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AUGUSTO CÉSAR DE JESUS SANTOS

MAINTENANCE POLICIES FOR ENHANCING SYSTEM SUSTAINABILITY VIA THE DELAY TIME MODEL

Recife

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Thesis presented to the Graduate Program in Production Engineering at the Federal University of Pernambuco, as a partial requirement for obtaining the title of Doctor of Philosophy (PhD) in Production Engineering.

Research area: Operational research.

Supervisor: Prof. Dr. Cristiano Alexandre Virgínio Cavalcante.

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ABSTRACT

Although there are many maintenance models and policies that have been developed in the literature of reliability engineering, most take a purely economic perspective and very few consider the environmental aspect of sustainability. Models based on the delay time concept, for instance, have been widely applied in the development of maintenance policies for systems with at least one defective state prior to the failure. However, the environmental perspective is generally not taken into account in the modelling, which represents a significant gap in the literature. In addition, new environmental legislation encourages the reuse of components and products. In this context, this thesis develops novel maintenance policies to address the need for the reuse of items through delay time modelling. From a theoretical point of view, the novelty lies in the idea of repairing defective items for reuse, to avoid the acquisition of a new item and therefore of reducing relevant economic costs, industrial waste, and a negative environmental impact. To this end, the thesis proposes methods for determining the maximum level of the defective state for items to be reused and the proportion of items to be reused in the long term, depending on the reliability levels of new and reused items. These considerations in the development of new models make it possible to verify the potential for economic and environmental improvement in contrast with traditional models that do not consider reuse and that simply replace a failed item with a new one. From a practical perspective, the thesis creates novelty by proposing a method of mitigating the problem of generating waste from the disposal of items and equipment. The contribution of this thesis is highlighted in two ways: the expansion of the delay time model beyond the economic perspective that is traditionally considered and the possibility of mitigating a considerably important problem in the industrial segment. In terms of sustainability, the economic impact refers to the considerable reduction in the maintenance cost of certain systems due to component reuse. The environmental impact is linked to the possibility of reducing the volume of industrial components that are disposed of. The social impact is related to the discussion that the social dimension should be incorporated in maintenance models and policies.

Keywords: maintenance; delay time; reuse; industrial waste; second-hand items.

RESUMO

Apesar do grande número de modelos e políticas de manutenção existentes na literatura, a vasta maioria aborda uma perspectiva puramente econômica e poucos trazem contribuições que levam em consideração a perspectiva ambiental da sustentabilidade. O modelo delay time, por exemplo, tem sido amplamente aplicado para modelar a manutenção de diversos tipos de sistemas nos quais ao menos um estado defeituoso antecede a falha. No entanto, a perspectiva ambiental geralmente não é considerada na modelagem, sendo um importante gap na literatura dado o cenário atual em que a preservação ambiental se mostra relevante para a sociedade como um todo. Outrossim, novas legislações ambientais têm encorajado a prática de reuso de componentes e produtos, indicando-a como uma estratégia eficiente na redução de custos e preservação ambiental. Nesse contexto, esta tese introduz a possibilidade de reuso de componentes por meio de novas considerações na modelagem delay time. Do ponto de vista teórico, a inovação é apresentada na simples ideia de reparar o item defeituoso de forma a reutilizá-lo novamente, evitando, dessa forma, a aquisição de um item novo e seus respectivos custos econômicos e ambientais. Para introduzir esta possibilidade, novas considerações são inseridas nos modelos propostos, como por exemplo, a determinação do nível máximo do estado defeituoso para o componente ser reusado e a proporção de componentes a serem reusados no longo prazo a depender de características relacionadas com a confiabilidade dos componentes novo e reusado. Essas considerações no desenvolvimento dos novos modelos possibilitam verificar o potencial de melhoria econômica e ambiental em relação aos modelos tradicionais que não consideram reuso, mas simplesmente a substituição do componente por um novo. De uma perspectiva prática, a novidade contribui com a sugestão de uma alternativa para a mitigação do problema de geração de resíduos provenientes do descarte de componentes e equipamentos. Como visto, a contribuição deste trabalho é destacada de duas formas: a expansão da aplicação do modelo delay time para além da perspectiva econômica tradicionalmente empregada e a possibilidade de mitigação de um problema consideravelmente importante no segmento industrial. Em termos de sustentabilidade, o impacto econômico se refere à redução do custo de manutenção devido ao reuso de componentes. O impacto ambiental está associado à redução de resíduos e o impacto social está relacionado com a discussão sobre da inclusão da dimensão social da sustentabilidade em modelos e políticas de manutenção.

Palavras-chave: manutenção; delay time; reuso; descarte industrial; itens de segunda mão.

LIST OF FIGURES

Figure 1 -	The basic structure of the thesis..	20
Figure 2 -	Classification of maintenance methods..	23
Figure 3 -	Delay time concept..	29
Figure 4 -	Document selection process...	37
Figure 5 -	Number of published articles over the years.....................................	39
Figure 6 -	Occurrence and co-occurrence of keywords.....................................	40
Figure 7 -	Number of citations per author and number of articles per author...	42
Figure 8 -	Co-authorship representation...	43
Figure 9 -	Taxonomy of maintenance policies and models for reuse or remanufacturing...	45
Figure 10 -	Timeline of reviewed papers and their most common strategies..	57
Figure 11 -	Application of model strategies over the years..................................	58
Figure 12 -	Application of business strategies over the years..............................	59
Figure 13 -	Application of sustainability strategies over the years.......................	60
Figure 14 -	Framework for reintroducing a reused item into the system.............	66
Figure 15 -	Cost to repair a defect...	67
Figure 16 -	Comparison between traditional and proposed models for different % of reused items..	70
Figure 17 -	Cone crusher example..	74
Figure 18 -	All possible cases of model 2 and cost structure...............................	78
Figure 19 -	The expected cost of using a determined % of reuse items according to the reduction in the scale parameter of the distribution of the arrival of minor defects...	84
Figure 20 -	Effect of misclassification on the optimal inspection interval...........	85
Figure 21 -	Effect of misclassification on the optimal long run cost per unit time...	86
Figure 22 -	Impact of a false-negative..	90
Figure 23 -	Model 3, case 1..	92

Figure 24 - Model 3, case 2.. 93
Figure 25 - Model 3, case 3.. 94
Figure 26 - Model 3, case 4.. 95
Figure 27 - Model 3, case 5.. 96
Figure 28 - Model 3, case 6.. 97
Figure 29 - Model 3, case 7.. 97
Figure 30 - Model 3, case 8.. 98
Figure 31 - The expected cost of using a determined % of reused items according to the reduction in the scale parameter of the distribution of the arrival of defects.. 103
Figure 32 - Effect of q in the (K, Δ, T).. 105
Figure 33 - Comparison of policies for 80% of reused components..................... 106
Figure 34 - (a) Behavior of Δ for different dependability values of a reused component. (b) Behavior of (Δ) for different reliability values of a reused component.. 110

LIST OF TABLES

Table 1 - Main and most influential sources of publication.. 40
Table 2 - Most cited papers... 41
Table 3 - Papers with focus on the reuse or remanufacturing of products.................. 46
Table 4 - Papers with focus on the reuse or remanufacturing of industrial items........ 53
Table 5 - Proposed models and their main characteristics.. 63
Table 6 - Comparison between traditional and proposed models............................... 69
Table 7 - Sensitivity analysis under the variation of β_h and η_h.................................. 71
Table 8 - Notation for Model 2... 75
Table 9 - Parameters considered in model 2.. 82
Table 10 - Effect of different reliability between new and reused components............ 83
Table 11- Notation for Model 3... 88
Table 12 - Parameters considered in Model 3... 100
Table 13 - Effect of heterogeneity of components... 102
Table 14 - Effect of heterogeneity of components for the small percentages of reused components.. 104
Table 15 - Effect of dispersion on the time to arrival of a defect of the reused component.. 105
Table 16 - Effect of false-negative in K, Δ, T and pure inspection policies.................. 108
Table 17 - Effect of false-negative on a pure inspection policy.................................... 109

CONTENTS

1	**INTRODUCTION**	**15**
1.1	CONTEXTUALIZATION OF THE PROBLEM	16
1.2	THEORETICAL AND PRACTICAL JUSTIFICATION	17
1.3	AIM AND OBJECTIVES	19
1.4	METHODOLOGY	19
1.5	LAYOUT OF THE THESIS	20
2	**THEORETICAL BACKGROUND AND LITERATURE REVIEW**	**21**
2.1	MAINTENANCE DEFINITION AND CLASSIFICATION	21
2.1.1	**Definition**	**21**
2.1.2	**Classification**	**22**
2.2	SCHEDULE MAINTENANCE	24
2.2.1	**Age-dependent maintenance policy**	**24**
2.2.2	**Periodic maintenance policy**	**25**
2.2.3	**Sequential maintenance policy**	**26**
2.2.4	**Failure limit policy and repair limit policy**	**27**
2.3	DELAY TIME MODELLING	**27**
2.3.1	**Traditional Delay Time model**	**28**
2.3.2	**Recent advances in Delay Time models**	**31**
2.3.3	**Delay Time models in the context of second-hand items**	**33**
2.4	MAINTENANCE POLICIES AND MODELS: A REVIEW OF STRATEGIES FOR REUSE AND REMANUFACTURING	**34**
2.4.1	**Methodology**	**34**
2.4.1.1	Search strategy	35
2.4.1.2	Document selection	36
2.4.1.3	Relevant topics for the bibliometric analysis	37
2.4.1.4	Research questions for the literature review	38
2.4.2	**Bibliometric analysis**	**38**
2.4.2.1	Publication trends	38
2.4.2.2	Occurrence and co-occurrence of keywords	39
2.4.2.3	Main and most influencial sources of publication	40

2.4.2.4 Most influential papers........ 41

2.4.2.5 Author influence and co-authorship........ 41

2.4.3 Literature review........ 43

2.4.3.1 Maintenance models focused on products........ 45

2.4.3.1.1 Preventive Maintenance (PM) and Condition-Based Maintenance (CBM) 47

2.4.3.1.2 PM, warranty policies and upgrade actions........ 48

2.4.3.1.3 PM and warranty policies in sensor-embedded products........ 49

2.4.3.1.4 Warranty policies and upgrade actions........ 50

2.4.3.1.5 Warranty policies........ 51

2.4.3.2 Maintenance models focused on industrial items........ 52

2.4.3.2.1 Preventive Maintenance (PM)........ 54

2.4.3.2.2 Condition-Based Maintenance (CBM) or Reliability model........ 56

2.4.3.3 Research questions and Gaps to be investigated........ 56

2.4.3.3.1 Response to the research questions........ 56

2.4.3.3.2 Main gap in the literature........ 61

2.4.3.3.3 Final considerations and link to the models proposed in this thesis........ 61

2.5 SUMMARY OF THE CHAPTER........ *62*

3 INTRODUCTORY DELAY TIME MODEL FOR THE REUSE OF ITEMS........ 63

3.1 FRAMEWORK FOR REINTRODUCING A REUSED ITEM INTO THE SYSTEM........ **64**

3.2 THE MODEL........ 66

3.2.1 Numerical examples........ 68

3.2.2 Sensitivity analysis........ 70

3.2.3 Considerations on the initial model........ 71

3.3 SUMMARY OF THE CHAPTER........ 72

4 CONSIDERATIONS ON ITEM HETEROGENEITY, AND INSPECTION ERRORS........ 73

4.1 MODEL 2........ 73

4.1.1 Practical motivation........ 73

4.1.2 Notations and assumptions........ 74

4.1.3 Development of the model........ 76

4.1.4 Numerical examples... 81
4.1.5 Considerations on Model 2.. 87
4.2 MODEL 3... 88
4.2.1 Notations and assumptions.. 88
4.2.2 Development of the model.. 89
4.2.3 Calculation of the decision criterion... 91
4.2.4 Numerical example... 99
4.2.4.1 Effects of heterogeneity of components and different reliability levels....... 101
4.2.4.2 Effects of false-negatives.. 107
4.2.5 Considerations on Model 3.. 110
4.3 SUMMARY OF THE CHAPTER.. 111
5 CONCLUSIONS.. 113
5.1 ECONOMIC, ENVIRONMENTAL AND SOCIAL IMPACTS………..... 115
5.2 LIMITATIONS AND POSSIBLE FUTURE INVESTIGATIONS............ 116
REFERENCES.. 119

1 INTRODUCTION

This thesis addresses the current concern of sustainable industrialization by proposing new maintenance policies and models in the context of the reuse or remanufacture of items. Historically, maintenance models have been widely applied in different contexts to define adequate policies that are able to optimise important aspects, such as, reliability and cost. Among the distinct types of models developed, the delay time concept has been extensively investigated in the literature due to its simplicity and multiple possibilities of application (WANG, 2012). However, it has not been considered in the context of the reuse or remanufacturing of items. Thus, this thesis makes use of delay time models to develop maintenance policies that combine economic benefits and the environmental preservation of natural resources.

The link between maintenance and sustainability fills a significant gap in the maintenance related literature (SANTOS, CAVALCANTE, RIBEIRO, 2021; SANTOS, CAVALCANTE, 2022; SANTOS, CAVALCANTE, WU, 2022) and also addresses an important concern of society about the increase in the generation of industrial waste (Statistical Office of the European Union, 2020). In addition, the development of models focused on the reuse of items aids industrial companies to face contemporaneous challenges such as new environmental legislation and the necessity of friendly environmental practices in industry (RAHIMIFARD et al., 2009; SIBIDÉ et al., 2015; ISO, 2017). This conjuncture motivates the development of the present thesis and emphasises its importance not only in academic terms but also in practical terms, due to the consideration of sustainability, which is an important element in today's society.

In order to investigate how maintenance models can incorporate the concept of reuse and then to propose novel models, this thesis first examines the related literature to check how reuse or remanufacture has been considered. Subsequently, the thesis discusses three delay time models in the context of reuse of items. These models present an important novelty in Delay Time Theory because they expand the economic perspective initially considered by Christer (1976) to the environmental perspective, which is decisive for today's reality of industrial operations.

1.1 CONTEXTUALIZATION OF THE PROBLEM

Despite the evolution of sustainable practices in society, there are many challenges to promote prosperity while protecting the planet. These challenges are incorporated in the “17 Sustainable Development Goals to transform our World”, created by the United Nations to address the multiple existing sustainability problems (UNITED NATIONS, 2022). One example of such problems that impacts society as a whole is the dynamic of disposal, which makes the problem of waste in landfills more critical. In the European Union, the total waste generated in 2016 by all economic activities was 2538 million tonnes, of which up to 10% was generated by the manufacturing sector (STATISTICAL OFFICE OF THE EUROPEAN UNION, 2020). Considering this substantial quantity of waste material from the manufacturing sector, the need to develop new strategies for reusing items or products is imperative. In addition to this perspective, the use of second-hand items can also reduce the waste and contamination inherent in the process of producing a new item.

Consequently, new legislation has been encouraging the reuse of items or products. In the context of international commerce, ISO 20245/2017 lays down screening criteria for second-hand items that are traded between countries (INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, 2017). ISO proposes some guidance on the evaluation requirements, such as safety, quality, product information and usage, which facilitates the trade of second-hand items. Another important type of regulation that contributes to second-hand items management is the take-back legislation, which has extended manufacturers’ responsibility for their products to include giving advice on recovering and disposing of their products safely (RAHIMIFARD et al., 2009). Sibidé et al. (2015) highlight that new legislation has encouraged the introduction of second-hand products in the market due to a combination of initiatives that promote and infer the quality of reused systems or products, such as, the upgrade of a used system before resale, warranty coverage and price reductions. These initiatives promote the reinsertion of reused items into systems because they can provide a cheaper and warranted system with similar operating conditions. As a result, recovery strategies have become more common in industries in order to comply with legislation, to reduce negative environmental impacts and, in some cases, to save costs.

Despite the considerable quantity of waste material from the manufacturing sector and the new legislation regarding the reuse of items or products, reuse-related actions have not been proportionally studied in the context of maintenance models (SANTOS, CAVALCANTE, RIBEIRO, 2021; SANTOS, CAVALCANTE, 2022; SANTOS, CAVALCANTE, WU, 2022).

In general, the approaches to the concept of reuse that have been used most are based on reverse logistics (ROUDBARI, GHOMI, SAJADIEH, 2021; PARK et al., 2020) and the circular economy (JOUSTRA, FLIPSEN, BALKENENDE, 2021; MARTINA, OSKAM 2021; CONDOTTA, ZATTA 2021). Regarding maintenance models, the literature generally deals with warranty policies due to the necessity of determining a type of assurance for second-hand products to be safely used and also to meet customers' requirements (SU, WANG, 2014, 2016; WANG, LIU, ZHANG, 2018; PARK, JUNG, PARK, 2020).

Vis-à-vis the gap associated with the reuse or remanufacturing of items in the maintenance-related literature and the importance of these concepts to improve the relationship between industry and society, this thesis focuses on the development of maintenance models that encompass both concepts. The idea is to introduce novel models that not only contribute to advances in theory but also may be useful in providing economic benefits allied to environmental preservation. In fact, the models proposed in this thesis demonstrate how the delay time can be applied to the context of reuse, amplifying its importance by dealing with the environmental perspective of sustainability instead of only the economic perspective which is predominantly adopted in maintenance models.

As seen, the thesis focuses on the problem of not considering the reusability of items in maintenance models and proposes the first delay time models for reuse. It generates novelty in Delay Time whilst reflecting the growing awareness of the need to protect the environment by means of avoiding the unnecessary production and disposal of industrial items. For this reason, with regard to the 17 sustainable goals mentioned at the beginning of this section, this thesis can be directly associated with two of them, namely, Goal 9, due to the promotion of sustainable industrialization and goal 12, due to the reinforcement of sustainable production patterns (UNITED NATIONS, 2022).

1.2 THEORETICAL AND PRACTICAL JUSTIFICATION

As demonstrated in the previous section, the reuse of items or products may be one important strategy to reduce the significant levels of industrial waste. As a consequence, reuse or remanufacturing has gained increased attention in the literature due to its potential for reducing costs and negative environmental impacts. However, they have not been extensively studied in maintenance models and, when they are considered, the approach is traditionally focused on the product sold by companies (products that are sold in second-hand markets) rather than the industrial items (industrial components that are reused in-house) (SANTOS, CAVALCANTE, 2022). This context is also reinforced by a recent study that indicates that second-hand items have been investigated in replacement policies to a very limited extent in comparison to new items (PARK, JUNG, PARK, 2020). In addition, the model used in this thesis, the delay time model, has not yet been investigated in the context of reuse (SANTOS, CAVALCANTE, RIBEIRO, 2021; SANTOS, CAVALCANTE, 2022).

This background shows the overall context that justifies the development of this thesis. From a theoretical perspective, the thesis is justified due to its assumptions being solid and supported by the needs of sustainability development in the context of maintenance. More specifically, it contributes to expanding Delay Time Theory to the perspective of environmental sustainability by taking into consideration the reuse of items. In Delay Time Theory, a technical system can have three distinct states: “good state”, “defective state” or “failed state”. Before the system fails, it spends a period of time in a defective condition, which can be seen as an opportunity to avoid the failure by means of performing periodic inspections (CHRISTER 1976; BAKER, CHRISTER,1994; WANG 2008; WANG, 2012; CAVALCANTE, LOPES, SCARF, 2018; CAVALCANTE, SCARF, BERRADE, 2019; CAVALCANTE, LOPES, SCARF, 2021). With this in mind, the novelty of this thesis is presented in the simple idea of repairing a defective item in order to use it later again, thus avoiding the purchase of a new item and the cost and environmental impact of doing so. In order to introduce this possibility, innovative considerations are presented, such as, determining the maximum level of defective state that nevertheless allows the item to be reused and the proportion of reused items to be used in the long-run depending on their reliability level.

Beyond this theoretical justification, the thesis is also justified in practical terms due to the possibility of applying it in the industrial sector to improve maintenance actions and reduce the large amount of waste generated. The former is obtained from the definition of optimal maintenance actions by using the models and the latter can be achieved by applying the proposed models in practice, which can lead to reducing the volume of component waste. Thus, reuse has been described as an important strategy to ensure sustainability by preserving natural resources (LO, YU, 2013). Yeh, Lo, Yu (2011) and Lo and Yu (2013) refer to reuse as one of the most efficient strategies for reducing purchasing costs and contributing to environmental protection. According to these authors, reuse conserves natural resources, saves production costs and protects the environment. Thus, integrating the concept of reuse into maintenance models brings not only theoretical development in the modelling perspective but also establishes a new way of considering the practical problem of how to reduce industrial waste.

1.3 AIM AND OBJECTIVES

The aim of this thesis is to develop maintenance models that promote sustainability by means of reducing waste and preserving material resources due to reuse actions. The objectives of the research are:

- To conduct a critical and comprehensive literature review of maintenance policies and models that incorporate reuse strategies;
- To propose the introduction of the concept of reuse of items in delay time models;
- To study the effects of misclassification errors due to the incorrect identification of distinct defective states;
- To examine the effects of imperfect inspections by considering that an existing defect might not be detected;
- To investigate the consequences of different reliability between new and reused items and their optimal proportion;
- To encourage the adoption of the environmental perspective of sustainability when formulating maintenance models.

1.4 METHODOLOGY

This section succinctly presents the methodology with regard to the approach, nature and the procedures of this research. A more detailed description of the methodology related to the procedures of particular analyses is given throughout the text to facilitate comprehension of the latter.

Concerning the approach, this thesis adopts both qualitative and quantitative approaches to illustrating the findings obtained, where the qualitative approach is used to review the related literature and identify knowledge gaps, and the quantitative approach is used to develop a mathematical formulation, find numerical results and organise them in order to guide discussion on what has been investigated. Regarding the nature of the research, this study can be considered as applied research due to its being directed in practice towards solving specific problems. With respect to the procedures, an initial investigation of the conceptual basis and the related literature is undertaken followed by a more specific bibliometric and literature review of maintenance policies and models in the context of reuse. Subsequently, novel delay time models in the context of reuse are presented and the insights from them are discussed.

1.5 LAYOUT OF THE THESIS

This thesis is divided into 5 chapters: 1. Introduction; 2. Conceptual basis and literature review; 3. Delay time and reuse: the introductory model; 4. Considerations on item heterogeneity and inspection errors; 5. Conclusions.

The first chapter contextualizes the problem, presents the theoretical and practical justification, defines the aim and the research objectives, and succinctly describes the methodology adopted.

The second chapter approaches the maintenance and maintenance models in a broader perspective. Then, it focuses on the type of model considered in the thesis, the delay time model, and finalises examining how reuse has been investigated in maintenance models (SANTOS, CAVALCANTE, WU, 2022).

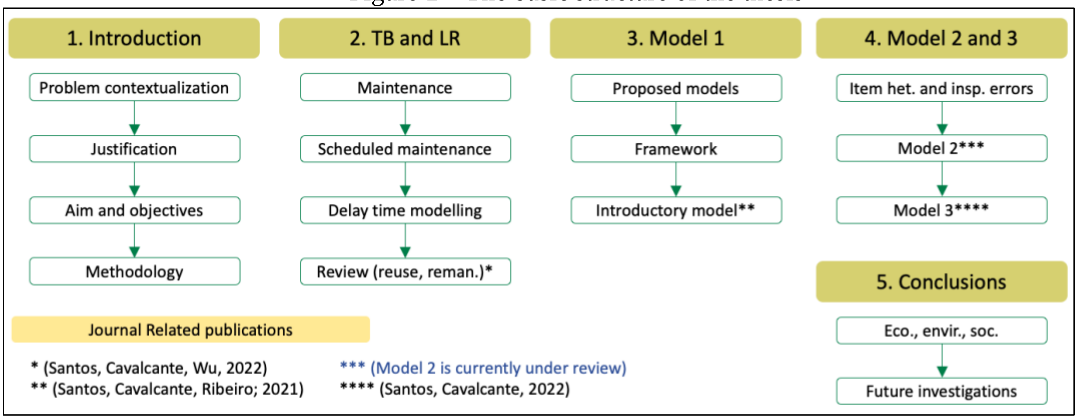
The third chapter presents the framework that relates the delay time model with the context of reuse of items, explains the link between these concepts and presents the introductory delay time model for second-hand items. This investigation is also described in part of the paper (SANTOS, CAVALCANTE, RIBEIRO, 2021).

The fourth chapter presents the considerations on item heterogeneity and inspection errors. It is based on (SANTOS, CAVALCANTE, WU, 2021) that investigates a system with two defective states and on (SANTOS, CAVALCANTE, 2022) that investigates item heterogeneity and false negatives.

The fifth and last chapter presents the final considerations about the work, indicates its potentialities and limitations, and suggests some possibilities for future lines of research.

The basic structure of the thesis and its chapters and related publications are illustrated in Figure 1.

Figure 1 – The basic structure of the thesis



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2 THEORETICAL BACKGROUND AND LITERATURE REVIEW

This chapter presents the theoretical background and conducts a critical and comprehensive literature review related to the development of the thesis. First, a definition and a general classification of maintenance are provided. From this initial classification, preventive maintenance is further categorized and reviewed according to the different approaches described in the literature. Thereafter, a section about Delay Time Theory is presented. Finally, a bibliometric and literature review of maintenance models and policies relating to reuse and remanufacturing is introduced. The last two sections focus on the new proposed delay time models for reuse of items.

2.1 MAINTENANCE: DEFINITION AND CLASSIFICATION

This section refers to the definition and classification of maintenance. It is important to define the concept of maintenance because it has evolved over time, predominantly due to the change of perspective in the type of maintenance action adopted. For example, in the past, when repair was predominantly applied, the repair was seen as a "necessary evil" because it occurred upon failures, which means that the negative consequences due to the failures had already been established. Maintenance can also be performed preventively to avoid future failure of a system. As such, the two main classification of maintenance, which are discussed in this section, is Corrective Maintenance, and Preventive Maintenance which is subdivided into Schedule Maintenance, Condition-Based Maintenance and Predictive Maintenance.

2.1.1 Definition

The term "*maintenance*" has been defined by different authors. According to Hu, Fan and Wang (2022, p.13), "maintenance refers to all technical and management activities, including monitoring, carried out to maintain or restore the state in which the product is capable of performing specified functions". Similarly, Zwingelstein (2003) defines maintenance as the set of activities executed in equipment or systems to assess, maintain and restore the operational capacity of the system. Likewise, O'Connor and Kleyner (2012) define maintenance as an action that aims to prevent a failure from happening in a system, or if it has occurred, it is the action that repairs the failure, allowing the system to return to operation.

Similarly, some standards generally follow the same rationale in the definition of maintenance. For instance, the European Standard for Maintenance Terminology (EN

13306:2017) considers maintenance as the "combination of all technical, administrative and managerial actions during the life cycle of an item intended to retain it in, or restore it to, a state in which it can perform the required function" (EUROPEAN COMMITTEE FOR STANDARDIZATION, 2017, p. 8). This definition is also considered in the Brazilian Standard for reliability and maintainability (NBR5462:1994) (ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS, 1994, p. 6).

As can be seen in the above-mentioned definitions, one important similarity among all of them is the fact that maintenance is considered from two different perspectives. The first one relates maintenance to an action that allows a failed item to be restored to operation (corrective perspective) and the second one relates maintenance to an action that prevents the failure from occurring (preventive perspective). No matter the definition of maintenance, it must encompass these two perspectives that basically cover the range of possibilities for all types of maintenance. These distinct perspectives of maintenance are also used to determine the general classification of maintenance methods, as presented in the following section.

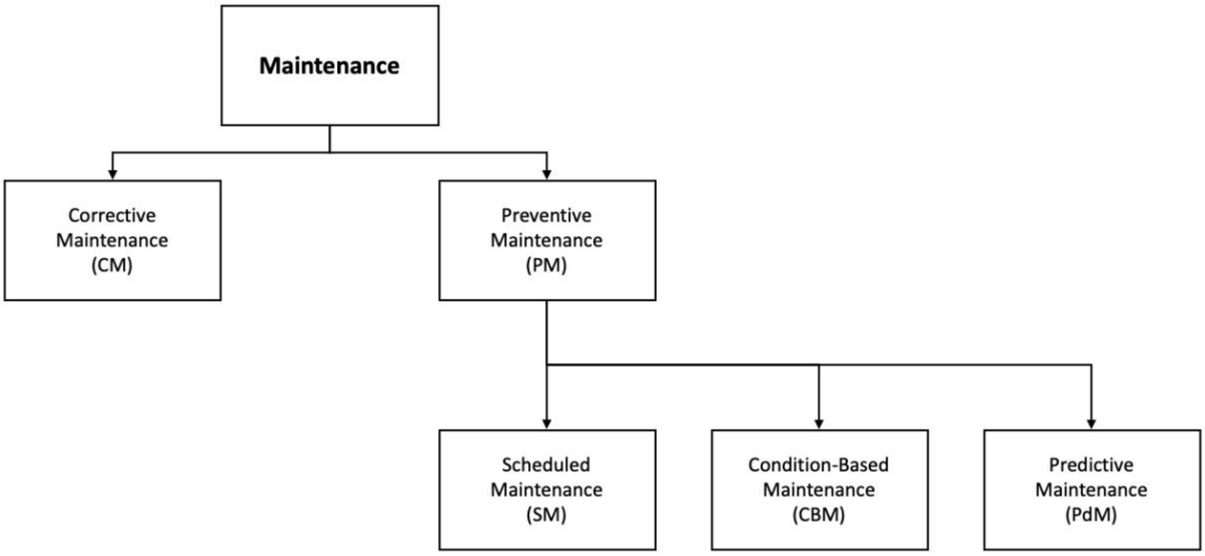
2.1.2 Classification

According to Hu, Fan and Wang (2022), maintenance can be divided into *Corrective Maintenance* (CM) and *Preventive Maintenance* (PM). CM was the main maintenance method until 1940. After people realised that the cost of performing only corrective actions would be higher than the cost of arranging maintenance actions to prevent the failure from occurring, PM started to be systematically adopted. Both types of maintenance are succinctly explained as follows.

CM aims to restore the item to the operating condition after a failure has interrupted the process and this has made it impossible for the the item to execute its required function (CARTER, 1986; ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS, 1994). This type of maintenance is generally more costly because it occurs after the interruption of the process due to a failure, and this generates some negative consequences such as production losses, a longer period of system unavailability during the repair, etc.

PM aims to keep equipment in a satisfactory operating condition, through the systematic activities of inspection and/or replacement to eliminate possible failures in the future (CARTER, 1986; HU, FAN, WANG, 2022). Depending on the type of information used in maintenance decisions, PM can be subdivided into Scheduled Maintenance (SM); Condition-Based Maintenance (CBM), also known as narrow nCBM; and Predictive Maintenance (PdM), also known as broad bCBM. This simple classification was suggested by Hu, Fan and Wang (2022) and may differ from other types of classifications. It was adopted in this thesis due to the convenience of associating types of maintenance policy to each specific subcategory of PM, which improves how to present and classify the literature studied. The classification of maintenance methods according to Hu, Fan and Wang (2022) is illustrated in Figure 2.

Figure 2 – Classification of maintenance methods



Source: adapted from Hu, Fan and Wang (2022, p. 16)

Scheduled maintenance refers to organizing maintenance actions based on the characteristics of the failure rate or the distribution of the lifetime of the system. Some examples of maintenance policies that are associated with scheduled maintenance are: age-dependent maintenance policy, periodic maintenance policy, sequential maintenance policy, repair limit policy and failure limit policy. nCBM evaluates the status of the system by monitoring and analysing some indexes, such as, temperature, pressure, vibration, etc to verify if the maintenance action is needed at that specific moment, and, if so, what type of method should be used. Likewise, bCBM or Predictive Maintenance uses the same strategy but to indicate the remaining life of degraded components (HU, FAN, WANG, 2022).

As the models proposed in this thesis are related to scheduled maintenance policies, a more detailed explanation and a critical and comprehensive review of recent literature on each type of scheduled maintenance is presented in the following section.

2.2 SCHEDULED MAINTENANCE

In this type of PM, a maintenance action is scheduled based on a specific characteristic of the system that reaches a determined threshold. This characteristic can be the age of the system, the time between inspections, the repair level, the failure level, etc. As such, it is essential that the failure rate or the distribution of the lifetime of the system is known in order to develop a scheduled maintenance policy.

2.2.1 Age-dependent maintenance policy

As the name suggests, this type of policy is based on the age of the system since the beginning of its operation. The most well-known age-dependent policy is the age replacement policy proposed by Barlow and Hunter (1960). In this policy, the system will be replaced when it reaches a determined time T or, in the event of a failure, prior to this time.

More recently, other policies based on the age of the system have been proposed. Sheu et al. (2018) propose generalised age maintenance policies for a system with random working times. The authors consider two distinct types of failures. In the first type, the system is repaired by minimal repair and in the second type the system is rectified by replacement. In the proposed models, the system can be preventively replaced at time $T\,(> 0)$ or on other particular occasions. Badía, Berrade and Lee (2020) compare age replacement policies with replacement after a determined number of minimal repairs. Authors consider a system under two types of age-dependent failures, namely, revealed minor failures and unrevealed catastrophic failures. In the model, periodic inspections and preventive replacements are also considered to determine the long-run cost per unit of time. Polotski, Kenne and Gharbi (2019) suggest a joint production and maintenance optimal policy for hybrid manufacturing-remanufacturing systems under age-dependent deterioration. The authors consider that the system is failure-prone and the deterioration is characterised by an increasing failure rate, which leads to the loss of machine availability. For this reason, an age-dependent maintenance policy is considered.

Other papers consider an age-dependent maintenance policy associated with other types of policy. Wang, Qiu and Wang (2021), for instance, propose a condition-based and age-based replacement policy and inventory policy for a series system with two non-identical units. In their proposal, one unit is subject to soft failure and condition-based maintenance and the other unit is subject to hard failure and maintenance actions are based on its usage. Scarf et al. (2009) propose an age-based inspection and replacement policy for heterogeneous components. Special attention should be given to this paper because one of the proposed models in this thesis is based on it. Scarf et al. (2009) consider a population of weak and strong components. The periodic inspections are conducted in order to detect the defective state, especially in the weak components that have a shorter expected life. The age replacement is also performed at time T to avoid the failure of the system. The authors minimise the long-run cost per unit time by optimising the number K of inspections to be performed, the age replacement time T, and the optimal inspection interval Δ. This is the reason why this model is also known as $K\Delta T$ model.

In this thesis, an age-based maintenance policy similar to the $K\Delta T$ is also considered and presented in Chapter 4. This contribution can also be verified in Santos and Cavalcante (2022). Essentially, the previous $K\Delta T$ model presented by Scarf et al. (2009) is considered with a different perspective to be applied in the context of reuse of items. The weak components are considered as the reused items and the strong components are considered as the new items. Further, the analysis indicates the proportion of reused items that returns economic and environmental benefits, according to their reliability. Both papers combine the age-replacement policy with periodic maintenance policy. The latter is approached in the following section.

2.2.2 Periodic maintenance policy

As the name suggests, in this type of policy the system will be periodically maintained after a fixed time interval T. Some papers that consider this strategy have already been mentioned in the previous section (SCARF et al. 2009; SANTOS, CAVALCANTE, 2022). Other important periodic maintenance policies that have been considered are the block replacement policy, in which the system is replaced at each time interval T (BARLOW, PROSCHAN, 1965; NAKAGAWA, 1979) and the pure inspection policy, in which the system is inspected at each time interval T (BARLOW, PROSCHAN, 1965).

In addition to these important policies, other periodic policies have been recently studied and proposed based on Delay Time Theory. Some of those that are strictly related to this thesis are the delay time models for second-hand items (SANTOS, CAVALCANTE, WU, 2021) in which inspections occur at a fixed time interval T. In these papers, the optimal interval is determined according to the proportion of new and reused items to reduce maintenance cost and improve the impact on the environment.

Like the ones mentioned at the beginning of this Section (SCARF et al. 2009; SANTOS, CAVALCANTE, 2022), other papers also consider a periodic maintenance policy as a particular case of a more general policy, and some of these will be described in the next Section that reviews the sequential maintenance policy.

2.2.3 Sequential maintenance policy

A sequential maintenance policy refers to PM that is executed at unequal time intervals. Barlow and Proschan (1962) compare a sequential maintenance policy with the age replacement policy. More recently, the sequential maintenance policy has been considered in some delay time models, to adjust the inspection interval according to some characteristics of the system. Some interesting papers that deal with this perspective using the delay time concept are presented as follows.

Wang (2000) considers multiple nested inspections of a production plant at different intervals. The inspections are assumed to be ordered in a way that more extensive inspections contain the activities of less extensive inspections. Wang (2009) suggest two different inspections with different time intervals for a system subject to two types of deterioration. The minor inspections are carried out periodically and the major inspections are executed regularly at longer intervals. Wang, Zhao and Peng (2014) propose a two-level inspection policy for a system based on a three-stage failure process. A minor inspection identifies the minor defective stage with a certain probability, and the severe defective stage. A major inspection identifies both defective stages perfectly. Once the system is found to be in the minor defective stage, a shortened inspection interval is adopted, characterising a sequential maintenance policy.

Similar to these papers presented by Wang and discussed in the previous paragraph, Ma et al. (2017) consider a system subject to two types of failures. The first failure mode is the traditional 0-1 logic failure and the second one is described by a two-stage failure process. Preventive replacement is used to avoid the possible failure due to the former failure mode and adjustable inspections are used to identify the defective stage of the latter failure mode. In Ma et al. (2017), the inspection periods get shorter according to a constant ratio, which characterises the sequential maintenance policy. Similarly, Zhang et al. (2021) modelled a two-phase inspection policy, assuming imperfect inspections, which are subject to false positives and false negatives. The authors minimise the maintenance cost, the optimal inspection interval and the number of inspections in each phase based on the renewal reward theorem.

More recently, Alberti et al. (2022) propose a flexible two-phase inspection-maintenance policy for safety-critical systems considering revised and non-revised inspections. In the first phase, inspections are carried out with a constant frequency and in the second phase inspections occur with varying time intervals. This sequential maintenance policy generalises the pure age-based replacement policy, the pure inspection policy, the $K\Delta T$ policy presented by Scarf et al. (2009), and the sequential policies proposed by Ma et al. (2017) and Zhang et al. (2021).

As can be seen, the models that have been developed more recently usually combine more than one type of policy. As a consequence, better results can be obtained in terms of cost since the optimization of a more general policy provides the best cost relation among the particular policies analysed. Other important types of schedule maintenance policies indicated by Hu, Fan and Wang (2022) are the repair limit policy and the failure limit policy, which are succinctly commented in the next section.

2.2.4 Failure limit policy and repair limit policy

According to Hu, Fan, and Wang (2022), both types of policies consider a given index value to determine the maintenance action. In the former, PM is conducted after the failure rate or other reliability indexes reach a specified threshold (BERGMAN, 1978). In the latter, after a component fails, the index value is evaluated. Further if the index value exceeds the preset threshold value, replacement will be carried out. The cost and time are indexes generally used in the repair limit policy. For example, Nakagawa and Osaki (1974) propose a repair time limit policy, under which if a failed component cannot be fixed within a certain time period, it must be replaced. An analogous idea is presented in the model proposed (model 1) in Chapter 3 of this thesis. In this model, the time in the defective state is considered as an index that determines whether or not the current defective item can be reused.

These categories finalise the classification of the scheduled maintenance policies. As can be seen throughout this section, some models that can establish policies can be classified in one or more categories, depending on their particular cases or on the type of action adopted. Some delay time models presented have this characteristic because they comprise multiple possibilities of maintenance actions depending on the state of the system. As the delay time is the main concept used in the development of the models proposed in this thesis, the next section reviews it from an initial conceptual basis up to the recent advances reported in the literature.

2.3 DELAY TIME MODELLING

This section reviews some developments relating to the delay time models. First, the concept is explained, and this is followed by the presentation of the traditional delay time model for single-component systems. Then, recent advances in the literature are discussed in general terms and more specifically regarding second-hand items.

Delay Time was originally proposed by Christer (1976). In this modelling, the degradation of a component is characterised by three distinct stages: operational, defective, and failed. As such, during the time before the component fails, the component spends a certain amount of time in a defective state. This time is defined as delay time. More precisely, the delay time is the period from the arrival of the defect until its detection or it transforms into a failure (BAKER, CHRISTER, 1994).

In the literature, the delay time models have been developed under two different perspectives: models that consider single-component systems and models that consider a complex plant. The next section covers the first perspective, which is the one used as the basis for developing the models proposed in this thesis. A discussion of both perspectives can be found in Christer and Waller (1984), Lee (1999), Wang (2008) and Santos (2019).

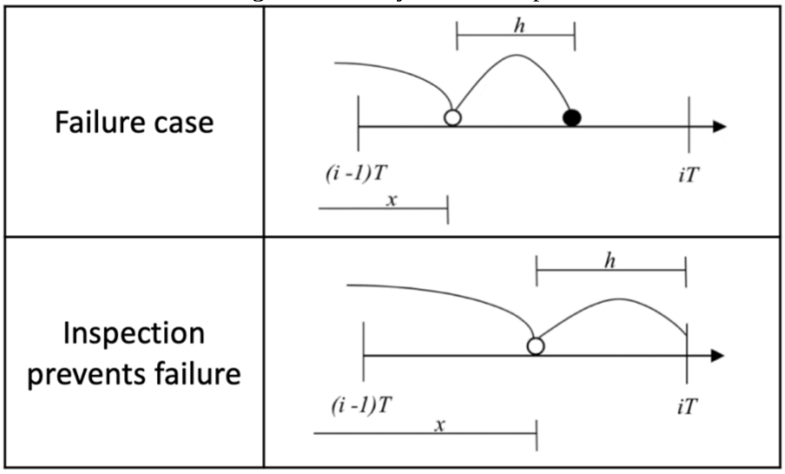
2.3.1 Traditional Delay Time model

Many authors have described how the traditional delay time model can be simplified. In this section, this idea is presented according to Santos, Cavalcante and Ribeiro (2021) to facilitate the comparison and understanding of the models proposed and presented in Chapters 3 and 4.

Regarding single-component systems, they can be interpreted as a component and a socket working together to perform an operational function (ASCHER, FEINGOLD, 1984; SCARF, CAVALCANTE, 2012). If a specific component is responsible for the most recurrent failures of a system with multiple components, the system can be modelled as a single-component. As such, a single-component system is also considered a complex system with an individual component that causes the most recurrent failures.

In this regard, the delay time model for a single-component system considers that a failure in its main component is regarded as a two-stage process. A defect arrives in the component at time x, followed by a failure after an interval h. This interval represents a chance to inspect the system and correct the defect before it becomes a failure (Figure 3).

Figure 3 – Delay time concept



Source: Santos, Cavalcante, Ribeiro (2021)

So, the delay time concept may be applied to define a regime of inspections that minimise the expected long-term maintenance cost, $C(T) = \frac{U(T)}{V(T)}$, which is the ratio of the expected cost $U(T)$ over the expected cycle length $V(T)$.

The following assumptions may be considered in the basic delay time model for single-component systems.

1) The component can be either in a good, defective or failed state.
2) The system fails when the component fails.
3) The delay time h is independent of the arrival time of the defect x.
4) An inspection takes place every T arbitrary unit of time and costs C_i monetary units.
5) Inspections are perfect; hence, the defect is always identified at inspection.
6) The defect found at an inspection is repaired instantly and costs C_p monetary units.
7) The failure is repaired as soon as it happens and costs C_f, such that $C_f > C_p > C_i$.
8) The arrival time of the defect, x, is distributed according to a known distribution, the probability density function of which is $f_x(x)$.
9) The probability density function of delay time h, $f_h(h)$, and its distribution function represented by $F_h(h)$ are also known.

Considering the mentioned assumptions and Figure 3, $U(T)$ can be determined based on two different possibilities: a failure occurs within the inspection interval $(x + h \in$

$[(i-1)T, iT])$ or an inspection prevents a failure from occurring $(x \in [(i-1)T, iT])$, but $(x + h > iT)$, so $U(T)$ can be calculated from Equation (1).

$$U(T)=\sum_{i=1}^{\infty}[iC_i+C_p]\int_{(i-1)T}^{iT} f_x(x)R_h(iT-x)dx+\sum_{i=1}^{\infty}[(i-1)C_i+C_f]\int_{(i-1)T}^{iT} f_x(x)F_h(iT-x)dx \tag{1}$$

Analogously, the expected length of a cycle, $V(T)$, can be calculated by Equation (2).

$$V(T)=\sum_{i=1}^{\infty}iT\int_{(i-1)T}^{iT} f_x(x)R_h(iT-x)dx+\sum_{i=1}^{\infty}\int_{(i-1)T}^{iT} f_x(x)\left[\int_{0}^{(iT-x)}(x+h)f_h(h)dh\right]dx \tag{2}$$

The first term in both Equations (1 and 2) represents the case in which the failure does not occur within the inspection interval, and the second term represents the complementary case in which the failure occurs within the inspection interval.

The optimal inspection intervals should be set so that the rate of expected cost over expected cycle length is minimised. Usually, the cost of failure is superior to both the cost of repairing a defective item and the cost of inspection (from hypothesis 7: $C_f > C_p > C_i$), due to the inconveniences brought to the system. Therefore, an inspection interval is determined to ensure the integrity of the component and to reduce failures (SANTOS, CAVALCANTE, 2018).

In the literature, this model that considers perfect and fixed-length inspections in single-component systems has been considerably adapted to meet different contexts. Some authors adopt imperfect inspections, different inspection lengths, other types of maintenance actions, more defective states (BERRADE, CAVALCANTE, SCARF, 2017; CAVALCANTE, SCARF, BERRADE, 2019; ZHANG, SHEN, MA, 2021; MENGYING, JIANHUA, XIAO, 2021; SANTOS, CAVALCANTE, RIBEIRO, 2021; SANTOS, CAVALCANTE, WU, 2021; PENG et al., 2022; CAVALCANTE et al., 2022; SANTOS, CAVALCANTE, 2022). All of these recent developments as well as the possibility of using second-hand items (SANTOS, CAVALCANTE, RIBEIRO, 2021; SANTOS, CAVALCANTE, WU, 2021; SANTOS, CAVALCANTE, 2022) are shown in the following sections.

2.3.2 Recent advances in delay time models

This section reviews what has been recently studied in terms of delay time models. In a general view, the most recent delay time models deal with the idea of executing an opportunistic maintenance. However, other important topics have been considerably studied, such as imperfect inspections and the induction of defects.

The first part of this section should initially mention a paper that served as the foundation for many different delay time models, including model 3 in this thesis. Scarf et al. (2009) propose a two-phase maintenance policy for a single component from a heterogeneous population. The first phase refers to periodic inspections and the second phase refers to PM. The authors optimise the number K of inspections to be performed, the age replacement time T, and the optimal inspection interval Δ. Their paper represented an important landmark in Delay Time Theory, and its main idea of having more than one phase has been considerably studied in delay time models, as we can see in the following paragraphs.

Regarding the opportunistic maintenance policies, Cavalcante, Lopes and Scarf (2018) propose a policy for one-component systems of variable quality. The influence of opportunities in a hybrid inspection and replacement policy is considered. Similar to Scarf et al. (2009), Cavalcante, Lopes and Scarf (2018) consider an initial inspection phase followed by a wear-out phase. However, random events that offer opportunities for replacement are considered.

Following the same idea of having different phases in an opportunistic maintenance model, two-phase and three-phase maintenance models are proposed in Cavalcante, Lopes and Scarf (2021) and Melo, Cavalcante and Scarf (2022), respectively. The former proposes an inspection and replacement policy for a system when maintenance actions are performed on a periodical basis. The focus is not on scheduling maintenance intervals but on the types of maintenance. Possibilities of time and resource limitations are also modelled by the consideration of defaults. The latter proposes a hybrid maintenance policy that considers periodic inspection and opportunistic replacement. Rather than the inspection and wear out phase, the authors consider an opportunistic phase in which preventive replacement is performed early if an opportunity arises. The model is especially applied in remote systems with restricted access and high logistics costs, such as offshore wind farms.

Liu et al. (2021) integrate opportunistic maintenance and imperfect inspections. The delay time is considered to evaluate the reliability of a system with sufficient inspection data but insufficient failure data. This consideration of imperfect inspections is an important characteristic that has been studied in a couple of maintenance models. Zhang, Shen and Ma

(2020), for example, propose a delay time model that takes into consideration both imperfect repairs and non-constant probabilities of inspection errors. Scarf, Cavalcante and Lopes (2019) propose a delay time model for critical systems subject to random inspections. The model can be applied to systems in which production is prioritised over maintenance in such a way that inspections are impeded or occur on an opportunistic basis.

Systems with hidden failures have also been investigated. Cavalcante, Scarf and Berrade (2019) suggest a delay time model for protection systems in which the inspections provide imperfect information about the state of the system. The authors show that preventive replacement mitigates low-quality inspection and that inspections are cost-effective when inspections errors are low. Zhang, Shen and Ma (2021) consider a PM policy for systems with hidden failures. The authors consider both competing risks of degradation and random shocks. The failures can only be detected by periodic inspections in which the optimal inspection interval is determined based on the delay time concept.

Other important topics in the delay time theory are as follows. Two failure modes are investigated in Peng et al. (2022). They propose a PM for heterogeneous parallel systems with two failure modes. One is regarded as a one-stage catastrophic failure and the other refers to a two-stage delay time failure. Similarly, stochastic dependence between two interacting components are studied in Berrade, Scarf and Cavalcante (2018). They investigate the inspection and maintenance of a two-component system with stochastic dependence, in which failure of component 1 may cause component 2 to become defective. The application of the policy is shown in a real system that cuts rebar mesh.

Postponed replacement and induction of defects have also been explored. Berrade, Cavalcante and Scarf (2017) study postponed replacement. They analyse cases in which maintenance might not be performed immediately after the detection of a defect in the system. Moreover, Cavalcante et al. (2022) suggest a framework to assess the impact of human and environmental/managerial factors on inspection quality in terms of defect induction. More specifically, the influence of disruptive external events on the probability of human error is discussed. As such, the proposed delay time model incorporates the probability of defect induction at inspections according to the disruptive external events.

Finally, Mengying, Jianhua and Xiao (2021) propose a joint maintenance and spare ordering policy that considers the inspection, PM, and quality control in a four-state single-unit manufacturing system. Mahmoudi et al. (2017) suggest a delay time model for complex infrastructures that can fail due to different causes from distinct environmental and operational conditions. The model deals with multiple defect types and multiple inspection methods.

The papers mentioned show that Delay Time Theory has been considerably used to model different characteristics of systems subject to defective state prior to the failure. As seen, delay time models are generally developed based on an economic perspective. The next section discusses a few models that have considered both economic and environmental perspectives in the context of the delay time models. More specifically, it focuses on second-hand items, the main focus of this thesis.

2.3.3 Delay time models in the context of second-hand items

As shown in the previous section, different delay time models have been proposed in the literature. Despite the distinct assumptions in each one, all of them only consider the economic perspective in the modelling, by means of minimising the total expected cost of maintenance. Models that take into account the environmental aspect of sustainability are not commonly found in the maintenance-related literature in general nor more specifically in the delay time models.

Within the delay time models, the environmental aspect of sustainability is considered in the framework proposed by Jones, Jenkinson and Wang (2009) to reduce downtime and maintenance-related costs. The difference from the other papers is the consideration and discussion of environmental-related costs.

Regarding the specific approaches of reuse or remanufacturing, Santos (2019) and Santos, Cavalcante and Costa (2020) suggest that the lower the level of degradation of a component, the lower is the effort to repair it for a future reinsertion in the system. However, no other paper in the literature up to the development of this thesis has proposed anything similar in this regard, which emphasises the novelty and contribution of their study. As a consequence, the following papers that consider the delay time models in the context of second-hand items that resulted from this thesis have been published.

From the initial idea presented in Santos (2019) and Santos, Cavalcante and Costa (2020), Santos, Cavalcante and Ribeiro (2021) proposed the introductory delay time model for second-hand items. Essentially, the current state of a defective item is used to determine whether or not it can be reused, based upon the amount of time it has been in the defective state.

Later, Santos, Cavalcante and Wu (2021) considered a system that is subject to two defective states prior to the failure, in which the component can be reused if it is detected in the first defective state and cannot be reused if it is detected in the second defective state or if it fails. This idea is described in Chapter 4.

Similarly, Santos and Cavalcante (2022) assess the viability of considering different percentages of reused items in an inventory. The authors compare the reliability of new and reused items and discuss up to what level of reliability a used item can differ from a new one and still be economically and environmentally viable. This contribution is also described in Chapter 4.

The above-mentioned papers reflect the complete consideration of related papers that deal with second-hand items in delay time models. This limited number of studies regarding second-hand items is also verified in a more general context of maintenance models, as verified by the literature review presented in the next section.

2.4 MAINTENANCE POLICIES AND MODELS: A REVIEW OF STRATEGIES FOR REUSE AND REMANUFACTURING

In this section, a bibliometric analysis is presented along with a literature review on maintenance policies and models for reuse and remanufacturing. The former shows publication trends, the most influential sources of publication, the most cited authors, etc. The latter categorises the existing work in terms of its focus on products sold by companies or industrial items. A taxonomy is proposed and each paper is then analysed, according to the model strategy, business strategy and sustainability strategy. From this discussion, some essential research questions are answered and the main gap in the literature is identified and discussed. A further discussion of this topic can be found in (SANTOS, CAVALCANTE, WU, 2022).

In addition to describing and classifying existing literature, this section also serves as a motivation for developing the models in this thesis. The study clearly indicates that the proposed models are unique both in terms of the approach to Delay Time Theory and also in terms of their consideration of the environmental perspective of sustainability.

The following sections present the methodology, the bibliometric analysis and the literature review.

2.4.1 Methodology

The methodology uses bibliometric analysis and literature review as research methods. The former is useful in identifying trends in the literature (MUHURI, SHUKLA, ABRAHAM, 2019) and the latter provides a search and screening of publications based on their subject matter (SAIHI, BEN-DAYA, AS'AD, 2022). The methodology of this specific part of the thesis consists of four major steps: search strategy, document selection, relevant topics for bibliometric analysis, and research questions for the literature review. Each one of them is presented as follows.

2.4.1.1 Search strategy

The purpose of the study is to investigate how maintenance policies and models in the context of reuse and remanufacturing have evolved over time, so the following keywords: “maintenance policy”, “maintenance model”, “reuse”, “remanufacturing”, and “second-hand” were chosen. The term “second- hand” was chosen because it is usually considered to refer to used items (products, equipment, or components). Similarly, the terms "reuse" and "remanufacturing" were also selected since they tend to be associated with maintenance activities. Reuse is the process of using a product item or a piece of material again for the same purpose, whether in the original form or with little modifications (UNITED STATES ENVIRONMENTAL PROTECTION AGENCY, 2022). When a product item is not waste and is used again for the same purpose that it was created for, it can be termed "direct reuse" (WAKIRU et al. 2021). Remanufacturing refers to the process of reconditioning a used component to match the performance specifications of a new component (WAKIRU et al., 2021; PATERSON, IJOMAH, WINDMILL, 2017). These enhancements to the component or product are provided by maintenance activities. Conversely, other terms related to sustainability, such as recycle or recover, are less relevant to the actions that maintenance policies or models can suggest. In general, they are associated with other types of processes that do not fall within the purview of maintenance activities. “Recycle” refers to a set of procedures for collecting, processing, and returning waste products as raw materials (UNITED STATES ENVIRONMENTAL PROTECTION AGENCY, 2022; PATERSON, IJOMAH, WINDMILL, 2017). The term “recover” refers to the process of disassembling, sorting, and cleaning gathered products after the end of their useful life in order to reuse them (LIYANAGE, BADURDEEN, 2009).

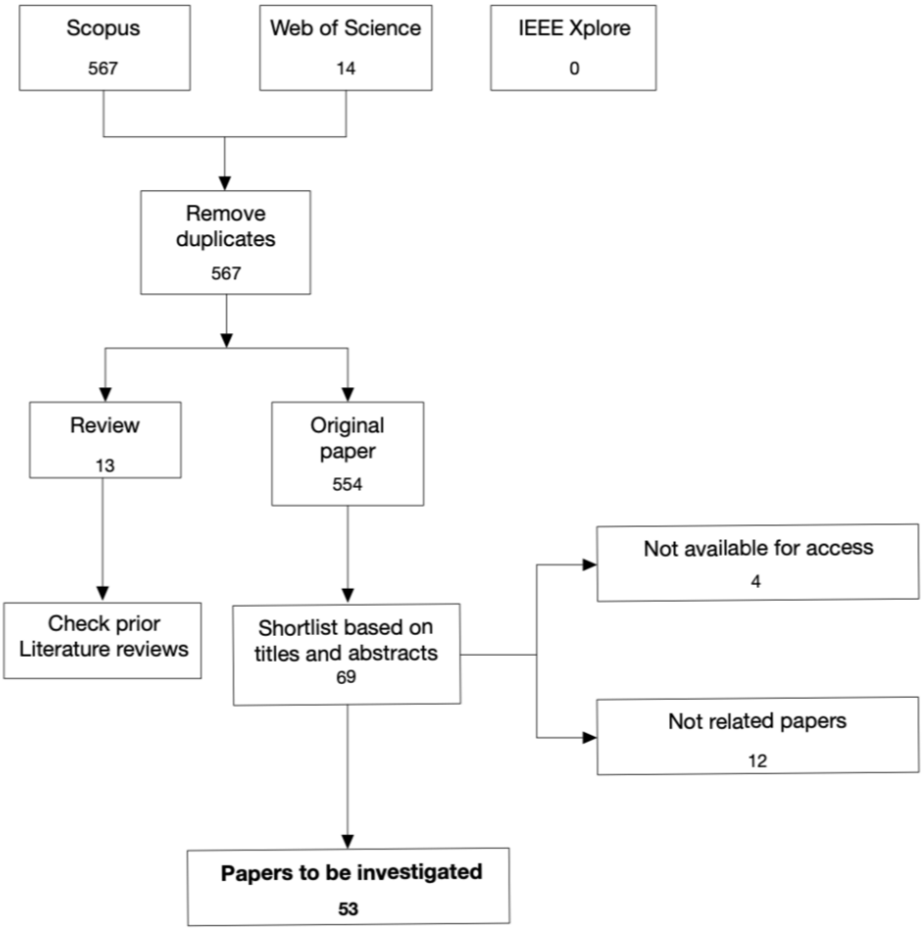
Following the description of the keywords, the Boolean operators "AND" and "OR" were used to create a link between them, resulting in the following search string (specified inside the square bracket): [(("maintenance model" OR "maintenance policy") AND ("reuse" OR "remanufacturing" OR "second-hand"))]. This search string was modified to match the search mechanisms of the three databases examined: Scopus, Web of Science, and IEEE Xplore. Those three databases were chosen to increase the chances of identifying further related papers. Due to the same reason, the search field was defined as “all”, taking into account all available content of the documents in these databases. Finally, the publication type was set to journal articles (or journal papers) and reviews. The analysis includes articles and review papers. The former are used to construct the proposed review and the latter are utilised to double-check if other similar reviews have been reported previously. There was no time interval established in order to vary all possible data regardless of publication year.

2.4.1.2 Document selection

The mentioned search string led to 581 initial articles appearing in Scopus (567 articles) and Web of Science (14 articles). IEEE Xplore did not return any results, given the search strategy adopted and described in the previous section. After obtaining the data from the two databases, the duplicated articles were checked. 14 articles were found in the Web of Science database and also in the Scopus database. Hence, the Scopus database was used for the analysis due to its representation of the entire dataset gathered from our search strategy. The data listed in the .csv file includes information about author, title, year, abstract, author keywords, etc.

The first filter of the data removed 13 review papers that were collected for reanalysis of the literature review. Thereafter, of the 554 original papers, 485 were discarded based on title and abstract, leaving 69 to be reviewed in detail. Four of the remaining 69 articles were unavailable for access, and 12 were categorised as unrelated. The discarded articles refer to topics that are outside of the scope of this literature review. Some examples are: production remanufacturing strategy, friendly production, non-conforming products, sustainable operation, quality assessment of used-products, smart manufacturing, carbon emissions, perishable inventory, energy consumption, renewable energy, etc. Following the selection process, 53 papers were analysed in detail. The document selection procedure is depicted in Figure 4.

Figure 4 – Document selection process



Source: Santos, Cavalcante, Wu (2022)

2.4.1.3 Relevant topics for the bibliometric analysis

The themes selected for scrutiny in the bibliometric analysis were as follows:

i. Publication trends: to check the amount of publications over time.

ii. Occurrence and co-occurrence of keywords: to measure the most prevalent keywords and examine their relationships.

iii. Main and most influential sources of publication: to categorise the sources' popularity.

iv. Most influential papers: to highlight the most important papers.

v. Author influence and co-authorship: to indicate the authors' influence.

Topics i, iii and iv were examined using *Microsoft Excel* because of its simplicity of organising and filtering information obtained from the Scopus database. Topics ii and v were analised using *VOS viewer* since the method of obtaining and examining the required information from the Scopus .csv file is convenient and also due to its excellent visualisation features.

2.4.1.4 Research questions for the literature review

The following research questions (RQ) were created to guide the literature review by addressing some key research themes.

RQ1: How have maintenance models and policies evolved historically in terms of consideration of reuse and remanufacturing?

RQ2: What types of model strategies have been considered over time to address reuse and remanufacturing?

RQ3: Which business strategy has been predominantly adopted in maintenance models or policies: second-hand market, in-house maintenance, or leasing?

RQ4: Which sustainable strategy has been predominantly adopted in maintenance models or policies: reuse or remanufacturing?

RQ5: What has been proposed in terms of reuse?

RQ6: What has been proposed in terms of remanufacturing?

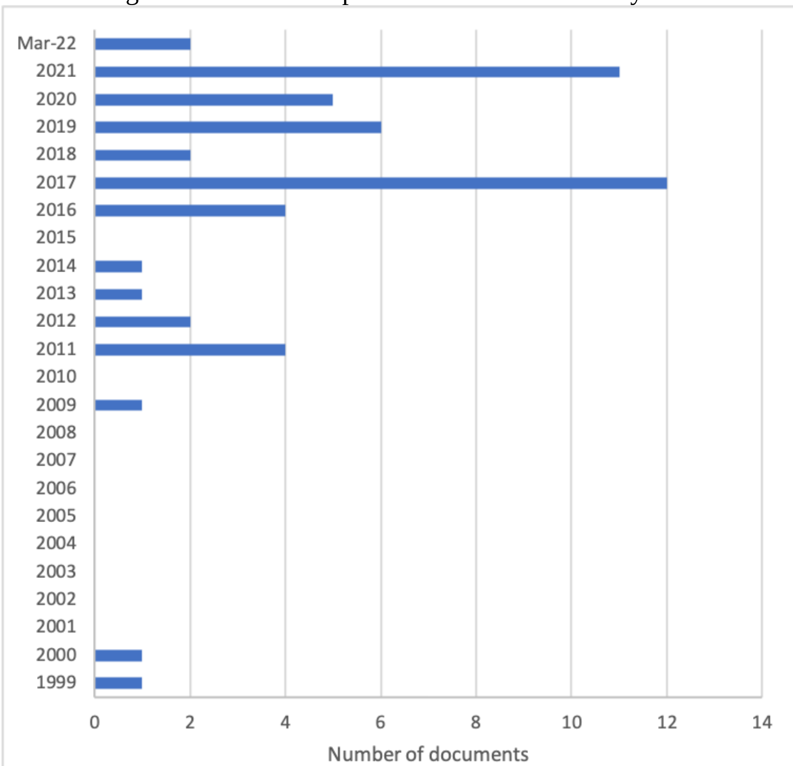
2.4.2 Bibliometric analysis

Following the methodology defined in Section 2.4.1, the bibliometric analysis examines the 53 original articles that discuss maintenance policies or models in the context of reuse and remanufacturing. Unlike the literature review presented in Section 2.4.3, the bibliometric analysis focuses on publication trends, sources of publication, and influential authors. Hence, the purpose of the current section is to provide an overview about how many, where, and by whom the maintenance policies and models for reuse and remanufacturing have been published.

2.4.2.1 Publication trends

Over the last ten years, the number of studies examining maintenance strategies or models with a focus on reuse or remanufacturing has risen considerably. Figure 5 shows the bar chart of the numbers of original articles published. Historically, three distinct periods can be considered: low, moderate and high development. The first stage corresponds to the period before 2010, in which very few papers were published, indicating that reuse was not usually analysed in maintenance policies. The second phase comprises the following 6 years, from 2011 to 2016, when a modest level of scientific production on the topic is observed, compared to the entire period. Finally, the third phase begins in 2017 with the first peak of publications on this topic and continues until the end of the analysed period (March of 2022). Possible reasons for this significant development may be related to the advent of concerns about the impact of industries on the environment and the greater academic interest in developing strategies to improve the relationship between the environment and society.

Figure 5 – Number of published articles over the years.



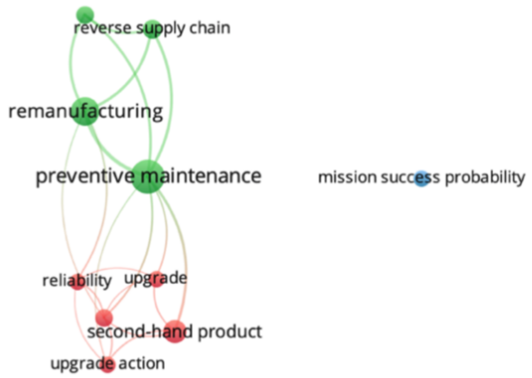
Source: Santos, Cavalcante, Wu (2022)

2.4.2.2 Occurrence and co-occurrence of keywords

The frequency of keywords in papers can be used to quickly identify the most frequently used terms that summarise the articles produced in a given field. Within the scope of this analysis, the most recurring keywords, according to the *VOS viewer*, are: preventive maintenance, remanufacturing, second-hand product, reverse supply chain, sensor embedded products, and warranty. As illustrated in Figure 6, these keywords can be grouped into three separate clusters depending on their co-occurrence. Preventive maintenance, remanufacturing, and reverse supply chain are all part of the first cluster (green). Second-hand products are linked to upgrade actions in the second cluster (red). Finally, the third cluster (blue) is concerned with the probability of mission success.

Figure 6 – Occurrence and co-occurrence of keywords.

Co-occurrence of keywords



Keyword	Occurrences
Preventive maintenance	22
Remanufacturing	16
Second-hand product	10
Reverse supply chain	7
Sensor embedded products	6
Warranty	6
Reliability	5
Upgrade action	5
Upgrade	5
Mission success probability	5

Source: Santos, Cavalcante, Wu (2022)

2.4.2.3 Main and most influential sources of publication

The main and most influential sources of publication can be used to identify journals that have been published papers in the subject. The first is determined by the number of papers published, while the second is determined by the number of citations received by these papers until March 2022. Table 1 organises and ranks the most important and prominent sources of publication, first by number of articles and then by number of citations. The journal Reliability Engineering and System Safety, which has a larger number of papers and citations than other sources, is the main and most influential source on the topic addressed in this research.

Table 1 – main and most influential sources of publication

Journal	**Number of papers**	**Number of citations**
Reliability Engineering and System Safety	**14**	**144**
International Journal of Production Research	3	45
Proceedings of the Institution of Mechanical Engineers, Part O: Journal of Risk and Reliability	3	40
Computers and Industrial Engineer	2	99
International Journal of Production Economics	2	72
Journal of Manufacturing Systems	2	32
Applied Stochastic Models in Business and Industry	2	24
Open Cybernetics and Systemics Journal	2	2
Others	23	308

Source: Santos, Cavalcante, Wu (2022)

2.4.2.4 Most influential papers

Table 2 lists the most influential papers based on the number of citations they received until March 2022. They use different techniques to deal with the subject of this study. From this table, maintenance policies and warranty policies for second-hand products are the topics that have been most widely researched. Furthermore, the majority of citations include papers in which the maintenance model or policy is centred on the product rather than the industrial items. This appears to be a pattern in this area and will be further investigated in the literature review (Section 2.4.3).

Table 2 – most cited papers

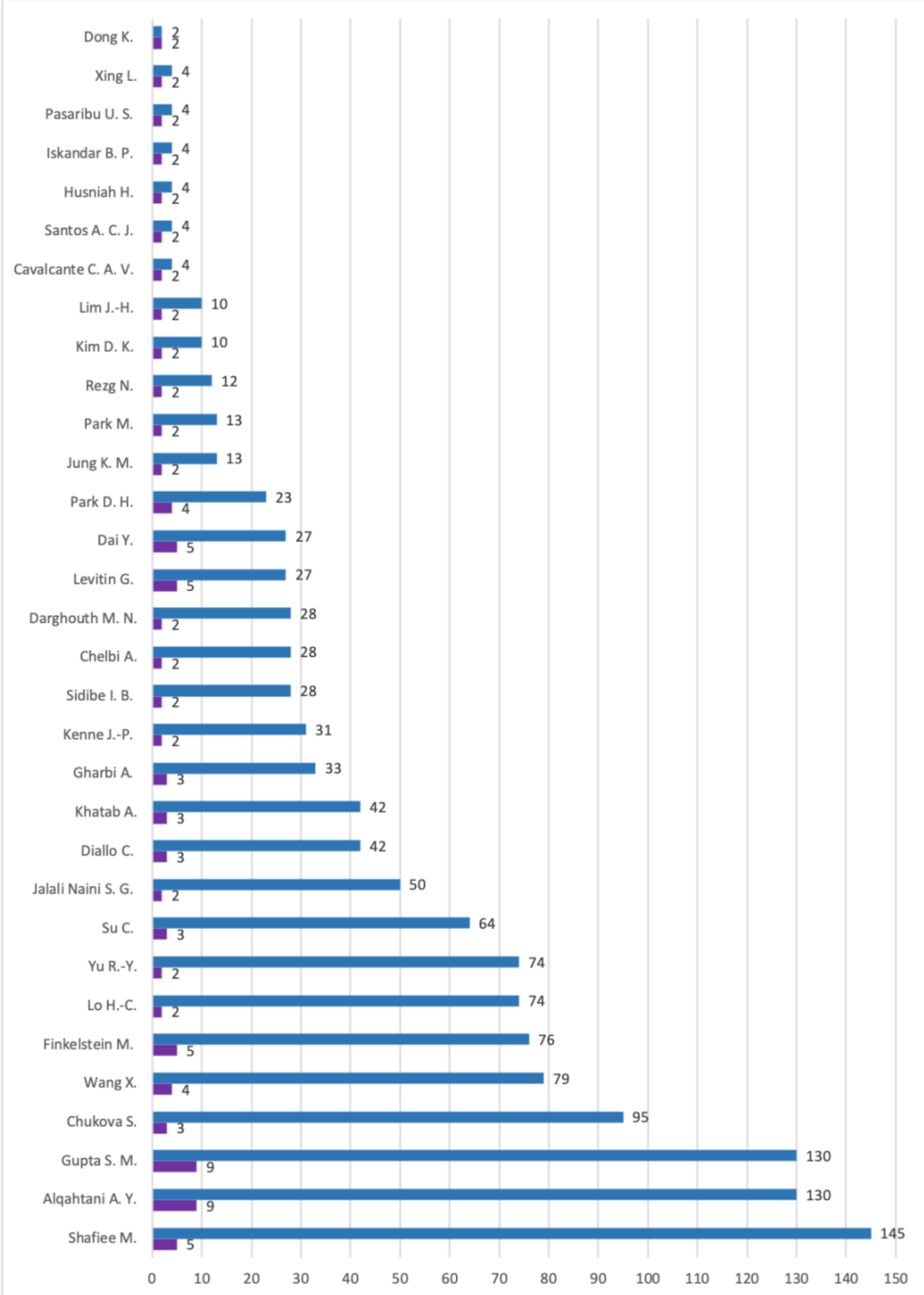
Paper	**Citations**	**Year of publication**
Warranty cost analysis for second-hand products (CHATTOPADHYAY, MURTHY, 2000)	74	2000
A bivariate optimal imperfect preventive maintenance policy for a used system with two-type shocks (CHEN, 2012)	53	2012
Warranty and maintenance analysis of sensor embedded products using internet of things in industry 4.0 (ALQAHTANI, GUPTA, NAKASHIMA, 2019)	49	2019
On optimal upgrade level for used products under given cost structures (SHAFIEE, FINKELSTEIN, CHUKOVA, 2011)	48	2011
A study of maintenance policies for second-hand products (YEH, LO, YU, 2011)	46	2011
Warranty as a marketing strategy for remanufactured products (ALQAHTANI, GUPTA, 2017f);	44	2017
On the investment in a reliability improvement program for warranted second-hand items (SHAFIEE et al., 2011)	42	2011
Joint determination of price and upgrade level for a warranted second-hand product (JALALI NAINI, SHAFIEE, 2011)	41	2011
Investigating reliability improvement of second-hand production equipment considering warranty and preventive maintenance strategies (DARGHOUTH, CHELBI, AIT-KADI, 2017)	28	2017
A study of quality management strategy for reused products (LO, YU, 2013)	28	2013

Source: Santos, Cavalcante, Wu (2022)

2.4.2.5 Author influence and co-authorship

Figure 7 depicts the influence of authors who have published at least two publications on the topic under consideration in this review until March 2022. The number of citations and papers were used to determine the level of influence. This data was extracted from a Scopus.csv file using the *VOS viewer software*. It is worth noting that all author names were manually validated before being extracted from the Scopus database to eliminate errors caused by the same author being listed in different ways in different publications. Before the analysis, six inconsistencies were noticed and corrected.

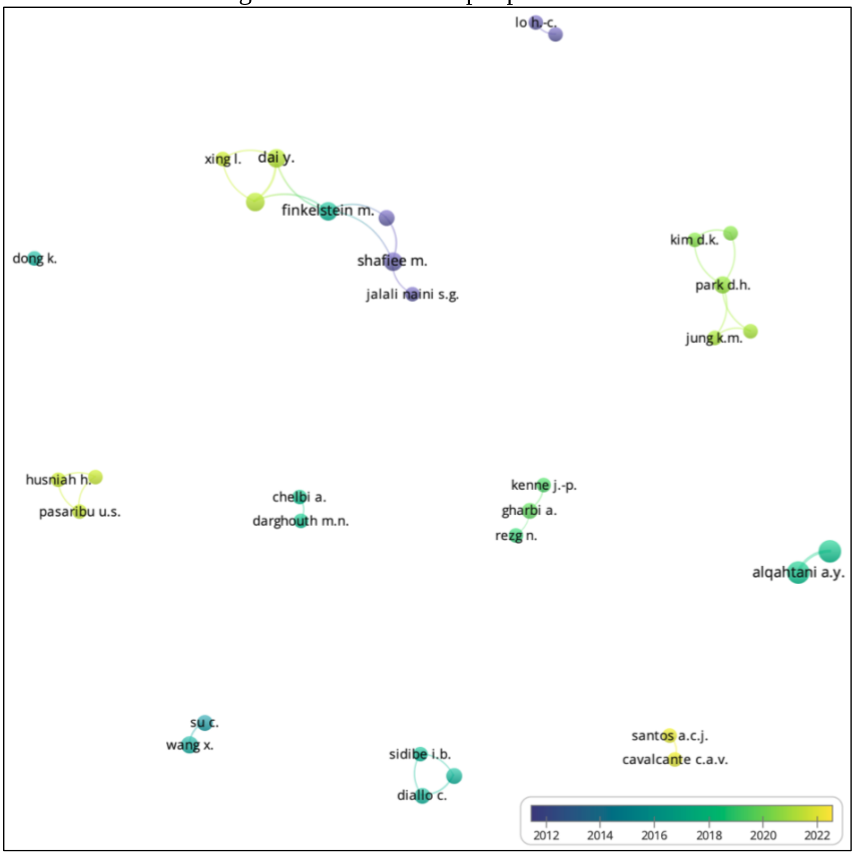
Figure 7 – number of citations per author (blue) and number of articles per author (purple)



Source: Santos, Cavalcante, Wu (2022)

In total, 32 authors with at least two publications on this topic were found and considered in the analysis. Shafiee, M., Alqahtani, A. Y., and Gupta, S. M. are the most referenced authors in this field, with the two last named having the highest number of publications: nine. This set of authors (shown in Figure 7) can be grouped into 12 clusters based on co-authorship (shown in Figure 8). It is also feasible to get an idea of authors who have recently published on this topic by looking at this figure.

Figure 8 – co-authorship representation



Source: Santos, Cavalcante, Wu (2022)

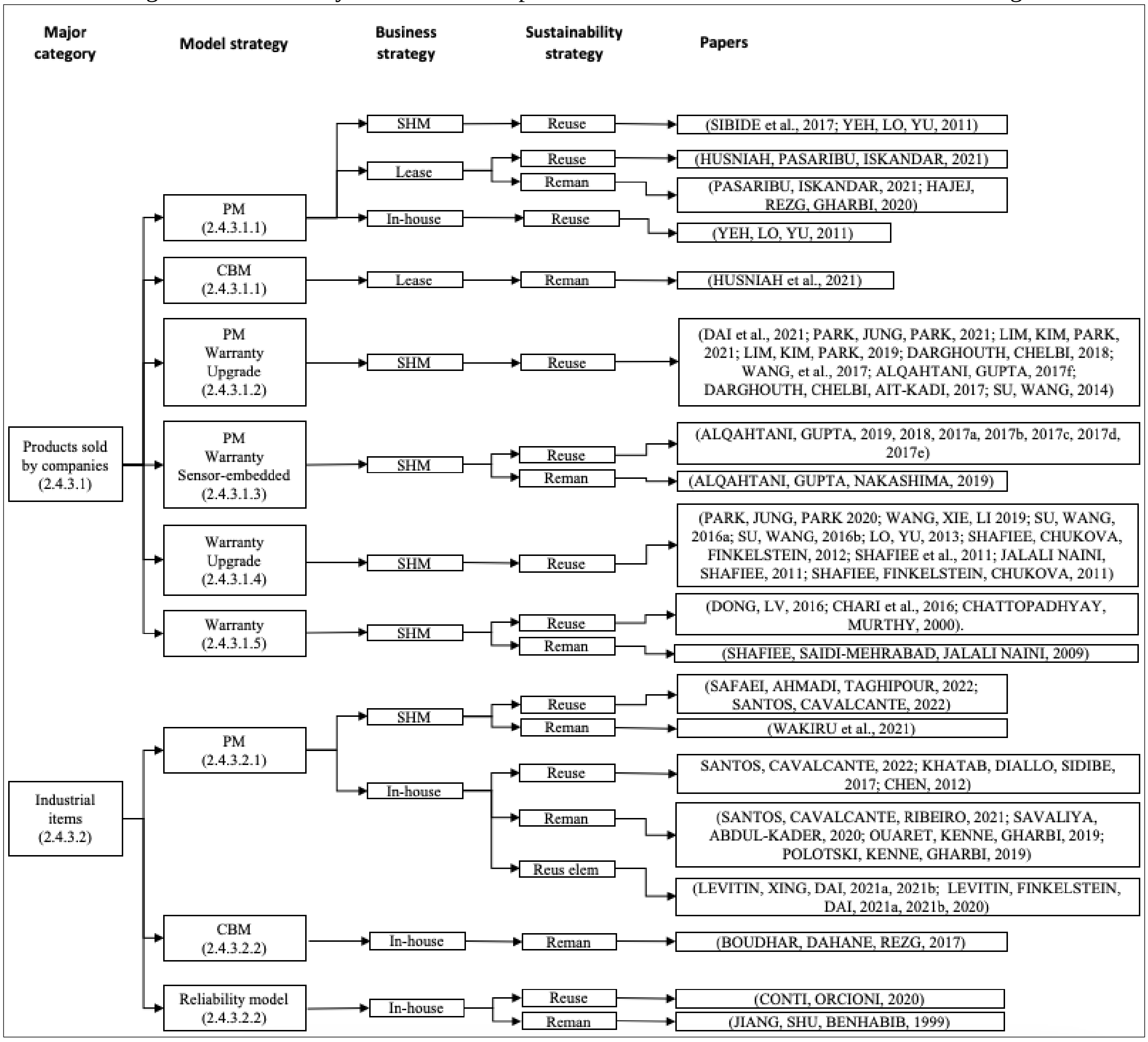
2.4.3 Literature review

This section provides information of relevant literature on maintenance strategies and models in the context of reuse and remanufacturing. In this context, two distinctive major categories are immediately discernible. The first one includes models that deal with the reuse or remanufacturing of product items (sold by companies in second-hand markets or leased by companies). This group of papers accounts for 68 percent of the total number of papers examined in this literature review. The other major category, which accounts for 32% of the papers, concerns the product items that are used in industrial processes and can be reused or remanufactured to reduce maintenance costs.

In both major categories, the papers were examined and organised according to the following categories: “model strategy”, “business strategy”, “sustainability strategy” and "sustainability impact". The categories "model strategy" and "business strategy" were considered based on the type of strategies usually used in the selected papers. The categories "sustainability strategy" and "sustainability impact" were defined according to the previous definition of the scope of this review (models for reuse and remanufacturing), and according to the triple bottom line of sustainability (economic, environmental, and social perspective) (HAMMER, PIVO, 2017).

The classification of the maintenance policies and models for reuse or remanufacturing was based on the two major categories mentioned and, on the categories, "model strategy", "business strategy" and "sustainability strategy". The category "sustainability impact" was not included in the taxonomy because papers solely focus on the economic perspective of sustainability, with the exception of Santos and Cavalcante (2022) and Santos, Cavalcante and Ribeiro (2021). Figure 9 depicts the taxonomy and the sections in which each part of it is analysed.

Figure 9 – Taxonomy of maintenance policies and models for reuse or remanufacturing



Source: Santos, Cavalcante, Wu (2022)

2.4.3.1 Maintenance models focused on products

This major category represents most of the papers that deal with reuse or remanufacturing in maintenance models or policies. In total, 36 papers were organised and examined. In this category, the model strategy was subdivided into Preventive Maintenance (PM), Condition-Based Maintenance (CBM), Warranty policies, and Upgrade action. The business strategy was subdivided into Second-Hand Market (SHM), Lease, and In-house maintenance. The sustainability strategy was subdivided into reuse and remanufacturing (reman). Lastly, the sustainability impact was considered in economic (eco), environmental (env) and social (soc) perspectives (not considered in the following table because all the papers only considered the economic perspective). Table 3 illustrates how each publication was classified in each of the categories studied.

Table 3 – papers with focus on the reuse or remanufacturing of products

Paper	Model strategy				Business strategy			Sustainability strategy	
	PM	CBM	Warranty	Upgrade	SHM	Lease	In-house	Reuse	Reman
(DAI et al., 2021)	X		X	X	X			X	
(PARK, JUNG, PARK, 2021)	X		X	X	X			X	
(HUSNIAH et al., 2021)		X				X			X
(PASARIBU, ISKANDAR, 2021)	X					X			X
(LIM, KIM, PARK, 2021)	X		X	X	X			X	
(HAJEJ, REZG, GHARBI, 2020)	X					X			X
(PARK, JUNG, PARK, 2020)			X	X	X			X	
(LIM, KIM, PARK, 2019)	X		X	X	X			X	
(ALQAHTANI, GUPTA, NAKASHIMA, 2019)	X		X		X				X
(WANG, XIE, LI, 2019)			X	X	X			X	
(ALQAHTANI, GUPTA, 2019)	X		X	X	X			X	
(ALQAHTANI, GUPTA, 2018)	X		X	X	X			X	
(DARGHOUTH, CHELBI, 2018)	X		X	X	X			X	
(WANG et al., 2017)	X		X	X	X			X	
(ALQAHTANI, GUPTA, 2017f)	X		X		X			X	
(DARGHOUTH, CHELBI, AIT-KADI, 2017)	X		X	X	X			X	
(ALQAHTANI, GUPTA, 2017a)	X		X		X			X	
(ALQAHTANI, GUPTA, 2017b)	X		X		X			X	
(HUSNIAH, PASARIBU, ISKANDAR, 2021)	X					X		X	
(ALQAHTANI, GUPTA, 2017c)	X		X		X			X	
(SIBIDE et al., 2017)	X				X			X	
(ALQAHTANI, GUPTA, 2017d)	X		X		X			X	
(ALQAHTANI, GUPTA, 2017e)	X		X		X			X	
(SU, WANG, 2016a)			X	X	X			X	
(DONG, LV, 2016)			X		X			X	
(CHARI et al., 2016)			X		X			X	
(SU, WANG, 2016b)			X	X	X			X	
(SU, WANG, 2014)	X		X	X	X			X	
(LO, YU, 2013)			X	X	X			X	
(SHAFIEE, CHUKOVA, FINKELSTEIN, 2012)			X	X	X			X	
(SHAFIEE et al., 2011)			X	X	X			X	
(JALALI NAINI, SHAFIEE, 2011)			X	X	X			X	
(YEH, LO, YU, 2011)	X				X		X	X	
(SHAFIEE, FINKELSTEIN, CHUKOVA, 2011)			X	X	X			X	
(SHAFIEE, SAIDI-MEHRABAD, JALALI NAINI, 2009)			X		X				X
(CHATTOPADHYAY, MURTHY, 2000)			X		X			X	
Total	20	1	30	19	32	4	1	31	5
Percentage	56%	3%	83%	53%	89%	11%	3%	86%	14%

Source: Santos, Cavalcante, Wu (2022)

As shown in Table 3, warranty policies are used as a model strategy in 83 percent of the articles. 89 percent of them concentrate on a business strategy related to the second-hand market. The concept of reuse is considered in 86% of publications. However none of them provides an analysis of the environmental or social aspects of sustainability. The taxonomy shown in Figure 10 is used to organise the discussion of each paper as follows.

2.4.3.1.1 Preventive Maintenance (PM) and Condition-Based Maintenance (CBM)

The articles that use PM or CBM in the context of reuse or remanufacturing are approached in this first category. Sibide et al. (2017) propose a replacement policy for second-hand products that begin their second life cycle in a harsher environment. An age-replacement policy is used to describe the stochastic degradation of a system with a random initial age. The objective is to establish the optimal replacement age by minimising the expected total maintenance cost rate in the second operating environment. Similarly, Yeh, Lo and Yu (2011) propose two periodic PM policies with the goal of lowering the high failure rate of second-hand products. The expected maintenance cost is minimised by determining the optimal number of PM actions and the corresponding maintenance level to be performed.

In Husniah, Pasaribu and Iskandar (2021), Hajej, Rezg and Gharbi (2020) and Qian and Dong (2017), PMs are applied considering the leasing strategy. In Husniah, Pasaribu and Iskandar (2021), the PM of leased used equipment is explored, and the model is optimised by using an enumeration approach. The authors consider a maintenance strategy based on the fixed failure rate reduction method. As in Sibide et al. (2017) and Yeh, Lo and Yu (2011), reuse is adopted as a sustainability strategy in Husniah, Pasaribu and Iskandar (2021), while the following papers - Pasaribu and Iskandar (2021), Hajej, Rezg and Gharbi (2020) and Husniah et al. (2021) - consider leasing as a business strategy and adopt remanufacturing as a sustainability strategy. Pasaribu and Iskandar (2021) propose a multi-period lease contract for remanufactured products. They assume that PMs improve the reliability of the remanufactured products by means of reducing the failure rate. However, the improved reliability is still lower than the reliability of a new product. In their approach, the lessor can choose the maintenance policy as well as the price and period for the lease contract. In Hajej, Rezg and Gharbi (2020), the case of returned-used products in the lease contract with or without a PM monitoring option is explored. The effect of the degradation on the failure and emission rates is used to establish the optimal PM strategy that minimises the total cost of production, maintenance, and carbon emission. Still in the leasing context, a CBM policy is proposed in Husniah et al. (2021) for leased remanufactured products that work in different environmental circumstances. The condition of the remanufactured product is assessed on a regular basis to reduce unnecessary maintenance and the risk of future failure.

As is shown in the previous paragraph, considering the business strategy, the majority of papers that employ just PM or CBM policies in the context of second-hand products focus on leasing, followed by the second-hand market. In terms of the sustainability strategy, reuse and remanufacturing are used at a similar frequency. Finally, the sustainability impact is assessed only from an economic perspective. This is a feature that can be found in all papers focused on second-hand products.

2.4.3.1.2 PM, warranty policies and upgrade actions

In the articles cited above, PM actions were regarded as the principal maintenance strategy in the context of reuse or remanufacturing of products (CBM in Husniah et al. (2021)). However, many papers combine PM actions to warranty policies and upgrade actions (DAI et al., 2021; PARK, JUNG, PARK, 2021; LIM, KIM, PARK, 2021; LIM, KIM, PARK, 2019; DARGHOUTH, CHELBI, 2018; WANG, et al., 2017; ALQAHTANI, GUPTA, 2017f; DARGHOUTH, CHELBI, AIT-KADI, 2017; SU, WANG, 2014). Dai et al. (2021) examine PM strategies for second-hand products covered by a 2D warranty (which takes into account the age and usage of the product) from the point of view of both dealers and customers. Three types of PM options are considered: PM during the warranty period, PM after the warranty period, and PM during the lifespan of the product. Also, it is considered that the dealer may perform free upgrades prior to reselling the product. The objective is to determine how much the customer is willing to invest in PM actions and how much the dealer is willing to accept for PM services. Wang et al. (2017) also consider a 2D warranty policy in a product whose degradation process can be affected by variations in the intensity of customer usage. Additionally, different strategies for PM are discussed in Darghouth, Chelbi, and Ait-kadi (2017), with periodic actions having the same efficiency level of maintenance, while periodic multiphase actions have a varied degree of efficiency. Park, Jung and Park (2021) propose a non-renewing warranty policy with a periodic PM strategy to prevent products from degrading. The optimal warranty period is determined by optimising the expected cost rate during the maintenance cycle. The authors propose a refund rather than replacing a second-hand product. Lim, Kim, and Park (2019) examine an optimal post-warranty maintenance policy for second-hand products with a fixed warranty period. It is considered that a product under warranty must be maintained by the user. Also, upon expiration of the warranty, users are still responsible for maintaining the product for a fixed period of time. When the maintenance period ends, the product is replaced. The objective is to determine the optimal maintenance period after the warranty expiration. In Darghouth and Chelbi (2018), the sales volume is included in a decision model for second-hand products subject to PM, upgrade level, and warranty. Lim, Kim, and Park (2021) suggest a post-warranty strategy for second-hand products with a variable self-maintenance period. The product is assumed to be replaced with another one on the first failure after a fixed period of self-maintenance. In Su and Wang (2014), an optimization model for second-hand products sold with the non-renewing free repair warranty policy is proposed. To maximise a dealer's expected profit, the best upgrade level and PM policy are determined jointly. Upgrade actions occur at the end of a product's past life and during the warranty period, while PM actions occur when the product reaches a pre-specified threshold. Finally, the warranty is viewed as a marketing strategy in Alqahtani and Gupta (2017f).

In these papers, the second-hand market is considered as the business strategy and reuse is considered as the sustainability strategy. Moreover, sustainability impact is assessed only in economic terms.

2.4.3.1.3 PM and warranty policies in sensor-embedded products

Another classification that is well defined in the taxonomy includes the papers that examine PM and warranty policies together in the context of sensor-embedded products (ALQAHTANI, GUPTA, NAKASHIMA, 2019; ALQAHTANI, GUPTA, 2019; ALQAHTANI, GUPTA, 2018; ALQAHTANI, GUPTA, 2017a, 2017b, 2017c, 2017d, 2017e).

One-dimensional warranties with an upgrade level are considered in Alqahtani and Gupta (2019) and Alqahtani and Gupta (2018), and those without an upgrade level are studied in Alqahtani, Gupta and Nakashima (2019) and Alqahtani and Gupta (2017b, 2017c). Furthermore, two-dimensional warranty policies are proposed in Alqahtani and Gupta (2017a, 2017d, 2017e).

Regarding one-dimensional warranties without an upgrade level, Alqahtani and Gupta (2019) propose a simulation model for sensor-embedded remanufactured products from the perspective of the remanufacturer. When a product has reached the end of its life cycle, it is upgraded. Also, to maximise the remanufacturer's profit, PM actions are executed during the warranty period when the remaining life of the product exceeds a prespecified value. Alqahtani and Gupta (2018) present an analogous proposal which adopts a combined money-back guarantee warranty policy with the PM strategy.

Considering one-dimensional warranties without an upgrade level, in Alqahtani, Gupta and Nakashima (2019), the concept of the Internet of Things is applied to warranty and the maintenance analysis of sensor-embedded products. In Alqahtani and Gupta (2017b), a variety of warranty policies is considered. In Alqahtani and Gupta (2017c), a method is proposed to minimise the cost incurred by the remanufacturers and to maximise consumer confidence in buying remanufactured products.

Likewise, a similar methodology is proposed in the context of two-dimensional warranty policies in Alqahtani and Gupta (2017e) and the impact of offering renewing warranties on remanufactured products is assessed in Alqahtani and Gupta (2017a, 2017d).

All these papers consider the second-hand market as the business strategy and reuse as the sustainability strategy, except Alqahtani, Gupta and Nakashima (2019) which considers remanufacturing as the sustainability strategy.

2.4.3.1.4 Warranty policies and upgrade actions

In another set of papers, warranty and upgrade are discussed without necessarily including or emphasising PM actions (PARK, JUNG, PARK 2020; WANG, XIE, LI 2019; SU, WANG, 2016a; SU, WANG, 2016b; LO, YU, 2013; SHAFIEE, CHUKOVA, FINKELSTEIN, 2012; SHAFIEE et al., 2011; JALALI NAINI, SHAFIEE, 2011; SHAFIEE, FINKELSTEIN, CHUKOVA, 2011).

Park, Jung, and Park (2020) investigate an optimal warranty policy for second-hand products in order to determine the optimal length of a warranty period from the dealer's perspective. The maintenance policy is based on a two-stage system of repair or full refund. If the failure cannot be repaired during the warranty period, a full refund is given to the user, and the maintenance cycle ends. Wang, Xie and Li (2019) develop an upgrade model for complex second-hand systems sold with a non-renewing free repair/replacement warranty. The authors distinguish two categories of components: repairable (which can be imperfectly upgraded with varying degrees) and non-repairable (which can only be replaced if necessary). From the dealer's perspective, the goal is to determine which components to upgrade and how much to upgrade in order to minimise total expected servicing costs.

Su and Wang (2016a) propose a pre-sale upgrade model for repairable used products sold with a two-dimensional warranty policy. The policy is designed to minimise the dealer's total expected servicing cost, which is represented by the amount of warranty and upgrade servicing costs. In Jalali Naini and Shafiee (2011), the authors also deal with the dealer’s point of view. They suggest a decision model to determine the optimal price and upgrade strategy of a warranted second-hand product, consequently, maximising the dealer's expected profit. Similarly, Shafiee, Finkelstein and Chukova (2011) investigate the optimal expected upgrade level to maximise the dealer’s expected profit. The authors consider the concept of reliability improvement, also used in Su and Wang (2016b) and Shafiee et al. (2011). Su and Wang (2016b) propose a two-dimensional free repair warranty policy to minimise the dealer's total expected servicing costs per unit sale. In this policy, the effects of reliability improvement actions on the past age and past usage of a used product are considered separately, based on the pre-sale reliability improvement model. Shafiee et al. (2011) present reliability improvement programs for used products sold with failure-free warranties. The optimal improvement decision problem is addressed using both stochastic reliability improvement and an investment cost-benefit model.

Finally, Lo and Yu (2013) suggest a profit model that takes into account upgrading and minimal repair during the warranty period. The authors determine what upgrade level and warranty length will maximise the producer's expected profit per used product. Shafiee, Chukova, and Finkelstein (2012) develop a model for determining the optimal upgrade action which takes into account both upgrade cost and the reduction of expected warranty costs. The authors illustrate their findings with a practical application on electric drills.

All these papers consider the second-hand market as the business strategy and reuse as the sustainability strategy. The sustainability impact is considered only in economic terms.

2.4.3.1.5 Warranty policies

In addition to the papers already mentioned, some consider warranty without necessarily including PMs or upgrade actions (DONG, LV, 2016; CHARI et al., 2016; SHAFIEE, SAIDI-MEHRABAD, JALALI NAINI, 2009; CHATTOPADHYAY, MURTHY, 2000). Dong and Lv (2016) propose a warranty policy that takes the user's perspective into account. The authors compare non-renewable free replacement-repair warranties and non-renewable pro rata replacement-repair warranties through numerical examples. Chari et al. (2016) propose a warranty policy that incorporates new and reconditioned components in replacements for products under warranty. The objective is to maximize the manufacturer's total profit based on warranty length, sale price, age of reconditioned components, and percentage of reconditioned components utilised. Shafiee, Saidi-Mehrabad and Jalali Naini (2009) examine the warranty and the sustainable improvement of used products remanufactured with a failure free warranty. These models can be used by dealers as a tool for deciding whether to invest in remanufacturing projects and how much. Chattopadhyay and Murthy (2000) developed probabilistic models to predict the expected warranty costs to the manufacturer when the items are sold with free replacements and pro-rata warranties.

All these papers consider the second-hand market as the business strategy and reuse as the sustainability strategy, except that by Shafiee, Saidi-Mehrabad and Jalali Naini (2009) which considers remanufacturing as the sustainability strategy. In the next section, the maintenance models focused on industrial items are discussed.

2.4.3.2 Maintenance models focused on industrial items

This major category represents a relatively small number of papers that deal with the concept of reuse or remanufacturing in maintenance models or policies. A total of 17 papers were found and examined (Table 4). In this **major** category, the model strategy is sub-divided into Preventive Maintenance (PM), Condition-Based Maintenance (CBM), Reliability model, Mission, and Shocks. The business strategy was sub-divided into second-hand market (SHM) and in-house maintenance. The sustainability strategy was sub-divided into reuse, remanufacturing (reman) and reusable elements. Finally, the sustainability impact was observed in terms of economic (eco), environmental (env) and social (soc) perspectives (not considered in the following Table because economic perspective is considered in all papers, the environmental perspective is considered only in two papers (SANTOS, CAVALCANTE, 2022; SANTOS, CAVALCANTE, RIBEIRO, 2021) and the social perspective is not considered in any of them.

Table 4 – papers with focus on the reuse or remanufacturing of industrial items

Paper	Model strategy					Business strategy		Sustainability strategy		
	PM	CBM	Relia model	Mission	Shocks	SHM	In-house	Reuse	Reman	Reusable elements
(SAFAEI, AHMADI, TAGHIPOUR, 2022)	X					X		X		
(SANTOS, CAVALCANTE, 2022)	X					X	X	X		
(LEVITIN, XING, DAI, 2021a)	X			X			X			X
(LEVITIN, XING, DAI, 2021b)	X			X			X			X
(WAKIRU et al., 2021)	X					X			X	
(LEVITIN, FINKELSTEIN, DAI, 2021a)	X			X	X		X			X
(LEVITIN, FINKELSTEIN, DAI, 2021b)	X			X	X		X			X
(SANTOS, CAVALCANTE, RIBEIRO, 2021)	X						X		X	
(LEVITIN, FINKELSTEIN, DAI, 2020)	X			X	X		X			X
(CONTI, ORCIONI, 2020)			X				X	X		
(SAVALIYA, ABDUL-KADER, 2020)	X						X		X	
(OUARET, KENNE, GHARBI, 2019)	X						X		X	
(POLOTSKI, KENNE, GHARBI, 2019)	X						X		X	
(KHATAB, DIALLO, SIDIBE, 2017)	X						X	X		
(BOUDHAR, DAHANE, REZG, 2017)		X					X		X	
(CHEN, 2012)	X				X		X	X		
(JIANG, SHU, BENHABIB, 1999)			X				X		X	
Total	14	1	2	5	4	2	15	5	7	5
Perc	82%	6%	12%	29%	24%	12%	88%	29%	41%	29%

Source: Santos, Cavalcante, Wu (2022)

Table 4 illustrates that 82% of the papers consider PM policies as a model strategy for reusing or remanufacturing. About 88% of them focus on in-house maintenance as the business strategy. Regarding the sustainability strategy, 41% consider the concept of remanufacturing, 29% reusable elements (term related to reused items in mission success probability models), and 29% reuse. Finally, concerning the sustainability impact, only 12% (2 papers) bring a discussion regarding the environmental perspective of sustainability. A summary of each paper is presented in the following sections. First, models that consider PMs (SAFAEI, AHMADI, TAGHIPOUR, 2022; SANTOS, CAVALCANTE, 2022; LEVITIN, XING, DAI, 2021a, 2021b; WAKIRU et al., 2021; LEVITIN, FINKELSTEIN, DAI, 2021a, 2021b; SANTOS, CAVALCANTE, RIBEIRO, 2021; LEVITIN, FINKELSTEIN, DAI, 2020; SAVALIYA, ABDUL-KADER, 2020; OUARET, KENNE, GHARBI, 2019; POLOTSKI, KENNE, GHARBI, 2019; KHATAB, DIALLO, SIDIBE, 2017; CHEN, 2012) are discussed in section 2.4.3.2.1. Then, the CBM model (BOUDHAR, DAHANE, REZG, 2017) and reliability models

(CONTI, ORCIONI, 2020; JIANG, SHU, BENHABIB, 1999) are reviewed in Section 2.4.3.2.2.

2.4.3.2.1 Preventive Maintenance (PM)

PM is the dominant model strategy used in the context of reuse or remanufacturing of industrial items. Among the papers analysed, Safaei, Ahmadi and Taghipour (2022), Santos and Cavalcante (2022), Khatab, Diallo and Sidibe (2017), and Chen (2012) consider reuse as a sustainability strategy. Wakiru et al. (2021), Santos, Cavalcante and Ribeiro (2021), Savaliya and Abdul-Kader (2020), Ouaret, Kenne and Gharbi (2019) and Polotski, Kenne and Gharbi (2019) consider remanufacturing and Levitin, Xing and Dai (2021a, 2021b), Levitin, Finkelstein and Dai (2021a, 2021b) and Levitin, Finkelstein and Dai (2020) consider reusable elements.

Regarding the papers that consider reuse, Safaei, Ahmadi and Taghipour (2022) propose a maintenance policy for *k-out-of-n:*F systems. As part of PM, both age replacement and minor repairs are included. The paper considers that some parts of the multi-component system might still be useful after replacement, so they could be sold as second-hand items. Santos and Cavalcante (2022) develop a model to assess the feasibility of considering different percentages of reused items in an inventory. The authors consider the effect of different reliability levels of new and reused items in the system and verify at what level of reliability a reused item may differ from a new one and still be economically and environmentally viable. Diallo and Sidibe (2017) developed a model for determining the optimal acquisition age, upgrade level, and imperfect PM strategy jointly. Upgrades can be made before the system is put into operation. In addition, the system is prevented from deteriorating when it reaches a minimum level of reliability. Chen (2012) proposes an imperfect PM policy for a used system with variable damage based on a cumulative damage model. The system is subject to shocks that can result in accidental damage or complete failure of the system. Hence, PM policy is based on both scheduled time and the number of shocks.

Regarding remanufacturing, Wakiru et al. (2021) propose an integrated methodology for optimising maintenance, remanufacturing, and multiple spare strategies (new and remanufactured exchange) in a multi-component system with dependencies. Based on the delay time concept, Santos, Cavalcante and Ribeiro (2021) model the possibility of reuse of an item, considering its defective condition. The model can be applied to any item that wears out over time and may be replaced by a new one or by a refurbished one. As in Santos and Cavalcante

(2022), the environmental perspective of sustainability is also taken into consideration in Santos, Cavalcante and Ribeiro (2021) as the authors emphasise the importance of reusing items for the environment, instead of just demonstrating its economic benefits. Savaliya and Abdul-Kader (2020) suggest a simulation-based experimental methodology to determine the optimal PM frequency and buffer allocation in a remanufacturing line. Ouaret, Kenne and Gharbi (2019) consider the control of a hybrid manufacturing/remanufacturing system subject to random failures and repairs. The model accounts for the heterogeneity of returned products in the deterioration of the remanufacturing machine and also covers imperfect repairs and replacements. Similarly, Polotski, Kenne, and Gharbi (2019) also examine variations in type and quality of returned products. Using a combined optimization of manufacturing, remanufacturing and maintenance policies, their paper assesses the recovery of machine availability through remanufacturing.

In terms of reusable elements, Levitin, Xing and Dai (2021a) evaluate the probability of the mission success of a standby system with reusable elements and an imperfect storage unit. Additionally, Levitin, Xing, and Dai (2021b) propose a dual-unit standby system with non-identical reusable units that perform the mission task alternately according to a replacement schedule. In this system, when one unit is operating, the other unit undergoes maintenance. Levitin, Finkelstein and Dai (2021b) and Levitin, Finkelstein and Dai (2021a) consider, respectively, homogeneous, and heterogeneous warm-standby systems that perform missions of a fixed duration. Both papers assume a random environment subject to shocks, and use preventive replacements to reduce the probability of failure. Upon replacement, elements can be reused as standby elements. Likewise, this idea is also discussed in Levitin, Finkelstein, and Dai (2020).

Visibly, most papers that use PM as the main model strategy also consider in-house as the business strategy, which indicates that reuse or remanufacturing is regarded as an activity that can take place in the process without the need to acquire or sell used items. Additionally, remanufacturing is the main strategy for sustainability, followed by reuse. Finally, it is important to note that, out of all the articles reviewed in this literature review, only Santos and Cavalcante (2022) and Santos, Cavalcante and Ribeiro (2021) emphasise the importance of reuse in terms of the environmental perspective.

2.4.3.2.2 Condition-Based Maintenance (CBM) or Reliability model

There are few papers that use CBM or reliability models for modelling reuse or remanufacturing. Hence, those different types of models are examined together in this section.

Regarding the CBM model, Boudhar, Dahane and Rezg (2017) propose a condition-based replacement policy for stochastic degradation. In the model, replacement spare parts can either be new or used (found in previous replacements of the machine).

In terms of reliability models, Conti and Orcioni (2020) propose a model that takes into account the failure probability of a used component in a new machine. Using historical data, the authors show that reuse of components may improve equipment reliability. Zhang, Shu, and Benhabib (1999) describe a reliability model that facilitates designs for reuse of items. This model facilitates decisions during the development and use of remanufactured systems in terms of life-cycle replacement requirements. These papers present in-house maintenance as a business strategy and focus just on the economic impact of sustainability.

This section finalises the classification of maintenance models and policies applied to the context of reuse or remanufacturing. The ideas and strategies presented and grouped within the proposed taxonomy enable us to answer the research questions and this is now done in Section 2.4.3.3.

2.4.3.3 Research questions and Gaps to be investigated

This section provides answers to the research questions set out in Section 2.4.1.4 based on the insights obtained from bibliometric analysis and literature review. Additionally, the main gap in the literature is presented.

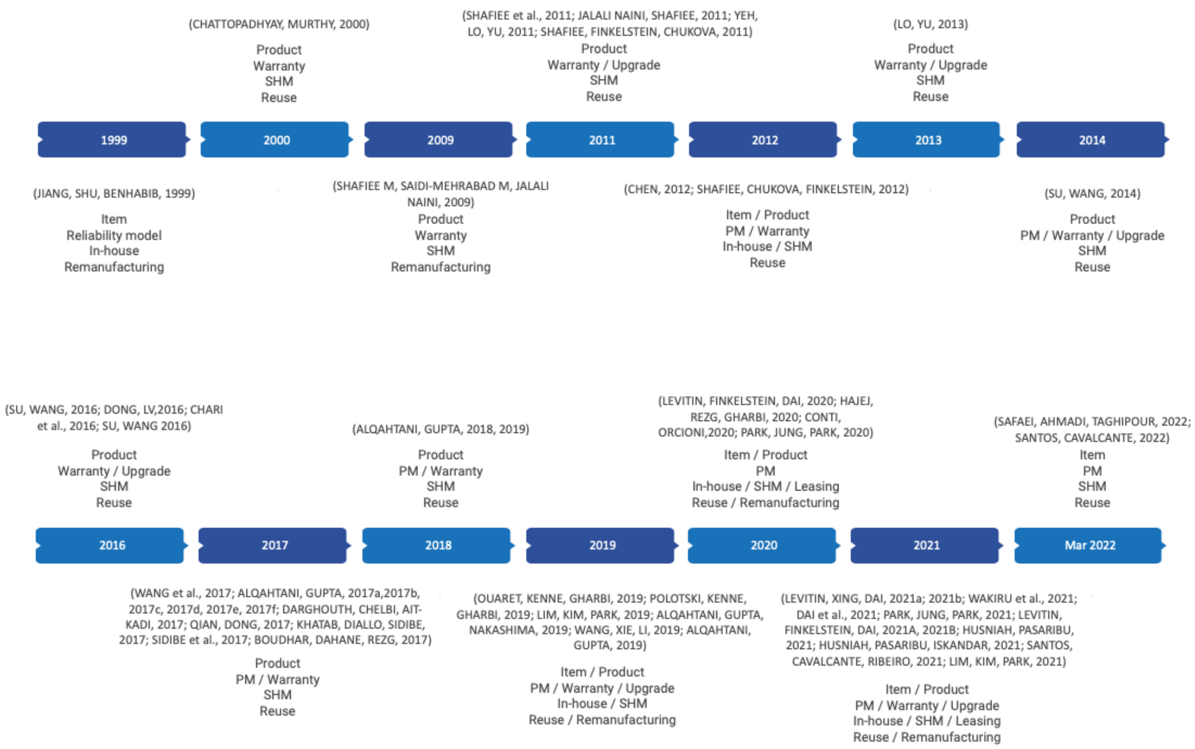
2.4.3.3.1 Response to the research questions

As noted in Section 2.4.1.4, six research questions were formulated to guide the literature review and address important topics to be investigated. According to the preceding analysis presented in Sections 2.4.2 and 2.4.3, the answers to all of them can be observed as follows.

RQ1: How have maintenance models and policies evolved historically in terms of consideration of reuse and remanufacturing?

This question aims to provide a more general perspective on all of the aspects analysed in this paper. Analysing the papers according to the date of publication in Figure 10, we can easily see that both major categories focused on products sold by companies and on items that are used in the industrial process and were frequently considered over the years. Additionally, the warranty and upgrade have generally been adopted as model strategies over the years. Also, PM policies were beginning to be focused on the context of reuse and remanufacturing from 2012 on. Regarding the sustainability strategy, both reuse and remanufacturing were widely employed over the years. These findings show that the different strategies adopted by the authors are influenced more by the context of the problem analysed than by a tendency to apply one strategy rather than another. Traditional strategies, such as PM, warranty policies, and upgrade actions, which have been used for a long time, are still being used in various applications. A detailed analysis of the model strategy, business strategy, and sustainability strategy is presented in the next three research questions.

Figure 10 – Timeline of reviewed papers and their most common strategies



Source: Santos, Cavalcante, Wu (2022)

RQ2: What types of model strategies have been considered over time to address reuse and remanufacturing?

The majority of model strategies utilised in the analysis were used extensively over time. Three of them, however, deserve special attention due to their recurrence in many different publications. As can be seen in Figure 11, the most usual model strategies are PM, Warranty and Upgrade, which can be used together or separately according to the context analysed. In general, they are used together when dealing with second-hand products. Alternatively, they can be applied separately, for example, when performing maintenance on second-hand industrial items.

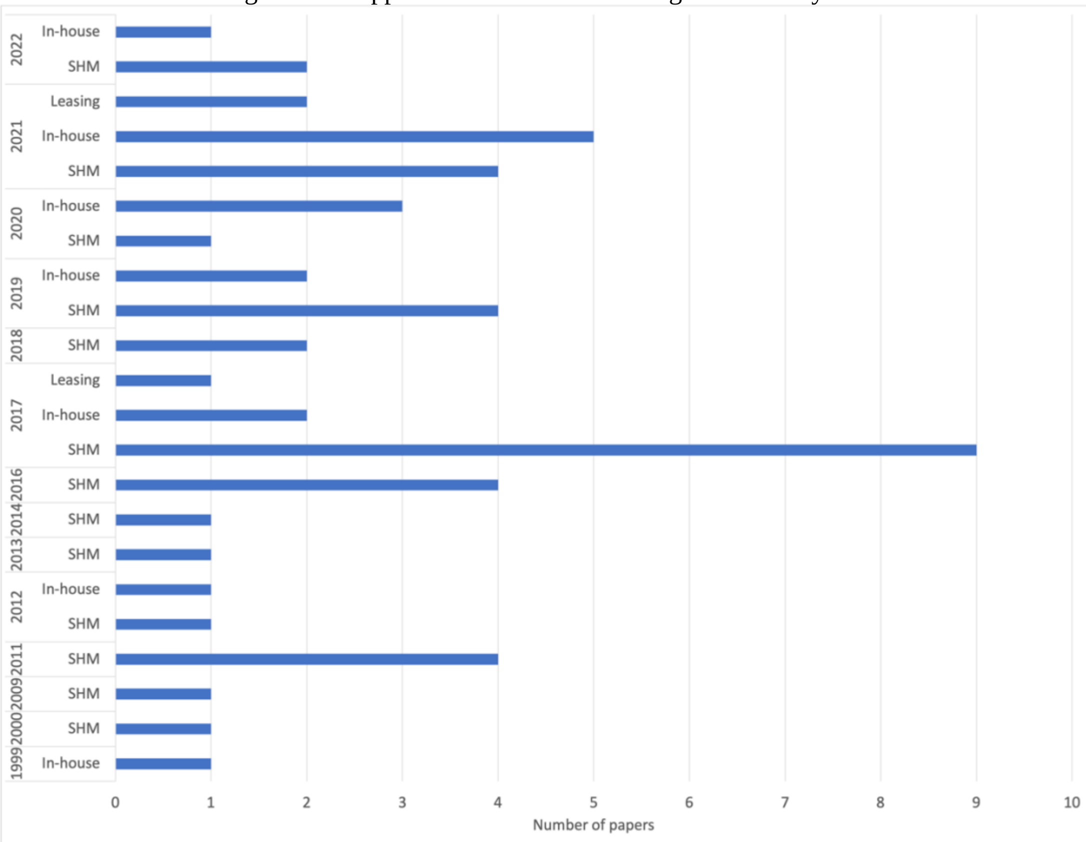
Figure 11 – Application of model strategies over the years

Source: Santos, Cavalcante, Wu (2022)

RQ3: Which business strategy has been predominantly adopted in maintenance models or policies: second-hand market, in-house maintenance, or leasing?

Regarding the business strategies considered, the second-hand market and in-house maintenance have been predominant over time (Figure 12). It was also verified that the adoption of the business strategy is associated with the type of approach considered in the model. For models that consider the approach focused on products sold by companies, the second-hand market strategy has been extensively applied (89% of the papers). In contrast, models that consider the approach focused on the reuse of industrial items generally adopt the in-house maintenance strategy to gain economic advantages.

Figure 12 – Application of business strategies over the years

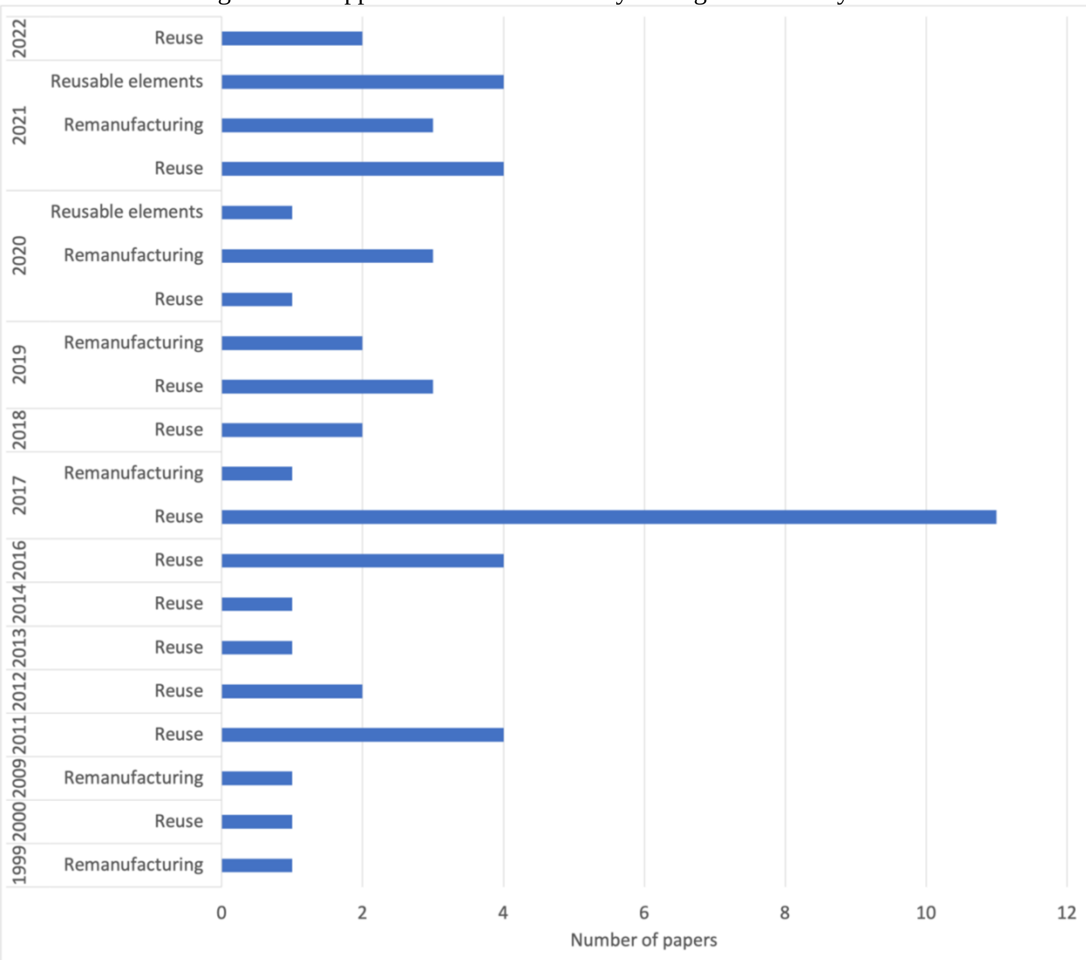


Source: Santos, Cavalcante, Wu (2022)

RQ4: Which sustainable strategy has been predominantly adopted in maintenance models or policies: reuse or remanufacturing?

Both strategies, reuse and remanufacturing have been extensively used over the years (Figure 13). However, the reuse strategy has been adopted in more papers. When considering products sold by companies, 86% of the papers emphasised reuse as a sustainable strategy. Considering the papers focused on industrial items, almost 60% are focused on reuse (reuse or reusable elements in Table 4).

Figure 13 – Application of sustainability strategies over the years



Source: Santos, Cavalcante, Wu (2022)

RQ5: What has been proposed in terms of reuse?

As Table 3 shows, reuse is mainly applied as a sustainability strategy to PM, Warranty and Upgrade models for second-hand products sold in second-hand markets. It has also been investigated in PM models that were developed to consider the possibility of the in-house maintenance of industrial items that can be repaired so they can be reused again (Table 4). Each type of application is described in Section 2.4.3. For reference, papers that deal with reuse can be identified in Tables 3 and 4.

RQ6: What has been proposed in terms of remanufacturing?

Regarding remanufacturing, it has traditionally been used to offer sustainability solutions to either used products sold on second-hand markets or for industrial items. Tables 3 and 4 indicate papers that consider remanufacturing as a sustainability strategy. Each one of them is described in Section 2.4.3, according to the taxonomy previously proposed.

2.4.3.3.2 Main gap in the literature

The main gap in the literature is the negligence of environmental and social perspectives of sustainability, regardless of the sustainability strategy adopted (reuse or remanufacturing). According to Tables 3 and 4, only two papers consider the environmental aspect of sustainability (SANTOS, CAVALCANTE, 2022; SANTOS, CAVALCANTE, RIBEIRO, 2021) and none of them considers the social aspect. This result presents an interesting finding: even though sustainable strategies have been incorporated into maintenance models and policies, especially in recent years, the main motivation for using them is purely economic. Even those papers that support environmental questions (SANTOS, CAVALCANTE, 2022; SANTOS, CAVALCANTE, RIBEIRO, 2021) develop them based on a conjecture from an economic analysis. Therefore, future studies should focus on exploring the triple bottom line of sustainability (HAMMER, PIVO, 2017) that comprises economic, environmental, and social aspects.

2.4.3.3.3 Final considerations and link to the models proposed in this thesis

This bibliometric analysis and literature review was performed in order to check how maintenance policies and models have been developed in the context of reuse and remanufacturing. Using the approach adopted in this study, these topics have not been examined previously.

The bibliometric analysis revealed an increase in the number of papers related to this theme over recent years, particularly in the last five. PM was the most frequent keyword used, suggesting that it is the most widely adopted model strategy, which was later confirmed in the literature review. Regarding the sources of publication, the journal Reliability Engineering and System Safety is the main and most influential source with 14 papers and 144 citations, which places it far ahead of the other journals.

The literature review revealed two major approaches: The first category comprises 68% of the papers and refers to models relating to the reuse or remanufacturing of products, and the second category represents 32% of the papers and refers to industrial items that are reused or remanufactured. The model strategies most used in the first category were PM, Warranty and Upgrade, and in the second category the model strategy most used was PM. The main business strategies in both approaches were the second-hand market and in-house maintenance, respectively. The main sustainability strategy was the reuse, considered in 86% of the papers with the first approach and in nearly 60% of the papers with the second approach. Regarding what has been proposed in terms of maintenance model for reuse and remanufacturing, reuse is mainly considered in PM, Warranty and Upgrade models in the first major approach and in PM models, in the second major approach. Remanufacturing has been mostly adopted in PM models in both approaches.

The main gap is the neglect of environmental and social dimensions of sustainability due to the emphasis on the economic perspective. The result does not imply that the neglected aspects cannot be improved by applying these models. This means, however, that the advance in these areas comes primarily from improvements in the economic perspective, the perspective that drives the evolution of maintenance models also in this specific context. Finally, this review highlights the novelty and importance of the models presented in this thesis. As demonstrated, Santos and Cavalcante (2022) and Santos, Cavalcante and Ribeiro (2021) are the only authors who consider the environmental dimension of sustainability in maintenance models and policies rather than just the economic perspective commonly applied.

2.5 SUMMARY OF THE CHAPTER

This chapter provided a conceptual basis for and a literature review of the concepts that are most relevant and related to the topic of this thesis.

First, the concept of maintenance was defined and classified, followed by a discussion on the different types of maintenance policies for single-component systems. In addition to the idea behind each type of policy, some recent developments were also presented.

Afterwards, the delay time model was addressed, emphasising the original idea presented by Christer (1976), the recent advances, and what has been proposed in the context of reuse.

Thereafter, a review of maintenance models and policies in the context of reuse and remanufacturing was presented, showing what has been proposed over the years, and illustrating the relevance of the papers developed from this thesis.

In the light of this contextualization of maintenance models and policies in a general context as well as more specifically within the context of reuse and remanufacturing, the next chapter introduces the Delay time model for second-hand items.

3 INTRODUCTORY DELAY TIME MODEL FOR THE REUSE OF ITEMS

This chapter presents the introductory delay time model for the reuse of items (components) (SANTOS, CAVALCANTE, RIBEIRO, 2021). First, a general view of the proposed models in this thesis is presented. Then, the focus is placed on the initial model (Model 1), which serves as the basis for the development of the other proposed models.

The initial model discussed in this chapter represents the simplest version of the delay time model for the reuse of items, in comparison with the other proposed models. The idea is to explain how reuse can be considered in Delay Time Theory with few modifications and new simple considerations. This first model is simple due to the consideration that new and reused items have the same reliability characteristics and also due to the fact that reuse is or is not considered depending on a threshold defective level. As such, the idea is to propose a simple but illustrative model that emphasises the possibility of considering reuse in the delay time modelling. Models 2 and 3, however, consider different assumptions that can be interpreted as being more realistic. As a result, the complexity of these models is higher than in the Model 1. As such, for didactic purposes, they will be presented in Chapter 4, after Model 1 is introduced. Table 5 shows a comparison of the models and indicates the purpose and characteristics of each one.

Table 5 – Proposed models and their main characteristics

Proposed model	Purpose	Characteristics
Model 1	Introduction of the first delay time model for the reuse of items	• Single-component system. • Consideration of a threshold defective level for reusing the current component. • New and reused components have the same characteristics.
Model 2	Analysis of component heterogeneity and misclassification problems	• Single-component system. • Two-defective states. • Threshold level for reusing the current component is established by the type of defective state. • Heterogeneity of components. • Misclassification errors.
Model 3	Analysis of component heterogeneity and inspection errors	• Single-component system. • Two-phase model (Inspection phase and wear-out phase). • Heterogeneity of components. • Inspection error (false negative at inspection). • The focus is not on the reuse of the current component but on the proportion of new and reused components to be used in the long run.
Related papers: Model 1: (SANTOS, CAVALCANTE, RIBEIRO, 2021); Model 2: (SANTOS, CAVALCANTE, WU, 2021); Model 3: (SANTOS, CAVALCANTE, 2022).		

Source: The Author (2022).

As can be seen in Table 5, Model 1 focuses on the introduction of the reuse in the delay time model under a more basic perspective. The aim is to seek to understand how the concepts of reuse and delay time can be considered together. In order to explain how these concepts can be linked, a framework is presented in Section 3.1, prior to presenting the model in Section 3.2.

Models 2 and 3 deal with three important characteristics that could be found in real contexts, such as the heterogeneity of components, misclassification error and inspection error. The first refers to the practical consideration that a reused component may be less reliable and have a shorter lifetime compared to a new one. The second is related to the misclassification of the defective state, in cases in which more than one defective state is considered in the model (as in Model 2). For instance, the component is in a minor defective state and is identified at the inspection as being in a major defective state or *vice-versa*. The third consideration refers to a practical situation that can be common depending on the level of experience and training of the maintenance personnel: the non-identification of an existing defect.

Given this initial overview of what is approached in each model. The very first idea of considering the possibility of reuse in delay time models is presented in a framework and the introductory delay time model for the reuse of items is subsequently proposed.

3.1 FRAMEWORK FOR REINTRODUCING A REUSED ITEM INTO THE SYSTEM

The purpose of this section is to describe how the delay time concept can be applied in the context of reuse of items. In the first instance, it is important to clarify that not every component can be replaced by a reused one due to the characteristics intrinsic to a new component that cannot be ensured by a reused one. Some components, however, can be refurbished and reused depending on their state at the end of their previous life cycle. As an example, a mechanical item that undergoes wear over time but is not severely damaged might be refurbished and reused. In these cases, repairing the degraded part may be easier, compared to the effort needed to create a new item.

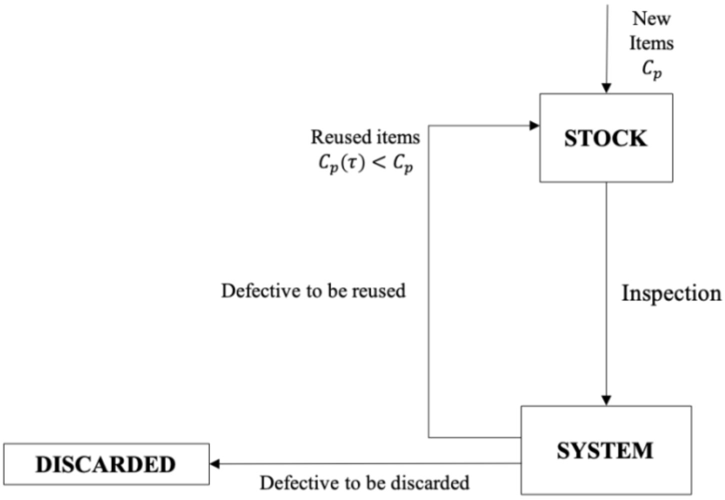
The framework and the model presented in this chapter are based on the assumption that the component under analysis can be refurbished and reintroduced into the system if its condition has not seriously deteriorated. This is crucial to highlight since it is one of the essential links between the concepts of delay time and reuse of items. To make use of delay time, it is necessary to consider a defective state before the occurrence of the failure. In practice, this characteristic describes how mechanical components wear out over time. The wear may be physical, chemical, age, corrosion, loss and/or fatigue degradations (CARTER, 1986). Due to the characterization of a defective state and the signs of oncoming failure, the delay time concept may be useful to determine an optimal inspection time based on the degradation characteristics of the system or component being inspected.

Although the level of the defective state may influence the level of repair required to reintroduce the item back into the system, this has not been addressed in the delay time related literature yet. This chapter, therefore, presents the framework that analyses the repair cost as a function of the time in the defective state and proposes the necessary adjustments in the first delay time model for the reuse of items. Both the framework and the modifications in the model are determined based on the following considerations.

- In this chapter and in the following one, the nomenclature items and components refer to the same thing. There is only one difference between the two: the former is more commonly used in the context of reuse and the latter in the context of delay time theory. In addition, it is important to differentiate between τ and h when defining sojourn time in the defective state. In this chapter, τ represents the sojourn time in the defective state until the defect is detected in the following inspection, so that, $\tau = iT - x$. Similarly, the delay time h corresponds to the sojourn time in the defective state when the failure occurs. It is a random variable with the probability density function represented by $f_h(h)$.
- The component can be good, defective or failed;
- Inspections are performed to detect the state of the system and prevent failures.
- If the component is severely defective (delay time longer than a maximum limit, $\tau > m_l$), it is discarded and replaced by another one.
- If the component is not severely defective (delay time shorter than or equal to a maximum limit, $\tau \leq m_l$) it is refurbished, sent to the spare part stock and replaced by another one.
- If the current component cannot be reused, the repair cost is C_P.
- If the current component can be reused, the repair cost is $C_P(\tau) < C_P$.
- $C_P(\tau)$ is a function of the time in the defective state.

In this first idea, it is important to emphasise that the components are always replaced. Whenever a component with a defect has been in the defective state for more than m_l, it is discarded and replaced with a new or refurbished one. However, in the case that sojourn in the defective state is less than m_l, the current component is still replaced, but it is refurbished and sent to the spare parts stock at a lower cost, $C_P(\tau)$, thus reducing the repair cost C_P. An overview of the process for reintroducing a refurbished item into a system and the effect it has on repair costs is shown in Figure 14.

Figure 14 – framework for reintroducing a reused item into the system



Source: Santos, Cavalcante, Ribeiro (2021)

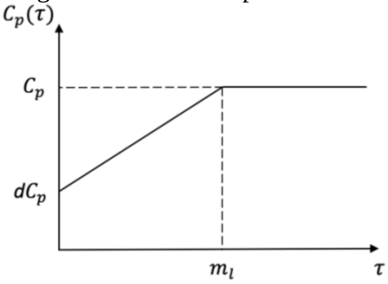
3.2 THE MODEL

In this section, the first delay time model for reused items is introduced. This proposal is based on modifications to the traditional delay time model for single-component systems discussed in Section 2.3.1. The decision criterion is the long-run cost per unit of time, $C(T)$, the decision variable is the optimal interval between inspections, T, and all the other terms presented are parameters of the model.

In this proposal, the cost of repairing a defect can be reduced, as has already been discussed in Section 3.1. In the model, a defective item can be restored to work in the system (instead of being discarded, as assumed in the traditional approach). Also, the formulation of how the period of time spent in the defective state influences the feasibility and cost of the repair is taken into consideration.

Similarly to the traditional model, the proposed model presented in this section assumes that before the component fails, it stays for a period of time in the defective state or that a defect is detected and repaired at an inspection. In the latter case, the time in the defective state represents an opportunity to reduce the repair cost. If the component is replaced before the threshold limit for refurbishment (m_l), the used component is sent to be repaired and reused again later. In this case, the repair cost grows linearly from a set percentage d of C_p up to C_p, when the m_l is reached (Figure 15). If the component is replaced after the threshold limit for refurbishment (m_l), the current component is discarded and the repair cost is equal to the cost of replacement by a new component. Consequently, the cost of repairing a defect is defined by parts as shown in Equation (3). Also, Equation (1) is modified to Equation (4).

Figure 15 – cost to repair a defect



Source: Santos, Cavalcante, Ribeiro (2021)

$$C_p(\tau) = \begin{cases} dC_p + \dfrac{(1-d)C_p}{m_l}\tau & if\ \tau \le m_l \\ C_p, & if\ \tau > m_l \end{cases} \tag{3}$$

$$U(T) = \sum_{i=1}^{\infty} \int_{(i-1)T}^{iT} \int_{iT-x}^{\infty} [(i)C_i + C_p(iT-x)] f_h(h) f_x(x) dh dx + \sum_{i=1}^{\infty} \int_{(i-1)T}^{iT} [(i-1)C_i + C_f] f_x(x) F_h(iT-x) dx \tag{4}$$

The time in the defective state after which it is no longer possible to repair the item in order to reintroduce it to the system is characterised by the maximum limit m_l described in Equation (3). The m_l value can be defined as a percentile of the delay time distribution. The use in practical cases depends on this length and its specification. In practice, a company can determine a percentage of reused items to be used in the long run due to many distinct reasons, for example, the availability of new and reused items in specific periods of time, the possibility of economic savings, etc. When the company defines the percentage of reused items in the long run, the m_l value can be determined as demonstrated as follows.

Similarly to the traditional model, the proposed model involves inspection of the component at each time T, but the choice of whether or not to refurbish it is based on the component's degree of degradation, which is related to the amount of time it has spent in the defective state. Therefore, Equation (5) represents the probability of an item being repaired and reused again. This can be viewed as a sustainability metric in the long run analysis because it calculates the percentage of reused items, I_R.

$$I_R = \int_0^{ml} f(h)dh \tag{5}$$

From Equation (5), which is valid only for model 1, the m_l value can be determined. Considering that delay time follows a Weibull distribution, $f(h) = \left(\frac{\beta}{\eta}\right)\left(\frac{h}{\eta}\right)^{\beta-1} e^{-\left(\frac{h}{\eta}\right)^{\beta}}$, and $F(h) = 1 - e^{-\left(\frac{h}{\eta}\right)^{\beta}}$, the $I_R = F(m_l) = 1 - e^{-\left(\frac{m_l}{\eta}\right)^{\beta}}$ and m_l is determined as shown in Equation (6).

$$m_l = \eta\left[-\ln(1 - I_R)\right]^{\left(\frac{1}{\beta}\right)} \tag{6}$$

The time in the defective state from which it is no longer possible to repair the item in order to reintroduce it to the system is determined by Equation (6). Clearly, it is derived from the defined percentage of reused items and from the scale and shape parameters of the Weibull distribution. Thus, from a practical point of view, the maintenance manager defines the percentage of items that must be reused and the model establishes the optimal inspection interval that minimises the cost per unit of time in the long run.

One significant contribution of this model is the potential for reducing the repair cost. Likewise, its importance is also associated with environmental sustainability, since the model considers the reintroduction of a repaired item into the system. The key contribution is the development of a novel inspection strategy that takes into account the percentage of reused items that must be considered for single-component systems over the long run.

3.2.1 Numerical examples

By utilising an illustrative case, this section compares the traditional and the proposed models. The optimal interval between inspections, T, and the respective expected cost over an inspection cycle, $C(T) = \frac{U(T)}{V(T)}$, are determined and compared. $C(T)$ is determined from $U(T)$

in Equation (4) and $V(T)$ in Equation (2). m_l is obtained from Equation (6) based on the I_R defined by the company and on the parameters of delay time distribution.

The function that represents the arrival of defects in the system $f_x(x)$ follows a Weibull distribution with shape parameter $\beta_x = 3$ and scale parameter $\eta_x = 5$; and the delay time function $f_h(h)$ follows a Weibull distribution with $\beta_h = 2.5$ and $\eta_h = 1$. The inspection cost is $C_i = \$0{,}05$ per inspection, the failure cost is $C_f = \$4$ per failure, the cost to repair a defect is $C_p = \$1$ (monetary unit) per repair (in the case of replacement of a new item) and the percentage d, from which the repair cost grows linearly up to C_p, is 0.2.

The optimal time T (years) between inspections and the expected cost $C(T)$ for the traditional and proposed models are shown in Table 6. It is also important to clarify that the time spent on an inspection is worthless when compared with the time between inspections.

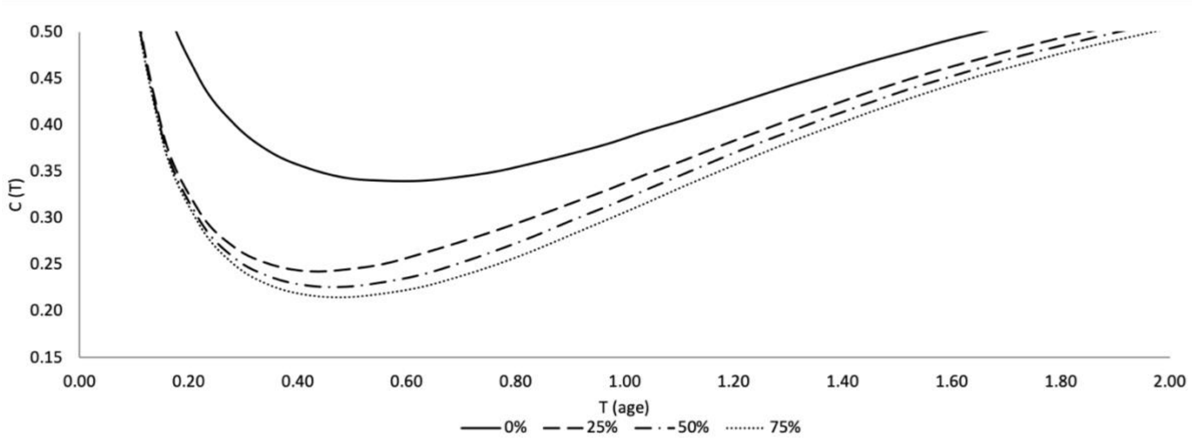
Table 6 – Comparison between traditional and proposed models

Model	I_R	m_l	T	% Reduction in T	$C(T)$	% Reduction in $C(T)$
Traditional	0	0	0.58	-	0.34	-
Proposed	25	0.61	0.44	24.40	0.24	28.30
	50	0.86	0.46	20.40	0.23	33.60
	75	1.14	0.48	18.10	0.22	36.70

Source: Santos, Cavalcante, Ribeiro (2021)

From Table 6, the optimal period between inspections T is reduced when a percentage of reused items is considered. One may initially assume that a shorter T could guarantee that it would be possible to reuse more items, but the results indicate that this is not necessarily true. Although the inspection period will be shortened, the model sets a larger reduction for small I_R since the m_l value is smaller when the I_R is low. When the reuse is considered, more inspections are provided in the long run, but the related expected cost is reduced up to 36.7% when 75% of the components are reused. Also, the results indicate that a higher percentage of reduction in the cost is obtained mainly for small I_R, for instance, the cost reduction from 0 to 25 of I_R is around 28% and from 50% to 75% of I_R it is 3.1%. This greater incremental decrease in the cost for small I_R is important for the managers to consider changing the traditional non-reuse rule to the reuse of at least a small percentage due to the reduction in the maintenance cost. In practical terms, the policy shows that the more that items are reused, the greater will be the savings on the cost, regardless of the increase in the periodicity of inspections. Figure 16 shows the reduction in $C(T)$ behaviour when there is an increase in the I_R. The behaviour of the model under different distribution parameters for delay time is also examined in the following section.

Figure 16 – Comparison between traditional and proposed models for different % of reused items



Source: Santos, Cavalcante, Ribeiro (2021)

3.2.2 Sensitivity analysis

This section examines the sensitivity to variations in the shape β and scale η parameters of the Weibull distribution. The base case presented in the preceding section is compared with the cases in which each parameter value $\beta_h = 2.5$ and $\eta_h = 1$ is reduced and increased by 20%, $\beta_{h(-20\%)} = 2$, $\beta_{h(+20\%)} = 3$, $\eta_{h(-20\%)} = 0.8$, $\eta_{h(+20\%)} = 1.2$.

For the same I_R, the effect of β_h and η_h on the proposed delay time model is as follows. Lower β_h indicates that the time in the defective state is more dispersed over time, which makes inspection less effective. As a result of this effect, the model suggests a more frequent inspection policy, thereby increasing the expected costs. A higher β_h value, however, reduces the dispersion of the time in the defective state, leading to more efficient inspections, which may reduce the frequency of inspections. As a result, the expected cost is reduced. This result can be considered counterintuitive due to the fact that a higher β_h value can be interpreted as a more intensive failure process. However, it is important to emphasise that a higher β_h **value** implies a more concentrated distribution, in a way that the variations in the arrival of a failure are reduced, so that the determination of an inspection interval is more accurate. On the other hand, a lower β_h and, consequently, a more dispersed time for the arrival of a failure, makes the model anticipate the inspections in order to detect possibly earlier failures. Regarding the effect of η_h, a lower η_h represents a shorter mean delay time, which results in more frequent inspections and a higher expected cost. In contrast, when the mean delay time is longer, the model sets fewer inspections and reduces the optimal expected cost. Table 7 shows this behaviour in both the traditional and proposed models.

Table 7 – Sensitivity analysis under the variation of β_h and η_h

Model	I_R	Base case	$\beta_h = 2$	$\beta_h = 3$	$\eta_h = 0.8$	$\eta_h = 1.2$
				T		
Traditional	0	0.58	0.55	0.62	0.49	0.67
Proposed	25	0.44	0.40	0.47	0.38	0.50
	50	0.46	0.43	0.49	0.40	0.52
	75	0.48	0.44	0.51	0.41	0.54
				$C(T)$		
Traditional	0	0.34	0.36	0.33	0.36	0.32
Proposed	25	0.24	0.27	0.23	0.27	0.22
	50	0.23	0.25	0.21	0.25	0.21
	75	0.22	0.24	0.20	0.24	0.20

Source: Santos, Cavalcante, Ribeiro (2021)

Regarding the comparison within the cases and with changes in the I_R, the decreases in the optimal interval between inspections and in the expected cost are maintained when the proposed model is compared with the traditional one, no matter the changes in shape and scale parameters. For all analysed cases, regardless of β_h and η_h values, a higher I_R can lead to greater savings in the total expected cost, but the incremental reduction in the cost is higher for small I_R. As a consequence, the highest reduction in the optimal expected cost occurs when the I_R is high, the delay time is less dispersed and the mean delay time is longer.

Finally, the model shows that reusing an item reduces the total expected cost even with a higher frequency of inspections. This effect becomes more pronounced with an increase in the percentage of reuse. The appeal of reusing items, which is usually justified by environmental concerns, can now be expressed in terms of economic results for the single-component systems that can be modelled by the proposed delay time model.

Some important considerations on this initial model and a discussion about further developments are presented in the following section.

3.2.3 Considerations on the initial model

As part of advances in delay time modelling, this introductory model takes into account the possibility of reusing an item to minimise costs and to reduce the environmental impact. The results emphasise the economic and environmental importance of reusing defective items that can be refurbished in order to reintroduce them into the system. The framework that simply illustrates this reintroduction process was created and the initial proposed modification to the delay time model was developed. An important contribution is the development of a delay time model that accounts for reused items in the long run, which is a novelty. In addition, it is important to mention that, by using this model, one can achieve better results using the same degree of managerial effort as by using the traditional delay time model for single-component systems.

A limitation in this first model is the assumption that the reused item has the same characteristics as a new one. Even though this is true in some contexts, future studies could benefit from examining the possibility of considering a heterogeneous population of new and reused items (Chapter 4).

Another limitation is the fact that the economic advantages of reuse is linked to the specific relation between the cost of refurbishment of a defective item and the cost of a new item. Although this seems to be very practical in some components, it may not be observable in other ones. A good example for practical application is a hammer that is a component part of a shredder machine. In this component, the refurbishment process corresponds to adding metallic mass to its head. The total cost of refurbishment is related to the quantity of lost mass which can be linked to the time in the defective state. Thus, there is a clear economic advantage to reusing a hammer when the cost to reintroduce it in the system after a refurbishment is a small percentage of the cost of a new hammer. However, it is important to mention that this type of behaviour may not be observed in other types of items.

3.3 SUMMARY OF THE CHAPTER

This chapter introduced the delay time model in the context of reuse of items. First, a brief comparison among the three proposed models in this thesis was presented. Then, the introductory model is explained and analysed. This chapter serves as an introduction for a better understanding of the following models presented in Chapter 4.

4 CONSIDERATIONS ON ITEM HETEROGENEITY AND INSPECTION ERRORS

This chapter introduces two novel delay time models in the context of reuse. Model 2 takes into account the heterogeneity of components and misclassification problems and Model 3 considers both the heterogeneity of components and false-negative at inspections (SANTOS, CAVALCANTE, 2022).

4.1 MODEL 2

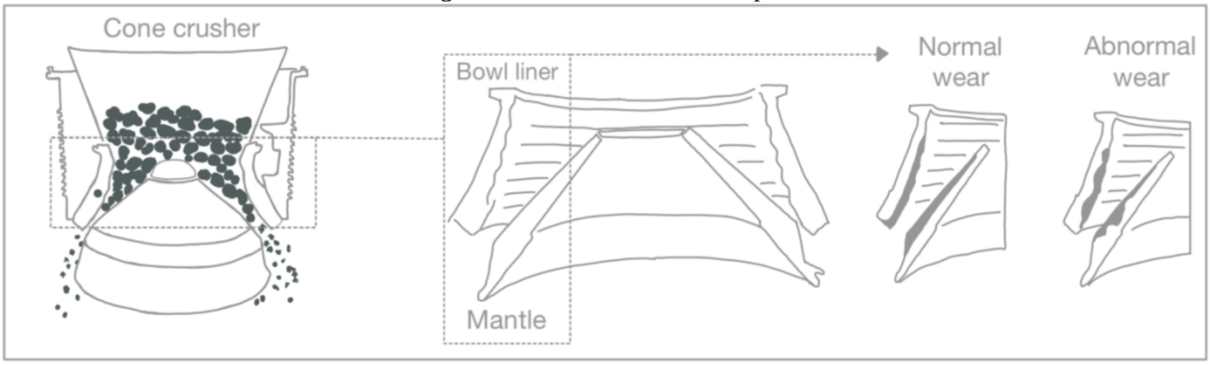
Model 2 was initially developed from an insight from a practical context in which a single-component system is subject to two defective states prior to the failure. As such, the development of this model is first explained by the practical motivation that led to doing so.

4.1.1 Practical motivation

Along with the theoretical development, maintenance models should also be applied in practice to demonstrate their applicability in the real world (SCARF, 1997). As such, this section describes the degradation process of a single-component system that inspired the development of Model 2.

Essentially, the system under maintenance consists of the bowl liner and the mantle on a cone crusher. These components operate together as a component and a socket that perform one operational function and, therefore, can be considered as a single-component system (ASCHER, FEINGOLD, 1984; SCARF, CAVALCANTE, 2012). During operation, the system undergoes continuous wear because it crushes hard materials into small pieces (SINHA, MUKHOPADHYAY, 2015), as shown on the left of the illustration in Figure 17. This progressive wearing progression is intrinsic to the process and is one of the main causes of failures (METSO OUTOTEC, 2021; SINHA, MUKHOPADHYAY, 2015). Moreover, due to different material gradations, normal wear can progress to a more severe stage of degradation, as shown on the far right of Figure 17.

Figure 17 – Cone crusher example.



Source: Adapted from Metso Outotec (2021) and Santos, Cavalcante and Wu (2021).
Note: On the left, an outline of a cone crusher. In the middle, the bowl liner (external element) and the mantle (internal element). On the right, representations of normal wear (considered as a minor defective state) and abnormal wear (considered as a major defective state).

Figure 17 shows that the system has two distinct defective states, namely a minor defective state and a major defective state. In the event that a component is found to be in a major defective state (with abnormal wear), it can no longer be refurbished or reused anymore. The reasons for this could be associated with a technical impossibility or the fact that the refurbishment is not economically effective compared to the cost of replacing the component with a new one. This issue poses a challenge as to when to preventively maintain the system to reduce costs. This challenge is due to the fact that used items are normally more prone to failure and require more inspections and maintenance, whereas brand-new items are more reliable and require less maintenance. Thus, the relevant costs are different: even though maintenance is required more frequently for used items than for new ones, used components cost less to acquire, especially when they are refurbished on-site. Furthermore, they are more resource-efficient and environmentally friendly than brand new ones.

Considering this context, Model 2 aims to establish the optimal time to perform inspections, in such a way that the cost of maintaining the system in a regime of inspections is minimised in the long run.

4.1.2 Notations and assumptions

To provide a reference guide to the terminology adopted in Model 2, the notation used for it is presented in Table 8.

Table 8 – Notation for Model 2

T	Inspection interval
$C(T)$	Long run cost per unit of time (cost rate)
I_R	Percentage of reused components. Also, the mixing parameter in Equation (7)
x, y, h	Sojourn times in the good state, in the minor defective state and in the major defective state, respectively
β_{x1}, β_{x2}	Shape parameters for Weibull distribution of the sojourn time in the good state in reused components and in new components, respectively
β_y, β_h	Shape parameters for Weibull distribution of the sojourn times in the minor and major defectives states, respectively
η_{x1}, η_{x2}	Scale parameters for Weibull distribution of the sojourn time in the good state in reused components and in new components, respectively
$\eta_y,\ \eta_h$	Scale parameters for Weibull distribution of the sojourn times in the minor and major defectives states, respectively
$f_1(x), f_2(x)$	Probability density functions of the sojourn time in good state in reused components and in new components, respectively
$f_x(x)$	Mixture distribution of the the sojourn time in the good state, based on the R_{items}
$f_y(y), f_h(h)$	Probability density functions of the sojourn time of minor defect and major defect, respectively
p, q	Probability of a minor and a major defective component being correctly classified, respectively
C_i, C_d	Cost of inspection and disposal cost of a major defective or failed component, respectively
C_{error}, B_r	Penalty cost for not classifying the real state of a major defective component and sending it for repair, and bonus due to the reuse of the current component classified as minor defective, respectively
C_{ritem}, C_{nitem}	Cost of using a reused component and cost of acquiring a new component, respectively
C_{r_r}, C_{r_nr} $C_{r\_nr\_e}$	Replacement costs when the current component is in the minor defective state and is correctly classified, when it cannot be reused but is not failed, and when it cannot be reused and is incorrectly classified as reusable
C_{pen}, C_f	Penalty cost due to failure and cost of failure, respectively

Source: The Author (2022).

Model 2 also considers the following assumptions.

1. Components can be classified into four states: good, minor defective, major defective, and failed. A minor defect does not cause severe damage to a component, whereas a major defect does. Components can be new or reused. The component will be disposed of if it has a major defect or fails.
2. The lifetime distributions of used and new components in the good state may be different.
3. Components are inspected in order to detect their state and prevent their disposal. Upon inspection, the minor defective component can be correctly classified with probability p, being reused, or mistakenly classified with probability $(1-p)$, and is disposed of. Upon inspection, the major defective component can be correctly classified with probability q, and is disposed of, or can be mistakenly classified with probability $(1-q)$, and is initially sent for repair but is then and is disposed of as well. An extra penalty cost due to this decision error is considered, C_{error}.

4. Inspections are conducted every T units of time. Each inspection costs C_i.
5. If the component cannot be reused, there is an additional cost C_d due to its disposal. If the component can be reused, there is a discount B_r due to its refurbishment.
6. If failure occurs, there is an additional penalty cost C_{pen} due to the negative impacts of a failure.
7. The sojourn time in the good state, x, is distributed according to a known mixed distribution (the distribution that incorporates the behaviour of both new and reused items in the good state) based on the level of I_R, for which the probability density function is $f_x(x)$, as stated in Equation 7.
8. The sojourn times in the minor defective state, y, and in the major defective state, h, are distributed according to known Weibull distributions, for which the probability density functions are $f_y(y)$ and $f_h(h)$, respectively. The component must pass through a minor defective state before a major defective state, and a major defective state before a failure.

4.1.3 Development of the model

The proposed model takes into account the two different defective states with distinct characteristics regarding the possibility of reuse to determine the optimal inspection interval T that minimises the long run cost per unit of time $C(T)$. The components are assumed to come from a stock of new and reused spare parts, with a random selection of one of them. The percentage of reused and new components to be used in the long run depends on the company's environmental and economic strategy. However, the model establishes the best cost relation according to the percentage of new and reused items adopted.

Upon inspections, if a component is found to be defective, it will be replaced with another one that can be new or reused (a previous component that has been refurbished and returned to the system). Depending on the state of the component or on the perception of the maintenance personnel about its state, the current component is disposed of with a cost C_d or sent for in-house repair with a bonus B_r due to the possibility of reuse. Reused components can have a different reliability than new ones due to the different lifetime distribution associated with their good state. This is a practical consideration because a reused component is unlikely to have the same characteristics as a new one. As such, the proposed model considers that the time in the good state (up to the arrival of the minor defect) is influenced according to the status of the component i.e., brand-new or reused. Therefore, the probability density function of the good state in the reused component $f_1(x)$ differs from that in the new component $f_2(x)$. In other words, the reused component can be in the good state with a different characteristic from a new one. As such, the probability density function that characterises the good state in a system sometimes consisting of a reused component and sometimes of a new component is considered as a mixture distribution based on the percentage of reused components I_R and new components $(1 - I_R)$ in the long run (Equation 7). The sojourn time in the minor and in the major defective states follows the same probability function in new and reused components, respectively $f_y(y)$ and $f_h(h)$.

$$f_x(x) = I_R f_1(x) + (1 - I_R) f_2(x) \tag{7}$$

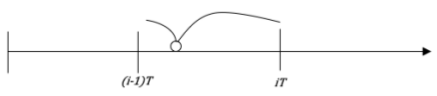
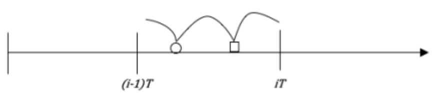
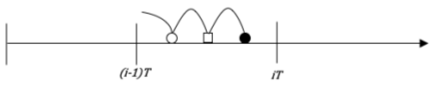
Given a specific I_R, it is possible to determine an acceptable level of reduction in the reliability of the reused component so that it would still be viable to introduce it in the system. This analysis can be performed by varying β_{x1} in comparison with β_{x2} and η_{x1}in comparison with η_{x2}. The former is to consider a higher dispersion and the latter is to consider a shorter time to the arrival of the minor defect in reused components. Both parameter distinctions reflect a practical fact that the refurbishment process may not be able to make the component as-good-as-new. This practical fact is also analysed in terms of a cost relationship established between the expected cost rate for varying combinations of new and reused components.

The model also takes into account the mistakes made during inspections when classifying the current state of the component. The probability of correctly classifying a reusable component is p, while the probability of incorrectly classifying it is $(1 - p)$. It is also possible to correctly classify a nonreusable component (currently in the major defective state) with a probability q and to mistakenly classify it with a probability $(1 - q)$. In the event of a failure, the component is always classified correctly since the process is interrupted.

Replacement costs for different classification possibilities are as follows: (1) if the component is in the minor defective state and is correctly classified, the cost of replacement is defined as (C_{r_r}), (2) if the component is in the major defective state (cannot be reused but is not failed yet), the cost of replacement is defined as (C_{r_nr}), and (3) if the component is in the major defective state and is mistakenly classified as reusable, the cost of replacement is defined as $(C_{r\_nr\_e})$. Notice that in the latter case, there is an additional error cost due to the misclassification error (Figure 18).

As for the decision variable T, the optimum value is found by minimizing the objective function, represented by the long run cost per unit of time $C(T)$. All possible disjunct and mutually exclusive renewal events between two consecutive inspections are referred to as cases and are illustrated in Figure 18. Each case is evaluated in terms of its probability, cost, and cycle length.

Figure 18 – All possible cases of model 2 and cost structure

The current component is in the minor defective state		Action and respective cost structure
Case 1		REUSE: when the component is correctly classified with probability p: $C_{r\_r} = (I_R)C_{ritem} + (1 - I_R)C_{nitem} - B_r$ NOT REUSE: when the component is mistakenly classified with probability $(1 - p)$: $C_{r\_nr} = (I_R)C_{ritem} + (1 - I_R)C_{nitem} + C_d$
The current component is in the major defective state or failed		**Action and respective cost structure**
Case 2		NOT REUSE: when the component is correctly classified with probability q: $C_{r\_nr} = (I_R)C_{ritem} + (1 - I_R)C_{nitem} + C_d$ *NOT REUSE: when the component is mistakenly classified with probability $(1 - q)$: $C_{r\_nr\_e} = (I_R)C_{ritem} + (1 - I_R)C_{nitem} + C_d + C_{error}$
Case 3		NOT REUSE: the component is failed. $C_f = C_{r\_nr} + C_{pen}$

* The component is initially classified as reusable but then in the repairing area it is found to be not reusable anymore. For this reason there is an additional cost C_{error} due to the judgement error.

Source: The Author (2022).

In case 1, the current component is in the minor defective state. Consequently, when it is classified correctly with probability p, the replacement cost C_{r_r} benefits from the bonus B_r. This is due to the fact that refurbishing an existing component costs less than buying a new one, and does not incur disposal expenses. When the minor defective component is mistakenly classified as being in a major defective state with probability $(1 - p)$, it is disposed of and replaced with a new one. As such, the replacement cost C_{r_nr} takes into consideration the disposal cost C_d and the purchase of a new component to maintain the stock at the same level since one component will be disposed of.

In case 2, the current component is in the major defective state. As such, when it is correctly classified with probability q, the replacement cost C_{r_nr} takes into account the disposal cost C_d. However, when it is mistakenly classified with probability $(1 - q)$, the replacement cost $C_{r\_nr\_e}$ adds the error cost C_{error} of sending one non-reusable component to the in-house maintenance.

In case 3, the component fails and the failure cost C_f accounts for the penalty cost of the failure C_{pen} and the replacement cost C_{r_nr}. The probability, the expected cost of a cycle and the expected length of a cycle for each case are as follows.

Case 1: The probability of a cycle ending at a positive inspection of a minor defective state is shown in Equation (8). Note that the minor defective state necessarily arrives within the interval between inspections $[(i-1)T, iT]$ and the major defective state does not arrive in the same interval, and this is the reason for the lower limit of the integral of $f_y(y)$ being $(iT-x)$.

$$P_1(T) = \sum_{i=1}^{\infty} \int_{(i-1)T}^{iT} f_x(x) \int_{iT-x}^{\infty} f_y(y) dy dx \tag{8}$$

The expected cost of a cycle ending at a positive inspection of a minor defective state is given by Equation (9). Note that the costs are associated with the probability of the correct or wrong classification of the minor defective state, p and $(1-p)$, respectively.

$$\begin{aligned} U_1(T) = {} & p\left[\sum_{i=1}^{\infty}\left[iC_i + C_{r\_r}\right] \int_{(i-1)T}^{iT} \int_{iT-x}^{\infty} f_x(x) f_y(y) dy dx\right] \\ & +(1-p)\left[\sum_{i=1}^{\infty}\left[iC_i + C_{r\_nr}\right] \int_{(i-1)T}^{iT} \int_{iT-x}^{\infty} f_x(x) f_y(y) dy dx\right] \end{aligned} \tag{9}$$

The expected length of a cycle ending at a positive inspection of a minor defective state is given by Equation (10).

$$V_1(T) = \sum_{i=1}^{\infty} \int_{(i-1)T}^{iT} \int_{iT-x}^{\infty} \left[iT\right] f_x(x) f_y(y) dy dx \tag{10}$$

Case 2: The probability of a cycle ending at a positive inspection of a major defective state is shown in Equation (11). Note that the minor defective state necessarily arrives within the interval between inspections $[(i-1)T, iT]$. The same occurs with the major defective state. For this reason the upper limit of the integral of $f_y(y)$ is $(iT-x)$. On the contrary, the failure does not occur in the same interval, for this reason the lower limit of the integral of $f_h(h)$ is $(iT-x-y)$.

$$P_2(T) = \sum_{i=1}^{\infty} \int_{(i-1)T}^{iT} f_x(x) \int_{0}^{iT-x} f_y(y) \int_{iT-x-y}^{\infty} f_h(h) dhdydx \tag{11}$$

The expected cost of a cycle ending at a positive inspection of a major defective state is given by Equation (12). Note that the costs are associated with the probability of the correct or wrong classification of the major defective state, q and $(1-q)$, respectively.

$$\begin{aligned} U_2(T) = q &\left[\sum_{i=1}^{\infty} \left[iC_i + C_{r\_nr} \right] \int_{(i-1)T}^{iT} f_x(x) \int_{0}^{iT-x} f_y(y) \int_{iT-x-y}^{\infty} f_h(h) dhdydx \right] \\ +(1-q) &\left[\sum_{i=1}^{\infty} \left[iC_i + C_{r\_nr\_e} \right] \int_{(i-1)T}^{iT} f_x(x) \int_{0}^{iT-x} f_y(y) \int_{iT-x-y}^{\infty} f_h(h) dhdydx \right] \end{aligned} \tag{12}$$

The expected length of a cycle ending at a positive inspection of a major defective state is given by Equation (13).

$$V_2(T) = \sum_{i=1}^{\infty} \int_{(i-1)T}^{iT} \int_{0}^{iT-x} \int_{iT-x-y}^{\infty} \left[iT \right] f_x(x) f_y(y) f_h(h) dhdydx \tag{13}$$

Case 3: The probability of a cycle ending due to a failure is shown in Equation (14). Unlike in case 2, the failure occurs in the same interval of the minor and major defective states, and for this reason the upper limit of the integral of $f_h(h)$ is $(iT - x - y)$.

$$P_3(T) = \sum_{i=1}^{\infty} \int_{(i-1)T}^{iT} f_x(x) \int_{0}^{iT-x} f_y(y) \int_{0}^{iT-x-y} f_h(h) dhdydx \tag{14}$$

The expected cost of a cycle ending due to a failure is given by Equation (15).

$$U_3(T) = \sum_{i=1}^{\infty} \left[(i-1)C_i + C_f \right] \int_{(i-1)T}^{iT} f_x(x) \int_{0}^{iT-x} f_y(y) \int_{0}^{iT-x-y} f_h(h) dhdydx \tag{15}$$

The expected length of a cycle ending at a failure is given by Equation (16).

$$V_3(T) = \sum_{i=1}^{\infty} \int_{(i-1)T}^{iT} \int_{0}^{iT-x} \int_{0}^{iT-x-y} (x + y + h) f_x(x) f_y(y) f_h(h) dhdydx \tag{16}$$

Since all possible cases were considered and $\sum_{i=1}^{3} P_i(T) = 1$, the exhaustiveness of the cases can be confirmed. Equation (17) shows the long run cost per unit of time $C(T)$ and Section 4.1.4 presents the numerical examples.

$$C(T) = \frac{\sum_{i=1}^{3} U_i(T)}{\sum_{i=1}^{3} V_i(T)} \tag{17}$$

4.1.4 Numerical examples

This section shows the application of Model 2 in a hypothetical single-component system subject to two defective states, such as that described in Section 4.1.1. The application was then inspired in the context of the bowl liner and the mantle in a cone crusher. However, it is important to mention that other types of systems with similar characteristics may be also considered if the data related to the degradation and costs are consistent with the ones used in the model.

The purpose of the present analysis is to investigate the effect of different reliability between new and reused components on the optimal inspection interval T and its respective cost rate $C(T)$. The first question is to determine to what extent the reliability of a reused component can differ from a new one and still remain economically viable, when there is a different percentage of reuse over time. Then, the influence of misclassification of minor and major defective states on T and $C(T)$ are analysed.

This analysis was conducted using the parameters listed in Table 9. Regarding the parameters of Weibull distributions, the shape parameter β_{x1} of the distribution of the arrival of minor defects in a reused component is marginally smaller than the shape parameter β_{x2} for a new component, due to its wider dispersion on the arrival of the minor defect. This is based on the fact that the reused component might not be as reliable as the new one, thus allowing the arrival of the minor defect to be more dispersed. Moreover, the sojourn time of the reused component in the good state is expected to be shorter than is that of the new one, which is the main difference between the two components. As a consequence, the scale parameter of the distribution of the arrival of minor defects in reused components, η_{x1}, varies as a percentage of the same parameter for new components, η_{x2}. As such, the effect of a shorter life in the reused component on T and $C(T)$ can be verified for different I_R. In addition, new and reused components have the same parameters defining the arrival of the major defective state and the failure. The component has a shorter and dispersed time in these states when compared to the time in the good state. Concerning the error parameters relating to the probability of misclassification of minor and major defects, they are initially set to zero, since an analysis of misclassification will be presented separately. With regards to the cost parameters, the acquisition cost of a new component $C_{nitem} = 1$ monetary unit was used as a reference for defining the other cost values. All of them are, therefore, defined as a proportion of this reference value, based on the related advantage or inconvenience. For example, the penalty cost due to a failure is five times the cost of purchase of a new component and 10 times the cost of using a reused component to replace a defective one. Also, the disposal cost has the same value as the bonus for a component being reintroduced into the system.

Table 9 – Parameters considered in model 2

Weibull distributions								Reuse	Error		Costs						
β_{x1}	η_{x1}	β_{x2}	η_{x2}	β_y	η_y	β_h	η_h	I_R	p	q	C_i	C_{nitem}	C_{ritem}	C_d	B_r	C_{error}	C_{pen}
2.5	varied	3	5	2.5	1	2.5	1	varied	0	0	0.05	1	0.5	0.1	0.1	0.05	5

Source: The Author (2022).

Concerning the effects of different reliability levels between reused and new components, the analysis contemplates reductions on η_{x1} up to 80% of η_{x2}, varying at a step of 10%. The variations in the optimal inspection interval T and its associated cost rate $C(T)$ are quantified for different I_R. In Table 10, considering cases 1, 10, 19 and 28, compared to case 0 that represents the non-reuse action, the greater the reuse percentage, the better the cost advantage under similar conditions of reliability. In fact, if the reliability between reuse and new components is similar, the reuse alternative is less costly. This is logical because the company uses a reused component analogous to a new one but with a discounted cost. The maximum cost reduction of 46.35% is obtained when all components are reused but act as new ones in terms of the time to the arrival of a minor defect. This result is also consistent with the one pointed out in Model 1. Remember that the same characteristic occurs: if reused and new items have the same reliability and the former is less costly than the latter, the model will suggest only the reused ones should be used.

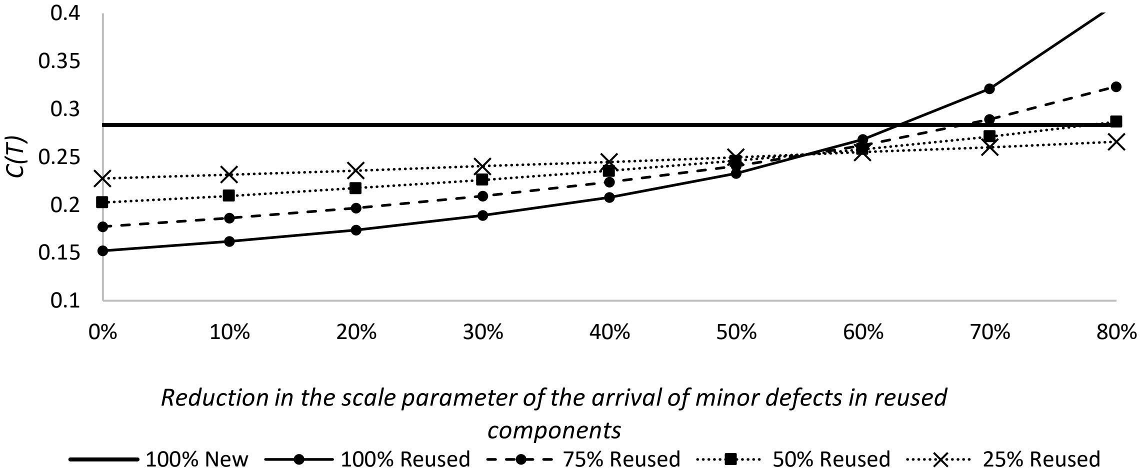
Table 10 – Effect of different reliability between new and reused components

	$Case$	η_{x1}	I_R	T	$C(T)$		$Case$	I_R	$\%Red\eta_{x1}$	T	$C(T)$
Non-reuse	0	5	0	1.06	0.28	Non-reuse	0	5	0	1.06	0.28
100% Reused	1	5	0	0.95	0.15	75% Reused	10	5	0	0.96	0.18
	2	4.5	10	0.94	0.16		11	4.5	10	0.95	0.9
	3	4	20	0.92	0.17		12	4	20	0.94	0.20
	4	3.5	30	0.91	0.19		13	3.5	30	0.93	0.21
	5	3	40	0.89	0.21		14	3	40	0.92	0.22
	6	2.5	50	0.88	0.23		15	2.5	50	0.92	0.24
	7	2	60	0.87	0.27		16	2	60	0.91	0.26
	8	1.5	70	0.87	0.32		17	1.5	70	0.90	0.29
	9	1	80	0.89	0.41		18	1	80	0.90	0.32
50% Reused	19	5	0	0.97	0.20	25% Reused	28	5	0	0.98	0.23
	20	4.5	10	0.97	0.21		29	4.5	10	0.98	0.23
	21	4	20	0.96	0.22		30	4	20	0.98	0.24
	22	3.5	30	0.96	0.23		31	3.5	30	0.97	0.24
	23	3	40	0.95	0.24		32	3	40	0.97	0.25
	24	2.5	50	0.94	0.25		33	2.5	50	0.97	0.25
	25	2	60	0.94	0.26		34	2	60	0.97	0.26
	26	1.5	70	0.95	0.27		35	1.5	70	0.97	0.26
	27	1	80	0.94	0.29		36	1	80	0.97	0.27

Source: The Author (2022).

However, if the reliability of reused and new components diverges, the cost savings may be insufficient to offset the worst performance of the system due to its short life and consequently a more likely failure. In effect, the more reused components are utilised in a system, the greater the cost when the reliability of a reused component is far different from that of a new component. Comparing cases 9, 18, 27 and 36 with case 0, there is a significant increase in the cost for high levels of reuse such as 100% and 75%; no significant increase for 50% of reuse and a small reduction in terms of cost for a low percentage of reuse of 25%. An important conclusion obtained from these results is as follows. A small percentage of reuse produces little benefit in terms of cost, but there is less interference in the system when the reliability of a reused component differs greatly from the reliability of a new component. A better visual representation of this behaviour can be found in Figure 19.

Figure 19 – The expected cost of using a determined % of reused items according to the reduction in the scale parameter of the distribution of the arrival of minor defects

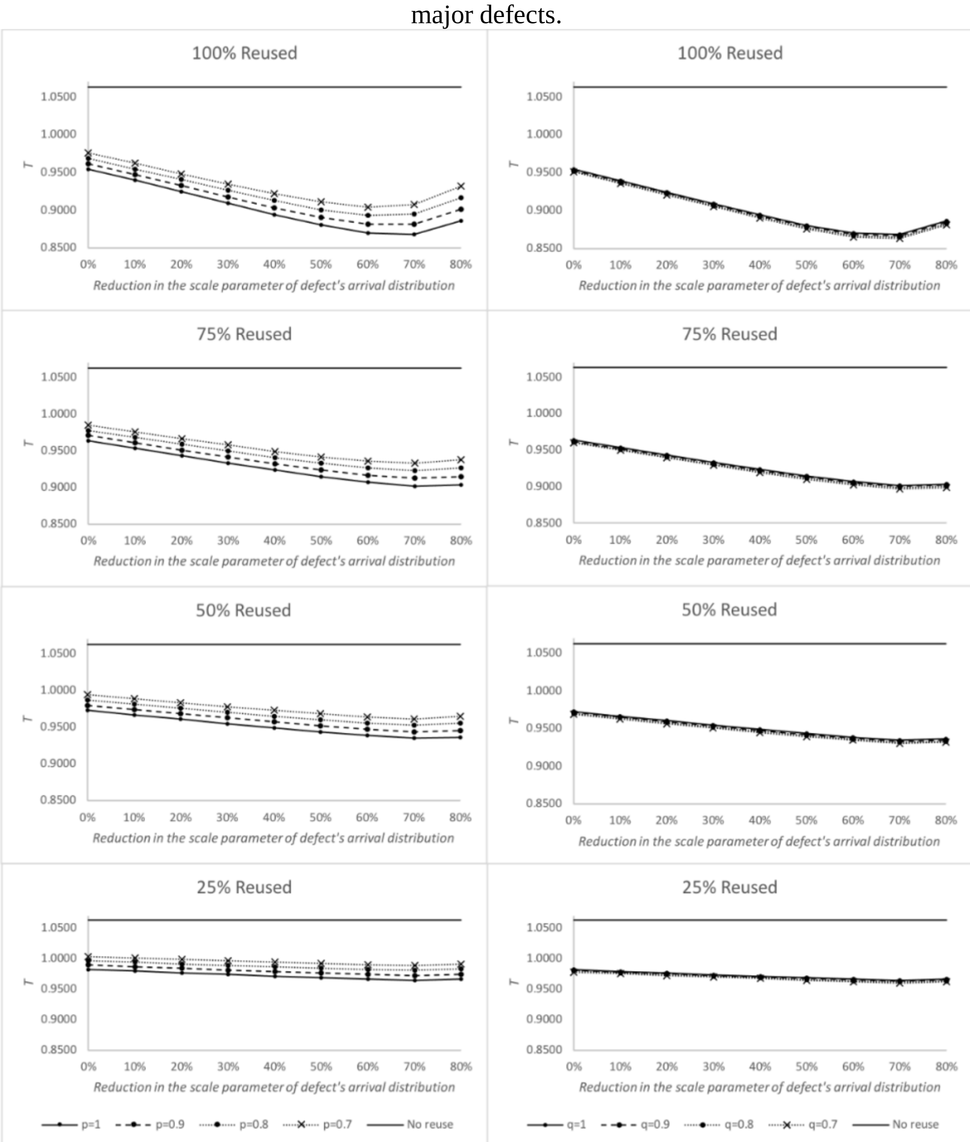


Source: The Author (2022).

In practical terms, when a company undertakes a refurbishment process that makes a reused component almost as reliable as a new one, it would make sense to use a significant percentage of reused components over time. Thus, an ideal refurbishment process can be both economically and environmentally beneficial. Nevertheless, when the company cannot provide an ideal refurbishment process, so that the reliability of the reused and new components are considerably different, the reuse action would not occur or would be sporadic. It is important to emphasise that the economic benefit can be reduced if the refurbishment cost to make the component as reliable as a new one is far different from the refurbishment cost to make the component usable but with a lower reliability. It is suggested that incorporating this analysis be addressed in future investigations.

Regarding the effects of having a misclassification of minor and major defects on the optimal time to perform inspection and on its respective cost, analyses show that misclassification problems have higher effects when they are related to minor defects. Considering the optimal time to perform inspections, T, the model suggests extending the interval between inspections when the probability p decreases. This is an expected behaviour because the model is trying to decrease the impact of the disposal cost of a reusable component. However, when the misclassification error refers to the major defect, the model indicates a very slight reduction in T, which is also an expected behaviour because the model is established to emphasise reused actions. Also, the suggestion of reducing T as q decreases is a suitable strategy to decrease the negative effects of misclassification of the major defect because when inspections are executed earlier, there is a higher chance for the system to be in the previous defective state (minor defective state). The effect of misclassification on the optimal inspection interval is shown in Figure 20.

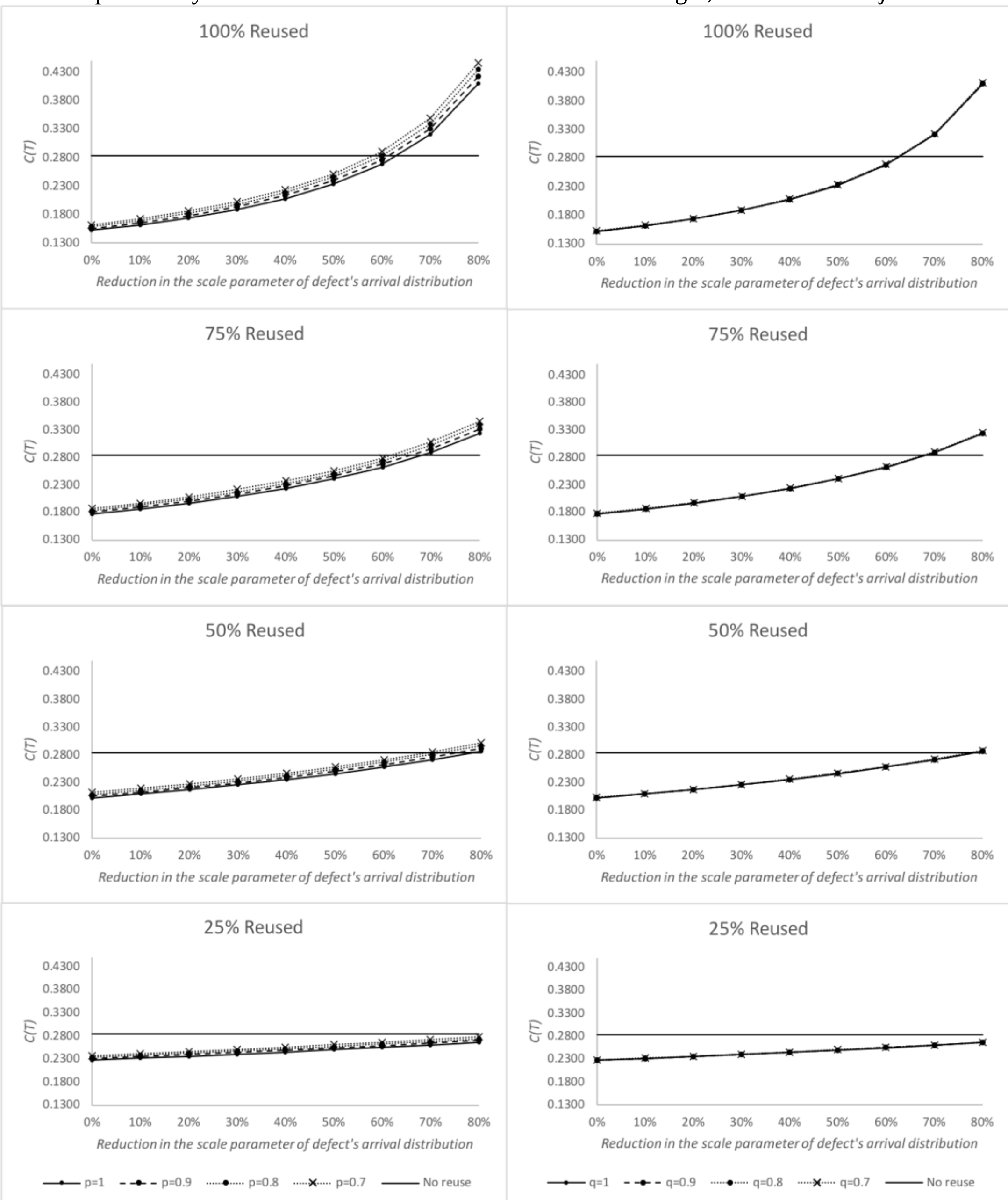
Figure 20 – Effect of misclassification on the optimal inspection interval. On the left, variation on the probability of misclassification of minor defects. On the right, the same for major defects.



Source: The Author (2022).

Regarding the optimal long-run cost per unit of time $C(T)$ (Figure 21), the highest increase in the cost rate is incurred due to the misclassification of the minor defect. Even with prior inspections recommended by the model to reduce the impact of misclassification on cost, there is an increase in the expected cost when considering low values of p. The effect of misclassification of the major defect is smaller, especially because the penalty cost for sending a non-reusable component to the stock of spare parts is considerably lower in comparison with the cost of not reusing a reusable one.

Figure 21 –Effect of misclassification on the optimal long run cost per unit time. On the left, variation on the probability of misclassification of minor defects. On the right, the same for major defects



Source: The Author (2022).

From a practical perspective, companies should focus on training actions to reduce the probability of errors in the classification of defects, prioritising the correct classification of the minor defect, the one that implies the highest cost rates when wrongly classified. It is important to mention that the training cost was not taken into consideration in the model because it is considered that the most experienced personnel in a company could teach and train the less experienced.

4.1.5 Considerations on Model 2

Model 2 was developed to be applied in single-component systems with two defective states prior to the failure. A practical example was shown in order to illustrate one possible application of the model. In the analysis, the two main characteristics considered were the heterogeneity of the components and misclassification errors. The former assumes the possibility of different reliability between reused and new components. It is interesting to investigate this because it may be one of the main difficulties faced in the process of reintroducing reused components into systems. The latter aspect is also crucial due to the characteristic of inspections being human-based in most contexts.

Taking practical insights from the numerical analysis, companies should pursue a refurbishment process that can elevate reused components to almost the same level of reliability as new components. In this way, a significant number of reused components can be introduced into the system. Alternatively, if the company is not able to provide a good refurbishment process, then reuse is not indicated extensively, only being considered occasionally. In addition, companies must emphasise training actions when adopting reuse policies so that misclassification errors can be reduced, especially when a reusable component is misclassified as non-reusable.

A limitation is the fact that the model can only be applied to single-component systems, which reduces the scope of practical application. However, in order to show applicability, Section 4.1.1 showed a detailed context in which the model can be used. Other cases that follow the same logic of the one illustrated may also take advantage of the proposed model.

Another limitation is the fact that the parameters considered in the model were ideally established based on what would be expected in terms of sojourn time in the good state and in the defective state and also in terms of a logical and appropriate cost relation.

Considering that the heterogeneity of components is one of the most important aspects to be considered in the context of reuse, the next section provides an analysis on this topic from a different perspective. In addition, another type of inspection error is studied in a two-phase delay time model.

4.2 MODEL 3

Similarly to Model 2, Model 3 assesses the feasibility of considering different percentages of reused components depending on their reliability level. However, Model 3 considers both an inspection phase and a wear-out phase and also deals with the possibility of having false-negatives at inspections.

4.2.1 Notations and assumptions

As a prelude to the introduction of Model 3, Table 11 gives its notation. This is intended to serve as a helpful reference guide to the terminology. For consistency, it is important to clarify that the terms "component" and "item" have the same meaning, as do the terms "second-hand item", "reused item" and "reused component".

Table 11 – Notation for Model 3

	Decision variables
K	Number of inspections during the inspection phase
Δ	Interval between inspections
T	Age at preventive replacement during the wear-out phase
	Decision criterion
$C(K,\Delta,T)$	Long-run cost per unit of time (cost rate)
	Model parameters
I_R	Percentage of reused items. Also, the mixing parameter in Equation (7)
x	Component age at arrival of a defect (or sojourn time in the good state)
h	Delay time from the arrival of a defect to the subsequent failure
$f_1(x)$	Probability density function of the sojourn time in the good state in reused components
$f_2(x)$	Probability density function of the sojourn time in the good state in new components
$f_x(x)$	Mixture distribution of the sojourn time in the good state, based on the $\%R_{items}$
$f_h(h)$	Probability density function of delay time
β_1	Shape parameter for Weibull distribution of the time in the good state in reused components
β_2	Shape parameter for Weibull distribution of the time in the good state in new components
β_3	Shape parameter for Weibull distribution of delay time
η_1	Scale parameter for Weibull distribution of the time in the good state in reused components
η_2	Scale parameter for Weibull distribution of the time in the good state in new components
$\%_{red}\eta_1$	% of reduction in η_1 compared to η_2
η_3	Scale parameter for Weibull distribution of delay time
α	Probability of a non-detection of an existing defect (probability of a false-negative)
C_i	Cost of inspection
C_q	Cost of acquisition of a new component
f	The percentage applied to C_p, for obtaining the cost of purchasing the reused item. $f < 1$
C_p	Replacement cost. Cost of replacement for a new or reused item
C_{pen}	Penalty cost for having a failure
C_f	Cost of failure

Source: Santos, Cavalvante (2022)

Model 3 also considers the following assumptions (SANTOS, CAVALCANTE, 2022, p. 4).

1. The component (item) can be either in a good, defective or failed state.
2. The system fails when the component (item) fails.
3. The delay time h is independent of the arrival time of the defect x.
4. An inspection takes place every $i^{th}\Delta$ unit of time up to $K\Delta$ and costs C_i monetary units.
5. There is a probability α of a non-detection of an existing defect (a false-negative).
6. C_q is the cost of purchasing the new item, which is reduced to fC_q when the reused item is purchased.
7. The replacement cost C_p is obtained from Equation (18) according to the population of reused and new items used.
8. At the critical age T, preventive replacement of component is instantaneous and the cost is C_p.
9. The lifetime of a reused item can be different from that of a new item.
10. The failure is repaired as soon as it happens and costs C_f, such that $C_f > C_p > C_i$.
11. The sojourn time in the good state, x, is distributed according to a known mixed distribution based on the level of I_R, for which the probability density function is $f_x(x)$.
12. The probability density function of delay time h, $f_h(h)$, and its distribution function represented by $F_h(h)$ are also known.

4.2.2 Development of the model

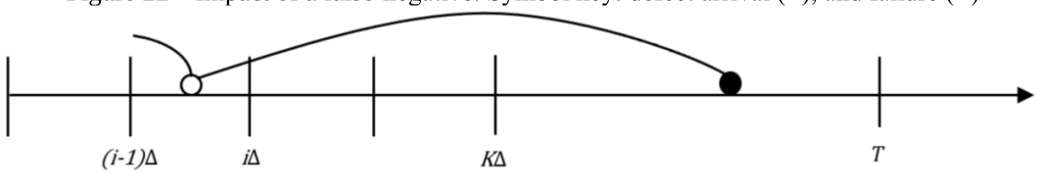
Model 3 aims to consider and investigate two important issues not yet extensively considered in the delay time models for second-hand items: heterogeneity of components and inspection error (false-negative).

The heterogeneity of components was initially investigated in Model 2, but is now analysed from a different perspective and in a different context. The idea is to propose a more general model since, in various cases, repaired components vary in lifetime distribution from new ones, as the new ones are expected to spend longer in a normal condition before their defects appear. In fact, the arrival times of defect and failure can vary depending on whether the component is reused or new. As such, in comparison with a new one, a reused component can have different density functions for the arrival time of the defect, $f_x(x)$, for the delay time, $f_h(h)$, or for both of them. Similarly to Model 2, Model 3 considers that $f_x(x)$ follows a mixture distribution that is based on the percentage of reused items, I_R. As such, I_R can be considered as the mixing parameter as previously shown in Equation (7). This Equation represents the mixture distribution function for $f_x(x)$. As stated, $f_1(x)$ represents the probability density function for the arrival of the defect in a reused item and $f_2(x)$ represents the same for a new item. The delay time density function $f_h(h)$ is considered to be the same for both new and reused components and is based on a known distribution.

As mentioned in the literature review, Scarf et al. (2009) considered mixture distribution in a maintenance model in which components come from a mixed population of strong and weak components. The idea in Model 3 is analogous, since a reused component may be weaker than a new one. This new perspective was introduced into Model 2 and considers that a new component is stronger than a reused one because it has not yet gone through degradation and refurbishment processes. In Model 3, similarly to Model 2, the new component is sourced from an external supplier while the reused component may be refurbished in-house.

A second issue is false-negatives, which recur in many practical situations and may impact maintenance policies. This impact can be considerably higher because existing defects that are not identified at an inspection may become failures. Figure 22 shows a defect that is not detected by any inspection and then turns into a failure in the wear-out phase.

Figure 22 – Impact of a false-negative. Symbol key: defect arrival (○); and failure (●)



Source: Santos, Cavalvante (2022, p. 4)

In addition, it is interesting to analyse how a false-negative impacts maintenance planning. Due to a false-negative, should the decision-maker be more cautious about maintenance planning? When undertaking maintenance planning, does the reuse of an item affect false-negative concerns? Could an alternative non-inspection policy be more suitable in the case of a high false-negative level? In Section 4.2.4.2, insights into these questions are addressed.

Analysing Model 3 can provide insights about using reused items with a different lifetime characteristic from new ones. One of the most important insights is determining when a reused item with reduced reliability can still guarantee economic and environmental benefits.

To understand how the economic and environmental dimensions are considered, it is useful to compare the cost and reliability of the reused item with the new item. The first thing to consider is that a defective or failed component can always be replaced by a new or reused one. Hence, if a reused item is priced at a fraction of a new one, it is always economically advantageous to replace them with reused items if their reliability is the same. However, the different reliability between new and reused items makes the reuse action economically effective within certain limits which can be investigated by using the model to analyse this.

Regarding the cost, the acquisition cost of a reused item is always less than the acquisition cost of a new one, C_q. The reduction factor is given by the fraction f in such a way that the cost C_p of replacing an item with a reused or new one is given by Equations (18) or (19). Similarly, the cost of failure is obtained as the sum of the replacement cost C_p and the penalty cost for having a failure and its inconveniences C_{pen}, as shown in Equation (20).

$$C_p = (I_R) f C_q + (1 - I_R) C_q \quad (18)$$

$$C_p = C_q[I_R(f - 1) + 1] \quad (19)$$

$$C_f = C_p + C_{pen} \quad (20)$$

In terms of reliability, the differences between the reused and new items are determined in terms of the scale parameter of the distribution that influences the time spent from when the component starts operating until the arrival of a defect, (η_1, for reused and η_2, for new) and the shape parameter of the distribution related to this time (β_1, for reused and β_2, for new). It is considered that a reused item necessarily has a broader dispersion related to this time ($\beta_1 < \beta_2$) and also that this time in a reused item can be the same as (for comparative analysis) or less than that of a new item ($\eta_1 \leq \eta_2$).

As such, the model tries to find a balance between the discount cost of reused items and the reduction in their reliability. The analysis of these issues determines the level of reuse that can establish both economic and environmental benefits.

Section 4.2.3 outlines the eight different cases of the model, the decision criterion, and its calculation.

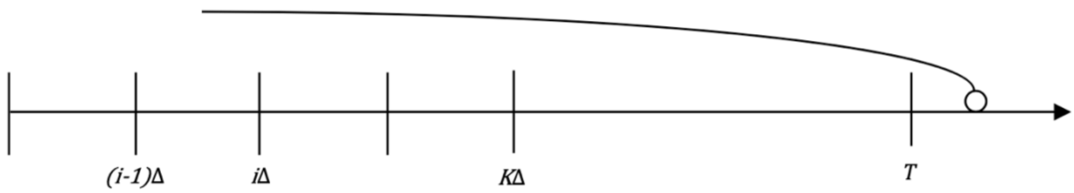
4.2.3 Calculation of the decision criterion

Similarly to Models 1 and 2, the decision criterion is the long run cost per unit of time (cost rate). However, in this current model, this cost is a function of the number of inspections during the inspection phase, K, the interval between inspections, Δ, and the age at preventive replacement during the wear-out phase, T. Three decision variables increase the decision-maker's options and make the model more general. Despite the optimization of three decision variables, it is not necessarily harder to make a decision because there is a decision criterion that summarises which alternative is the best. For each K value (integer), the algorithm searches for T and Δ values that provide the optimal cost rate.

For each n represented case, the description, the probability P_n, the expected cost per replacement cycle $U(K,\Delta,T)_n$, and the expected length of a cycle $V(K,\Delta,T)_n$ are shown as follows. Equations were developed using the same logic described in model 2. A further explanation of i and j indices is provided in case 4.

Case 1: The defect does not occur until the critical age T, when the preventive replacement is made (Figure 23).

Figure 23 – Model 3, case 1. Symbol key: defect arrival (○).



Source: Santos, Cavalvante (2022)

The probability related to case 1 is shown in Equation (21).

$$P_1 = \int_T^{\infty} f_x(x)dx = R_x(T) \tag{21}$$

The expected cost related to this case is presented in Equation (22). Both the replacement cost C_p and the cost KC_i of performing all K inspections are considered.

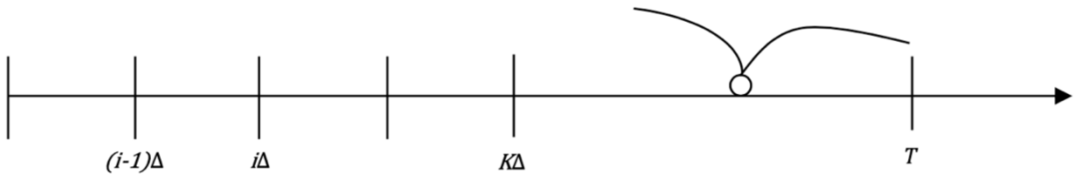
$$U(K,T)_1 = (KC_i + C_p)\int_T^{\infty} f_x(x)dx \tag{22}$$

The expected length of a cycle in which the defect does not occur until the critical age T is shown in Equation (23).

$$V(T)_1 = T\int_T^{\infty} f_x(x)dx = T\left[R_x(T)\right] \tag{23}$$

Case 2: Similarly to case 1, the cycle ends at age T. Nevertheless, the defect has already arrived in the wear-out phase (Figure 24). Note that the defect is certainly detected, and the component is replaced at age T.

Figure 24 – Model 3, case 2. Symbol key: defect arrival (○).



Source: Santos, Cavalvante (2022)

The probability of a defect arriving in the wear-out phase and the component being repaired at T is shown in Equation (24).

$$P_2 = \int_{K\Delta}^{T} f_x(x)\int_{T-x}^{\infty} f_h(h)dhdx = \int_{K\Delta}^{T} f_x(x)R_h(T-x)dx \tag{24}$$

Similarly to case 1, the cost of performing all K inspections, KC_i, is considered as well as the replacement cost C_p. The expected cost associated with case 2 is presented in Equation (25).

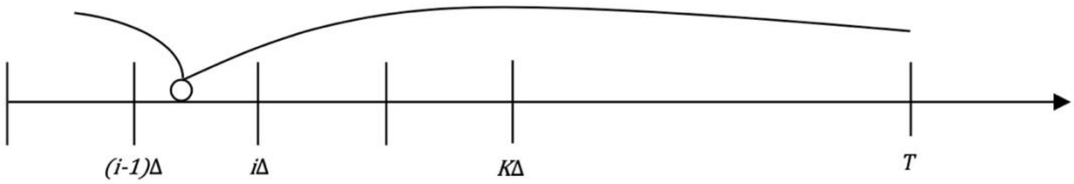
$$U(K,\Delta,T)_2 = \left[KC_i + C_p\right]\int_{K\Delta}^{T}\int_{T-x}^{\infty} f_x(x) f_h(h)dhdx \tag{25}$$

The expected length of a cycle in which the defect arrives in the wear-out phase and does not turn into failure is shown in Equation (26).

$$V(K,\Delta,T)_2 = T\int_{K\Delta}^{T} f_x(x)R_h(T-x)dx \tag{26}$$

Case 3: The defect arrives in the inspection phase, is not detected by the following inspections and does not turn into a failure until time T. Thus, the cycle ends at time T but the component passes a substantial time in the defective state (Figure 25).

Figure 25 – Model 3, case 3. Symbol key: defect arrival (○).



Source: Santos, Cavalvante (2022)

The probability related to this case is presented in Equations (27) and (28).

$$P_3 = \sum_{i=1}^{K} \alpha^{K-i+1} \int_{(i-1)\Delta}^{i\Delta} f_x(x) \int_{T-x}^{\infty} f_h(h) dh dx \quad (27)$$

$$P_3 = \sum_{i=1}^{K} \alpha^{K-i+1} \int_{(i-1)\Delta}^{i\Delta} f_x(x) R_h(T-x) dx \quad (28)$$

The expected cost related to this case (Equation (29)) considers the cost of all K inspections performed, KC_i, and the replacement cost C_p.

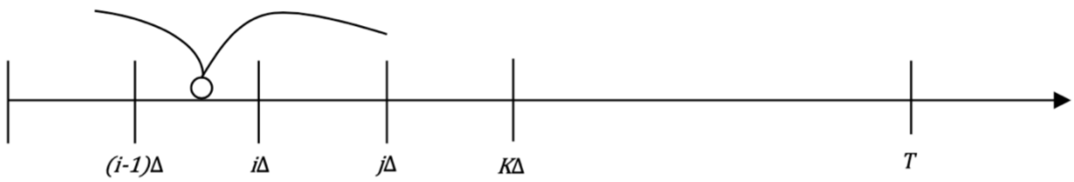
$$U(K,\Delta,T)_3 = \sum_{i=1}^{K} \left[KC_i + C_p \right] \alpha^{K-i+1} \int_{(i-1)\Delta}^{i\Delta} \int_{T-x}^{\infty} f_x(x) f_h(h) dh dx \quad (29)$$

The expected length of a cycle in which the defect arrives in the inspection phase and does not turn into failure until the preventive replacement at age T is shown in Equation (30).

$$V(K,\Delta,T)_3 = T \sum_{i=1}^{K} \alpha^{K-i+1} \int_{(i-1)\Delta}^{i\Delta} f_x(x) R_h(T-x) dx \quad (30)$$

Case 4: The defect arrives and is detected in the inspection phase (Figure 26). $i\Delta$ signifies the interval in which the defect arrives and $j\Delta$ represents the interval of its detection or the inspection of its detection. The defect can be detected at the first inspection after it occurs, in which $i\Delta$ is equal to $j\Delta$ or at any other inspection $j\Delta$, due to the possibility of false negative α. As such, the defect can be identified at the inspection right after its occurrence or at another inspection.

Figure 26 – Model 3, case 4. Symbol key: defect arrival (○).



Source: Santos, Cavalvante (2022)

The probability related to this case is presented in Equations (31) and (32). Notice that, $j-i$ indicates the number of false negatives, until the defect is detected. When $i = j$ there is no false negative, then α^0.

$$P_4 = \sum_{i=1}^{K}\sum_{j=i}^{K}\alpha^{j-i}(1-\alpha)\int_{(i-1)\Delta}^{i\Delta} f_x(x)\int_{j\Delta-x}^{\infty} f_h(h)dhdx \tag{31}$$

$$P_4 = \sum_{i=1}^{K}\sum_{j=i}^{K}\alpha^{j-i}(1-\alpha)\int_{(i-1)\Delta}^{i\Delta} f_x(x)R_h(j\Delta-x)dx \tag{32}$$

The expected cost associated with this case (Equation (33)) takes into account the cost of all inspections performed jC_i and the replacement cost C_p.

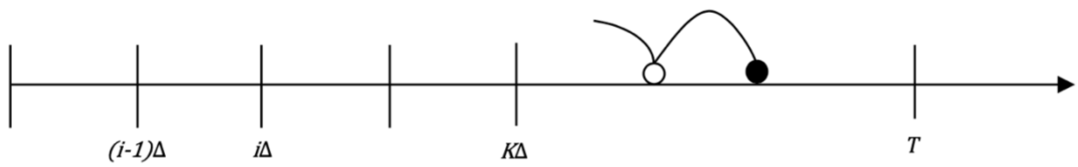
$$U(K,\Delta)_4 = \sum_{i=1}^{K}\sum_{j=i}^{K}\left[jC_i + C_p\right]\alpha^{j-i}(1-\alpha)\int_{(i-1)\Delta}^{i\Delta}\int_{j\Delta-x}^{\infty} f_x(x)f_h(h)dhdx \tag{33}$$

The expected length of a cycle in which the defect arrives in the inspection phase and is detected in inspection $j\Delta$ is shown in Equation (34).

$$V(K,\Delta)_4 = \sum_{i=1}^{K}\sum_{j=i}^{K}\alpha^{j-i}(1-\alpha)\int_{(i-1)\Delta}^{i\Delta}\int_{j\Delta-x}^{\infty}(j\Delta)\, f_x(x)\, f_h(h)dhdx \quad (34)$$

Case 5: differently from case 2, the defect arrives in the wear-out phase and turns into a failure before the critical age T (Figure 27).

Figure 27 – Model 3, case 5. Symbol key: defect arrival (○); and failure (●).



Source: Santos, Cavalvante (2022)

The probability associated with this case is shown in Equation (35).

$$P_5 = \int_{K\Delta}^{T} f_x(x)\int_{0}^{T-x} f_h(h)dhdx = \int_{K\Delta}^{T} f_x(x)F_h(T-x)dx \quad (35)$$

The expected cost related to this case (Equation (36)) considers the cost of all K inspections performed KC_i and the failure cost C_f.

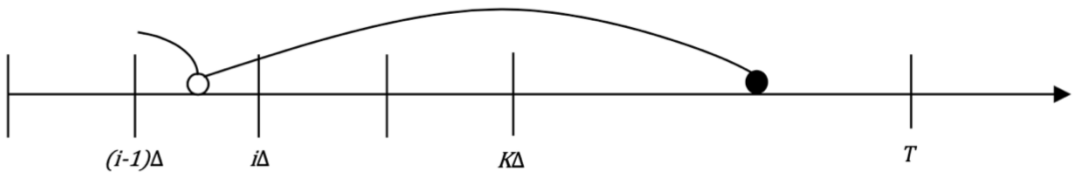
$$U(K,\Delta,T)_5 = (KC_i + C_f)\int_{K\Delta}^{T} f_x(x)F_h(T-x)dx \quad (36)$$

The expected length of a cycle in which the defect arrives in the wear-out phase and turns into a failure at age $(x+h)$ is shown in Equation (37).

$$V(K,\Delta,T)_5 = \int_{K\Delta}^{T}\int_{0}^{T-x}(x+h)\, f_x(x)\, f_h(h)dhdx \quad (37)$$

Case 6: differently from case 3, the defect arrives in the inspection phase and turns into a failure in the wear-out phase before the critical age T (Figure 28).

Figure 28 – Model 3, case 6. Symbol key: defect arrival (○); and failure (●).



Source: Santos, Cavalvante (2022)

The probability related to this case is shown in Equation (38).

$$P_6 = \sum_{i=1}^{K} \alpha^{K-i+1} \int_{(i-1)\Delta}^{i\Delta} f_x(x) \int_{K\Delta - x}^{T-x} f_h(h) dhdx \tag{38}$$

The expected cost related to this case (Equation (39)) considers the cost of all K inspections performed, KC_i, and the failure cost C_f.

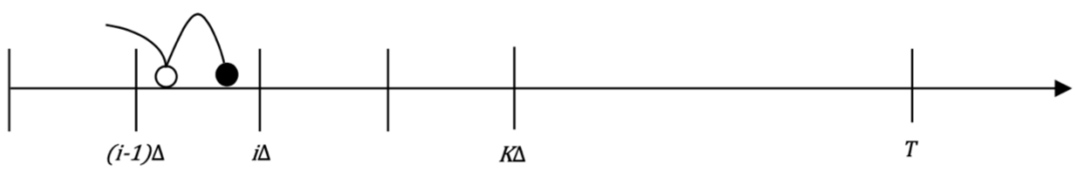
$$U(K,\Delta,T)_6 = \sum_{i=1}^{K} (KC_i + C_f) \alpha^{K-i+1} \int_{(i-1)\Delta}^{i\Delta} f_x(x) \int_{K\Delta - x}^{T-x} f_h(h) dhdx \tag{39}$$

The expected length of a cycle in which the defect arrives in the inspection phase and turns into a failure at age $(x + h)$ is shown in Equation (40).

$$V(K,\Delta,T)_6 = \sum_{i=1}^{K} \alpha^{K-i+1} \int_{(i-1)\Delta}^{i\Delta} \int_{K\Delta - x}^{T-x} (x+h) f_x(x) f_h(h) dhdx \tag{40}$$

Case 7: differently from case 3, the defect arrives in the inspection phase and turns into a failure in the same interval (Figure 29).

Figure 29 – Model 3, case 7. Symbol key: defect arrival (○); and failure (●).



Source: Santos, Cavalvante (2022)

The probability related to this case is shown in Equation (41).

$$P_7 = \sum_{i=1}^{K} \int_{(i-1)\Delta}^{i\Delta} f_x(x) \int_{0}^{i\Delta - x} f_h(h) dh dx = \sum_{i=1}^{K} \int_{(i-1)\Delta}^{i\Delta} f_x(x) F_h(i\Delta - x) dx \quad (41)$$

The expected cost associated with this case (Equation (42)) takes into account the cost of all $(i-1)$ inspections performed, $(i-1)C_i$, and the failure cost C_f.

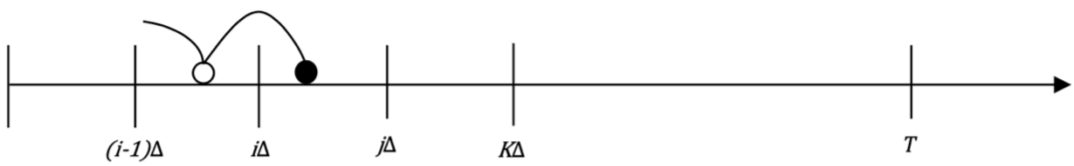
$$U(K,\Delta)_7 = \sum_{i=1}^{K} \left[(i-1)C_i + C_f \right] \int_{(i-1)\Delta}^{i\Delta} f_x(x) F_h(i\Delta - x) dx \quad (42)$$

The expected length of a cycle in which the defect arrives in the inspection phase and turns into a failure in the same interval at age $(x+h)$ is shown in Equation (43).

$$V(K,\Delta)_7 = \sum_{i=1}^{K} \int_{(i-1)\Delta}^{i\Delta} \int_{0}^{i\Delta - x} (x+h) f_x(x) f_h(h) dh dx \quad (43)$$

Case 8: differently from case 7, the defect arrives in the inspection phase and turns into a failure in another subsequent interval (Figure 30).

Figure 30 – Model 3, case 8. Symbol key: defect arrival (○); and failure (●).



Source: Santos, Cavalvante (2022)

The probability related to this case is shown in Equation (44).

$$P_8 = \sum_{i=1}^{K-1} \sum_{j=i+1}^{K} \alpha^{j-i} \int_{(i-1)\Delta}^{i\Delta} f_x(x) \int_{(j-1)\Delta - x}^{j\Delta - x} f_h(h) dh dx \quad (44)$$

The expected cost related to this case (Equation (45)) takes into account the cost of all $(j-1)$ inspections performed, $(j-1)C_i$, and the failure cost C_f.

$$U(K,\Delta)_8 = \sum_{i=1}^{K-1}\sum_{j=i+1}^{K}\left[(j-1)C_i + C_f\right]\alpha^{j-i}\int_{(i-1)\Delta}^{i\Delta} f_x(x)\int_{(j-1)\Delta-x}^{j\Delta-x} f_h(h)dhdx \tag{45}$$

The expected length of a cycle in which the defect arrives in the inspection phase and turns into a failure in another subsequent interval at age $(x+h)$ is shown in Equation (46).

$$V(K,\Delta)_8 = \sum_{i=1}^{K-1}\sum_{j=i+1}^{K}\alpha^{j-i}\int_{(i-1)\Delta}^{i\Delta}\int_{(j-1)\Delta-x}^{j\Delta-x}(x+h)f_x(x)f_h(h)dhdx \tag{46}$$

Finally, the cases mentioned represent the complete set of possible cases to be analysed, since $\sum_{n=1}^{8} P_n = 1$ is true. Equation (47) shows the long-run cost per unit of time $C(K,\Delta,T)$ and section 4.2.4 presents the numerical example.

$$C(K,\Delta,T) = \frac{\sum_{n=1}^{8} U(K,\Delta,T)_n}{\sum_{n=1}^{8} V(K,\Delta,T)_n} \tag{47}$$

4.2.4 Numerical example

This section illustrates the application of Model 3 in a single-component system that can be in three different states, normal, defective or failed. Defective and failed components are replaced with other ones that can be new or reused. There can be a difference in lifetime behaviour between the latter and the former, characterised by a distinct density distribution for the arrival time of the defect, $f_x(x)$. Choosing the percentage of new or reused components in the long run is based on the expected cost that results from having a mixture of them. If they have the same reliability, it is always better to reuse due to the discount in the repair cost. However, if the defective item is not quite as reliable as the new one, the repair discount may not be enough to guarantee cost-effective reuse. Therefore, the purpose of this analysis is to determine how much the reliability of a reused component may differ from that of a new one so that a determined percentage of reused components may be used in replacement practice.

The analysis was performed assuming that the decision variables would be maintained at their optimum values K, Δ, T, found by minimising the long-run cost per unit of time, $C(K, \Delta, T)$, based on the mathematical developments presented in Sections 4.2.2 and 4.2.3. In other words, the optimal combination of variables is provided for different percentages of reuse and different levels of reduction in the reliability of a reused component, comparing the expected cost in the long-run with the one obtained by the traditional approach (non-reuse). The analyses were performed to verify the effects of heterogeneity of components (Section 4.2.4.1) and false-negatives (Section 4.2.4.2) in the definition of the policy and on the long-run cost per unit of time. The parameters presented in Table 12 are mainly based on the K, Δ, T model proposed by Scarf et al. (2009), but some changes were required to adjust to the perspective of using second-hand items.

Table 12 – Parameters considered in Model 3

Weibull distributions						Costs				Error-related
Arrival of the defect – $f_x(x)$				Delay time $f_h(h)$		C_i	C_q	C_{pen}	f	α
Reused $f_1(x)$		New $f_2(x)$				0.025	1	9	0.2	0
β_1	η_1	β_2	η_2	β_3	η_3					
2.5	Varied	5	18	1	0.5					

Source: Santos, Cavalvante (2022)

As the time in the defective state is considered to be similar in both new and reused components. The length of time spent in the good state is the one that essentially differentiates a new and a reused component. For this reason, the differentiation between new and reused components is evaluated in terms of the sojourn time in the good state (or in terms of the time to the arrival of a defect) which are modelled according to Weibull distributions.

Regarding the Weibull distributions for the arrival of a defect, the value of $\beta_1 = 2.5$ was considered to increase the dispersion in the reused component in comparison to the new component. It is crucial to consider this because the refurbishment process that makes the defective component available again is not as ideal as the process that produces a brand new component. As a consequence, a smaller β value represents a greater variation in the arrival of defects. It is based on the belief that reused items have a lower level of reliability than new ones. As such, the defect in reused components can arrive over a more varied period of time when compared to the defect in new components. Also, η_1 should be more similar to η_2

otherwise it does not make sense to introduce a reused component with a totally different time to that of the arrival of the defect. As such, the scale parameter of the Weibull distributions η_1 and η_2 were evaluated varying η_1 as a percentage of η_2 to consider that a defect in reused components can emerge not only more dispersed around its expected value but it can also arrive earlier. These parameters are the ones that counterbalance the reduction applied to the repair cost of using a reused component.

Regarding the costs, it is important to reduce the inspection cost, so that the inspections can have a higher influence on the hybrid policy. Another adjustment is the way the failure cost is formed, considering the sum of C_p and C_{pen}. In practice, there is no modification in this parameter when compared to the one presented in Scarf et al. (2009). Moreover, the new parameters are the percentage q that establishes a discount for the reused item as compared to a new one, and the probability of a false-negative, α.

Finally, it is possible to verify the consistency of the model by setting the new mixing parameter (I_R) to 10%, $\eta_1 = 3$, $C_i = 0.05$, as in the base case of Scarf et al. (2009), not considering false-negatives and not considering a reduction in the cost due to reuse. This was the second validation of the model. The first one was established by verifying that the sum of the probability of all possible cases is equal to one.

The effects of heterogeneity of components and different reliability levels between reused and new components are presented as follows.

4.2.4.1 Effects of heterogeneity of components and different reliability levels

The heterogeneity of components makes the model more realistic because reused components can have a different reliability from new ones. The analysis of this important topic is based on the consideration described in Section 4.2.2 that the time of the arrival of the defect may be shorter in a reused component than in a new one. This difference is considered in the mixture distribution represented in Equation (7). In this Equation, $f_1(x)$ and $f_2(x)$ are Weibull distributions with the parameters described in Table 12.

As previously mentioned, the acquisition cost of a reused component is less than the acquisition cost of a new one. In the analysis, it was considered that it costs 20% of the cost of a new component. Therefore, the higher the level of I_R, the higher the proportion of replacements with a discount on repair costs, according to Equation 18. Based on this perspective, it is always better to reuse components when their reliability is equal to that of new ones. This analysis, however, puts two contrasting facts into perspective. When the difference in reliability increases, the cost reduction of using a reused item may not be sufficient to justify this action. This is an expected behaviour that is confirmed by the analysis of the model in Table 13. The behaviour of two particular cases is also presented, the pure inspection policy ($T = \infty$) and the pure preventive replacement policy ($K = 0$).

Table 13 – Effect of heterogeneity of components

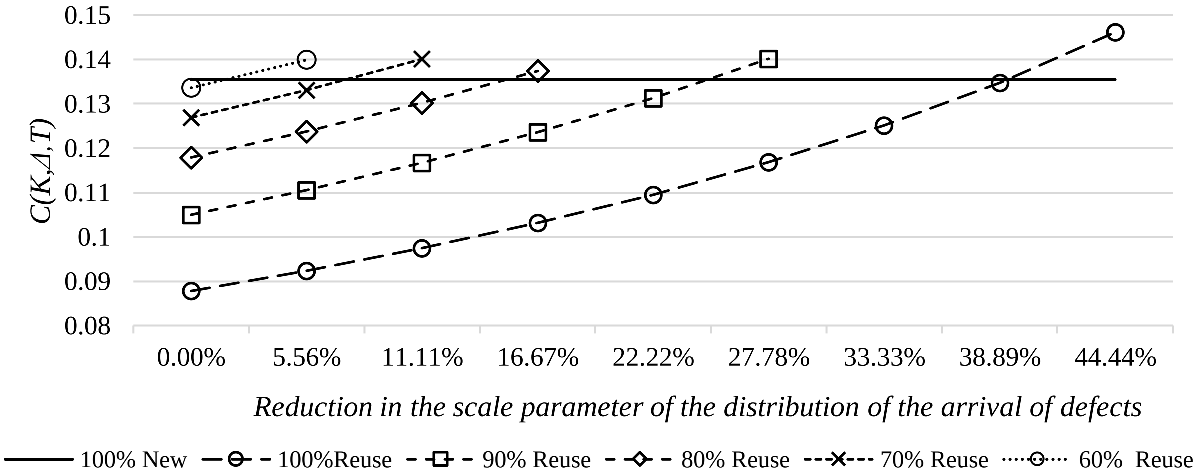
				K, Δ, T				$T = \infty$		$K = 0$	
	Case	η_1	$\%_{red}\eta_1$	K	Δ	T	$C(K, \Delta, T)$	Δ	$C(\Delta)$	T	$C(T)$
Non-reuse	0	18	0	0	-	9.15	0.14	0.27	0.28	9.15	0.14
100% Reused	1	18	0	0	-	3.54	0.09	0.31	0.24	3.54	0.09
	2	17	5.56	0	-	3.36	0.09	0.29	0.24	3.36	0.09
	3	16	11.11	0	-	3.18	0.10	0.28	0.25	3.18	0.10
	4	15	16.67	0	-	2.99	0.10	0.26	0.26	2.99	0.10
	5	14	22.22	0	-	2.81	0.11	0.25	0.27	2.81	0.11
	6	13	27.78	0	-	2.62	0.12	0.24	0.28	2.62	0.12
	7	12	33.33	0	-	2.44	0.13	0.22	0.30	2.44	0.13
	8	11	38.89	0	-	2.26	0.14	0.21	0.31	2.26	0.14
	9	10	44.44	0	-	2.07	0.15	0.19	0.32	2.07	0.15
90% reused	10	18	0	0	-	4.18	0.11	0.31	0.24	4.18	0.11
	11	17	5.56	0	-	3.96	0.11	0.29	0.25	3.96	0.11
	12	16	11.11	0	-	3.75	0.12	0.28	0.26	3.75	0.12
	13	15	16.67	0	-	3.53	0.12	0.26	0.26	3.53	0.12
	14	14	22.22	2	1.59	3.81	0.13	0.25	0.27	3.31	0.13
	15	13	27.78	2	1.48	3.55	0.14	0.24	0.28	3.09	0.14
80% reused	16	18	0	2	2.26	5.31	0.12	0.30	0.25	4.80	0.12
	17	17	5.56	2	2.15	5.05	0.12	0.29	0.25	4.55	0.12
	18	16	11.11	2	2.03	4.79	0.13	0.28	0.26	4.30	0.13
	19	15	16.67	2	1.91	4.53	0.14	0.26	0.27	4.05	0.14
70% reused	20	18	0	2	2.53	5.90	0.13	0.30	0.25	5.41	0.13
	21	17	5.56	2	2.41	5.63	0.13	0.28	0.26	5.15	0.14
	22	16	11.11	2	2.28	4.35	0.14	0.27	0.26	4.88	0.14
60% reused	23	18	0	2	2.82	6.51	0.13	0.29	0.26	6.04	0.14
	24	17	5.56	2	2.69	6.23	0.14	0.28	0.26	5.77	0.14

Source: Source: Santos, Cavalvante (2022, p. 8)

The following behaviour is observed from the analysis of Model 3 and its special cases. The higher the percentage of reuse, the higher the discount cost and the greater the possibility for considering a reused component even if it has a larger reduction in reliability when compared to a new one. In this particular set of parameters analysed, 100% of reused items can be considered if a reduction in the scale parameter of the distribution of the arrival of a defect is approximately up to 40%. The same analysis can be observed in 90%, 80%, 70% and 60%

of reuse if the reduction in the same parameter is approximately up to 22%, 11%, 5% and 0%, respectively. Figure 31 illustrates this behaviour by showing the expected cost of using a determined percentage of reused components according to a reduction in the scale parameter for the distribution of the arrival of defects.

Figure 31 – The expected cost of using a determined percentage of reused items according to the reduction in the scale parameter of the distribution of the arrival of defects.



Source: Santos, Cavalvante (2022, p. 9)

In Figure 31, there is a higher possibility of having distinctive characteristic lives between reused and new components when there is enough possibility for reducing the replacement cost. As such, if the company uses a considerable number of reused components, the reuse policy may be more cost-effective because the discount in the replacement cost counterbalances the fact of the time to arrival of a defect in reused items being less and its dispersion being higher. In the opposite case, the lesser quantity of reused components used in the long-run does not lead to a considerable decrease in the replacement cost. As a result, reused components are never suggested, no matter the level of reduction in the time to the arrival of defects.

Table 14 shows the results for small percentages of reused components, from 50% to 5%. One interesting point to observe is that even if the reused item has the same scale parameters for the arrival of the defect, the higher dispersion associated with this time means that the model does not provide a better expected maintenance cost. This behaviour occurs because the lower discount in the replacement cost does not justify the increase in the dispersion related to the time to arrival of the defect.

Table 14 – Effect of heterogeneity of components for the small percentages of reused components

				K, Δ, T				$T = \infty$		$K = 0$	
	$Case$	η_1	$\%_{red}\eta_1$	K	Δ	T	$C(K, \Delta, T)$	Δ	$C(\Delta)$	T	$C(T)$
Non-reuse	0	18	100	0	-	9.147	0.136	0.265	0.275	9.147	0.136
50% Reused	25	18	0	2	3.107	7.113	0.138	0.290	0.259	6.671	0.140
	26	17	5.56	2	2.980	6.851	0.144	0.280	0.262	6.408	0.147
40% reused	27	18	0	2	3.394	7.700	0.141	0.284	0.262	7.282	0.142
	28	17	5.56	2	3.282	7.476	0.146	0.276	0.265	7.056	0.149
30% reused	29	18	0	2	3.669	8.244	0.141	0.279	0.266	7.848	0.143
	30	17	5.56	2	3.582	8.075	0.146	0.273	0.268	7.678	0.148
20% reused	31	18	0	2	3.924	8.728	0.141	0.273	0.269	8.351	0.141
	32	17	5.56	2	3.861	8.619	0.144	0.270	0.270	8.243	0.145
10% reused	33	18	0	0	-	8.783	0.139	0.269	0.272	8.783	0.139
	34	17	5.56	2	4.124	9.098	0.141	0.267	0.273	8.734	0.141
5% reused	35	18	0	0	-	8.973	0.137	0.267	0.274	8.973	0.137
	36	17	5.56	2	4.242	9.308	0.139	0.266	0.274	8.950	0.138

Source: Santos, Cavalvante (2022, p. 9)

Table 15 is a good illustration of the consequence of dispersion on the time to arrival of the defect in reused components. This effect was not noticed in early results (Table 13), because the discount in the cost up to 60% of reused items counterbalances the effect of both a reduced time to arrival of the defect and increased dispersion associated with this time. From 50% of reused items to smaller values, the discount in the replacement cost does not counterbalance this effect. Actually, it does not counterbalance even the effect of having a broader dispersion around the time to the arrival of the defect. This increase in dispersion (by reducing β_1 value when compared to the β_2 value) must be considered because it characterises a practical perspective that the reused item may not have been refurbished in a way to assure the exact reliability behaviour, here, modelled by the arrival of the defect and delay time. Table 15 illustrates a straightforward analysis of dispersion considering the special case of a pure preventive replacement policy ($K = 0$). In the case with no change in dispersion, a decrease in the cost is achieved due to the discount achieved by reusing an item. However, in the case of changing the dispersion, an increment to the cost is verified because the discount in the repair cost is not enough to counterbalance the variation in the dispersion.

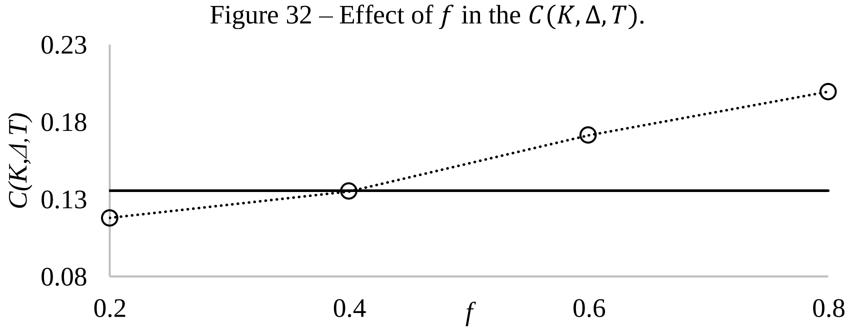
Table 15 – Effect of dispersion on the time to arrival of a defect of the reused component

	Different dispersion		Similar dispersion	
	$\beta_1 = 2.5$ and $\eta_1 = 18$		$\beta_1 = 5$ and $\eta_1 = 18$	
	T	$C(T)$	T	$C(T)$
Non-reuse	9.147	0.136	9.147	0.136
50% Reused	6.671	0.140	8.288	0.090
40% reused	7.282	0.142	8.481	0.099
30% reused	7.848	0.143	8.675	0.109
20% reused	8.351	0.141	8.844	0.118
10% reused	8.783	0.139	9.001	0.127
5% reused	8.973	0.137	9.075	0.131

Source: Santos, Cavalvante (2022, p. 9)

Clearly, the parameters that characterise the lifetime distribution of the reused component in comparison to the new one are crucial for determining the percentage of reused and new components with a delay time reuse policy. In the analysis of Model 3, the scale and shape parameters of the distribution of the arrival of defects were considered. They describe the time at which defects arrive and the dispersion of their arrival. In addition, they are the parameters that are susceptible to the greatest changes in practical applications because the expected time in the good state is generally longer than the time in the defective state. Apart from the analysis of the influence of these important parameters, the parameter f, which determines the discount on the cost of using reused items, is also decisive in determining the reuse percentage. The influence of different f values can be clearly seen in Figure 32, which illustrates the long-run cost per unit of time, $C(K, \Delta, T)$, considering 80% of reuse and ($\beta_1 = 2.5$ and $\eta_1 = 18$). In this particular case, the effect of a small discount on C_q ($f = 0.6$ and $f = 0.8$) increases $C(K, \Delta, T)$ up to a level that results in reuse being no longer suggested.

Figure 32 – Effect of f in the $C(K, \Delta, T)$.



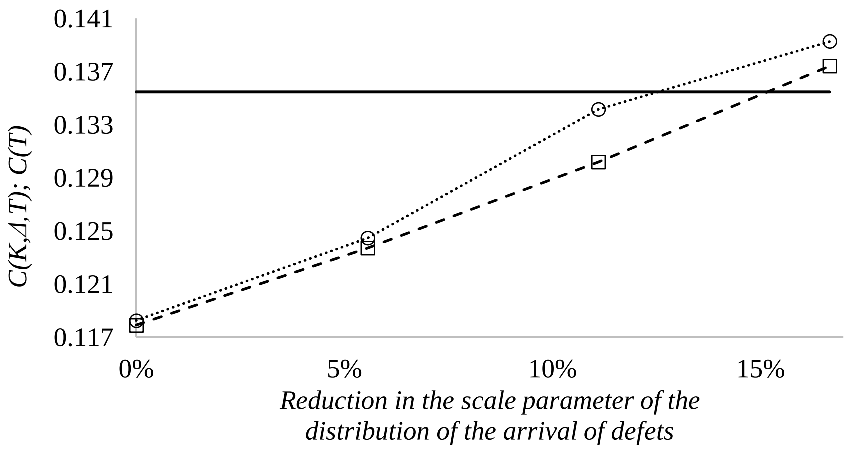
Source: Santos, Cavalvante (2022, p. 9)
Note: The continuous horizontal line represents the optimal cost of only using new components. The dashed line represents the proposed two-phase policy.

To sum up the discussions about the effects of heterogeneity of components and different reliability levels of reused components, the decision to use a reused component has most to recommend it when the purchase cost of the reused component is significantly less than the acquisition cost of the new one. Even though reusing a component can result in substantial cost savings, it only generates economic benefits when the reuse rate is high. Furthermore, the model also shows that the lifetime characteristic of the reused component can differ from that of a new one up to certain levels of time and dispersion. The more the reduction in the reliability of the reused component is, the higher must be the discount on the repair cost by using it. These characteristics were already expected. However, the model confirms them in a mathematical way and shows which factors are most likely to influence the decision to reuse components in a given industry.

In practical terms, the refurbishment process should be able to approximate the reliability of a reused component to the reliability of a new one. This consideration is essential because it allows a reuse policy to bring not only environmental benefits for society but also economic recompense for the industry.

Lastly, comparing Model 3 and its special cases, the pure inspection ($T = \infty$) and no inspection (pure preventive replacement, $K = 0$), the proposed model obtains equal or better cost relations. Figure 33 shows a comparison between the two best cost-effective policies for the set of parameters analysed, (K, Δ, T) and $(K = 0)$.

Figure 33 – Comparison of policies for 80% of reused components.



Source: Santos, Cavalcante (2022, p. 10)
Note: The continuous horizontal line represents the optimal cost of only using new components. The dashed line represents the two-phase proposed policy. The dotted line represents the pure preventive particular case. The pure inspection case is not in the graph because it has the worst performance, which is very distinct from these ones.

The behaviour of the system for the parameters considered does not encourage inspection actions. Consequently, the pure inspection policy ($T\ and\ K = \infty$) obtained the worst results in terms of cost. Depending on the system analysed, this fact can be recurrent in many practical applications. However, it is important to consider the possibility of inspections because they are widely used in practical contexts. Furthermore, a more general model should be developed so that decision-makers can choose among different policy options, for instance, when both (K, Δ, T) and ($K = 0$) return similar benefits in terms of cost.

All the analyses reveal two important facts when considering the effects of heterogeneity of components and the different reliability levels of reused components. These can be summarised as follows:

(i) The use of second-hand components should not be incremental. As soon as the decision has been made to reuse a component, reuse action must be undertaken at a considerably higher level than non-reuse action.

(ii) When compared to new components, reused components must not only be more cost-effective, but must also provide similar levels of reliability.

The following section examines the effects of false-negatives on the proposed model and on its special case of pure inspection. Though false-negatives in the proposed model may only have minor effects, it is important to examine the impact of these recurrent events in practice.

4.2.4.2 Effects of false-negatives

This section investigates the effects of false-negatives on Model 3 and on its particular case of pure inspection. In general, inspections may be viewed as imperfect because it is common for existing defects to go unnoticed in some practical contexts. Table 16 shows the behaviour of the model when subjected to different levels of false-negative, α.

Table 16 – Effect of false-negative in K, Δ, T and pure inspection policies

				K, Δ, T				$T = \infty$	
		η_1	$\%_{red}\eta_1$	K	Δ	T	$C(K, \Delta, T)$	Δ	$C(\Delta)$
$\alpha = 0$	Non-reuse	18	0	0	-	9.147	0.136	0.265	0.275
	80% reused	18	0	2	2.263	5.310	0.118	0.3012	0.247
		17	5.56	2	2.146	5.053	0.124	0.288	0.253
		16	11.11	2	2.028	4.792	0.130	0.276	0.259
		15	16.67	2	1.909	4.529	0.137	0.264	0.266
$\alpha = 0.05$	Non-reuse	18	0	0	-	9.147	0.136	0.261	0.284
	80% reused	18	0	0	-	4.797	0.118	0.299	0.257
		17	5.56	0	-	4.551	0.125	0.285	0.263
		16	11.11	0	-	4.303	0.134	0.273	0.269
		15	16.67	0	-	4.052	0.139	0.261	0.276
$\alpha = 0.1$	Non-reuse	18	0	0	-	9.147	0.136	0.258	0.294
	80% reused	18	0	0	-	4.797	0.118	0.297	0.267
		17	5.56	0	-	4.551	0.125	0.283	0.273
		16	11.11	0	-	4.303	0.134	0.270	0.280
		15	16.67	0	-	4.052	0.139	0.258	0.287

Source: Santos, Cavalcante (2022, p. 11)

The consequence of having a false-negative, in the specific case analysed, modifies the recommended policy from a policy with inspections at each Δ period of time and preventive replacement at time T to a pure preventive policy at time T. The behaviour is expected, since both policies establish similar cost relations, with a better cost achieved by the hybrid policy in the absence of false-negatives (Figure 33). Thus, for this particular case, the incremental cost of having false-negatives exceeds the cost of not having inspections. Consequently, the pure preventive policy is recommended even for small false-negative values.

As shown in the two last columns of Table 16, the effect of increment on cost value is evident in the analysis of false-negatives on pure inspection policies. In each specific case of non-reuse and reuse, there is a decrease in time Δ and an increase in the cost $C(\Delta)$, when the false-negative α increases. Table 17 presents these variations in percentage terms. Note that the percentage of variation in both Δ and $C(\Delta)$ for non-reusing cases and reusing cases with distinct η values are similar in extent.

Table 17 – Effect of false-negative on a pure inspection policy (percentual variation in Δ and $C(\Delta)$)

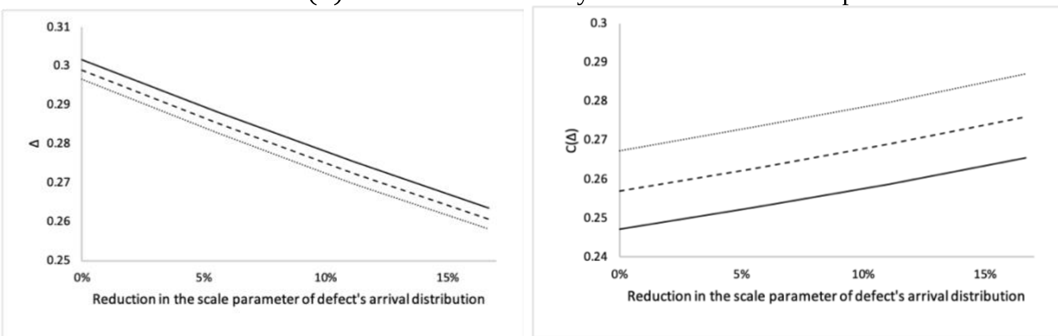
				$T = \infty$			
		η_1	$\%_{red}\eta_1$	Δ	%Reduction in Δ	$C(\Delta)$	%Increase in $C(\Delta)$
$\alpha = 0$	Non-reuse	18	0	0.265	-	0.275	-
	80% reused	18	0	0.302	-	0.247	-
		17	5.56	0.288	-	0.253	-
		16	11.11	0.276	-	0.259	-
		15	16.67	0.264	-	0.266	-
$\alpha = 0.05$	Non-reuse	18	0	0.261	1.28%	0.284	3.20%
	80% reused	18	0	0.299	0.86%	0.257	3.96%
		17	5.56	0.285	1.01%	0.263	3.96%
		16	11.11	0.273	1.09%	0.269	3.98%
		15	16.67	0.261	1.10%	0.276	3.95%
$\alpha = 0.1$	Non-reuse	18	0	0.258	2.38%	0.294	6.57%
	80% reused	18	0	0.297	1.62%	0.267	8.17%
		17	5.56	0.283	1.87%	0.273	8.15%
		16	11.11	0.270	2.07%	0.280	8.15%
		15	16.67	0.258	2.05%	0.287	8.14%

Source: Santos, Cavalcante (2022, p. 11)

Table 17 provides the most interesting insight into the false-negative analysis in the reusing policy considered by Model 3. False-negative effects are not greater for reused components than for new ones. In practical terms, there is no concern about using reused components due to false-negatives because the fact that a reused component may be less reliable does not mean that it may be more challenging to find current defects. Therefore, the same inspection personnel who inspect a traditional non-reuse policy may also be able to inspect a reuse policy.

Finally, Figure 34 depicts the behaviour of Δ and $C(\Delta)$ from Table 17, in a context of only reused components and considering cases in which they have distinct reliability. Observe that the decrease in the inspection interval Δ and the increase in the total expected cost in the long-run $C(\Delta)$ follow a similar behaviour for all α values. In addition, the higher the α value is, the greater the decrease in the inspection interval and the greater the increase in the cost, for all levels of reliability analysed.

Figure 34 – (a) Behaviour of Δ for different dependability values of a reused component.(b) Behaviour of $C(\Delta)$ for different reliability values of a reused component.



(a) (b)

Source: Santos, Cavalcante (2022, p. 11)

Note: The continuous line represents $\alpha = 0$. The dashed line represents $\alpha = 0.05$. The dotted line represents $\alpha = 0.1$

4.2.5 Considerations on Model 3

Model 3 (SANTOS, CAVALCANTE, 2022) extends Model 1 by considering two important issues that are important for the second-hand context with regard to the proposal of a maintenance policy: the heterogeneity of components and imperfect maintenance. The model also increases the possibility of applying the K, Δ, T model presented in Scarf et al. (2009), by considering a mixed population of reused and new components, instead of weak and strong ones. Though they have similarities, other important characteristics in this new context of reuse have been introduced into Model 3.

In terms of practical applicability, the model introduced two important aspects of delay time for second-hand components. Both the heterogeneity of components and false-negatives have important consequences on determining the periodicity of maintenance and its respective cost. These characteristics are essential for the model to be applicable in practice since they are present in a wide variety of situations. First of all, when an item is reused, its lifetime characteristic may be different from that of a new one, due to factors such as prior degradation and repair. As a second consideration, human inspections are subject to errors that should be taken into account, at least those that might cause undesirable consequences.

The most interesting insights from the analysis of Model 3 are associated with the heterogeneity of components and the different reliability levels of reused items. According to the results, it is important to reuse as many items as possible with the same characteristics as a new one. In the event that this fact does not occur, which is commonly the case, what should be observed in order to define a reuse policy? As a response to this question, the analysis points out that reusing with economic benefits depends on the discount cost of reused components as well as on the level of reduction in their reliability. This conflicting interaction can simply be summarised as follows: the greater the reduction in reliability of the reused component, the cheaper its acquisition cost should be. Otherwise, the cost discount may not be enough to mitigate the interferences caused by a component with a different characteristic.

In view of these facts, two important practical insights are revealed. First, if the company decides to use reused components, it should do so in a high percentage, as the cost reduction will be enough to offset the lesser reliability of these items. This contradicts what might be generally believed regarding the gradual and progressive migration of a non-reuse policy to a reuse policy. Moreover, this result highlights the need for industries to reuse more items. Aside from this point of view, another important practical repercussion is brought to the remanufacturing processes: in addition to producing more cost-effective components, they must maintain similar levels of reliability between reused and new ones.

In terms of false-negatives, the analysis shows that even small values of false-negatives can lead to a modification in optimal policy, such as suggesting that inspections should no longer be conducted. Even though the model did not suggest performing inspections when false-negatives were considered in the specific case analysed, the analysis of false-negatives in non-reuse and reuse policies yields an interesting practical result. As observed, reused components are not more prone to false-negatives than new components. Despite the fact that reused components may be less reliable than new ones, it is not harder to detect a defect in a reused component. Since there is no significant difference between the false-negative aspect when using reused or new components, it cannot be assumed that reusing items requires more training for the labour force.

In summary, both aspects introduced in model 3 should be carefully considered prior to establishing a reuse policy. When heterogeneity is not taken into account when this is necessary, the percentage of reuse will be incorrect, resulting in more failures and higher costs. Similarly, when false-negatives are not considered, inspection times and their corresponding costs can be incorrectly determined. A limitation of the model is that it is only applicable to single-component systems. In future lines of research, it might be interesting to extend Model 3 to multi-component systems.

4.3 SUMMARY OF THE CHAPTER

This chapter introduced three important concepts into two novel models. Model 2 introduced the heterogeneity of components and misclassification errors. Model 3 presented another perspective for the consideration of heterogeneity between new and reused components and also included an analysis on the influence of false-negatives in inspections. Together with Chapter 3, this chapter represents the main contribution of this thesis. While the previous chapter introduced a simple novelty into delay time theory, the current chapter discussed practical issues that can improve the applicability of delay time models in the context of reuse.

5 CONCLUSIONS

For the purposes of promoting economic benefits and environmental preservation, this thesis used the delay time model to develop maintenance policies for items that will be reused. The existing literature on this area has rarely conducted such research. As such, the thesis generated novelty. For instance, the only published papers that consider delay time in the context of reuse are those cited in this thesis. It represents, therefore, an initial contribution to this area, a sign that points out one direction for allying both economic and environmental perspectives in delay time models. In addition, the investigation indirectly addressed an important issue present in many industries: the excessive disposal of industrial components or equipment.

In addition to the introduction of this new perspective and possibility, the thesis presents a bibliometric analysis and a literature review focused on reuse and remanufacturing practices in maintenance models as a whole. From this research, the lack of studies that associate these subjects was observed. Despite the significant development of studies in the last five years, the number of papers and their citations do not match with the importance of these themes. Clearly, academia had a late development in establishing a connection among them. Hopefully, the current trend shows an increase in the investigations of maintenance models focused on reuse or remanufacturing. Possible reasons for this change may be associated with the advent of concerns about the impact of industries on the environment and the greater academic interest in developing strategies to improve the relation between the environment and society.

Following the presentation of the state of the art regarding the main concepts in this thesis, three delay time models were proposed in order to present the new contributions for the reuse of items.

Model 1 proposed the first and simplest delay time model for the reuse of items. It considered a threshold defective level to determine whether or not the current item can be reused. The model also assumed that a reused item has the same reliability as a new one but is much cheaper. As such, when the defective item is in a state that allows it to be reused, it is always better to reuse it rather than to buy a new item. This initial conclusion was quite simple and important because it shows that the logic of the model is correct and also indicates one important issue to be investigated, namely the effects of considering a reused item with a lower reliability than a new one. This issue was later investigated in models 2 and 3.

In Model 2, different reliability between reused and new items was considered in systems subject to two defective states. The first defective state represents the threshold level for reusing the current item and the second defective state represents a more degraded state at which the item can no longer be reused. In Model 3, different reliability between reused and new items was considered in a two-phase model with an initial inspection phase, followed by a wear-out phase. It was demonstrated in both models that the reliability of new and reused items should not be drastically different; otherwise the effects of having a much cheaper reused item instead of a new one does not counterbalance the effects of having a considerably lower reliability. This is the main finding of both models in terms of the analysis of different reliability. One practical implication is strongly associated with the refurbishment process, which should guarantee almost identical levels of reliability in reused items in comparison with new ones.

Other important contributions are related to inspection errors. Model 2 analysed misclassification error in the assessment of the current defective state, for example, when there is more than one defective state. To reduce this type of error, the model suggested that training actions should be adopted especially when there is a chance of a reusable component being misclassified as non-reusable. Model 3 analysed the effects of not detecting an existing defect at inspection. The possibility of false negatives is an inconvenience for both non-reuse or reuse policies. But, in both cases, the negative consequences in terms of cost are to the same extent. It was verified that the fact of a reused component being less reliable does not mean that it may be more challenging to find current defects. This suggests that the maintenance personnel traditionally considered in non-reuse policy can also be considered in the inspection of non-reuse policies.

In conclusion, this thesis addressed the concern of sustainable industrialization by linking two important concepts, delay time and reuse, that have not hitherto been investigated together in the existing literature. The initial results from this novel association showed that allying environmental preservation in maintenance models is possible, lucrative and mutually beneficial for both industry and society.

In a general view, delay time models can be applied in industrial sectors, such as, building maintenance, manufacturing plant, the energy industry, the transportation industry, and the electronics industry (WANG, 2012). The same can be considered for the proposed delay time models, particularly in the cases when the component can be easily and cheaply repaired. Some examples are the repair of the hammer of a shredder machine, mentioned at the end of Section

3.2.3, and the repair of the bowl liner and the mantle of a cone crusher, mentioned in Section 4.1.1.

Some relevant considerations on economic, environmental and social impacts are addressed in Section 5.1.

5.1 ECONOMIC, ENVIRONMENTAL AND SOCIAL IMPACTS

The economic, environmental and social dimensions of sustainability were addressed in this thesis due to the innovative link between the delay time and reuse/remanufacturing concepts. Some potential impacts in these dimensions are as follows.

Firstly, it is worth mentioning that the concept of reuse combines the economic and environmental dimensions of sustainability because, in the context analysed in the thesis, the most economic action is also the most ecological one. This is a very positive point of the models presented, since, in other contexts, it is common for more environmentally sustainable proposals to be less economically viable. In practical terms, the models presented in the thesis combine and promote economic and environmental sustainability by providing joint benefits in both dimensions: the acquisition and use of cheaper components with less negative impact on the environment. As a result, the models may be more likely to be used in the practice of maintenance management because of the link between these two dimensions of sustainability and the benefits arising from this union.

Aside from the purely economic and environmental dimensions, the reuse of industrial components also produces social benefits. One of them is the possible decrease in the disposal of industrial waste and all the related negative effects on society. In the European Union, for example, industrial waste represented 10% of total waste in 2016 (STATISTICAL OFFICE OF THE EUROPEAN UNION, 2020). The treatment and disposal of this type of waste is more expensive and difficult compared to domestic waste, and can even cause accidents that affect both operators who work in the disposal procedure, as well as the population surrounding the disposal areas.

Another social benefit linked to the reuse of components is the creation of new markets focused on second-hand items. These markets involve not just the specific people who work on item restoration, but the entire reuse-related supply chain. Finally, the change in perception about a concept traditionally seen only from an economic perspective stands out as a social benefit. It is believed that this new innovative look at the subject can influence new researchers to use techniques that promote sustainable development in their maintenance models. The measurement of this last aspect can be verified through the interest and citation of articles related to the thesis in works by other researchers who are attentive to the theme and also advocate tackling sustainability questions within their respective areas of study.

Succinctly, the main impacts can be pointed out as follows:

Economic impact:

- The proposed models can enable considerable reduction in the maintenance cost of certain systems by incorporating a sustainable strategy of component reuse.

Environmental impacts:

- The thesis considers the reuse of components in maintenance models, thus offering an alternative to disposal action and encouraging the practice of reconditioning components.
- The thesis proposes a strategy to reduce the disposal of industrial components.

Social impact:

- The thesis emphasises that efforts should be made to incorporate the social dimension of sustainability into maintenance models.

5.2 LIMITATIONS AND POSSIBLE FUTURE INVESTIGATIONS

The limitations of this thesis are mainly associated with *(i)* the consideration of single-component systems rather than multi-component systems and *(ii)* the utilisation of parameters based only on related-literature rather than real data. Concerning the first limitation, as this research is the first investigation that relates reuse to delay time models, it is important to develop the idea from the very basic modelling, as illustrated in Model 1, and then provide the adjustments necessary to make the models more applicable (Model 2 and 3, and subsequent models that can be proposed in the future also for multicomponent systems). For this reason, the investigation relates to single-component systems. Regarding the second limitation, it is due to the difficulty in accessing and collecting real data from industries, especially the data related to defects and failures. Frequently, companies are not comfortable about providing this type of data, even for academic purposes.

In terms of future studies, in a more general perspective, there is a lack of investigation of reuse and remanufacturing in maintenance models. Even when these concepts are investigated, they are generally considered in economic terms, and thus neglect the importance of the environmental dimension of sustainability. Therefore, the exploration of both economic and environmental dimensions of sustainability in maintenance models represents the most important possibility for future investigations. In fact, it can make new models more innovative and with a sense of environmental responsibility. Some examples of models that can inevitably take a significant advantage of reuse and remanufacturing are as follows:

- Condition-based maintenance models. The literature review found that there are only a couple of papers investigating the problem of reuse and remanufacturing. However, given the fact that many systems, chiefly infrastructure systems such as bridges and water networks, were built many decades ago and they are approaching the end of their design lives, there is a need to develop a collection of approaches to assessing the conditions of such systems for the purposes of reuse and reconstruction (which may be considered synonymous with the concept of remanufacturing).
- Mission abortion models: new investigations may consider how new and reused components with distinct reliability affect the decision on whether to abort or complete the remaining part of the mission.
- Selective maintenance models (RIBEIRO, 2021): new investigations may usefully consider the effect of replacement action between missions with new, remanufactured and reused components.
- Maintenance models for redundant systems: can consider measures like "component maintenance priority" to establish which components may have redundant second-hand components (WU et al., 2016).
- Predictive maintenance models: can help to monitor and repair reusable items in advance to a critical stage at which reuse/remanufacturing would no longer be possible.
- End-of-life models. The effort to reduce the disposal of industrial items inevitably increases the effort of manipulation and retrieval of parts and materials. Therefore, a more incisive development of mathematical models to deal with the end-of-life processing (disassembly, shredding, and materials separation and retrieval) must be granted to bring not only efficiency of this process, but also to allow the growth of reused and remanufactured items in industry.

More specifically, in terms of the delay time model, the concept of reuse can be applied in more sophisticated models that encompass different characteristics presented in practical systems. A major step toward the future will be the application of reuse in delay time models for multicomponent systems.

Additionally, two important developments can be helpful for researchers that may want to consider the above mentioned suggestions in their proposed maintenance models and policies. The first is to draw up frameworks for characterising environmental and social costs associated with maintenance. The second is the implementation of case studies to investigate how the maintainability in a system's first life can be optimised in order to facilitate reuse and remanufacturing.

Finally, it is important to mention that these suggestions represent only a direction for future studies. As such, new investigations can also take different routes due to the large number of possibilities for the application of reuse-related techniques in maintenance models and policies.

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