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Management of obsolescence during the maintenance phase in a circular economy context: state-of-the-art

Manel GRARI, Maria DI MASCOLO, Zineb SIMEU-ABAZI

Univ. Grenoble Alpes, CNRS, Grenoble INP, G-SCOP, 38000 Grenoble, France
Institute of Engineering Univ. Grenoble Alpes

Abstract— It is well known that the dependability of equipment on a production site is strongly linked to the quality of maintenance operations. This paper explores the state of the art in obsolescence management during the crucial maintenance phase and in the context of circular economy principles. Through a systematic review of the literature, the study investigates strategies and methodologies employed to address equipment obsolescence while embracing principles of sustainability and resource efficiency. The research methodology involves defining and combining relevant keywords, utilizing research databases, and implementing filters to obtain a comprehensive selection of pertinent articles. Content analysis reveals insights into the distribution of articles across different categories and time periods, highlighting evolving scholarly interest in these topics. Various approaches to obsolescence management in maintenance are identified, including traditional replacement methods, remanufacturing, and system complexity reduction. Case studies provide practical insights into the application of these strategies, demonstrating their effectiveness in extending asset lifespans and optimizing maintenance practices. Furthermore, the integration of circular economy principles into maintenance strategies presents opportunities for enhancing sustainability and resource efficiency in asset management practices. The findings underscore the importance of continued research in this area to control costs and improve availability over the entire life cycle of equipment.

Keywords—*Obsolescence; Maintenance; Circular economy; Repairing; Remanufacturing; Sustainability*

I. INTRODUCTION

In the dynamic landscape of our modern world, the relentless pace of technological progress has become a transformative force, reshaping industries, and redefining our relationship with innovation. Over the past decade, suppliers have consistently pushed the boundaries of technological capabilities, introducing novel items endowed with higher performance metrics than their predecessors. This constant evolution is captured by various synonymous terms such as technological change, improvement, development, evolution, and advances, each reflecting the perpetual state of innovation that characterizes our era. In this case, we bring up obsolescence, which refers to the state or condition of a product, equipment, or technology becoming outdated or no longer usable due to various factors such as technological advancements, changes in industry standards, discontinued parts or components, or lack of availability of support services [1]. Obsolescence can drive

up costs due to the difficulty in finding replacement parts, leading to decreased productivity and competitiveness [2, 3]. It also poses risks of non-compliance with regulations, necessitates workforce retraining, and contributes to environmental challenges through increased waste [4]. Effective management is crucial to mitigate these impacts and sustain operational efficiency and reliability [5]. That's when the role of maintenance in a circular economy context comes in play. Maintenance operations evolved into more intricate processes, leading manufacturers to consolidate them. Concurrently, within the framework of economic expansion, the circular economy endeavors to supplant the conventional "end-of-life" paradigm by prolonging product lifespan [15]. This approach represents one of the contemporary and promising strategies for addressing the constraints of repair shops facing obsolescence, facilitating the remanufacturing [2], or recycling of certain components within such establishments. So, one interesting research question is: How is obsolescence managed in the maintenance phase while taking in consideration circular economy aspects? To answer this question, this study aims at conducting a state of the art on this matter. In Section 2, we outline our methodological approach, which involves initially defining and combining relevant keywords through preliminary research and searching for articles in defined databases. After that, we apply filters to ensure the selection of representative and relevant literature. Following the filtering process, we conduct a cross-analysis of the resulting articles. Section 3 then presents the findings of our literature review, with the conclusion provided in Section 4.

II. RESEARCH METHODOLOGY

A. *Defining and combining the relevant keywords*

The selected keywords serve as valuable entry points to navigate through the vast array of scientific papers within various databases. They act as pivotal descriptors, encapsulating the essence of the content found within these papers. To find the most pertinent keywords for our research, we identify those aligned with the core themes of obsolescence, maintenance, and circular economy. By integrating these three words, we use the "AND" and "OR" operators to generate diverse combinations, thus facilitating a comprehensive initial search of relevant literature. Once these combinations are

generated, we delve deeper into the literature to identify keywords intricately linked to our study. We aim to find keywords that facilitate a nuanced exploration of the connection between equipment obsolescence in maintenance practices and the principles of the circular economy. This process yields the final list of keywords (Table I) and their combination (Table II) with each other.

TABLE I. LIST OF KEYWORDS USED IN THE STUDY FIELD

Obsolescence	Maintenance	Circular Economy
"Obsolescence" "Lifecycle" "Technological Obsolescence"	"Maintenance" "Repair shops" "Workshops" "Centralized repair shops" "Cost optimization"	"Circular economy" "Sustainability" "Recycling" "Repurposing" "Remanufacturing" "Reusing"

TABLE II. COMBINATION OF KEYWORDS

Obsolescence AND Maintenance	Circular Economy AND Maintenance
("Obsolescence" OR "Lifecycle" OR "Technological Obsolescence") AND ("Maintenance" OR "Repair shops" OR "Workshops" OR "Centralized repair shops" OR "Cost optimization")	("Circular economy" OR "Sustainability" OR "Recycling" OR "Repurposing" OR "Remanufacturing" OR "Reusing") AND ("Circular economy" "Sustainability" "Recycling" "Repurposing" "Remanufacturing" "Reusing")

B. Research databases

The scientific community has access to multiple databases for finding papers pertinent to their research. To refine the scope of results and gauge the relevance of found papers, we've chosen Beluga (beluga.univ-grenoble-alpes.fr), a platform of the University of Grenoble Alpes UGA. This platform allows filtering results based on title, abstract, full text, and other criteria. For this study, we conducted searches across various databases accessible through Beluga, including IEEE, ScienceDirect, Google Scholar, and Web of Science.

As an example, we searched for the combination "Obsolescence" AND "Maintenance" and found the results given in Table III.

TABLE III. RESULTS OF THE SOURCES

Sources	Filters	
	Title or Abstract	Full text
Google Scholar (scholar.google.com)	46	118 000
IEEE (ieeexplore.ieee.org)	103	3 836
Science Direct (Sciencedirect.com)	52	6 214
Web of Science (Grenoble online)	236	252

C. Defining filters

The aim of defining filters for our literature review is to obtain relevant papers that correspond to the studied topic. This involves establishing inclusion criteria to identify papers that possess characteristics pertinent to our study, as well as exclusion criteria to eliminate papers lacking relevance. Initially, we consider all papers related to our keywords individually, without employing any combinations, to gain a comprehensive understanding of the subject. Subsequently, we quantitatively search for papers containing at least one combination of keywords in their titles or abstracts. Following this, we qualitatively eliminate redundant papers, focusing on those that specifically address our topic or its major components. Finally, we obtain our 22 papers, which we will analyze in depth in the next section, by using the methodology summarized in Figure 1.

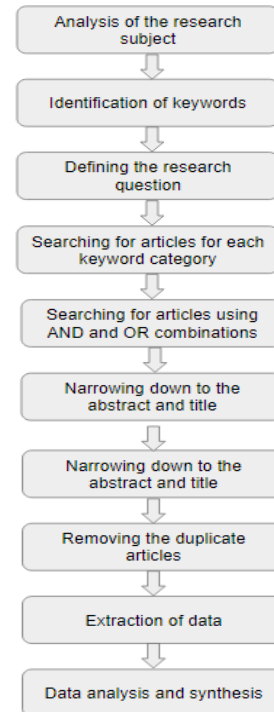


Fig. 1. Methodology to find relevant articles

III. RESULTS OF CONTENT ANALYSIS

In our effort to locate relevant papers on our topic, we have identified a total of 22 relevant articles, categorized as displayed in table IV. It is outstanding that the combination of obsolescence with maintenance yields the highest number of articles (14 in total), although still a relatively modest figure compared to other research domains. Moreover, the combination of maintenance with circular economy yields even fewer articles, indicating a relatively limited exploration of circular economy within the context of maintenance. Lastly, when obsolescence, maintenance, and circular economy are combined, only two articles are found, underscoring the rarity of literature in this intersection.

TABLE IV. REPARTITION AND CONTRIBUTION OF THE ARTICLES

Obsolescence	Maintenance	Circular Economy	Results	
			Nb Number of articles	References
●	●		14	From [1] to [14]
	●	●	8	[2], from [15] to [21]
●	●	●	3	[2], [22]
16	22	10	22	

The 22 articles under study span from 1994 to 2023 and can be categorized into four main periods, as depicted in Figure 3. It is evident that during the 1990s, there were relatively few articles addressing obsolescence in maintenance and circular economy in maintenance. In fact, only one article was identified from this period, written in 1994. Subsequently, over the following decade, a modest increase in the number of articles occurred. However, the most significant surge in publications occurred during the 2010s, indicating heightened scholarly interest in these topics. Regarding the current decade, the number of articles is relatively low, possibly due to the incomplete nature of the decade at the time of analysis.

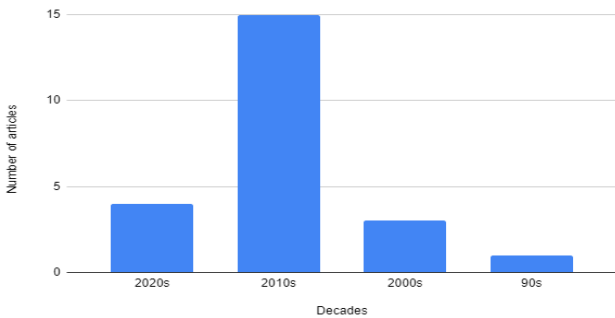


Fig. 2. Evolution of the articles through the decades

For our research analysis, we will segment our work into three categories, as outlined in Table IV, and thoroughly examine each of these categories.

- *Obsolescence management in maintenance:*

According to our results, addressing equipment obsolescence remains a challenge that requires additional research. The selected articles cover various fields. Table V delineates the specific areas or domains covered by each article:

TABLE V. FIELDS OF THE ARTICLES

Domain	Military and Aerospace	Industrial and Manufacturing	Automated Test Equipment (ATE) Systems	Cross-Domain (Applicable across industries)
References	[8], [9], [11]	[3], [12], [14]	[4], [8], [10]	[1], [2], [5], [7]

The articles provide insights into addressing equipment obsolescence in maintenance through various solutions illustrated in Table 6. These solutions range from commonly used approaches, such as implementing different replacement strategies (discussed in articles [1], [6], [7], [8], [10], [11], [14]), to methods like remanufacturing, as seen in article [2]. The most used replacement methods are stocking spare instruments as a short-term solution [4] and replacement through a secondary market as another option for addressing test equipment obsolescence [9]. On the other hand, the practice of continuous maintenance, encompassing both preventive measures and repairs, emerges prominently in the literature [4], [6], [7], [9], [10], and [14]. It is portrayed as a sustainable long-term strategy aimed at mitigating the impacts of obsolescence, thereby prolonging the operational lifespan of assets, rather than confronting obsolescence head-on. Yet another intriguing approach involves reducing system complexity [5], which entails minimizing reliance on components prone to obsolescence. This strategy aims to proactively sidestep the challenges associated with obsolescence altogether. However, some articles primarily focus on obsolescence analysis rather than obsolescence solutions, such as identifying key performance indicators (KPIs) for assessing maintenance work [12] or propose models for evaluating component obsolescence. For instance, the KPIs offer a qualitative assessment of maintenance performance based on predetermined benchmarks, while the obsolescence model identifies components at risk. Additionally, one article discusses a cost analysis-driven approach for selecting the most suitable obsolescence method [13].

TABLE VI. OBSOLESCENCE SOLUTIONS STATED IN THE ARTICLES

References	Obsolescence solutions			
	Replacement strategies	Preventive maintenance / Repair	Reducing system complexity	Remanufacturing
[1], [8], [11]	●			
[4], [6], [7], [9], [14]	●	●		
[2]				●
[10]	●	●	●	
[5]			●	

While most articles discussed in this paper offer analytical studies of obsolescence, three articles used case studies. The first one consists of a case study of an avionics obsolescence replacement program that utilized existing automated test stations (ATS) and developed test program set (TPS) assets for manufacturing, integration, acceptance, and maintenance [8]. The study demonstrates how careful consideration of the entire unit under test (UUT) lifecycle can save non-recurring costs for all test types, with higher capability automated test stations offering cost-effective solutions for future obsolescence upgrades. In paper [11] we find another case study in the military and aerospace domain consisting of the replacement of pulse and arbitrary waveform function generators in the Hybrid Test Set (HTS) AN/USM-484 test system. The paper outlines the implementation and qualification process of this replacement strategy, highlighting its benefits in extending ATE life cycles, preserving investment in test programs, and enhancing system performance and reliability. Finally, the last study highlights the significant role of end-users and maintenance functions in influencing core conditions and remanufacturing decisions [2]. An integrated methodology is proposed to optimize maintenance, remanufacturing, and multiple spare strategies, with a case study illustrating its effectiveness in providing decision support. These findings underscore the importance of considering end-user influence and maintenance strategies in remanufacturing decision-making.

- *Circular economy in maintenance:*

The circular economy concept aims to revolutionize traditional "end-of-life" approaches by emphasizing the closure of material loops and extending the lifespan of products [15].

Despite its potential, circular economy principles, including reuse, remanufacturing [2], and recycling, are not fully integrated into repair shop strategies [16]. In this research, we could only find 8 articles regarding circular economy in maintenance or in repair shops in general. However, some authors suggest that incorporating circular strategies presents an opportunity to address resource waste by reintegrating scraps into the value chain [15]. Strategies such as remanufacturing, reuse, repurposing, and recycling can supply repairable components necessary for repair shops [21]. While there are existing methods to enhance repair shop productivity, embracing circular economy principles can further enhance sustainability by closing material loops [20]. Although circular economy practices are not yet widespread, some studies have explored methods such as Stochastic Petri Nets and Non-Linear programming combined with optimization for performance evaluation and implementation [18, 20, 17]. Additionally, surveys have been conducted to assess the implementation of circular strategies across various companies [19, 21].

References	Method used					
	Analytical	Simulation	Exact	Heuristic	Survey	Case study
[18]	●	●				
[20]			●			
[17]		●		●		
[19], [21]					●	
[2]						●

TABLE VII. METHODS OF CIRCULAR ECONOMY USED BY THE AUTHORS

- *Obsolescence and circular economy in maintenance:*

When attempting to integrate the concepts of "obsolescence," "maintenance," and "circular economy" and considering the associated keywords, we found only two relevant articles. This indicates that, while circular economy principles are already considered rare in repair shops, incorporating the dimension of obsolescence further narrows down the scope, resulting in a limited number of articles (just two)

First, we have an introduction of a methodology for addressing Test Program Set (TPS) and Automatic Test System (ATS) obsolescence while enhancing sustainability by employing Synthetic Instrumentation (SI) technology [22]. It discusses the challenges posed by obsolescence in the electronics industry

and the Department of Defense (DOD), emphasizing the need to maintain critical systems and components in a state of readiness. The methodology aims to modernize ATS by replacing traditional instruments with synthetic instrumentation, thereby reducing TPS rework costs, decreasing maintenance expenses, and improving the sustainability of legacy systems. The other paper [2], as we stated in the previous section, proposes an integrated methodology to optimize maintenance, remanufacturing, and multiple spare strategies when facing obsolescence.

Given the rarity of existing research on this topic, it is prudent to concentrate on obsolescence management during the maintenance phase, considering the principles of the circular economy. By doing so, we aim to contribute valuable insights to the existing literature through our study.

IV. CONCLUSION

In conclusion, the research methodology outlined in this study facilitates a systematic approach to investigating the intersection of obsolescence management, maintenance practices, and the principles of the circular economy.

The study identifies various strategies for addressing equipment obsolescence in maintenance, ranging from traditional replacement methods [1] to more innovative approaches like remanufacturing [2] and system complexity reduction [5, 10]. Case studies provide valuable insights into practical applications of these strategies [2, 8, 11], demonstrating their effectiveness in extending asset lifespans and optimizing maintenance practices.

Furthermore, the integration of circular economy principles into maintenance and repair shop strategies presents opportunities for enhancing sustainability and resource efficiency [16]. While existing methods show promise in improving repair shop productivity [18], adopting circular economy principles can further advance sustainability efforts by closing material loops and reducing waste [15].

Despite the limited number of articles exploring the intersection of obsolescence, maintenance, and the circular economy, the research underscores the importance of continued investigation in this area. This work on the literature review of obsolescence in maintenance within a circular economy context has provided an opportunity to identify and address various research questions. These include the management of spare parts, the establishment of predictive maintenance for obsolescence, and the evaluation of maintenance costs associated with obsolescence. By focusing on obsolescence management during maintenance and integrating a predictive approach to maintenance needs, along with principles of the circular economy, researchers can bring forth interesting developments to the existing literature and advance sustainable asset management practices.

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