to define whether or not to store it in the last member of the supply chain. And, also, not included in the Table 7 but quite important to the study, are two performance managements, delivery time and repair time (HOUTUM & KRANENBURG, 2015).

It will be also included, in order to measure repair time, a variable called Standard Time. It is the minimum time among all repairs in which a specific SKU is used and compared with the delivery time from immediate upstream member to the destination, which has three different speeds, depending on the order class placed. The most critical class, which consequently needs faster deliveries, is called VOR (Vehicle Off Road), related to an order whose delivery of the part is mandatory for a certain vehicle return to operation. The second one is called DO (Day Order), also critical but not connected to a vehicle off road. And the last one, not critical, is called SO (Stock Order), which is mainly related to stock replenishment at the point of use.

One variable to be considered to move an SKU from MTO to MTS (Make to Stock) is the minimum quantity of picks reached per year. The term pick means how many times a SKU was ordered in a specific period of time (1 year for example), and a minimum value is chosen to define if an item will be put in stock, based on its unit price (HML classification). It means that the more expensive the item the more picks are necessary to move it to MTS.

In addition to unit price (HML) also the consumption pattern of the item (FSN) is used to classify the SKUs. When crossing both controls a Table Matrix with different inventory strategies is defined. Considering that the lower the demand, the greater the uncertainty, and the closer the SKU is to zero demand, the greater the obsolescence costs will be, the inventory carrying cost becomes even worst for low runner parts.

Considering that availability is the main driver for spare parts in capital goods industry, Olivotti et al. (2018) and Costantino et al. (2018) studied about HA-HCLDS items (High Availability, High Cost and Low Demand Systems), as explained before, it will be considered in the framework proposed all items with demand lower than 0.5/month. The main objective is to identify possibilities to move SKUs from MTS to MTO (from reactive to proactive approach). It means that all parts with demand pattern higher than 0.5/month will be considered out of scope.

And, in addition to this proactive approach, Houtum et al. (2015) affirms that decompositions should be avoided into lower-level constraints and decisions should be integrated as far as possible. And, also, that pooling effect should be created, stating that the more the demand can be bundled before they are matched, less buffering is needed.

To complement the argument, it is important to mention that, in Constantino et al. (2018) study, it is presented 4 different categories of demand, and the conclusion that HA-HCLSDS parts have erratic or lumpy demand, due to large variations in quantity, as presented in the Table 8.

Table 8. Demand Patterns Categories

Category	Description
Smooth demand	Regular demand over time with a limited variation in quantity.
Intermittent demand	Extremely sporadic demand, with no accentuated variability in the quantity of the single demand.
Erratic demand	Regular distribution over time, but large variation in quantity.
Lumpy demand	Extremely sporadic demand, great number of zero-demand periods and large variation in quantity.

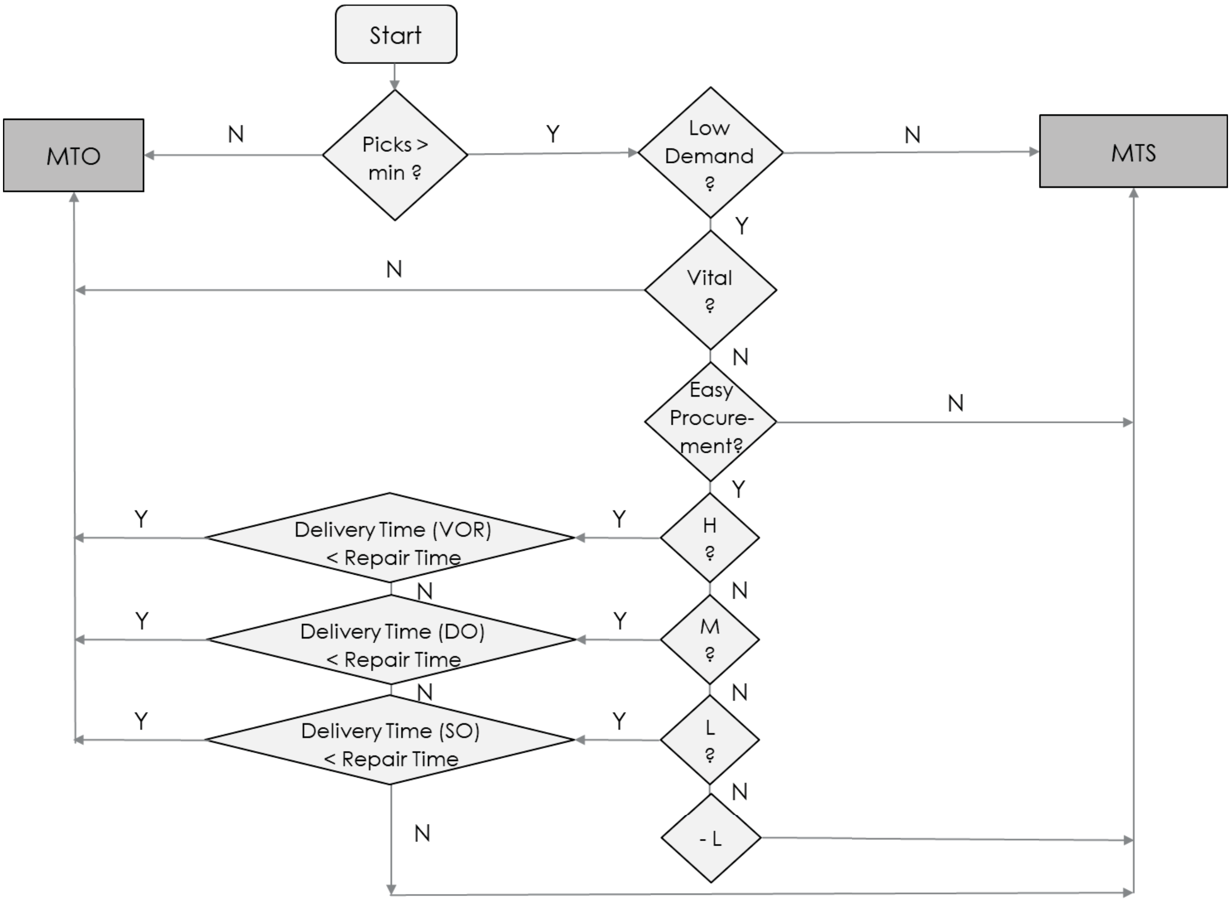
Source: Costantino et al. (2018)

And returning to Houtum et al. (2015) and taking a step back within the supply chain members, it is possible to conclude that in the previous member from where the part is used, the demands are more integrated, consequently avoiding decompositions.

And this member of the supply chain, based on Basten et al. (2014) study, can be considered as a single location model for inventory, that should occur when all items can be supplied fast enough from one stock point to the final destination. And, even if it is a relatively large region, it is still recommended when lateral transshipments are seldomly used.

Due to these findings, and considering additional source of data available to be included in the analysis, the Figure 5 was defined for a new proposal for stock decision making at SKU level.

Figure 5. Inventory Strategy Flowchart



SOURCE: The author (2023)

Finally, the proposed framework consists of using different classifications and a greater number of variables, often available, but not used in their full potential by most companies. Therefore, it is believed that, with the use of unexplored data, and with a consistent method, it is possible to evolve towards a better decision making in relation to spare parts inventory management.

6. APLICATION AND EVALUATION

6.1. Pilot 1 - Real Context Model Application in Brazil

The first application was carried out in a dealer group located in Paraná State, in Brazil. This group has a great interest in applying new techniques to reduce the number of spare parts in stock without jeopardizing customer satisfaction. Lean principles have been applied in the last recent years, mainly connected to workshop, to reduce vehicle lead time door to door, especially under lubrication services. But little effort had been made to improve inventory management.

As first analysis we realized that only two variables out of Table 7 were used in the algorithm of the company studied (HML and FSN) for inventory definition, resulting in a very poor analysis, compared to the potential, if additional source of data were used. In that algorithm the SKU is considered MTS (Make to Stock) when the minimum quantity of picks per year is reached. And its minimum value to define if an item will be put in stock is based on its unit price (HML classification) and presented in the Table 9.

Table 9. Pick Quantity

Price Class	1	2	3	4	5	6	7	8	9
Unit Price (USD)	0.00 to 0.60	0.61 to 1.80	1.81 to 4.80	4.81 to 10.20	10.21 to 29.60	29.61 to 83.00	83.01 to 166.40	166.41 to 332.40	from 332.41
Min Picks Qty	1	1	1	2	2	3	3	4	5

SOURCE: The author (2023)

Also, in the current algorithm, the unit price (HML) and also the consumption pattern of the item (FSN) are currently classified in 9 different classes (A to I). When crossing both controls a Table Matrix with 81 different inventory strategies is defined. In each of them there is a parametrization for Safety Stock and Lot Size. The lead time from Oder to Deliver (OtD) is also considered and added to the Safety Stock, to define the Order Point for each SKU/location. However, it is not considered in the calculation for slow mover parts (first 3 columns). Parts with zero demand in the last 12 months are taken out from the first column and analyzed separately into a family called Dead

Stock. But, even with this reduced scope, for the pilot dealer chosen, all spare parts within this analysis range represented 39% of the inventory value and 66% of all SKUs, as presented in the Table 10.

Table 10. Table Matrix

	Dead Stock	A	B	C	D	E	F	G	H	I
Demand Range	0	< 0.3	< 0.5	< 1.2	< 2.0	< 3.7	< 6.5	< 13	<35	>=35
% Stock Value	14%	14%	11%	17%	12%	8%	7%	4%	6%	6%
% SKUs	28%	28%	10%	16%	6%	5%	3%	2%	1%	1%
	Into the scope			Out of the scope						

SOURCE: The author (2023)

Some parts were selected from the pilot dealer within the spectrum of analysis (demand pattern below 0.5 un/month), and it was realized that all of them had intermittent or lumpy demand. However, the same parts, when considering Central Warehouse demand, resulted in erratic pattern. Despite the variation in quantity, once spare parts context is under study, the regular distribution allows predictability, less likely if the demand is decomposed at the dealer level.

For VED analysis, the variable Vital Code is available, and divided in 4 different groups, as showed in Table 11.

Table 11. Vital Code Description

Code	Definition	Description
1	Priority parts	Parts decided to have in stock, like Menue, IPS, Yacht, sales campaign, etc.
2	Service parts	Maintenance parts like chemicals, filters, belts, impellers, etc.
3	Consumption parts	Repair parts, regulary used, like pistons, upper gear, ECUs, etc.
4	Seldom needed parts	Remaining items like crankshafts, flywheel, brackets, etc.

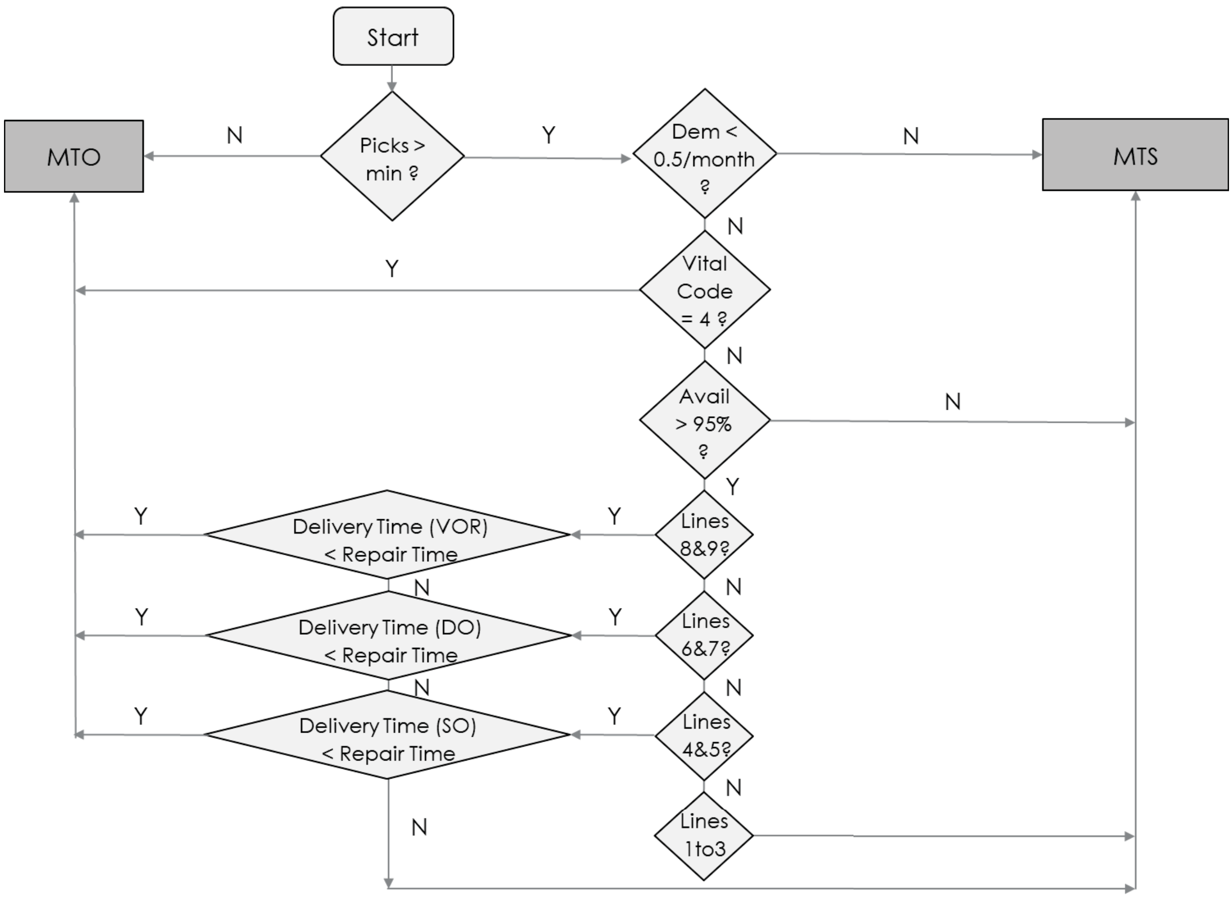
SOURCE: The author (2023)

In the flowchart only Vital Code 4 are directly moved to MTO, considering that seldom needed parts are less critical and can wait the delivery lead time from the distribution center. Parts with other codes are moved to the next step.

For SDE analysis, a variable available at SKU level (but also not used before), is part availability. It is possible to take all orders from a specific period of time, and calculate how many where immediate delivered. It was considered two years period and 95% as minimum availability level.

Therefore, out of the Figure 5, the following definitions of cut-off points for the chosen variables were considered, as presented in the Figure 6.

Figure 6. Inventory Flowchart for Pilot



SOURCE: The author (2023)

After reaching the minimum quantity of picks per year (Table 9), what in the current algorithm decides for keeping the item in stock, the first question of the framework is related to demand pattern, segregating only low runner parts, as defined ‘into the scope’. The next one is related to vitality, moving to MTO directly seldom needed parts (Vital Code 4, as already explained). In sequence, the next question is related to availability at the central warehouse, which has the responsibility to keep inventory to serve the entire region. If the availability of the SKU is lower than 95%, the framework recommends keeping the item in stock at the dealer level. However, if a high level of availability has been reached in the last 12 months at the central warehouse, the SKU proceeds to the next and final level of analysis. If it is a high-cost part (H), levels 8 and 9 presented in the Table 9, an SKU will not be stocked if an expedited VOR freight is fast enough to meet a repair need in time. For medium cost parts (M), levels 6 and 7 of Table 9, an SKU will not be stocked if a DO (Day Order) delivery time can meet repair needs and, for low cost parts (L), levels 4 to 5 of Table 9, an SKU will not be stock only if a common freight, SO (Stock Order) can meet repair needs. And, finally, for extremely low cost items, levels 1 to 3 of Table 9, the framework suggests the SKUs continue to be moved directly to MTS, even being a low runner part.

In order to test the proposed framework, and following Pareto's law, it was selected high and medium cost parts (H and M), levels 6 to 9 of Table 9, what resulted in 57 SKUs to be submitted to the proposed flow chart. Following the sequence presented it was realized that only 2 SKUs had availability lower than 95%, being, therefore, kept as MTS, and for other 5 SKUs the VOR delivery time was not enough to attend repair time, being also maintained as MTS, to do not impact the final customer. However, the other 50 SKUs could be moved from MTS to MTO, responsible for 23% of all stock value at the pilot dealer.

6.2. Pilot 1 Evaluation

In the last months the consumption of those items was monitored and, once consumed at the pilot dealer, they were not replenished.

The main KPIs (Key Performance Indicator) monitored since week 43 2021 were: Dead Stock: all parts in stock with zero consumption in the last 12 months (1), ToR (turn over rate): indicates the number of times the stock in a business has 'turned over', or been replaced, in a year (2), Emergency Orders: % of Day Order and VOR (3) and DSI (Dealer Service Index): % of inventory sufficient to meet at least a week's average demand (4).

The first comparison is related to the pilot dealer (before and after the framework implementation) and second between the pilot dealer figures with all group consolidated figures in the same period (total of 7 dealers belong to the group mentioned). Table 12 showed their following evolution.

Table 12. KPIs comparison

N	KPI	W2143 Pilot Dealer	W2232 Pilot Dealer	W2232 Group (7 dealers)
1	Dead Stock	10.7%	4.8%	12.9%
2	ToR	9.2	12.2	7.6
3	Emergency Orders	16.6%	12.5%	12.4%
4	DSI	92.2%	92.5%	92.2%

SOURCE: The author (2023)

Summarizing the pilot results, it turns out that the percentage of dead stock (parts without any demand in the last 12 months) was reduced by 55%, and it is also possible to noticed that the pilot was already superior to the group in general, which is 2.7 times higher (worse). Considering ToR the pilot reached 12.2 turns, achieving the first position in 2022, not only into the group, but also between all groups in the country, composed by 104 dealers.

Although this objective was not set when the framework was implemented, the percentage of emergency orders also reduced, from 16.6 to 12.4%. The other dealers result also reached the same level (12.5%). The conclusion we take from this fact is that the team's skills have been improved, not only technically, but also in attitude, once, since the pilot's launch, meetings have taken place in a bi-weekly basis. The same conclusion we draw about DSI (Dealer Service Index), that is a projection of availability at the dealers, measured through the percentage of parts in stock equal to or greater than one week of average demand.

The conclusion is that parts management in general have been carried out with much more care than before the framework implementation in the pilot dealer.

6.3. Pilot 2 - Real Context Model Application in Chile

The second application was carried out in a dealer group located in Chile, about 500 Km South from Santiago, where the Distribution Center to that country is located. There are 2 dealers (A and B) close to each other, about 120 km, and their main customer attend forestry industry. For this customer, parts unavailability is quite sensitive, once the forestry company operates in 3 shifts, and, due to safety legislations, the vehicles must be in perfect conditions to do not take the risk of being prevented from operating. If the part is not available at the dealer, the attendance from DC in Santiago takes 24 hours if an emergency order is placed, not enough to guarantee customer satisfaction. There were 43 complains during Q1 and Q2 in 2023 due to lack of parts at the dealers in study, and a new pilot was started, having as the main objective to reduce the occurrences of lost sales.

As explained before, from the Table 9, the more expensive the piece, the greater the number of picks needed to change the strategy and keep it in stock. As expected, the first option discussed was reducing the minimum number of picks into the algorithm responsible for automatic replenishment at the dealers, consequently ensuring a greater number of items in stock. However, this option was excluded once there is no interest in investing in inventory for all customers, but only for those with Gold Maintenance Plan (forestry industries for that specific region). It is important to mention that this customer represents 10% of sales for A and 16% for B dealers and, also, the fact that a unique algorithm for a dealer, that do not allow any kind of customization at the customer level, is an important limitation of the company under analysis.

In order to achieve the objective to reduce sales lost it was considered the parts consumed for that customer only, that were first segregated in different demand patterns, and, consequently, calculated safety stock necessary to achieve 95% reliability. The result was that a total of 176 PNs for both dealers (A and B) were necessary to be included in stock, in addition to what was already being done by the algorithm on a daily basis. Such investment would increase the dealers' stock by around 5% in value.

Those 176 items were defined considering their demand pattern and its consequent methodology for safety stock definition. And, once the algorithm would not be changed, all orders should be placed manually, suggested by a tool created in

Power BI to standardize the process, avoiding change criteria and, consequently, different decision makings.

VED analysis was also considered in the study, but different of what was carried out in pilot 1, that is, some non-vital parts could be delivered after 24 hours, as long as it did not impact the vehicle uptime, as well as body-white items, whose service is slow and waiting for the next day it would not be a problem. Due to that, 72 out of 176 were flagged as PARTS TO ANALYSE within the tool developed, .enabling a reduction in stock increase, making that the investment of about 5% in a first analysis can be reduced to just 2% if such flagged items are actually kept only in the central warehouse.

At this time of the project, it was also suggested analyzing the possibility of reducing the stock of items available at both dealers, not only carrying out an analysis similar to pilot 1, but including also the studies presented by Mehdizadeh (2020), about decentralizing supply chain, mainly when facing a large geographical area, and also by Howard et al (2011), about possibilities to offer a regional support warehouse. Based on that it was proposed putting in place the same framework created and tested already in a Brazilian dealer.

Returning to the Table Matrix, that classifies the unit price (HML) and the consumption pattern of the item (FSN), and considering the same range of values, it was verified that for the bigger dealer (A), the first 3 columns of the table (slow movers) represented 57% of the inventory value and 76% of all SKUs, as presented in the Table 13.

Table 13. Table Matrix Dealer A – Pilot 2

	Dead Stock	A	B	C	D	E	F	G	H	I
Demand Range	0	< 0.3	< 0.5	< 1.2	< 2.0	< 3.7	< 6.5	< 13	<35	>=35
% Stock Value	14%	34%	9%	15%	10%	5%	2%	2%	2%	6%
% SKUs	28%	38%	11%	13%	3%	3%	2%	1%	1%	1%
	Into the scope			Out of the scope						

SOURCE: The author (2023)

And for the smaller one (B), the first 3 columns of the table (slow movers) represented 65% of the inventory value and 78% of all SKUs, as presented in the Table 14.

Also, it is important to notice that the Demand Range is slightly different from both houses. Once the second one is small, the distribution changes in order to better split all items, and guarantee the 81 different strategies are working, with parts spread all over it.

Note that the maximum Demand Range into the scope zone is reduced from 0.5 to 0.4 un per month for the smaller one.

Table 14. Table Matrix Dealer B – Pilot 2

	Dead Stock	A	B	C	D	E	F	G	H	I
Demand Range	0	< 0.2	< 0.4	< 0.7	< 1.0	< 1.8	< 3.0	< 6.0	<15	>=15
% Stock Value	27%	27%	12%	10%	6%	5%	3%	3%	3%	6%
% SKUs	37%	29%	12%	9%	4%	4%	2%	2%	1%	1%
	Into the scope			Out of the scope						

SOURCE: The author (2023)

Looking at the figures related to low runner parts from both dealers it can be realized that there is a great opportunity to apply the same framework tested in pilot 1. However, due to the fact that the main trigger to start analyzing inventory strategy for this second pilot was increase uptime due to customer complain, and also that delivery times from the main warehouse in Santiago are long, such application was seen as risky at first time by the company.

Despite that, a similar, but different option, was analyzed. The new proposal consisted of taking the low runner parts that were into the scope of the framework (demand range below 0.5 units per month) but available in both dealers. It was appropriate once the delivery time from A to B was only 2 hours, much less when compared to the central warehouse performance.

Then, it was realized that 10% of stock can be reduced in total (considering the sum of both dealers stock). The study resulted that 461 PNs available in dealer A could start supporting also dealer B demands, and, due to that, not necessary to be stocked in that second dealer anymore. So, A started also to operate as a support warehouse to B, a condition never considered before.

Looking at the KPIs for both dealers, as presented in the Table 15, we see a great opportunity for improvement, mainly Dead Stock and ToR, whose performance is much lower than the one achieved in Brazil.

Table 15. KPIs comparison

N	KPI	W2335 Dealer A- Chile	W2335 Dealer B - Chile	Q1 2024 Dealer B (target)
1	Dead Stock	14.5%	28.2%	23%
2	ToR	3.2	3.4	4.3
3	Emergency Orders	21.1%	30.5%	-
4	DSI	94.3%	94.0%	-

SOURCE: The author (2023)

Although the last one (Dealer Service Index) is better here when compared pilot 1, it can be achieved without the cost to others KPIs being so high. Due to that the team already suggested a target to reduce dead stock and increase turn over rate, to be delivered until Q1 2024, as presented also in the Table 15.

6.4. Pilot 2 Evaluation

Even though it has started recently, it was already possible to verify the potential of implementing the framework developed also in this pilot in Chile. In the first analysis it was demonstrated that the stock increase should be reduced in 60% (from 5% to 2% of the overall stock in the region). In addition to this it was a presented a surprising 10% reduction in the total value of stock, simply by using the same framework but considering the main warehouse as a support warehouse, since the central one is distant and can impact customer satisfaction due to long delivery times.

7. CONCLUSION

The initial results of the pilot 1 have been discussed with the dealer group, which considered the problem to be solved significant, and the improvements quite satisfactory.

However, when discussing the issue with the OEM, concerns about uptime were always mentioned, indicator whose loss is not under discussion, due to the direct impact to the final customer. Consequently, any application would be better received if connected to availability increase, which the team realized being possible in a second pilot, taking advantage of a recent project started in Chile. This project would have the scope of reviewing the entire inventory strategy for dealers in a specific region, aiming to increase the uptime of an important customer in the forestry sector, with gold maintenance contract.

Even though the project in Chile started aiming uptime increase, the framework application was valid to reduce the total to be stocked, once some parts could wait the order in the Central Warehouse to be dispatched. The OEM understood that it is not because some parts from a certain range that are missing, and with customer complaints, that all the parts that belong to it should be stocked. Furthermore, there is a great opportunity for reduction, not only by applying the framework, but also by a new modality implemented, which is the use of the largest dealer in the region functioning as a Support Warehouse.

Anyway, we can conclude that all objectives have been achieved, inventory management procedures identified, data-driven approach incorporated, and an adaptive framework proposed and applied in more than one real case.

7.1. Limitations

The first important limitation to be explored concerns the sample size. For pilot 1, a single dealer in Brazil located 400 km from DC, at first sight can be perceived small or not representative of the total population of interest, considering all the geographic area covered. However, about 40% of all dealers can be attended with lead times very similar to the chosen location, and which represent 70% of all sales in the region. This choice was also made considering the funds limitation, once choosing a dealer further away from DC would make the research more expensive.

Data is also a limitation. The repair time variable per item was considered as the fastest service that makes use of it, and did not prove to be easily automated, extracted from maintenance data. And the need for analysis and manual input makes increasing the total number of items a limiting factor.

Another important limitation concerns about the current OEM's beliefs and culture in spare parts management. Its main concern is to maintain high levels of parts availability at the dealer level and, as culturally believed, consequent high levels of customer satisfaction. Changing this belief is an arduous task, once JIT techniques are regularly connected to the manufacturing area, not aftermarket. But even being an arduous task, we believe that it is necessary to overcome this barrier. In addition, as a similar limitation, there are 13 different groups at the Brazilian dealer net, with also different goals, beliefs and culture. And, once the project has been expanded to South America, this limitation becomes even more significant.

7.2. Future Works

As next step a tool in Power BI will be developed to present the potential of the framework, where it will be possible to analyze stock reduction at the level of dealer and/or group. In addition, a higher quantity of part numbers will be included, without changing the parameters of the previously defined scope. Meanwhile the algorithm will be developed, to work automatically, considering the variables already proposed.

And, considering that the total stock at the dealer selected for pilot 1 represents less than 1% of all dealer's stock in Brazil, this project provides a great potential for spare parts inventory reduction. Replicating the findings can not only confirm their validity but also build confidence in the results. Also, after Covid-19, delivery times have been reduced all over the country, in order to meet new market demands. It is also possible to expand the scope of the research, by adding other classification types into the algorithm (pending from Table 7 for example), we see a great potential for improvement in this study.

And, as an extension of it, a better parts distribution all over the country shall be provided, ensuring that the part would not be missing or would not take too long to arrive in certain regions, what would also provide, in addition to inventory reduction, a greater customer satisfaction.

An issue not addressed yet in this study is concerned to the use of maintenance data for parts prediction, once there is a technical limitation related to information per vehicle nowadays. However, investments have been done to not only have information uploaded (mileage and services executed for example), but also estimate when the next service will occur, based on an algorithm. Due to that, the future research is related to suggesting parts for a specific service to occur in a specific date and location, moving from keeping stock to staging process only, once the part will simply wait for the time between arrival and use, which can be even customized by the tool. However, for that to happen, it is necessary that real time data is available for a significant number of vehicles. This initiative has been recently nominated as Pre-Planning.

Another important issue to highlight is the improvement in the team's skills, due to all discussions related to the subject from the moment the framework was first presented. Biweekly meetings on the subject have made the team question itself about processes and decisions already consolidated, about which little or no discussion occurred. And the creation of a forum where ideas and experiences are exchanged has been fundamental for the growth of the entire team, which did not have the habit of discussing why the inventory strategy was defined that way, and for so long. It was possible to comprehend also what was stated by Slater P (2016), affirming that most software packages for inventory management in use makes it easy for people to abdicate responsibility for decision making.

Based on this study it is believed that the benefits will be perceived throughout the total supply chain. Although initially only the last member (dealers) has the benefit of increasing turnover rate and health stock, the reduction of the bullwhip effect, due to the fact that orders will start being made based on the final customer demand, will also bring more stability to the OEM, which, in a second moment, will also reduce its inventories, as well as emergency orders.

Also, that both pilots are helping to raise the level of the organization, increasing the understanding of the whole supply chain, with cross-functional teams and more advanced options being proposed and implemented.

In addition, it is possible to intensify the use of lateral transshipment, not only for emergencies, but also as a strategic offer, and start discussions about the existence of support warehouses in South America, valid nowadays only in other continents, given all the lessons learned from such studies and the implementation of several pilots, always looking for the best logistics solution, which can meet both customer satisfaction and cost reduction.

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