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Repurposing as a Decommissioning Strategy for Complex Systems: A Systematic Review

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Managing the waste of decommissioned complex systems (e.g., aircraft and wind turbines) is a growing issue. In this review, we investigate repurposing as a potential solution. The objectives are to identify strategies that can enable repurposing and identify the research gaps hindering those strategies. We analyzed 104 journal articles published in the last decade. We identified four proactive strategies that can be applied before the decommissioning stage and three reactive strategies that can be applied after the decommissioning stage. The proactive strategies are local ecosystem-focused repurposing, modular design, efficient disassembly methods, and component-embedded design and health information. The reactive strategies are decision support methods for repurposable component selection, function and context-based repurposing opportunities, and business models for repurposing. Six research gaps were identified, hindering the strategies due to the lack of support methods for repurposing, strategy scope limitations, and repurposing opportunity limitations. We identified that two repurposing examples were most commonly studied (wind turbine blades and electric vehicle batteries). Addressing the research gaps through design could uncover new repurposing opportunities. The resulting opportunities could follow similar processes addressed under the two well-researched examples, enabling repurposing as an advantageous and sustainable decommissioning strategy for complex systems. [DOI: 10.1115/1.4067090]

Keywords: repurposing, circular economy, sustainability, decommissioning, end of life, complex systems, literature review, sustainable design

1 Introduction

A complex system could be an aircraft, a supply chain, a government, a financial system, or a school [1]. We focus on complex systems from a mechanical engineering point of view. We consider a complex system to be a large-scale (1000s of parts) mechanical system with a long life cycle (in the decade range) that weighs in the multiple-ton range (e.g., aircraft, trains, wind turbines). They are systems of subsystems containing many components that interact with each other.

Decommissioning is the process of withdrawing a system from service and dealing with the withdrawn system. During this process, the system is disassembled and dismantled either for disposal or to be utilized again, enabling multiple life cycles [2]. The current decommissioning processes generate large quantities of waste. For example, new aircraft models are rapidly replacing current models, with the expectation of 11,000–18,000 aircraft being decommissioned by 2030. The COVID-19 pandemic complications will accelerate this trend [3,4]. Liu and Barlow [5] estimate that there will be 43 million tons of wind turbine blade waste by 2050. Furthermore, 130 million electric vehicles will be in the EU by 2030 [6]. In this review, we aim to investigate repurposing as a solution for this issue.

1.1 The Circular Economy and Complex Systems. The Circular Economy is "*an economic system that replaces the 'end-of-life'* (decommissioning) *concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes*" [7]. Reike et al. [8] summarized all the circular economy strategies as a ten-R (10R) typology. The 10Rs divide between shortest (Refuse, Reduce, Resell/reuse, Repair), medium (Refurbish, Remanufacture, Repurpose), and long (Recycle, Energy Recovery, Re-mine) loops. We focus on handling the waste of already decommissioned systems. Therefore, the shortest loops are not considered in this study. Medium-loop options are encouraged rather than long loops since they retain a higher portion of the value of the original product [8,9]. Repurposing involves reusing decommissioned products in different applications and fields to preserve their added value and target new markets [10], making it unique among the three medium loops.

Complex systems meet the medium-loop options criteria (high material value, high initial/production cost, reliable cores, subassemblies, modular functionality, etc.) [11]. However, the life cycle of a complex system is long, ranging in the vicinity of two to four decades [12,13]. Many changes in technology, product development, manufacturing, and decommissioning options occur

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during the system's life cycle. For example, the transformation of vehicle propulsion technology from internal combustion to electric power hinders the refurbishing/remanufacturing of engine parts [14,15]. Furthermore, the upgrades and modifications throughout the system's life cycle change the configuration between the decommissioning and design stages [16]. Therefore, the medium-loop options, such as refurbishing and remanufacturing, become obsolete for some components. In some cases, refurbishing/remanufacturing might not be the best option due to the risk of cannibalization of the new product [17,18]; lack of competitive advantage due to the increased cost of remanufacturing [19]; performance and technology improvements in the competitors and the industry [20,21]; and the extreme safety and performance requirements in some sectors such as aviation and marine [22].

The above reasons prevent refurbishing/remanufacturing, forcing long-loop options [23]. However, using long-loop options on decommissioned components is not beneficial if they have remaining embedded value and useful life. For example, an electric vehicle battery is at 80% capacity at the decommissioning stage [24]. Therefore, repurposing could act as a circular decommissioning option between refurbishing/remanufacturing and the long-loop options.

1.2 The Potential of Repurposing. Repurposing can preserve the remaining functional value by extending the life span while delaying the long-loop options. Additionally, the revenue generated from repurposing can bear the expenses for the long-loop options [25]. Cusenza et al. [26] state that repurposing delays the recycling stage of electric vehicle batteries by ten years. Therefore, repurposing buys time for improving recycling technology and facilities [26]. Delaying recycling is crucial since only 42% of batteries (by weight) are recycled in the United States [27]. Similarly, wind turbine blades have no well-established recycling methods [28]. Therefore, most of the blade material ends up in the cement industry as low-value filler material [29]. Taking the automotive industry as an example, Soo et al. [30] argued that improving material circularity through design for recycling alone is coming to its technological limit.

Repurposing prevents purpose-built components, enabling environmental, economic, and raw material consumption benefits. For example, repurposing electric vehicle batteries for stationary energy storage applications instead of manufacturing new batteries leads to less environmental impacts and economic benefits in both utility (reduced levelized cost of electricity by 12–57% and carbon emissions by 7–31%) and residential applications (reduced levelized cost of electricity by 15–25% and carbon emissions by 22–51%) [31,32]. Furthermore, Ramoni and Zhang [33] conclude that processing and reassembling electric vehicle batteries to be repurposed is much less expensive than manufacturing new batteries for stationary applications. Similarly, the cost modeling presented by Steckel et al. [34] concludes that the upfront costs of repurposed battery systems are 64.3–78.9% of new ones. From a raw material consumption point of view, Kamran et al. [35] predict that repurposed energy storage systems could entirely replace purpose-built ones in the United Kingdom by 2050 without affecting raw material requirements for electric vehicle battery manufacturing. Similarly, Nagle et al. [36] concluded that repurposed wind turbine blade parts could replace two quantities of coated sheet steel in construction since their design life is 20–30 years, and the blades would last 60 years.

Repurposed complex system components can perform better than the conventional (purpose-built) components they replace. For example, a structural analysis of repurposed wind turbine blade segments concluded that they perform better than traditional construction materials such as wood, aluminum, and steel [37]. Additionally, repurposing could share the environmental impact of the manufacturing stage, similar to remanufacturing [38].

Therefore, repurposing is a potential solution for the issue of decommissioning complex systems. It is worth exploring due to its advantages and compatibility with complex systems, as discussed above.

1.3 Definitions. The concept of repurposing can be broken down into the following definitions based on our previous work [39].

1.3.1 Repurposing Pathways. Repurposing can be categorized into four pathways based on the component's function and the context (parent system category) in which it performs. We can change both function and context, change either the function or the context or maintain the original function and context.

Let's consider the simple example of a daily planner. The different types of pages are the components here, and the daily planner is the context. The original function of a daily planner page could be to provide a space to mark scheduled or special events. We could maintain the same function and context after its initial use. For example, erasing the page's written content and date stamps and using it to write again. Otherwise, we could maintain the original function and change the context. For example, tearing out the remaining pages to use as a shopping list. Also, we could change the page's function while still being in the same context. For example, tearing out a page to use as a bookmark for the daily planner. Finally, we could change both the function and the context, for example, by tearing out a page to make a paper airplane. Figure 1 summarizes the four pathways and the example. It is to be noted that maintaining both the original function and the context essentially covers refurbishing and remanufacturing, which, while valuable strategies, are not the focus of this study. The reader is encouraged to refer to Nag et al. [40] for an analysis of the same function and context strategies.

1.3.2 Repurposing Strategies. The strategies to repurpose a complex system can be divided into two types. The strategies applied where the system is already decommissioned will be addressed as *reactive strategies*. The strategies applied at the concept stage or before the complex system's decommissioning will be addressed as *proactive strategies*. For example, selecting repurposable components through remaining useful life calculations is a reactive strategy. Deciding the optimum time to decommission a component to be repurposed based on its remaining useful life is a proactive strategy.

Decommissioned systems will produce *upstream components* to be repurposed. Using those upstream components, we can develop *downstream products* through repurposing. For example, when repurposing a wind turbine blade to build a bridge [41], the upstream component would be the wind turbine blade, and the downstream product would be the bridge. Starting with decommissioned components instead of materials and standard parts could limit concept design capabilities. It will require creativity and innovation to utilize the repurposable attributes of the upstream components.

The objectives of this review are to identify reactive and proactive strategies that can enable repurposing and to identify the research gaps hindering those strategies. Section 2 presents the systematic review process followed to achieve the objective, including the inclusion and exclusion criteria, and literature search strategy. Section 3 presents the identified reactive and proactive strategies and discusses the current research gaps. In Sec. 4, we discuss the barriers to repurposing and how the reactive and proactive strategies can overcome them. Then, we summarize the entire review with a figure (Fig. 4) showing the reactive and proactive strategies, the barriers to repurposing, and the research gaps to be addressed to improve the strategies. Finally, we discuss how most of these research gaps can be addressed through design methods.

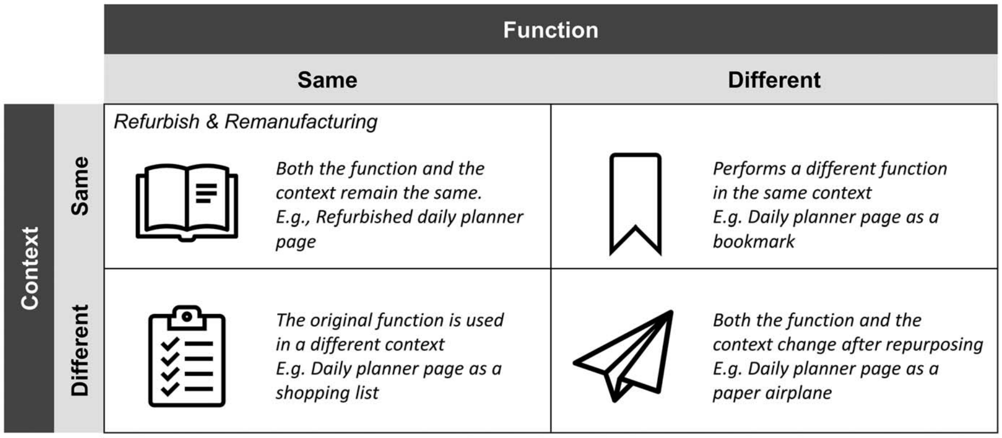

Fig. 1 Pathways for repurposing

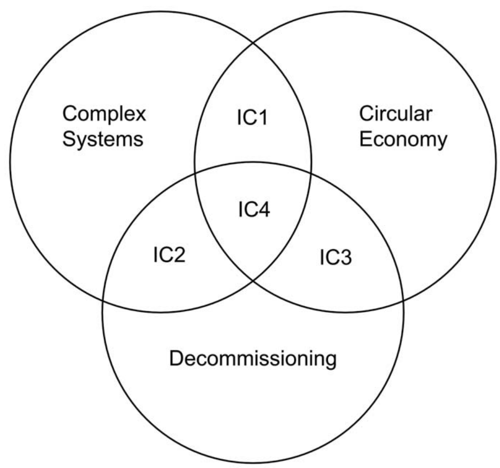

Fig. 2 Inclusion criteria for the review

2 Methods

This review follows the PRISMA 2020 statement [42] guidelines for a systematic review. The PRISMA 2020 statement contains a checklist with recommendations for each section to ensure accurate and standardized reviews. The guidelines promote transparency and comprehensiveness, making the results reproducible, unbiased, and expandable.

2.1 Inclusion Criteria. The inclusion criteria were developed to cover three areas: circular economy, complex systems, and decommissioning. The criteria are as follows: IC1: studies that explore complex systems in the context of a circular economy, regardless of decommissioning, IC2: studies that explore the decommissioning of complex systems, regardless of the circular economy, IC3: studies that explore decommissioning within a circular economy context, regardless of complex systems, and IC4: studies that explore complex system decommissioning within a circular economy context, considering all three areas. The inclusion criteria thereby include broader terms than repurposing to avoid missing literature. Then, exclusion criteria were applied to focus the search on papers on repurposing. Figure 2 visualizes the inclusion criteria.

2.2 Exclusion Criteria. Four exclusion criteria were used to eliminate out-of-scope studies. They are EC1: studies that focus on research topics outside of repurposing (e.g., "A State-of-the-Art Review of Radioactive Decontamination Technologies" [43]), EC2: studies that would not be useful within the scope of complex systems (e.g., "Use to use—A user perspective on product circularity" [44]), EC3: studies that are useful within the scope of complex systems but not from a mechanical systems point of view (e.g., "Wind turbines designed for easy installation" [45]), and EC4: studies that only focus on long-loop options as a decommissioning strategy (e.g., "Recycling offshore wind farms at decommissioning stage" [46]).

2.3 Search Strategy. Table 1 presents the keywords used for the search, which were sought in a paper's title, abstract, and keywords. The Scopus and Web of Science databases were used as information sources. The papers were searched for each inclusion criterion separately and combined by removing the duplicates. For example, the IC3 search in Scopus would be TITLE-ABS-KEY (("decommission*" OR "end of li*" OR "end of service life" OR "end of use") AND ("circular design*" OR "circular economy" OR "remanufactur*" OR "repurpos*" OR "reus*")).

Specific keywords such as aircraft or ship were included to match our large-scale and mechanical complex system criteria. Therefore, we can obtain papers related to systems that might not have explicitly been called complex systems. The North American Industry Classification System was also applied to identify complex system keywords. Additionally, we conducted a separate search

Table 1 Keywords used for the search

Complex Systems	"aero*" OR "agriculture" OR "air conditioning" OR "aircraft" OR "automobile" OR "automotive" OR "aviation" OR "building*" OR "bus*" OR "commercial" OR "complex product*" OR "complex system*" OR "construction*" OR "energy" OR "farming" OR "heating" OR "heavy duty" OR "infrastructure" OR "machine*" OR "mechanical system*" OR "mining" OR "oil and gas" OR "power" OR "quarrying" OR "rail" OR "refrigeration" OR "rolling stock*" OR "ship*" OR "space" OR "train*" OR "tram*" OR "transport*" OR "truck*" OR "vehicle*" OR "wind"
Decommissioning	"decommission*" OR "end of li*" OR "end of service life" OR "end of use"
Circular Economy	"circular design*" OR "circular economy" OR "remanufactur*" OR "repurpos*" OR "reus*"

on "repurposing" in the design journals: *Journal of Mechanical Design*, *Journal of Engineering Design*, *Research in Engineering Design*, *Design Studies*, and *Design Science* to avoid missing design literature. The search scope included journal articles published within the last ten years. Only papers written in English were selected.

The rationale behind including IC1, IC2, and IC3 is to capture any studies that will be missed from IC4. For example, any complex systems that the specific keywords could not capture will be included through IC3 since complex system keywords do not limit it.

2.4 Study Selection Process. After removing duplicates, the search resulted in 13,349 journal articles. Limiting the review scope to the last 10 years (from March 30, 2023) resulted in 11,084 journal articles, 83% of the total search results (13,349 papers). The study selection process contained three steps. Figure 3 visualizes the study selection process.

(1) Title and keyword review: Eliminate the apparent mismatches (such as "A State-of-the-Art Review of Radioactive Decontamination Technologies" [43] and "Two-Path 77-GHz PA in 28-nm FD-SOI CMOS for Automotive Radar Applications" [47]), which resulted in 628 papers out of the 11,084 (6%).
(2) Abstract review: The exclusion criteria were followed, reducing the 628 papers to 317 papers (50%).
(3) Full paper reading: Out of the 317, the full paper reading resulted in 104 papers to be analyzed in this review (33%), of which 24 were review papers.

3 Results

3.1 Search Results. Out of the 104 papers, 83% addressed a complex system. Even though the rest of the papers either addressed consumer goods or were not focused on a particular system at all, they were included due to the applicability of their results to complex systems. Only 70% of the 104 papers directly addressed repurposing. The rest were included since they provided results applicable to this review's objective. For example, the method developed by Cong et al. [48] focuses on product recovery to support the circular economy, and the method presented by Asif et al. [49] focuses on designing products for multiple life cycles, considering three product design and obsolescence strategies. Even though these studies did not explicitly address repurposing, we included them because their results were applicable to repurposing. We discuss this further in Secs. 3 and 4. Furthermore, Reactive approaches were discussed in 71% of the 104 papers.

Twenty-four out of the 104 were review papers. Twenty-one out of the 24 focused on a specific industry or application. For example, nine reviews were on electric vehicle batteries [23,24,31,50–55], and six reviews were on wind turbines [13,28,56–59]. The reviews that did not focus on a particular industry gave overviews of the entire circular economy concept or multiple life cycle products [8,11,21,40]. To the best of our knowledge, this review is the first to focus on repurposing as a decommissioning strategy without limiting it to any particular industry. Therefore, we believe that this review can transfer the well-researched industry knowledge to other industries and lay a foundation for holistic and interconnected approaches to repurposing decommissioned complex systems.

Table 2 categorizes the papers according to the strategy and repurposing example. The papers categorized as "same" under both the function and the context columns focus on refurbishing/remanufacturing. Since this review focuses on repurposing, they are papers with methods or results applicable to repurposing.

3.2 Proactive Strategies

3.2.1 Local Ecosystem-Focused Repurposing. Transportation of decommissioned systems is difficult due to reasons such as the large size [56,59]. Therefore, it is challenging to process decommissioned systems from a central location. Additionally, the unpredictability of the number of systems to be collected/returned is a barrier to sustaining financial viability [31,65]. As a solution, location-targeted repurposing strategies can be created by predicting and monitoring the location and time of decommissioning. For example, diverse wind turbine blade models spread across various regions. Therefore, decommissioning/repurposing options should be customized based on the geographical location of the wind turbine [114]. Wang et al. [109] focus on the time of decommissioning through a quantitative method based on cost modeling. The method finds the optimum stage in the life cycle to decommission an electric bus to repurpose the battery as a stationary energy storage system. Furthermore, Konietzko et al. [111] introduce the concept of a *circular ecosystem*. It promotes stakeholder collaboration for repurposing on a larger scale (e.g., mobility of a city) rather than on the individual system scale. Ai et al. [110] conducted a material flow analysis to match the future decommissioned electric vehicle batteries with potential stationary energy storage applications in California, USA. They conclude that repurposing 50% of decommissioned batteries can support all existing wind and solar farms in the state with infrastructure support, effective policymaking, and transportation.

3.2.2 Modular Design. Modular design can facilitate module-level repurposing strategies. Asif et al. [49] introduced a method to design products based on three product design strategies: operational excellence, product leadership, and customer intimacy, as well as three product obsolescence types: emotional, functional, and technological. They argue that products designed for operational excellence that are highly reliable with a minimum cost are prone to functional obsolescence when the product fails to function. Products designed for product leadership equipping the latest technologies are prone to technological obsolescence due to technology shifts in the market. Products designed for customer intimacy focusing on the user experience are prone to emotional obsolescence when users desire newness. Usually, the whole product is discarded due to obsolete modules. However, the remaining modules can create a range of high-end to low-end products. Similarly, Kim and Moon [119] introduce a decision model to optimize product family design to reuse modules between high, medium, and low-end product families by analyzing the functional, spatial, and interface restrictions.

Kim and Moon [117] developed a mathematical model to assess a product's modularity from a recovery point of view. They focused on interface complexity, material similarity, and lifespan similarity to modularize the components. As a result, the desired recovery strategies are achieved with the least effort and cost. Similarly, Yan and Feng [115] recommend considering material similarity,

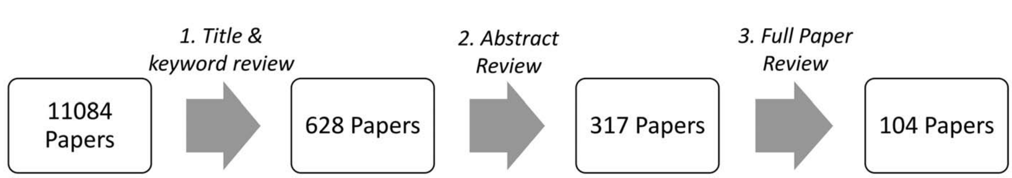

Fig. 3 The study selection process

Table 2 Categorization of papers according to the strategy and repurposing pathway

Strategy	Function	Context	System	Upstream component	Downstream application	Reference
Reactive	Same	Different	Electric vehicle	Battery	Stationary energy storage	[23–26,31–34,50–52,54,55,60–83]
			Ship	Battery	Stationary energy storage	[84]
	Different	Different	Ship	Ship components	Wave energy extractor, Construction	[85,86]
			Wind turbine	Turbine blade	Bridge, furniture, housing components, roof, substitution of sheet steel/concrete, and other applications	[36,37,41,56–58,87–90]
				Turbine base	Artificial reefs	[91]
			Automobile	Sheet metal-based components	Angle mesh steel, sheet metal-based components, mesh steel	[92–96]
	Same	Same	N/A			[17,18,20,25,38,58,82,97–108]
Proactive	Same	Different	Electric vehicle	Battery	Stationary energy storage	[35,53,109–112]
	Different	Different	Wind turbine	Turbine blade and other components	Furniture and other applications	[13,29,59,113,114]
	Same	Same	N/A			[4,13,19,21,22,28–30,40,48,49,59,112,115–121]
	N/A					[8,11,27]

component life similarity, and maintenance similarity when designing product modules to support decommissioning.

These methods focus on maintaining the original function and the context (refurbishing and remanufacturing). However, the modular architecture already facilitates module-level repurposing. As a result, including repurposing in the decision-making can improve these methods. For example, all the obsolescence types Asif et al. [49] introduced can be tackled by repurposing components outside the product family.

3.2.3 Efficient Disassembly Methods. Efficient disassembling techniques improve the upstream component recovery. Favi et al. [118] present a method to find the optimum decommissioning strategy through a disassemblability analysis. Recovering the most valuable components with the least disassembly effort is beneficial for cost-effective repurposing. Similarly, Cong et al. [48] present a method that identifies the most valuable components of the system and re-configures the system to recover those components efficiently. Furthermore, advanced disassembling techniques, such as active disassembly, improve disassemblability through reversible fasteners and rapid, nondestructive self-disassembly of products [118].

3.2.4 Component-Embedded Design and Health Information. Insufficient information on the decommissioned system's performance, condition, and remaining useful life affects the repurposing decisions. Therefore, the system's technical information and health monitoring data must be accessible [102,108]. For example, Joshi and Gupta [121] incorporate data from RFID tags and sensors in their multicriteria decision model to obtain reliable condition data. Joustra et al. [113] and Heath et al. [53] suggested including identifications such as embedded markings and labels to retrieve original design information at the decommissioning stage. Innovative business models and planning, such as leasing the complex system or components instead of selling [112], could support monitoring the product data.

3.3 Reactive Strategies

3.3.1 Decision Support Methods for Repurposable Component Selection. System level criteria (disassembling or dismantling difficulty and depth [97], number of components, level of integration), component level criteria (durability, condition, component weight), material level criteria (material value, calorific capacity, hazardous material content, material variety), and external factors (regulation support, customer preferences, price of the substitute) affect the decision on which decommissioned components to be repurposed [120].

At the decommissioning stage, each component or system is in a different state of condition, e.g., wear, degradation, fatigue. Standard metrics should be established to evaluate the state of each component or system before the decommissioning decision. Liao et al. [98] introduced a *quality coefficient* that assesses the overall quality of a system. The coefficient assists in determining whether to decommission the entire system or to focus on dismantling individual components, considering cost. Similarly, the *maximum off-load voltage difference at a low state of charge* was identified as an index to determine the capacity of decommissioned electric vehicle batteries [69]. The index helps decision-makers decide on decommissioning options rapidly. Furthermore, remaining useful life (RUL) was often identified as an index to determine the decommissioning option. Jiang et al. [103] introduced *life span equilibrium*, which compares the life span of a decommissioned component to the system's life span, considering the RUL. Similarly, Zhang et al. [106] consider the reliability of a component along with its RUL to determine the optimum decommissioning option.

Okumura [107] introduced two new factors, *relative* and *absolute deterioration,* to improve the lifetime estimations and categorize systems before going to the component level. Systems decommissioned due to replacements, lease term expirations, hibernations, and unsuitability for repair, from the user's perspective, come under relative deterioration. Absolute physical failures and being unfit for repair from a business point of view come under absolute deterioration. Similarly, Sawyer-Beaulieu and Tam [99] introduced *high-salvage* and *low-salvage* categories to differentiate decommissioned vehicles based on their usage years. Vehicles under the high-salvage category (usage less than nine years) are targeted for middle-loop options, and vehicles under the low-salvage category are targeted for long-loop options.

The studies mentioned above focused on technical and economic factors. A few studies took a comprehensive approach by including external factors such as regulation support, customer preferences [101,105,120], price of the substitute [120], environmental impact, labor time [116], jobs created, exposure to hazardous material [101], and metrics from UN sustainable development goals [87] for decommissioning decision-making.

Only three of the studies discussed above included repurposing as a decommissioning option during decision-making: Li et al. [69] with the same function and different context repurposing approach, Deeney et al. [87] with a different function and context repurposing approach, and Ma and Kremer [116] included repurposing in general. For example, Tsimba et al. [104] only consider remanufacturing worn-out gears and bearings using additive manufacturing technologies. Their conclusion was to remanufacture the gears and discard the bearings. Similarly, Sundararaman and Muthu [100] decided to dispose of the automobile components that cannot be remanufactured. Therefore, opportunities for repurposing were missed. Considering repurposing in these decisions could increase the value created by the decommissioning solutions.

3.3.2 Function and Context-Based Repurposing Opportunities. A downstream application is needed to repurpose the selected upstream components. The most frequent downstream application for keeping the same function, but for a different context, was repurposing decommissioned electric vehicle batteries to stationary energy storage applications. The function of energy storage remains the same while the context changes from electric vehicles to stationary applications. Decommissioned electric vehicle batteries retain nearly 80% of their original capacity [24]. Even though the battery's performance is below the requirement for automobile applications, the remaining capacity can be utilized in residential and commercial stationary applications [50,68]. Philippot et al. [82] explore a residential application where electric vehicle batteries are repurposed to store the energy generated by photovoltaic panels. Commercial applications such as load leveling, transmission support, grid frequency regulation [53], and energy arbitrage [54] are also possible. Another interesting application uses decommissioned electric vehicle batteries to store backup power for critical infrastructure in an emergency or a disaster [62,71]. To put things into perspective, approximately five decommissioned electric vehicle batteries could perform the same function using four new batteries [26].

During its lifecycle of approximately 30 years, a ship undergoes one to three cycles of retrofitting its battery system. The battery system is used for multiple energy requirements such as propulsion, emergency energy storage, hotel use, etc. These batteries are also replaced at 80% capacity, the same as electric vehicle batteries. Cost modeling by Lehmusto and Santasalo-Aarnio [84] suggests that the ship owner can benefit from 20% life cycle cost savings and an upfront retrofit discount of approximately 35% if they repurpose batteries for less demanding stationary applications.

Repurposing wind turbine blades was the most frequent application for changing both the function and context. The excellent structural properties of the composite material in the blade match or outperform the original material to be used in the downstream application [37,41,90]. It can be categorized into whole-blade repurposing and partial-blade repurposing. Suggested applications of whole-blade repurposing include land bridges, property walls, buoys or floats, powerline poles, and highway noise barriers. The blades can also be cut into small parts for numerous repurposing applications such as roofing, furniture, erosion control barriers, storage tanks, window shutters, and outdoor playground equipment [41,56–59,88,91]. While many studies provide concepts for repurposing wind turbine blades, few provide insights for implementation, such as cutting and fabrication methods [113] and effective blade segmentation methods [37].

In addition to the most frequent wind turbine blade repurposing, examples from other industries were identified. Studies by Abdullah [94,96] demonstrate the process of repurposing waste sheet metal from automobiles to fabricate metal meshes. The metal meshes can be used for fences, tubes, air cooler frames, and corrugated panels. However, the increasing complexity of car body designs could be a barrier to this method, resulting in poor quality meshes due to unevenness and discontinuities in the waste sheet metal [92]. A similar study demonstrates a method to repurpose sheet metal components from decommissioned systems by reshaping them through hydroforming [93]. Therefore, sheet metal components can have a second life as a different component (to serve a different function in a different context). Repurposing of ship components was also presented in a few studies. One study proposed repurposing structural steel and high-end stainless steel components from ships for construction [86]. Another study suggested using the entire decommissioned ship as a deep sea wave energy extractor by "tuning" the ship to have higher motion responses for sea waves [85].

We identified that two repurposing examples were by far the most commonly studied. Electric vehicle battery repurposing was the focus of 91% of the papers that discussed maintaining the original function while changing the context. Wind turbine blade repurposing was the focus of 58% of papers that discussed changing both the function and context. The electric vehicle battery repurposing had more in-depth research on implementation at scale than wind turbine blade repurposing. For example, experimental analyses conducted on several types of electric vehicle batteries currently available in the market have revealed that the type of thermal management in the battery system (active or passive) significantly affects the repurposing application [64,72]. One study concluded if the repurposing application is energy arbitrage, which is a high-performance application, the frequency of deep discharge cycling is almost five times higher in active-cooled battery systems than in passive-cooled systems [64]. Most other examples were in the concept stage, lacked detail on the actual implementation, or struggled to define a feasible repurposing pathway.

The wind turbine blade examples always appear to have significant downgrades in value (e.g., furniture). Furthermore, they were all for static load applications and never for dynamic applications. The lack of scalable repurposing ideas due to the complexity of changing component functions and contexts may be the cause. Focusing only on a few downstream applications will limit the potential of repurposing. For example, there is a shortage of stationary energy storage applications to repurpose the high numbers of decommissioned electric vehicle batteries [75]. Therefore, methods to find downstream opportunities are necessary to enable repurposing. To find downstream opportunities, we need to evolve the designer's thinking from the same function and context to an open approach where the function and context are not limited. Arabian and Shu [89] showed that using a scaled Alternative Uses Test ("*an established measure of creativity that involves asking participants to identify uses for common objects like bricks and paper clips*") as an intervention could support understanding the size of a large-scale complex system (wind turbine blade) when repurposing. They concluded that adding the scale helped generate realistic repurposing concepts. Furthermore, Sisson et al. [122] presented limited initial evidence of using gratitude to improve creativity to generate wind turbine repurposing ideas.

3.3.3 Business Models for Repurposing. It should be viable to repurpose upstream components to develop downstream products from a business perspective. For example, the process of repurposing electric vehicle batteries for stationary energy storage applications involves (1) collecting a sufficient amount of the decommissioned batteries, (2) screening them from pack level to cell level to evaluate their condition, (3) sorting them based on their design, chemistry, support systems, and condition, and finally, (4) reassembling according to the required capability [51–53].

Building on the above example, the collecting process is critical since a sufficient number of batteries should be processed and repurposed to cover the capital investments [25]. Requirements such as reverse logistics design, cleaning and inspection capabilities, disassemblability and depth, storage availability, and testing procedures are crucial to sustain the business model [83]. The screening process looks at the decommissioned batteries from the battery pack level to the detailed battery cell level. However, there is a trade-off between the disassembly cost and the screening accuracy upon deciding the screening level from pack level to cell level [51]. The sorting process depends on product characteristics such as the dimensions, architecture, performance, safety criteria, use constraints [83], battery chemistry, voltage range, energy capacity [51], and thermal management in the battery system [64]. The reassembling process will depend on the requirements of the downstream application. Factors such as performance requirements, spatial requirements, durability, reliability, usability, intellectual property issues, economic feasibility (short term or long term), regulations, and environmental aspects come into consideration [77,83].

4 Discussion

The proactive and reactive strategies discussed could enable repurposing by overcoming five barriers. The barriers are transporting the decommissioned system; unpredictability in the upstream component availability; expensive, complicated, and time-consuming disassembly and screening process; insufficient information on upstream component design and health; and identifying the downstream opportunities. Transporting the decommissioned systems to a central location to be repurposed could be costly and inefficient. Large-scale systems like wind turbines can be repurposed to meet the requirements of their local ecosystem. For example, repurposing an offshore wind turbine foundation as an artificial reef [91]. It prevents costly removal and transportation of the foundation. Transporting only the required modules to be repurposed can be facilitated through modular design. Other modules can be transported for their decommissioning options, such as remanufacturing, recycling, or disposal. Data-driven innovative reverse logistic strategies are also essential to plan transportation.

If the availability of upstream components is unpredictable, creating commercially viable repurposing strategies is difficult. Complex systems are generally lower in count than consumer products such as mobile phones, and their locations are predictable when a region (ecosystem) is considered. For example, the number of wind turbines or aircraft, their decommissioning dates, and their health can be monitored. Complex systems can be leased instead of sold to support health and decommissioning state monitoring further. Supplementing it with the region's material flow and the system's design data could support effective repurposing. Microsoft's Circular Center concept [123] aims to decommission its millions of servers and related hardware by processing them on-site with data-driven repurposing strategies. It is a great example of combining the upstream component data availability and ecosystem-focused repurposing strategies, even though they are not considered complex systems in this study.

Expensive, complicated, and time-consuming disassembly and screening processes can lead to the direct disposal of complex systems. Design for disassembly and active disassembly techniques could mitigate this barrier. If standard repurposability metrics and decision support frameworks can be utilized to identify the best repurposing opportunities, even destructive disassembling could be performed, bypassing the time-consuming disassembly processes. The above strategies will depend on the information regarding the system's health, remaining useful life, and design. Therefore, embedding design data identifiers in the systems and access to health monitoring data is crucial for successful repurposing strategies. However, standard repurposability metrics that rely on information, such as postdecommissioning nondestructive testing, could overcome the insufficient information barrier. For example, testing wind turbine blade parts or aircraft structural components using ultrasonic or X-ray methods could provide data on their repurposability.

To repurpose a complex system, we require downstream applications. We identified only two well-researched applications: wind turbine blades and electric vehicle batteries, which were discussed in 86% of the repurposing papers. Therefore, methods to find repurposing opportunities are required. For example, Kwon et al. [124] used visual similarity to find repurposing ideas for decommissioned wind turbine blades. Expanding the available options through similar methods can support repurposing as a complex system decommissioning strategy.

We identified research gaps to be addressed to improve the effectiveness of the reactive and proactive strategies. The modular design, ease of disassembly, and decision support strategies often focused on maintaining the original function and the context, i.e., refurbish/

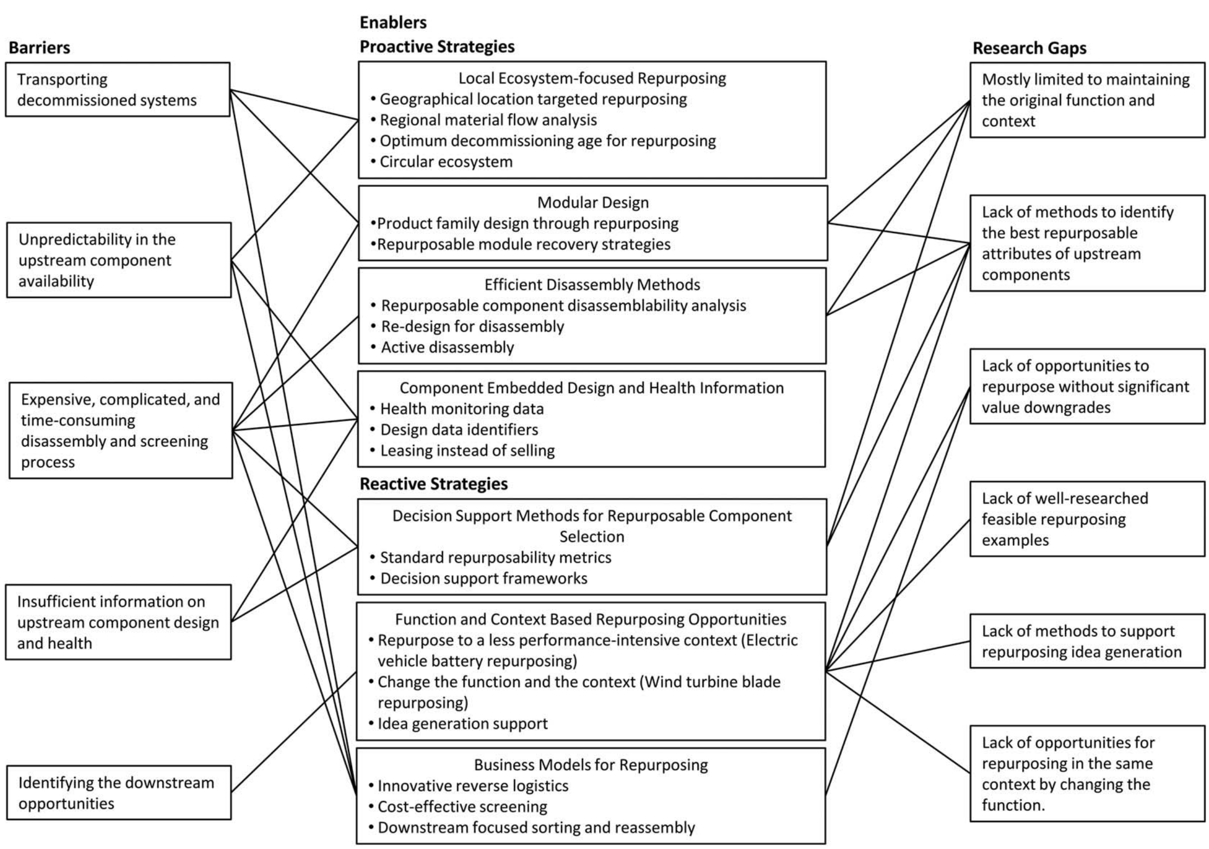

Fig. 4 The reactive and proactive strategies, the barriers to repurposing, and the research gaps to be addressed to improve the strategies

remanufacture. Only 14% of the discussed strategies included repurposing. However, including repurposing in those strategies could improve their outcomes. The components might not be suitable for performing the same function in the same context. However, changing the function, the context, or both could open new opportunities. For example, structural and geometrical attributes of a high-performance complex system component could still be utilized even though its main functionality is obsolete. Therefore, methods are required to identify the remaining functional and physical repurposable attributes. For example, a wind turbine blade is designed with high-performance material and structural, aerodynamic, and ingress protection attributes. Therefore, methods are required to efficiently utilize these attributes before moving to low-value repurposing applications such as furniture. Suppose only the context is changing when repurposing; in that case, it becomes an optimization problem between the level of functionality of the upstream component and the requirements of the downstream product. Furthermore, changing the function and the context opens many repurposing opportunities. Similarly, repurposing within the same context by changing the functions could bring unique benefits since the components could be most valuable in the context for which they were designed. However, we did not identify such examples in this review. Finding the best option out of potentially infinite possibilities could be challenging. Therefore, we need methods to find feasible repurposing opportunities. The resulting opportunities could follow similar processes addressed under the two well-researched examples and increase the benefits gained through repurposing.

Figure 4 provides a summary of the entire review. It outlines the barriers to repurposing and summarizes proactive and reactive strategies that can help overcome these barriers. Furthermore, the research gaps that must be addressed to enhance the strategies are identified and linked to the strategies.

5 Conclusions

The objectives of this review were to identify reactive and proactive strategies that can enable repurposing and identify the research gaps hindering those strategies. First, we broke down the concept of repurposing into four pathways by the component's function and context. We analyzed 104 articles published in the last decade based on the pathways and identified four proactive and three reactive strategies enabling repurposing. The proactive strategies include local ecosystem-focused repurposing, modular design, efficient disassembly methods, and component-embedded design and health information. The reactive strategies are decision support methods for repurposable component selection, function and context-based repurposing opportunities, and business models for repurposing.

Research gaps such as limiting the strategies for maintaining the original function and context, lack of methods to identify the best repurposable attributes of upstream components, lack of examples to repurpose without significant value downgrades, lack of well-researched feasible repurposing examples, lack of methods to support repurposing idea generation, and lack of opportunities for repurposing in the same context by changing the function need to be addressed to improve the identified reactive and proactive strategies.

The results indicate that repurposing has a lot of untapped potential as a complex system decommissioning strategy. Repurposing could be utilized alongside refurbishing and remanufacturing to enable multiple lifecycles for decommissioned components. Therefore, the maximum benefits can be obtained before the recycling and disposal stages.

Our future work will focus on improving the reactive strategy, *repurposing pathway-based downstream opportunities* since it has five connected research gaps that can be addressed through design methods. Focusing on a reactive strategy can start solving the immediate issue of handling the current waste and give recommendations for proactive strategies. The root cause for the research gaps is that we do not know the end goal when repurposing (I have this product, what do I repurpose it to?). Therefore, we need design methods or guidelines to systematically identify and break down a component's repurposable attributes. The identified attributes can be used to find repurposing opportunities through idea and concept generation. The concepts should be evaluated for feasibility and commercial viability.

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Conflict of Interest

There are no conflicts of interest.

Data Availability Statement

The datasets generated and supporting the findings of this article are obtainable from the corresponding author upon reasonable request.

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