

Sustainability and the waste hierarchy for machines

Part 2 – Machine Components





Executive Summary

This is the second in a connected two-paper series on sustainability and circularity in machine design. Paper 1 focused on the design of machines through case studies across different sectors. This second paper addresses the specific role of materials, component selection, integration and emerging technologies – particularly digital monitoring – in shaping the sustainability and circularity of machines and their constituent parts. It is recommended that Paper 1 is read first, as it introduces key concepts and higher-level strategies that are further explored here.

This paper sets out the necessary background before examining four broad categories of machine components – looking in detail at how materials selection, surface treatments, joining methods, design for disassembly and monitoring technologies affect circularity across the full component and machine lifecycle. Drawing on current industry practice, academic literature and technical input from experts, it explores both barriers and opportunities, assessing where interventions can deliver the most meaningful environmental and economic gains.

The design and integration of components have cascading effects across downstream lifecycle stages. This means that future-focused design decisions – from selecting more recyclable materials to improving modularity or incorporating condition monitoring – can reduce environmental impact, support resource efficiency and extend machine life. With around 80% of a product's environmental impact determined at the design phase [1], this paper connects detailed findings at the component level to broader concepts such as the 9Rs hierarchy introduced in Paper 1, showing where aligned actions can drive system-wide benefits.

Finally, the paper presents a set of strategic conclusions and prioritised recommendations for government, industry and academia. It identifies areas where targeted research, investment and policy could accelerate progress, as well as highlighting high-impact directions for future study.

Nomenclature

DfD	Design for Disassembly
DPP	Digital Product Passport
DOF	Degrees of Freedom
EoL	End of Life
EU	European Union
FMEA	Failure Mode & Effect Analysis
GHG	Greenhouse Gas
LCA	Lifecycle Analysis
MTC	The Manufacturing Technology Centre
MTP	Module Type Package
NMIS	National Manufacturing Institute Scotland
POL	Process Orchestration Layer
RaaS	Robotics as a Service
SME	Small Medium Enterprise
TCoO	Total Cost of Ownership
UK	United Kingdom
WEEE	Waste Electrical and Electronic Equipment

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1 Introduction

1.1 Background

Increased sustainability means fewer greenhouse gas (GHG) emissions and reduced pollution into the environment. The UK has several sustainability and economic initiatives, including the aim of achieving net zero emissions by 2050 – while balancing the need to develop the nations key growth sectors, such as advanced manufacturing. However, manufacturers are facing increased input costs and competition due to global events while simultaneously struggling to improve sustainability metrics.

One well-understood way to achieve sustainability and reduce input costs is by lowering energy consumption, since this directly contributes to emissions. Another widely discussed strategy is the implementation of a circular economy model – illustrated in Figure 1 [2]. The aim of this model is to address climate change and other global sustainability challenges “by decoupling economic activity from the consumption of finite resources” [3] .

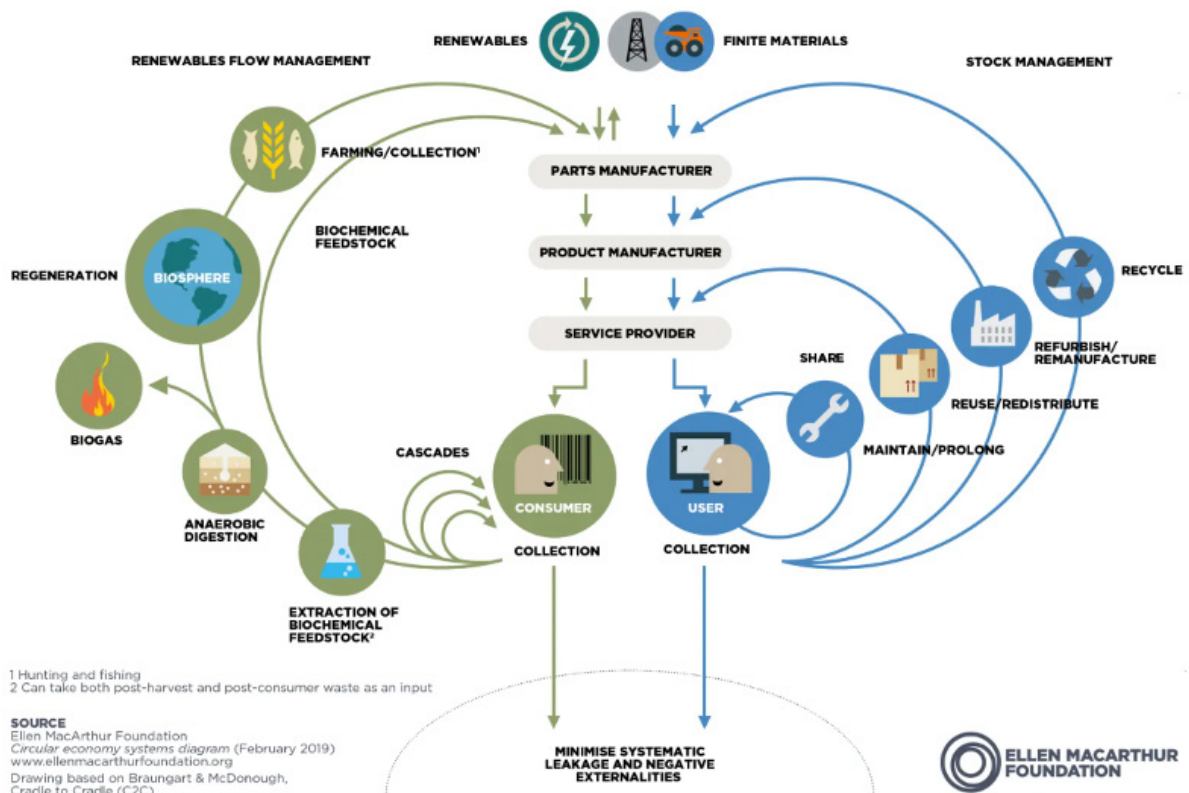


Figure 1 - Ellen MacArthur Foundation (2019) Circular economy systems diagram (Butterfly Diagram). Available at: <https://www.ellenmacarthurfoundation.org/circular-economy-diagram>.

The manufacturing sector will be the cornerstone of the UK's transition to a more circular economy. Increased circularity will bring with it the environmental, economic and strategic benefits outlined in the previous paper.

Less attention is given to machines compared to the products they produce. Industrial machines are often a long-term investment, presenting an opportunity to minimise total cost of ownership (TCoO) and environmental impacts during operation and as they reach end of life (EoL). This paper explores how the design and implementation of machine components can better incorporate sustainability and circularity.

Product lifecycles have been getting shorter [4] as globalisation and free trade have spread. This requires manufacturers to consider the modularity – and therefore flexibility – of their production lines. This is often, but not exclusively, driven by the following factors:

1. “They don't make them like they used to” – caused by cheap imports from rapidly industrialising nations, such as China, and a general race to the bottom on price
2. ‘Throw-away’ culture and premature obsolescence [5] driven by linear business models [6]
3. Shorter technology development cycles [7], evidenced by shrinking timescales between ‘industrial revolutions’, making it much harder to design with long lifespans

The rise of onshoring and global protectionism, the shift to more circular business models, and increased environmental awareness, are likely to reduce the prevalence of the first two drivers.

It is the third and final driver that will not only persist but accelerate over the coming decades. Companies are reviewing product lines more frequently and as a result the service lives of the machines making them are getting shorter. The adoption of AI and automation will only accelerate this further. Modularity in design – enabling repair and upgrade – is therefore crucial, because otherwise the performance of machines and products will not last. This requires attention to components, as their design and selection influences the sustainability and circularity of individual components and the entire machine.

When it comes to the design and selection of components and new machine technologies, the most relevant pieces of legislation are the updated EU Machinery Directive, existing WEEE Directive, and the EU's upcoming Ecodesign for Sustainable Products Regulation (ESPR).

For more details see the introductory section of Paper 1.

1.2 Methodology and Paper Structure

This paper used the three methods listed below to collect evidence (with the limitations outlined in Paper 1):

1. Academic literature
2. Online articles
3. Discussions based on industry and survey responses

Design choices should ideally be informed using a Lifecycle Analysis (LCA). This paper draws on the available literature and data to present broad conclusions about how certain component design and technology features can influence the overall sustainability and circularity of machines. These conclusions can guide smaller, component-level design choices where an LCA would be cost-prohibitive. Accordingly, this paper assesses the environmental impact of component design within machines in two ways:

1. How can trade-offs related to component design, selection, and integration increase the sustainability and circularity of machines during operation?
2. How can we apply circularity to components to improve their environmental impact over the machine's entire lifecycle?

For the second point, it is important to note that interventions may mean designing individual components so they move down

the waste hierarchy (discussed in Table 1), either to increase circularity or to improve the sustainability of the machine as a whole.

1.3 Frameworks and Strategies

This paper breaks the topic of machine components into the three broad topics: Materials (Section 2), Component Technology, Design, Selection and Integration (Section 3), and Monitoring Interventions (Section 4). Their impact in brief:

- Material selection of individual components is not made in isolation; it involves trade-offs between cost, functionality and environmental impact.
- Machine components are not isolated; their selection and design influence sustainability and circularity through the full machine and component lifecycle.
- Interventions that monitor the state of individual components can not only prevent critical failures and provide longer machine service lives, they can also provide insight into how the design has influenced the machine's sustainability (e.g. energy use) during service.

These three topics can significantly impact circularity and the sustainability of machine performance (e.g. energy consumption and pollution). They are discussed in more detail and related to the waste hierarchy in Table 1 below.

Table 1 – Mapping the waste hierarchy strategies discussed in paper 1 to component level interventions

Broader Strategy	R Strategy	Interventions
Smarter Machine Use & Manufacture	Refuse	<p>The following methods can be influenced to some extent by the selection, design and technology of components:</p> <ul style="list-style-type: none"> Remove the need for certain products the machine produces and thereby remove the need for a machine Remove the need for certain machines in a production line via top-level changes to production lines Design machines capable of producing products that fit within a circular economy or increase sustainability in another area of the economy Design machines robustly enough so that they are less likely to be replaced by newer, better-performing models Design machines that use components that have been recirculated
	Rethink	
	Reduce	
Lifespan Extension of Machine or Components	Reuse	<ul style="list-style-type: none"> Using durable materials, good element selection and machine design practices, and monitoring interventions can ensure: <ul style="list-style-type: none"> Potentially reusable machines last longer Potentially reusable components last longer
	Repair	<ul style="list-style-type: none"> Monitoring interventions can help: <ul style="list-style-type: none"> Predict when repairs are needed before any kind of critical failure Quickly diagnose what needs repairing Material selection can help ensure: <ul style="list-style-type: none"> Components themselves can be repaired (e.g. welding) Good element selection and design can ensure: <ul style="list-style-type: none"> Critical to repair and wear components are accessible The right parts fail or wear
	Refurbish	<ul style="list-style-type: none"> Case studies in Paper 1 show that refurbishment will involve disposing of many of the components discussed in this paper. Good selection and design of machine components and monitoring interventions can ensure: <ul style="list-style-type: none"> Critical components are accessible for refurbishment, upgrade or replacement so machines can continue to have a competitive function Likely-to-be-replaced components use compatible interfaces. Critical functions are not damaged when the machine reaches EoL as wear is concentrated on specific components
	Remanufacture	<ul style="list-style-type: none"> Similar to refurbishment, but requires testing and recertification so machine or component can be sold with a warranty.
	Repurpose	<ul style="list-style-type: none"> Component selection and design can enable some aspect of configurability Material selection can ensure enough component durability to enable the machine/component to function even if its performance is hampered
Useful Application of Materials	Recycle	<ul style="list-style-type: none"> Material selection and mix effects the economic and technical feasibility of both recycling and recovery
	Recover	

Similar to Paper 1, to connect detailed aspects of design and technology to broader ideas, this paper uses tags throughout for the following concepts:

- Key strategies in the waste hierarchy (Table 1 above) - **Blue**

- Key stages in a machine's life (Figure 2 below) - **Yellow**
- Design characteristics that enhance sustainability and circularity (Table 2 below) - **Red**

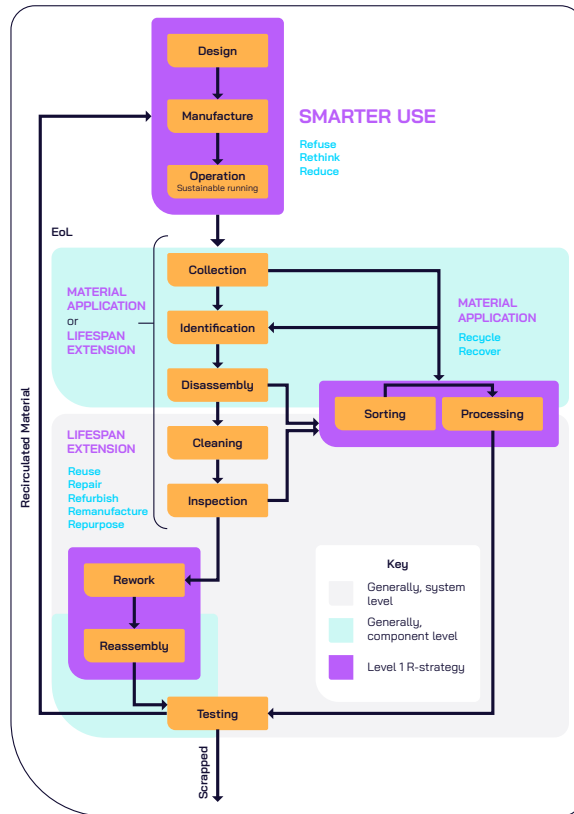
















Figure 2 - The machine lifecycle stages and the relevant waste hierarchy strategies

Table 2 - Full list and explanation of machine and component design characteristics and features

Icon	Design tags	Machine life stages	Explanation
Machine-Level Characteristics			
	Traceability (appears twice)	<ul style="list-style-type: none"> • Identification • Inspection • Test 	This can occur at the component and machine level and refers to the user's ability to quickly assess what part or machine they are working with and if modifications have been made
	Durability (appears twice)	<ul style="list-style-type: none"> • Operation 	The total service life of a component or machine
	Accessibility	<ul style="list-style-type: none"> • Disassembly • Reassembly • Inspection • Cleaning 	The ability to access components with the necessary tools



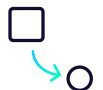



	Modularity	<ul style="list-style-type: none"> Disassembly Reassembly Inspection 	Individual modules that are clustered together and can be removed [8]
	Standardisation	<ul style="list-style-type: none"> Disassembly Reassembly Inspection 	The use of standard components that require standard tools
	Configurability	<ul style="list-style-type: none"> Operation Disassembly Reassembly Inspection 	The ability to alter a machine's parameters, e.g. to process a different size or geometry
	Redundancy	<ul style="list-style-type: none"> Disassembly Work 	The prevention of catastrophic machine failure via multiple sacrificial or wearable points of failure before a critical machine component is impacted
	Favourable Material Mix	<ul style="list-style-type: none"> Operation Sorting Processing 	The mix of different materials selected allows for material recovery at EoL and doesn't lead to premature component failure
	Digitally Monitored	<ul style="list-style-type: none"> Operation Inspection 	Using sensors and other digital tools to monitor the machine's health and key parameters
	Energy Efficient	<ul style="list-style-type: none"> Operation 	A design with energy use in mind and can compete with comparable machines on the metric of consumption
Component-Level Characteristics			
	Traceability (appears twice)	-	-
	Durability (appears twice)	-	-
	Residual Life	<ul style="list-style-type: none"> Rework Reassembly 	The useful life left in a component once it has separated from its constituent machine – differs to durability as the part needs to be useful and function in a new scenario
	Efficient Material Use	<ul style="list-style-type: none"> Manufacture Operation 	Component design that minimises material volume and weight, which can impact material depletion as well as efficiency and performance of the machine in service
Component Design Features			
	Material Selection	<ul style="list-style-type: none"> Inspection Rework Test Sorting Processing 	The selection of material can enable long service lives for components and/or enable material recovery at EoL
	Geometry	<ul style="list-style-type: none"> Disassembly Cleaning Rework Reassembly Test 	Geometry that enables long component service life and/or does not hinder the EoL stages (e.g. Disassembly) necessary for increased circularity
	Surface	<ul style="list-style-type: none"> Cleaning Inspection Rework Sorting Processing Test 	Surface features can make it economically and technically feasible to move components up the waste hierarchy at EoL, and careful design can help prevent failure in service

2 Materials Technology

Material Selection is intrinsic and affects machine component sustainability and circularity at all levels. This section discusses the options designers can consider to limit a machine’s environmental impact.

Table 3 lays out broader ideas that apply across material groups and shows how they relate to the **Level 2 R** strategies.

Table 3 – How materials technology and selection can be used to implement the waste hierarchy strategies

Component Category	Component Purpose and Description	
Reduce	Use novel manufacturing methods to produce components with reduced material quantities (e.g. topology optimised additively manufactured components)	
Repair	Use a material Surface that can be welded or is suitable for other forms of Rework	
Reuse and Repurpose	Select materials with high Durability for components that are likely to have large Residual Life (e.g. large steel machine structures)	
Remanufacture and Refurbish	High-value materials, if selected, are more economical to preserve	
Recycle	Select materials that can maintain their properties after recycling. (Note: only around 2% of plastics globally are currently recycled this way)	
Recover	Use materials or a Material Mix that are economical to incinerate (e.g. waste plastics have a high calorific power of 43 MJ/kg [9] and incineration can be combined with emission capture systems)	

Designers can mitigate the uncertainty around the exact EoL process by choosing materials that have many overlapping EoL possibilities (Figure 3), prioritising materials applicable to strategies higher up in the waste hierarchy.

For example, steel is a material that can be used across many of the waste hierarchy strategies.

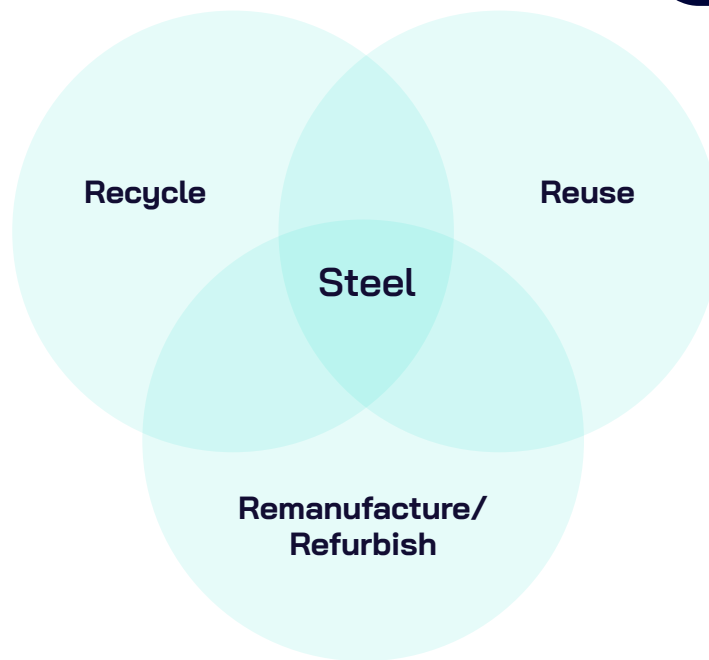


Figure 3 – Represents a material being applicable to many waste hierarchy strategies and therefore offering significantly increased potential for circularity

Looking ahead, more data and future developments in the subject area will enable further improvements in sustainability and circularity for machine design. The two material types most relevant to machines – and therefore the focus of this paper – are metals and polymers. The enhanced properties provided by more exotic materials (e.g. ceramics and composites) may offer full lifecycle benefits via more **Energy Efficient** designs, more durable machines (e.g. self-cleaning materials), and by enabling the manufacture of more sustainable and circular products. However, these materials are currently beyond the scope of this paper.

2.1 Polymers

Advancements in polymers are being driven by demands for more sustainable consumer products and packaging. However, they remain particularly relevant to certain machine

components, such as rubber seals and plastic journal bearings. There has been considerable criticism of the effectiveness of **Recycle** strategies for plastics, with 85% of plastic packaging worldwide ending up in landfill [10]. Criticisms include poor circularity due to the limited number of times a plastic can undergo ‘primary’ recycling, the lack of traceability regarding how many times polymers have been recycled, and difficulties in **Sorting** between different polymers and filtering out contaminants [11]. However, most of this polymer waste is generated from consumer products made by machines, rather than from the machine components themselves. For example, lightweight, multi-layered single-use packets constitute around 40% of the world's plastic packaging, but in the US only 2% of this packaging is recycled.

If it benefits machine performance to select a single-use polymer blend over a more recyclable polymer for a machine component, this remains the best option. The machine’s end function is more important

than the recyclability of its components. If a machine can produce more circular packaging options or products that enable sustainability in another area of the economy, then poor circularity for the few plastic machine components utilised are unlikely to positively tip the scale (a similar conclusion was reached in Paper 1). Given the low cost and weight of polymers, it is also important to consider the potential benefits of using plastics for moving components from an **Energy Efficient** design perspective.

There has been an increase in the capabilities of polymer machine components, and so the adoption of these components is expected to grow (the plastic bearing market is set to grow 3% annually until 2033 [12].) When designing or selecting polymer components, several broad **Material Selection** ideas apply, most of which focus on **Recycle** strategies:

- Limit the use of polymer blends (**Material Mix** within a component) that do not have well-established separation techniques [13]
- Ensure a compatible **Material Mix** between different components (e.g. PET and PE are considered well suited for recycling [14] but are severely limited when mixed with other plastics)
- If incompatible mixes are necessary, select plastics where relevant compatibilisers and upcycling additives are close to commercialisation [15]
- Limit the use of coloured additives, particularly those that use carbon to make a black pigment in plastics [16]
- Minimise certain thermosetting polymers (e.g. epoxy) that cannot be mechanically recycled [17]
- Choosing plastics that are not widely used can limit the possibilities of at EoL, as technology development is more likely to focus on widespread materials (e.g. 85% of global plastic production comes from PE, PP, PVC and PS thermoplastics [18])
- There are biodegradable and chemically degradable options, although these often do not have the required properties

The points above are not meant to be rigid rules. For example, some thermosets (does not soften when heated) are traditionally thought of as difficult to **Recycle** compared to thermoplastics [19], but they also offer greater **Durability**. Wider thinking also considers that plastic can reduce component cost (by 25-50%), and these savings may ultimately be invested in increasing sustainability and circularity in other, higher-return areas – such as **Energy Efficient** design.

2.2 Metals





As metal constitutes the majority of machine components, it is discussed frequently throughout this paper and will therefore not be expanded on separately here.

3 Component Technology, Design, Selection and Integration

In this paper, machine components are separated and discussed in the four broad

categories established in Paper 1 and set out in Table 4 below.

Table 4 - Component categories referred to in this paper

Component category	Component purpose and description	Example image
<p>COTS (Commercial Off-The-Shelf) components purchased from third-party manufacturers [20] [21] [22]</p>	<ul style="list-style-type: none"> COTS items are introduced to keep cost down and are convenient to replace. They are generally low-value, high-volume items. Examples: fasteners, spacers and shims, washers, gaskets, common joints, pipe fittings, couplings and collars, keys, bearings, springs, seals, gearboxes, pumps and motors. 	
<p>SOTS (Specialised Off-The-Shelf) components are also purchased from third-party manufacturers, but with more high-value niche applications</p>	<ul style="list-style-type: none"> High-value, low-volume parts used for specific industries and machine types. Examples: specialist light sources (e.g. X-rays), feed systems used in the packaging industry. 	
<p>Bespoke manufactured components that have to be fabricated</p>	<ul style="list-style-type: none"> They are for a specific purpose with specific geometries, surface finishes and treatments. Examples [23]: formed, machined, cut, 3D-printed or moulded parts. 	
<p>IEM (Intelligent Equipment Modules), i.e. electrical control systems and interfaces that are used in automated machinery</p>	<ul style="list-style-type: none"> Examples: PLCs (Programmable Logic Controllers), machine communication interfaces, input/output ports, memory modules, actuators and sensors. 	

3.1 Intelligent Equipment Modules (IEM) Components

Machines and components are increasingly communicating with one another as variations of the IoT concept (the ‘Internet of Things’ also discussed further in Section 4) [24] are ever more adopted across industry. Traditional control system interfaces often require reconfiguring or replacing of controls components when production line alterations or machine upgrades are required [25] (a conclusion reached in Paper 1).

A potential solution to the issue of compatibility between manufacturers is the adoption of industry standards, such as those developed by NAMUR in 2014. These include the MTP (Module Type Package) standards [26] [27], which were developed for IEM components. The MTP standard introduces a manufacturer-independent interface describing the functions of a module – for example, how individual actuators within a set can extend or retract in a specific order and distance to perform a given function. The module’s internal control system implements the function by delegating a task; as a result, “the higher-level control system doesn’t need to know how the module implements the function, just that it is being done”. A Process Orchestration Layer (POL) is used to send commands to the module, and since these commands are standardised across manufacturers, any similar module can be controlled without altering the POL.

When feasible, designers should select IEMs that meet standards like these because the enhanced **Modularity** and **Standardisation** brings the following benefits:

- Environmental – Ensures upgradeability, reducing the number of machines made redundant due to software issues or a

lack of compatibility between IEMs and controls components (an issue frequently observed in the case studies in Paper 1)

- Economic – Manufacturers can be more supplier-agnostic, mitigating against shortages of key strategic components
- Economic – Faster time to market and more flexible production lines

The importance of these standards is illustrated in an example from John Deere Tractors [28]. The company was accused of using the increasing prevalence and complexity of IEM components to prevent farmers from being able to **Repair** their own vehicles (although it is worth noting that some manufacturers claim repairs made by unqualified individuals pose a significant safety risk).

This section highlights the role industry standards can play in encouraging **Modularity**. It is important that these types of standards are expanded and enforced where economically viable – either by industry through procurement practices or government through regulation and legislation – and that new standards for other component types are developed.

3.2. Special Off-The-Shelf Components

The importance of higher-value SOTS components – particularly their **Configurability** to a machine’s function and therefore service life – is established in the case studies of Paper 1. Ensuring **Modularity** and **Accessibility** in machines containing SOTS components (e.g. high-value light sources) will prevent obsolescence and improve the economic feasibility of **Disassembly** at EoL.



3.3 Lifespan Extension of Metal Components

Much of the literature and media attention focuses on the **Recycle** element of components. However, further research could be used to determine the feasibility of **Lifespan Extension** strategies, which rank higher in the waste hierarchy. When looking to extend the lifespan of components with **Durability** and potential **Residual Life**, one challenge is recertifying those components in a second service life to meet the same requirements as new components – particularly in highly regulated sectors such

as aerospace [29]. However, this is generally not a limiting factor for most other sectors.

This section focuses on aluminium and steel components. These metals often make up most of a machine, are energy-intensive to extract and manufacture, and are highlighted by the EU as key materials for increased circularity. Given that both materials are considered durable (steel components have average lifespans of 35 years) and recyclable (70% of steel in Europe is recycled), the next logical step to increasing circularity appears to be **Lifespan Extension**. The strategic importance and relevance of these metals to machines is highlighted in Table 5 below.

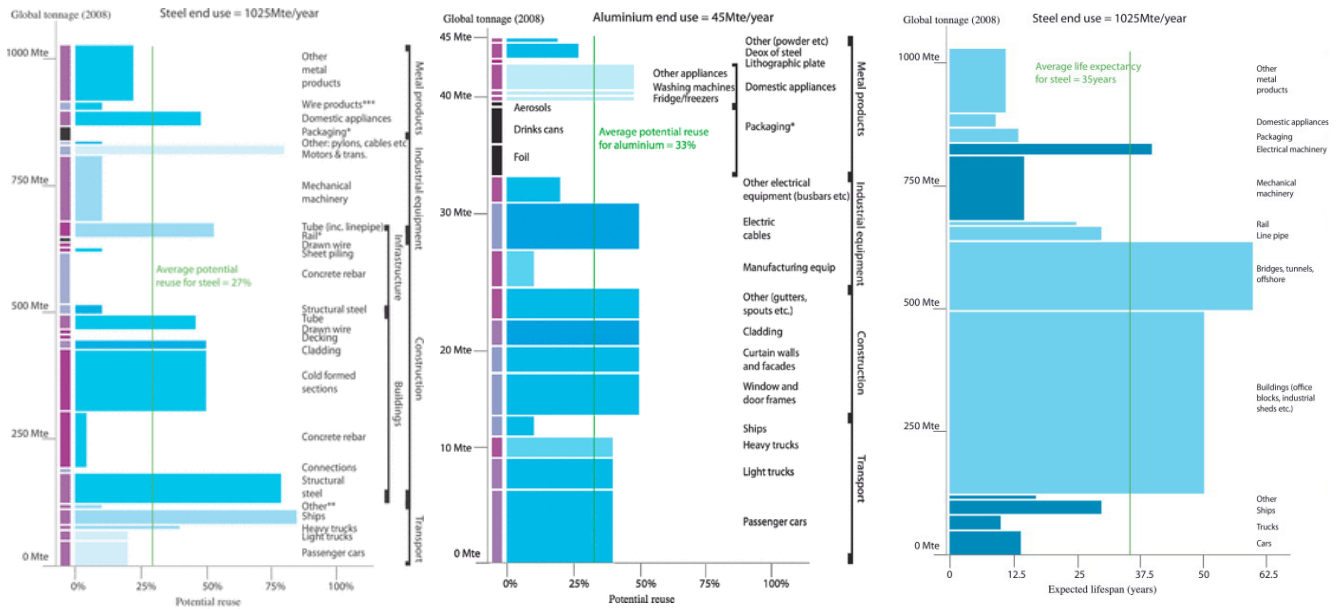
Table 5 – Strategic importance of aluminium and steel and why they are relevant to machine design

	Strategic Importance	Relevance to Machines
Steel	Steel is a major input for a large section of the UK economy. Its price is a driver of inflation, while producer decline presents a risk to military supply chains [30]	Steel is a versatile and widely used material in machinery [31], offering strength, heat resistance, corrosion resistance and low porosity
Aluminium	Aluminium production is a sector being hampered by energy prices, decarbonisation and competition. It has now been recognised as a critical mineral [32] and industry [33] for the UK, with significant emphasis on recycling	Aluminium alloys [34] are lightweight, malleable, corrosion resistant (thanks to a self-healing oxide film) and conductive

3.3.1 Opportunities and Challenges

According to one study [35] on component “reuse”, when it comes to machinery and manufacturing equipment, the assumed “reuse potential” (the proportion of components from that sector that are

potentially eligible for Lifespan Extension) for steel and aluminium components is lower than the cross-sector average (27% and 33%), sitting at ~10% (Figure 4).



How the components could be reused?

Remanufacture ■ Reform ■ Relocate ■ Cascade ■

What constrains the remaining components being resused?

Degraded ■ Inferior ■ Incompatible ■ Irretrievable ■

Key only applies to the two left charts

Figure 4 - Daniel R. Cooper and Julian M. Allwood (2012) Reusing steel and aluminum components at end of product life. Environmental Science & Technology, 46(18), pp. 10334–10340. Available at: <https://pubs.acs.org/doi/full/10.1021/es301093a>.

The same study identified four main reasons for a component to not be eligible for Lifespan Extension. The first two reasons would apply in any circumstance – even if the user was donating components for “reuse” from one machine to another identical machine, the component would still be unsuitable.

1. **Degraded** – the component is worn or damaged
2. **Irretrievable** – the component is destructive or uneconomical to extract

The remaining two reasons relate to compatibility with new machines, comparing existing components against newer technology:

3. **Inferior** – the component does not meet the required performance standards
4. **Incompatible** – will not function in new machines (e.g., uses non-standard sizes or has an unknown material specification)

Table 6 (data taken from the previously mentioned study) shows that most steel and aluminium machine components at EoL are “incompatible” with the latest machinery. Addressing this challenge is largely dependent on measures discussed in Section 3.3.2. Table 6 also shows that a large proportion of steel components are considered “irretrievable”, reinforcing the importance of applying ‘design for disassembly’ principles in machine design and developing more advanced EoL technologies.

Table 6 – Main reasons from study on why lifespan extension for steel and aluminium components was not feasible

Relative to Before Product Fabrication	Relative to New Components
Degraded: 23.8% steel; 27.1% aluminium	Inferior: 1.3% steel; 27.1% aluminium
Irrecoverable: 30.0% steel; 2.1% aluminium	Incompatible: 46.9% steel; 43.8% aluminium

Important notes and caveats:

- The viability of the **Lifespan Extension** strategies proposed in the study is dependent on external factors such as market conditions – and therefore price
- For these findings to be actionable at the design stage, more in-depth research would be required on the impact of factors like alloy composition, treatments, coatings, residual stresses, fatigue and component age
- Additional research is required to confirm the validity of the statistics discussed

Development of new EoL technologies for **Inspection**, **Rework**, and **Testing** of old metal components may invalidate these findings

3.3.2 Reforming of Bespoke Metal Components

According to Figure 4 in the previous section, the majority of both steel and aluminium components are best suited to “reforming”, a type of **Rework**. This insight could potentially

inform design practices, with the study finding that sheet metal components (typically brackets in a machine context) are particularly well suited.

However, the feasibility and benefits of sheet metal reforming are likely to depend on the application and nature of the component. Residual stresses and localised thinning areas are produced close to bends during sheet metal formation. The presence of areas characterised by “limited residual formability” likely requires processes that are capable of local forming actions that impact only specific areas of the component. Currently, there are few developed processes – and notably little research on hybrid processes [36] – that are well suited and have been tested in the literature. However, one such process (shown in Figure 5 [37]) is Single Point Incremental Forming (SPIF) and has been shown to work for 0.5mm thick AA-5754 H22 aluminium sheets.

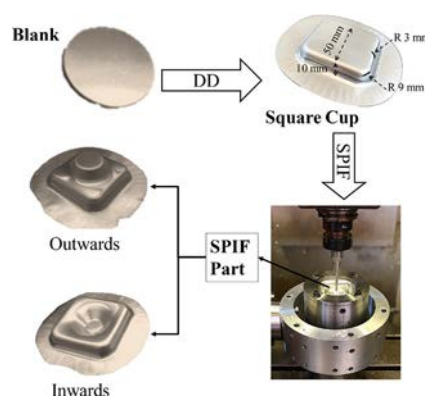


Figure 5 - A standard milling machine can utilise a blunt round tool to slowly press down and reform the metal along its toolpath - Ingarao, G., Zaheer, O., Campanella, D. and Fratini, L. (2020) Re-forming end-of-life components through single point incremental forming. Manufacturing Letters, 24, pp. 132–135. Available at: <https://www.sciencedirect.com/science/article/abs/pii/S221>

Ideally, the **Geometry** of these components might allow them to be **Reused** or **Repurposed** without reforming, but this will not always be feasible. There are a few factors in the design of these components that may influence how easy they are to

Rework:

- **Geometry** of relief and notches (required when bending sheet metal)
- **Geometry** and quantity of hem and curl features, which would not benefit a potentially reformed version of the component
- Whether the **Geometry** allows the part to be mounted for a reforming process
- Available areas with residual formability (depending on the magnitude and location of residual stresses created during the original manufacturing process)
- Material properties (e.g. grain direction and K-factor) of aged component
- Part condition at EoL – if a part experiences too much fatigue throughout service life it may not be strong enough to be used again
- Protective coatings (discussed further in Section 3.3.3.2) that can prevent degradation

It's important to note that designing specifically to ensure **Residual Life** appears to be a high-risk, potentially low-reward strategy, as there is no guarantee it will be economical to reform the component. For example, Machine Tools Technology (MTT) has confirmed that they typically find it more economical to manufacture a new sheet metal part rather than reform an existing one. Additionally, this topic has not been comprehensively studied and further work on reforming technology is needed before design recommendations can be substantiated.

3.3.3 Corrosion and Extending Component Service Life

Case studies in Paper 1 showed that when consumable components require fewer replacements, there is a worthwhile reduction in materials demand. Additionally, more resilient components may assist at the **Identification** stage by protecting component

markings and **Residual Life** in steel structures which was shown to enable the repeated **Lifespan Extension** of old machines.

Designers typically aim to avoid three main categories of degradation [38] [39]:

- Mechanical wear (propagation of cracks) and thermal degradation – mechanisms include yielding and fatigue, erosion, creep, and thermal decomposition
- Electrochemical corrosion – charge transfer reactions due to oxidation and reduction
- Less commonly applicable mechanisms, such as neutron radiation [40], relevant only to specific industries (not discussed)

In the design process, it is important to consider that these more complex effects (e.g. stress corrosion [41]) can act simultaneously and synergistically to damage components, and therefore degradation mechanisms cannot always be mitigated in isolation. Although theoretical calculations are imperfect (with up to 20% variation from real-world values for adhesion and abrasive wear [42]), using established machine design practices – which directly affect loading patterns and operating temperatures – alongside other established techniques (e.g., heat treatment [43]) generally prevents the mechanisms discussed above. Therefore, the remainder of this section focuses on preventing component corrosion and its impact.

3.3.3.1 Designing Out Corrosion

Electrochemical corrosion is the primary source of degradation for metal components [44]. Beyond sustainability and circularity, corrosion poses a significant safety [45] and economic threat – for example, metallic corrosion cost businesses in China \$310bn (3.34% of GDP) in 2014 [46]. The formation of rust can also cause damage to non-corroded moving components, as rust particles flake off and contribute to abrasive wear [47]. Fortunately, corrosion prevention methods can extend service life by up to 250% [48] depending on material and environment.

1. Straight oxidation – occurs wherever oxygen is present (except in precious metals), though the mechanisms below occur at a faster rate
2. Galvanic corrosion [49]– occurs when two metals with different electrode potentials are in contact in the presence of an electrolyte (e.g. water), causing one metal to act as an anode and the other a cathode
3. Differential aeration corrosion [50]– occurs “when a metal is exposed to different concentrations of oxygen. The part of metal which is more exposed to air act as cathode and remains unaffected. The other part of the metal, which is less exposed to air act as anode and undergoes corrosion”

Galvanic corrosion is impacted by the selected **Material Mix**, while the third mechanism occurs when design features allow a water line or pitting (where dust and mud particles deposited on the surface). Therefore, the design and operator practices listed below can help prevent corrosion.

- **Material Selection** (see Section 2) will always play a key role.
- Oil-based lubricants can provide a layer of protection in addition to their primary purpose of prolonging the life of moving parts (lubricant selection comes with its own trade-offs, discussed in Section 3.4.3).
- **Geometry** should minimise **Surface** areas exposed to substances that accelerate corrosion (e.g. water, salt [51] or abrasives) – for example, by eliminating cracks and pits where metal can retain water, designing for moisture drainage, and encouraging free movement of air [52]
- Reduced **Surface** roughness can reduce the component’s ability to form pits [53]
- If corrosion is a concern for a particular component, minimise its exposure to heat as this will accelerate the chemical reaction.
- **Digital Monitoring** can also have a role to play in reducing corrosion
- Environmental measures could control exposure to oxygen, sulphur, or chlorine

However, the primary method used to protect the **Surface** of metal components (mainly from moisture and salt) is surface treatment, which is discussed in the following section.

3.3.3.2 Surface Treatments Against Corrosion

There are several main types of surface treatments outlined below:

- **Protective cladding** – bonding protective layers to the **Surface** [54] [55] [56], which can be achieved in several ways, including powder coating, physical vapour deposition and polycoating (a thin adhesive plastic applied to sheet metal)
- **Metal plating** – applying a thin layer of metal to the material **Surface**. Unlike cladding, this involves a very thin coating and can be achieved using electro-chemical, chemical, mechanical and thermal processes
- **Sacrificial coatings** – designed to oxidise instead of the underlying metal **Surface**, through both cathodic protection (e.g. galvanising) and anodic protection. This can also be achieved via an electrical connection rather than a coating
- **Corrosion inhibitor additives** – substances with a high polar attraction to the metal, forming a chemical bond with the **Surface**. These additives have a polar head and a hydrophobic tail, creating a protective film against corrosion accelerants

When assessing the suitability of **Surface** coatings for components from an environmental impact perspective, a full lifecycle approach – including the possibility of multiple service lives – should be considered. Key factors to include are:

- Any impact on **Recycle** rates [57]
- Impact of the coating process on biodiversity and water supply
- Energy use during the coating process
- The possibility of designing out the need for a coating (a consultancy-style service that could be offered by metal coating providers to remain profitable and sustainable)



Coating will play a crucial role in the sustainability and circularity of machine components now and in the future. Therefore, designers could benefit from rough LCA-based guidelines on whether components should be coated and if so, which coating methods are least impactful to the environment — a concept like that suggested in Paper 1 and Section 3.4.3.1.

3.3.4 Geometric Factors of Component Design

3.3.4.1 Metrology and Tolerancing

Metrology is a key technology area during the **Inspection** and **Testing** phase at EoL, with developments including “mechanical detection (e.g. ultrasonic flaw detection, eddy current inspection and dimension measurement) and surface repair techniques” [58]. However, further detail on EoL technology and surface technologies (e.g. repellent/slick surfaces [59]) is outside the

scope of this paper, so the remainder of this section will focus on component design.

Material Selection and **Surface** geometry are often constrained by specific industries and applications. For example, product contact in process and packaging machines often requires the use of 316 stainless steel and strict surface roughness requirements.

However, when design freedom is allowed, it is important to consider the metrology of the **Surface** [60] as this is where cracks typically begin (since it experiences the most stress and is exposed to the environment).

These features can significantly impact component life expectancy and the feasibility of machine and component **Lifespan Extension**, with design trade-offs that are difficult to quantify and highly context-specific. Some of these features are listed in Table 7 below.

Table 7 – Metrology related design features and how they can impact machine and component circularity

Features impacting failure in original service life	Large Surface roughness on moving components can cause part seizure, increased wear and increases rates of asperity break off (increasing the number of abrasive contaminants [61])
	In machine tools (and all other machines), improper shaft and housing fits can lead to excessive wear and premature spindle or shaft failure [62] - Digital Monitoring data can help predict fit behaviours under varying conditions
	A softer and harder Material Mix can be beneficial for moving components (e.g. journal bearing on a shaft), as abrasive contaminants can become trapped in the softer material and prevent three-body abrasion
Features influencing the feasibility of machine component Lifespan Extension	Tighter fits make Disassembly harder [63]
	Tighter tolerances and Surface roughness requirements make parts more valuable at EoL

When considering **Lifespan Extension**, the selected **Manufacturing** method for a part or assembly can hinder the **Rework** and **Reassembly** stages. For example, one paper [64] found it possible to **Remanufacture** or

Refurbish piston connecting rods (Figure 6) by re-machining the mating faces between the end cap and rod, followed by a re-sizing of the big-end bore (crank shaft hole).

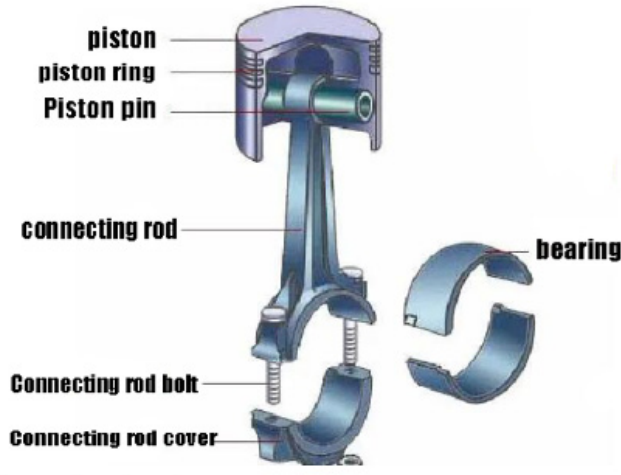


Figure 6 - Kia Motors (2025) Connecting Rod in the Engine. Available at: <https://kiamotors-portqasim.com/connecting-rod-in-the-engine/>

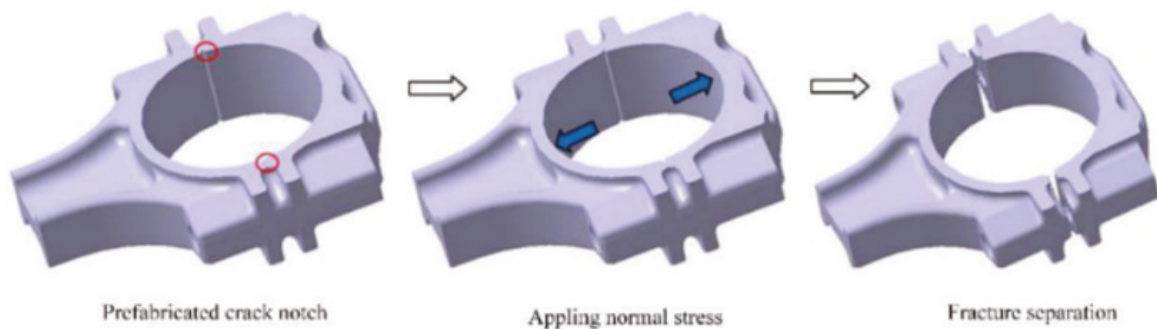


Figure 7 - Shi, Z. and Kou, S. (2018) Study on fracture-split performance of 36MnVS4 and analysis of fracture-split easily-induced defects. *Metals*, 8(9), 696. Available at: <https://www.mdpi.com/2075-4701/8/9/696>.

In contrast, rods that are manufactured via “fracture-splitting” (Figure 7) are scrapped at EoL due to their lack of a reworkable mating **Surface**. However, fracture-splitting reduces manufacturing time and cost, lowers component weight, improves **Efficient Material Use**, and enables a more **Energy Efficient** design – and given the rise of electric vehicles, the likelihood of multiple service lives is increasingly low.

3.3.4.2 Shafts and Spindles

This sub section focuses on three main areas

- How the design of shafts and shaft components impacts **Lifespan Extension**
- How design can affect shaft/spindle service life
- Shafts and spindles at EoL

Shafts and spindles can be a source of difficulty during **Disassembly** and **Reassembly** at EoL – one study [65] found that motor shafts often use more challenging joining types. **Accessibility** is a key characteristic that can be achieved through thoughtful shaft design. A less obvious example is the

inclusion of rotator provisions [66] for hand turning and visual inspection of moving parts. This would be beneficial during **Reassembly** and **Inspection**, and enable easier **Repair**, **Refurbish** and **Remanufacture** (with appropriate guarding where required).

Edge	Joining types	Access direction	Unfast rating	DFS	Tolerance (mm)	Recovery cost factor
A-C	Screw	0°	0.5	2	H8 (0.022)	0.6
B-D	Screw	0°	0.5	2	IT7 (0.018)	0.6
	Insert	90°	0.3	1	IT7 (0.013)	0.6
C-D	Bearing	90°	0.5	2	IT6 (0.012)	0.6
D-E	Interference fit	90°	0.5	2	IT6 (0.013)	0.7
D-I	Bearing	- 90°	0.8	2	IT7 (0.013)	0.7
D-K	Key	- 90°	0.5	1	IT7 (0.013)	0.7
	Insert	- 90°	0.3	1	IT7 (0.018)	0.6
G-H	Bearing	- 90°	0.5	2	IT6 (0.013)	0.7
I-J	Insert	90	0.3	1	IT7 (0.013)	0.6
J-ϕ	Bolt & nut	0.5	0.5	2	H8 (0.022)	0.6
J-L	Bolt & nut	0.5	0.3	2	IT7 (0.013)	0.6
J-M	Bearing	0.3	0.5	1	IT6 (0.022)	0.6
I-L	Insert	0.3	0.3	1	IT7 (0.035)	0.6
L-M	Bearing	0.8	0.8	1	IT6 (0.016)	0.7

Figure 8 - Fang, H.C., Ong, S.K. and Nee, A.Y.C. (2016) An integrated approach for product remanufacturing assessment and planning. *Procedia CIRP*, 40, pp. 262–267. Available at: <https://www.sciencedirect.com/science/article/pii/S2212827116001335>.

The selection and arrangement of key shaft components (such as collars, couplings, pins and keys) can have a large impact on the condition of the shaft and the ease of **Disassembly**, as shown in Figure 8 (taken from a study [67] on **Remanufacture**).

Difficulties can arise because:

- Fits or grub screws may damage the shaft.
- The removal process itself can cause damage
- Components may simply be difficult or time-consuming to remove

To assist **Disassembly**, techniques such as applying heat, vibration [68], or using “jack screws” (fasteners designed to push out press-fit parts [69]) can be employed.

The combined loading experienced by shafts and spindles [70] means that **Durability** – the ability to resist fatigue, avoid failure in service, and retain **Residual Life** – is a key

issue impacting machine circularity. The main causes of fatigue failure are improper assembly, use, and maintenance (~33%), followed by improper design (~23%) [71]. These issues are often best addressed through good execution of established machine design practices, which may include accounting for the variable loads, thermal expansion and potential misalignments that could accelerate failure. However, modern **Digital Monitoring** methods (discussed in Section 4) have a key role to play in preventing failure; they offer warnings during **Operation** and data insights for designers.

When considering potential shaft failure in drivetrains, a technique used in aircraft [72] is to ensure the shortest drivelines power the components with the largest power requirements.

- Simplifies the design, avoiding the need to strengthen the entire drivetrain and better enabling **Repair**

- Increases the **Durability** of drivelines powering the systems with the largest power requirements
- Reduces gearbox weight, offering potential **Energy Saving**

The **Repair**, **Refurbish** and **Remanufacture** of shafts and spindles in high-value applications has grown organically due to the significant cost of these components, as demonstrated by MTT’s dedicated spindle services [73] and the machine tool case studies in Paper 1. MTT confirmed that feasibility is determined by the spindles ability to be returned to a state that adheres to the relevant ISO standards, but this is not always feasible.

Material addition (e.g. **Rework** via welding)

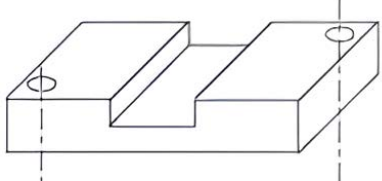
can be required for components at EoL when a shaft is worn in a critical area (e.g. where a bearing or collar sits). However, there are some workarounds:

- Using a bearing or collar wider than the affected area
- Using a bearing or collar with a slightly smaller inner diameter

3.3.4.3 Component Shape

Table 8 below summarises shape-related component features that impact circularity, focusing on aspects not already covered in previous sections.

Table 8 – Shape-related component features that can impact circularity at machine and component EoL

EoL Stage	Shape-Related Design Choice
Identification	The component’s shape makes its function easy to identify.
	Sufficient Surface area for durable part identification and labelling.
Cleaning	Small grooves limit Accessibility for simple cleaning techniques and can trap dirt.
	 <p>Figure 9 - Gambar Mekanikal (2008) How to make an isometric projection from orthographic projection (blog post). Available at: https://gambar-mekanikal.blogspot.com/2008/10/mengubah-proyeksi-orthografik-ke.html</p>
	Non-entrant shapes, such as sharp corners and internal pockets, also limit Accessibility for simple cleaning techniques and can trap dirt.
Inspection, Rework and Testing	Extra material (e.g. additional thickness) may enable rework (unlikely to be beneficial unless confident of a second service life).
	Clear, durable and accessible features that enable Digital Monitoring can reduce time and cost at EoL. Critical crack length should be considered, particularly from a safety and Repair perspective; ideally, cracks should be detectable before they become self-propagating.
	Notch sensitivity (impacted by Material Selection) and sharp corners in component Geometry raise stress concentrations [74] limiting Durability and Residual Life .

The shape of parts can enable **Modularity** via structures that allow separate component modules (e.g. gearboxes and motors) to fit together (discussed more in Section 3.4.4).



Figure 10 - Pump Power Australia (2025) Zenith Gear Pumps – BB-PEP Series (product page). Available at: <https://www.pumppower.com.au/product/zenith-gear-pumps-bb-pep-series/>.

Good **Accessibility** can be provided through **Geometry** that limits the number of unfastening access directions [75] for threaded fasteners and optimises the component's DOF (Degrees of Freedom) permitted by unfastening.

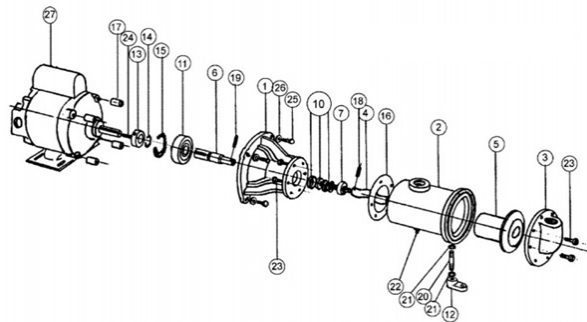


Figure 11 - Pumps & Parts Online (2016) 101M exploded view and parts list (product diagram). Available at: <https://www.pumpsandpartsonline.com/101m-exploded-view-and-parts-list/>

Disassembly and Reassembly

Standard DfA features that don't impact disassembly, such as asymmetric features to prevent incorrect assembly.

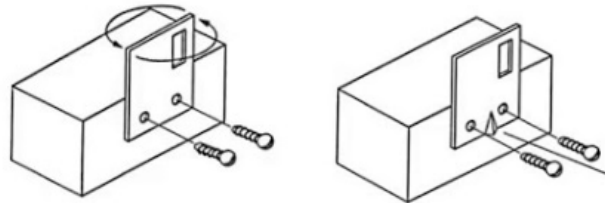


Figure 12 - University of Arkansas, Design for Assembly Principles, Available at: <https://uark.pressbooks.pub/mechanicaldesign/chapter/design-for-assembly-principles/>

Divots (e.g. square slots) can provide tool access points (such as for a screwdriver) to help pry components apart [77].

Components (e.g. shafts) can cause difficulty if the environment the machine will be decommissioned in is too small to house it. This can make manoeuvring or extracting the component at EoL or during **Repair** difficult.

3.3.4.4 Sacrificial Components

This section covers sacrificial components, but to avoid confusion, it is helpful to define related terms, as wear components and components to be sacrificed are often also labelled as sacrificial:

- **Sacrificial components** – enable circularity through increased machine service life, by protecting expensive or safety critical components
- **Wear components** – are designed to wear out to protect the wider system and include components such as piston sleeves [78] [79] and bearings
- **Components to be sacrificed** – are discarded in a **Remanufacture** or **Refurbish** project [80].



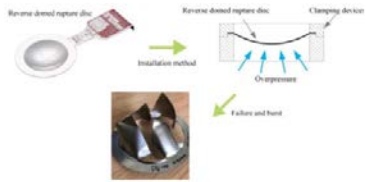
Good **Accessibility** to sacrificial components enables **System Redundancy** in machines

and their sub-assemblies. To keep costs down, some degree of redundancy is often deliberately designed into systems. Selecting potential sacrificial components should form part of the Failure Mode and Effect Analysis (FMEA) process during new machine design. Key criteria for identifying sacrificial components include:

- **Material Selection** that enables **Material Application** at EoL
- Smaller component volume to ensure **Efficient Material Use**
- Good **Accessibility** during **Disassembly**
- Relative motion to other components, indicating a likely point of failure or wear
- Low manufacturing and replacement cost

Some examples of sacrificial components are outlined in Table 9:

Table 9 - Example sacrificial components

Component	Component Description	Example Image
<p>Mechanical shear pin [81]</p>	<p>Similar in concept to the ‘shear neck’ in Figure 16, a bolt designed to fail and break the connection transferring torque from a power source or gearbox to a rotating machine element</p>	 <p>Figure 13 - Ariens Company (n.d.) What are shear pins and why do I need them (blog post). Available at: https://www.ariens.com/en-us/company/blog/277/what-are-shear-pins-and-why-do-i-need-them.</p>  <p>Figure 14 - MTD Parts (2024) Shear Pin Kit, .25 x 1.5" (OEM-738-04124) (product page). Available at: https://www.mtdparts.com/en_US/snow-blower-shear-pins/shear-pin-kit-.25-x-1.5inch/OEM-738-04124.html</p>
<p>Over pressure burst disks [82]</p>	<p>Thin metal sheets designed to rupture at a force equivalent to the vessel's burst pressure</p>	 <p>Figure 15 - Liu, L., Yuan, C., Li, W., Li, B. and Liu, X. (2021) Influence of moulding pressure on the burst pressure of reverse-acting rupture discs. Processes, 9(10), 1775. Available at: https://www.mdpi.com/2227-9717/9/10/1775.</p>
<p>Electrical fuses and galvanic anodes</p>	<p>See Section 3.3.3.2</p>	

Another noteworthy example comes from aircraft engines, where a sacrificial ‘shear neck’ [83] (shown in Figure 16) is used in the drivelines that provide power to accessory units from the external gearbox. The gearbox also powers vital engine units, such as oil and fuel pumps, and a sudden stop could

otherwise cause failure via shearing of the gear teeth. Given the critical, sacrificial nature of this part, the impact of features like grooves on **Cleaning** at EoL (as discussed in Section 3.3.4.3) is irrelevant compared to the potential material loss or, more importantly, the safety implications in aviation.

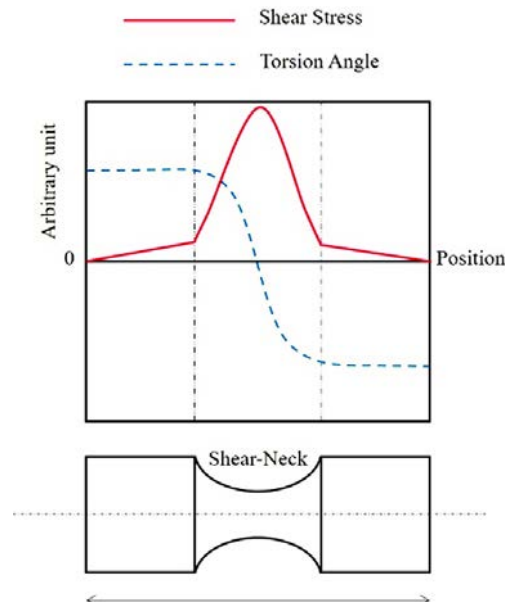


Figure 16 - Saraçyakupoğlu, T. (2021) Shear stress distribution on the shaft (Figure adapted from The Fractographic Investigation of an Aeroengine Accessory Gearbox Quill Shaft). Available at: <https://www.researchgate.net/figure/Shear-Stress-Distribution-on-the-S>

3.4 Commercial Off-the-Shelf Components

The design and integration of these standard components are crucial to cost-effective machine design. It is therefore important to consider not only the role they play in the sustainability and circularity of the machine as a whole, but also the circularity of these components at EoL.

3.4.1 Electrical components

All electrical and electronic components fall under the WEEE (Waste Electrical and Electronic Equipment) Directive unless specified otherwise [84]. They will soon be covered by upcoming EU legislation on the circularity of electronic components (see Paper 1 for more detail). As a result, many organisations are researching ways to increase circularity through redesign and new EoL technologies.

This scope includes both the IEM (Intelligent Equipment Module) components discussed in Section 4.1 and electro-mechanical components such as motors. These components are classified as both scrap metal and electronic waste, with case study and anecdotal evidence suggesting that they are discarded in favour of newer models – many likely ending in landfill – during machine **Remanufacture** and **Refurbish**.

There are three key approaches to increasing sustainability and circularity, with some detailed examples outlined in Table 10:

- System design – relevant for new machines
- Component selection – relevant for new and existing machines
- Component EoL strategy – relevant for existing machines

Table 10 - Example approaches to increasing sustainability and circularity

Category of R Strategy	Stage	Description
Smarter Product Use	Design	System design: Separating fluid (e.g. pumps) and electrical components (e.g. alternators), as done on aircraft accessory gearboxes [85], adds an element of System Redundancy by reducing the risk of fluid leaks causing additional failures.
Smarter Product Use	Design and Operation	Component selection: Motors account for 45% of global electricity consumption and 60% of the growth in energy demand over the past decade. It is estimated that upgrading every single motor to a more Energy Efficient model would lead to a global energy saving of 10% [86]. Motors are rated using efficiency classes that consider both energy efficiency and power consumption [87].
Lifespan Extension	Design	Component selection: Some OEMs are already utilising circular design practices, with ABB [88] hosting a full range of electronic products designed with circularity in mind.
Lifespan Extension	EoL	Component EoL strategy: Sourcing crucial individual components during machine Lifespan Extension can be achieved via distribution businesses like Radwell [89] who will buy, Repair, Refurbish and sell damaged or obsolete electronic components. This is ideally where most electronic components should end up at EoL.
Material Application	EoL	Component EoL strategy: Circularity can be achieved (depending on motor type) through buyback programmes, with companies like ABB reporting Recycle rates of 90-98.5% [90] for their motors.

The strategy that appears to offer the greatest sustainability impact is the use of **Energy Efficient** motors. As discussed in Paper 1, this requires sufficient **Modularity** and **Accessibility** in machine design (see Section 3.4.4) to ensure motors and other energy-related components can be continuously upgraded over the machine's lifecycle.

3.4.2 Pneumatics

Compressed air accounts for around 10% of UK industry's annual energy consumption [91], representing a large proportion of machine energy use. As discussed in the Paper 1 case studies, **Energy Efficient** design and **Operation** of pneumatic systems can have a disproportionate impact on a machine's lifecycle impact.

3.4.2.1 Findings from Discussion with Atlas Copco



This subsection draws on expertise from Lee Wilson of Atlas Copco, who provided insights and case studies for Paper 1. He highlighted a widespread lack of awareness about pneumatic technologies and their potential for **Energy Efficient** design. Compressed air is often mistakenly seen as 'free', rather than as the 'fourth utility of business', alongside gas, electricity, and water/steam. This knowledge gap often stems from educational blind spots on the mechanical and electrical systems used in machines. A lack of vigilance during **Operation** can be costly, with ~35% of a company's air losses attributed to

leaks alone. This is a particular issue for older machines which do not have **Digital Monitoring** of energy consumption (discussed further in Section 4) and is particularly prevalent in the Food & Drink industry. There are two main reasons for this inefficiency:

1. **Oversized components** – often resulting from the misuse of online tools. Safety margins are already built into many online calculators but are further compounded when designers add their own, additional safety factor.
2. **Unnecessarily high operating pressures** – many machines are designed or run at pressures beyond what is needed. Lowering system pressures by approximately 1 bar can reduce compressed air consumption by about 7% annually. This industry-wide issue has been highlighted by initiatives such as the “Strive to Five” campaign, which challenged companies to reduce pneumatic system pressure from the standard 7 bar to 5 bar.

From an EoL perspective, discarded pneumatic components are well-suited to **Recycle** as they are predominantly made from aluminium. Adherence to ISO standards in the field enables efficient **Disassembly**, thanks to **Standardisation** and high levels of **Modularity**. However, an emerging challenge is the increasing presence of low-cost uncertified imports that do not comply with ISO standards, reducing compatibility and recyclability. A further benefit is the inherent **Durability** of pneumatic components, which often last the full lifetime of the machine, aside from routine planned maintenance.

3.4.2.2 Findings from Discussion with SMC

Further discussions with Mark Nicol from SMC drew attention to several other important factors and potential issues outlined in Table 11:

Table 11 - Important factors and potential issues relating to pneumatics on machines

Machine lifecycle stage	Description
During design	<ul style="list-style-type: none"> • When a higher pressure is still required for a specific machine function, a pressure booster can be used for that single sub-system, keeping the pressure of the main system low • An air management system (such as those sold by SMC) can place the machine on stop or standby, or reduce the pressure whenever it may be left waiting – this is particularly useful for machines with lower utilisation
During Operation	<ul style="list-style-type: none"> • Poor air quality, generally caused by a lack of maintenance (e.g. filter or seal change), can lead to moist and contaminated air <ul style="list-style-type: none"> • This causes gradual component deterioration as grease and dirt sticks • In response, operators generally increase the system pressure • Mark also reiterated the importance of Digital Monitoring for informed decision making <ul style="list-style-type: none"> • It can't just be a simple real-time measurement like a pressure gauge; the data must be recorded • Differential gauges are important for measuring pressure drop across components and not just absolute pressure • Factory arrangements can impact leaks as it may be easy for operators to damage components – for example, via treading on a pipe

Mark similarly highlighted the prevalence and impact of air leaks (also discussed in Section 3.4.2.1), noting several other common causes:

- Component failure came down to **Durability** and proper maintenance
 - Leaky pipework
 - Cylinders no longer adequately sealed
 - Damaged valves
- Missing gauges mean that leaks are unlikely to ever be identified







An overall reduction in system pressure was identified as an important strategy in Paper 1 and Section 3.4.2.1 for existing machines. Mark described the methods for identifying the potential magnitude of any desired pressure reduction:

1. Lower the pressure across all machines
2. Note which machine functions are being inhibited and at what pressure
3. Make the necessary **Repair** and modifications on the components that were impacted the earliest, and define a new lower pressure that most of the system can tolerate

3.4.2.3 Section Conclusions

The discussion with both industry experts and the case study in Paper 1 yielded the following recommendations for academia and industry in Table 12:

Table 12 - Academia and industry recommendations for pneumatics

Recommendation	
Raise awareness of the financial and environmental impact air losses can have	
Increase leak monitoring via Digital Monitoring systems, an annual check and adequate maintenance practices	
Ensure appropriate component sizing	
Design for and operate lower system pressures	
Avoid cheap uncertified parts	
Customers should specify Energy Efficient in machine design requirements	

3.4.3 Bearings, Seals and Lubricants

When it comes to bearings, seals and lubricants, the options (not an exhaustive list) for increasing sustainability and circularity are laid out in Table 13.

Table 13 - Options for increasing sustainability and circularity for bearings, seals and lubricants

Option category	Option description
SUSTAINABILITY	1. Better component function – more effective lubricants (supercritical CO2 [92] would be a more exotic example), bearings and seals can lead to a more Energy Efficient design and Efficient Material Use [93] [94]
	2. 50% of lubricants worldwide end up in the environment [95]; biodegradable/plant-derived options can be friendlier to living organisms and reduce environmental impact during their Manufacture
Smarter Machine Use & Manufacture	3. Reduce the number of moving components, if feasible
	4. Consider designs that eliminate the need for support components (although this may be unrealistic in many cases). For example, self-lubricating options [96] or machined valves and seats, as used in engines, could remove the need for polymer seals – though the additional machining increases costs, energy use and material use, potentially outweighing the benefits
Lifespan Extension	5. Increased Accessibility to bearings, seals and lubricants and greater Modularity in design enables faster and therefore more economic Disassembly
	6. Select options with more DURABILITY to obtain economic benefits (such as reduced downtime and lower TCoO) and circularity advantages
	7. Update and execute established machine design practices, informing accurate maintenance plans and reducing unnecessary replacement
	8. Digital Monitoring can provide an automated way to monitor the condition of components and lubricants without downtime – the data collected can better inform the maintenance plans discussed above
Useful Material Application	9. Select from the growing number of Material Selection options that enable the Recycle of components such as seals [97]
	10. Limit Material Mix for components destined to be discarded, encouraging Recycle practices (this is discussed further in regard to fasteners in Section 3.4.5.1.1)

3.4.3.1 Calculations and Redesign

The change in ISO standards for bearing life is a good demonstration of what is discussed in point 7 of Table 13. Previous ISO standards [98] for calculating basic bearing life (known as L_{10}) defined L_{10} as the time taken for 90% of installed bearings to require replacement. Therefore, the mean time between bearing failures was sometimes ~5x longer than the basic life. L_{10} is a statistical quantity – true service life can be far greater when the root cause of failure is fully understood and mitigated.

Hence, updated ISO standards (2007) accounted for material fatigue stress limits

and solid contamination effects, allowing companies to extend bearing service intervals when operated under controlled conditions.

Better integration and further development of LCA software and databases may help to deliver on the options in points 1, 2, 4, and 6 in Table 13. Some form of basic LCA would be required to balance the iterative design and selection of components in a way that optimises for function (based on the considerations in Figure 17), sustainability and circularity over the full machine (and product) lifecycle(s).

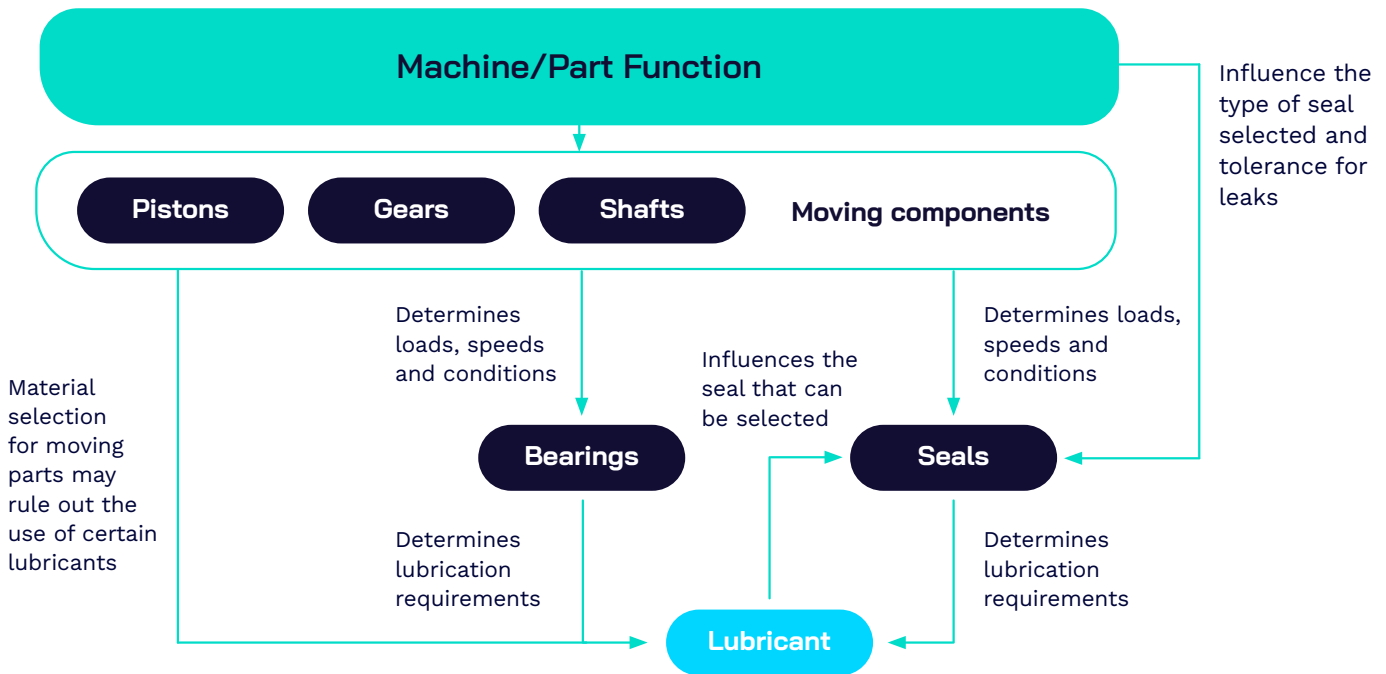


Figure 17 - bearing, seal and lubricant requirements considerations

An example related to Figure 17 would be the use of a more effective synthetic lubricant (something also advocated on MTT’s website [99]) or changing it more regularly – noting that the impact of increasing the quantity of lubricant consumed would likely be outweighed by longer-lasting or better-performing components.

The limitations of LCAs have already been somewhat discussed in Paper 1. While nothing prevents a designer performing an LCA in this context, it may prove too expensive given the low cost of bearings and seals.

3.4.3.2 Managing EoL

There are two likely possibilities that relieve designers of the burden of over-optimising the design or selection of bearings and seals for increased circularity at EoL:

1. It is likely that that when more circular versions of these components are developed, they will be interchangeable with what already exists (e.g. they will have to bear the same loads and use the same fits/sizes as existing bearings). Therefore, an EoL supply chain can develop organically.
2. If machines are designed to last for potentially decades, emerging EoL technology (e.g. metrology for inspecting **Residual Life** in components or more automated sorting for **Recycle**) may mitigate potential downsides at EoL.

Of the options in Table 13 - with the exception of options 2 and 7, **Useful Material Application** looks like the most economically feasible way forward for the following reasons:

- The potential lifecycle benefits of including single-use wear components in complex high-value machinery outweigh the value of their materials in a circular economy
- There are high volumes of these components in circulation, with the global bearing market being worth over \$100bn alone [100]
- These components are of low value individually
- Case studies show that the replacement of these components is essential during any **Repair** or other **Lifespan Extension** project
- These components already have good **Durability** / low failure rate [101]
- This approach would be the least disruptive, with long-standing design concepts/methods still valid when using, for example, recyclable seals

In summary, while careful selection and design of bearings, lubricants, and seals can improve machine sustainability and

circularity, common sense suggests that other, more pressing issues deserve priority.

3.4.4 Power Transfer Systems

One area where bearings, seals and lubricants can have a significant impact is in gearbox, clutch and braking systems – with bearings responsible for 70% of gearbox failure (compared to 24% for the actual gears) in wind turbines [102].

It is important that these systems are supplied as individual modules. They are often (but not always) purchased off-the-shelf for a relatively low cost. In some cases, the **Lifespan Extension** of bespoke larger systems can be profitable, evidenced by Renewable Parts [103] who **Remanufacture** the braking systems and gearboxes on wind turbines.



These power transfer systems are a significant source of downtime, with gearboxes alone accounting for 15% of unplanned industrial downtime [104]. Preventative maintenance is key and enabled by **Accessibility** and **Modularity**. Improvements in these systems can lead to the following benefits [105]:

- **Energy Efficient** design
- **Lifespan Extension** of the power transfer system itself
- Overall machine **Lifespan Extension**

The engineering drawing in Figure 18 is an example of **Modularity**, showing a gearbox mounted to a machine (as a single module) using easily removable standard fasteners (nuts and bolts). The interface between the gearbox and the machine is a simple spline and woodruff key to transfer torque, while a gasket sandwiched between two flat plates locates the gearbox and prevents oil leaks. This gearbox could be easily maintained, replaced or upgraded throughout the machine's life with limited downtime.

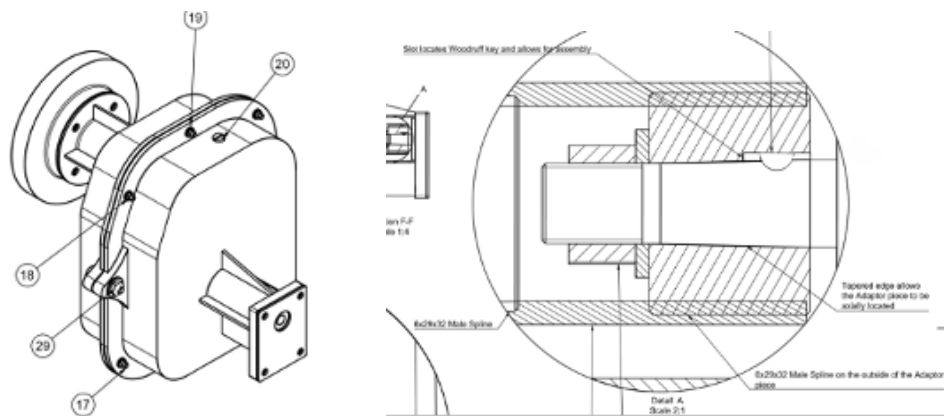


Figure 18 - Design of gearbox interface

3.4.5 Joining Methods

It has been well established that, when trying to increase circularity, the use of permanent joints should be avoided in favour of reversible joints like bolts for the following reasons:

- Increased expense and environmental impact during **Disassembly**
- Joint residue compromising purity during **Recycling**

3.4.5.1 Fasteners

From a circularity perspective, the **Durability** of fasteners plays a crucial role in avoiding the need for **Repair** and machine decommissioning due to critical failure. However, since fasteners are considered disposable, increasing the feasibility of **Material Application** at EoL is the more realistic option.

3.4.5.1.1 Fastener EoL

Avoiding fastener failure is often critical to machine function and safety. This can largely be achieved through good execution of established machine design and assembly practices (e.g. accurately calculating and applying the required preload [106]), given the high **Durability** of fasteners – with failure rates as low as 2% per million hours [107]. Due to the significant time and cost of accurately inspecting the potential **Residual Life** of individual nuts, bolts and washers

(with current technology), they are almost always replaced with new components [108] during machine **Lifespan Extension** projects (such as those in the Paper 1 case studies), regardless of condition.

When it comes to **Material Selection**, most fasteners are made from steel [109], a material that is easy to **Recycle**. In machines, loosening (primarily caused by vibration and cyclical thermal expansion) and fatigue (primarily caused by dynamic loading) are the major failure mode for fasteners. To counter the effects of loosening, many designers opt to use some form of thread-lock or a nylon insert. In addition to potentially hindering the **Disassembly** process, using any form of thread-lock produces an unfavourable **Material Mix** for recycling. Alternative ways of preventing thread loosening are shown in Figure 19 and Table 14. However, these are not widely adopted compared to threadlock. One explanation could be the additional assembly/design requirements (cost) or thread-lock's superior ability to prevent vibration by filling the air gap between internal and external threads [110].

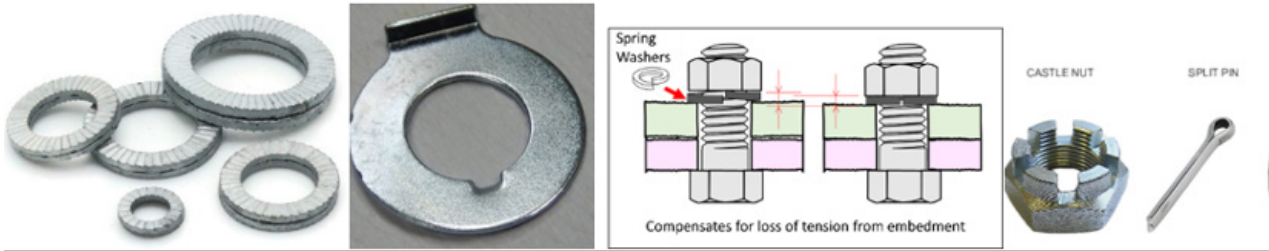


Figure 19 - left to right:

Amazon Sherex wedge washers, alloy steel locking washer set (product page). Available at: <https://www.amazon.com/Sherex-Wedge-Washers-Alloy-Locking/dp/B07WSFCZLB>.

Classic Bike Parts Cheshire BSA Triumph stator tab washer OEM no. 40-0455, 71-1731, 70-8043, 68-3025 (product page). Available at: <https://www.classicbikepartscheshire.com/engine-transmission-c37/bolt-sets-camshafts-nuts-washers-c129/bsa-triumph-stator-tab-washer-oem-no-40-0455-71-1731-70-8043-68-3025-p4232>.

Hardlock Nut Bolt locking methods (technical information page). Available at: <https://hardlock-nut.com/technical-info/bolt-locking-methods/>.

(No date) Equalizer bolt with cotter pin and castle nut - 7/8" diameter Redline Trailer Suspension Parts 166078. Available at: <https://www.etrailer.com/Accessories-and-Parts/Redline/166078.html> (Accessed: 28 August 2025).

Table 14 – Methods to prevent thread loosening

Method / Component	Category
Welding bolt and nut	Non-detachable
Thread-lock	Non-detachable
Double nut	Friction
Spring washer	Friction
Wedge locking nuts	Friction
Tab Washer	Mechanical-locking
F split pin washer	Mechanical-locking

Novel alternatives to thread-lock can be found in the literature [111] and are a potential area of future research, given the limitations of the methods in Table 14. These alternatives vary from simpler modifications, such as altering thread cross-sectional shape or using steeper thread lead angles, to more advanced solutions such as ratcheted nuts. However, it is important to understand that this remains

a low-impact design trade-off; many of these techniques are prohibitively expensive and far from commercialisation. Digital Monitoring [112] may provide a more effective method for replacing thread-lock, but no in-depth quantitative analyses are currently available to whether it is more economical than the novel alternatives proposed.

3.4.5.1.2 Integration of Fasteners in Design

'Fasteners and Design' is relevant during both **Disassembly** and **Reassembly**, DfD (Design for Disassembly) is a topic in itself (outside the scope of this paper), but there are a few basic fastener-related design ideas that can be adhered to:

- Limit the number of different unfastening directions/orientations [113]
- Use unfastening directions that enable **Accessibility** (mentioned in Section 3.3.4.3)
- Limit the number of fasteners where possible to reduce the number of operations
- Limit the number of types of fasteners to reduce tool changeovers
- Use **Standardisation** in fastener selection to ensure most facilities have the appropriate tools
 - (Note: there are trade-offs – for example, although tooling for a 12-point head is slightly less common, it can resist more torque before rounding, which can be highly disruptive at EoL; it also allows smaller heads, potentially improving **Accessibility** in tight recesses.)
- Make intelligent use of fasteners in design to assist with clustering into sub-assemblies (**Modularity**) and part consolidation [114]
- Follow a rough priority order [115] for joining methods when it comes to **Disassembly**: threaded fasteners, breakable snap fits, rivets, adhesive and welding

Potential alternatives for improved **Disassembly** are emerging. Novel technologies such as “active disassembly” [116] use smart materials (e.g., shape memory alloy clips) or built-in structures that can be activated using external stimuli (e.g., heat or radiation) to enable separation. Disbondable adhesives, discussed in the next section, are one example. However, further research is needed to confirm the economic viability of these techniques, and their functionality may remain limited under many real-world operating conditions.

3.4.5.2 Permanent Joints

When permanent joints (including welds or rivets) are the only viable option, designers should limit the size and number of components that utilise this type of joint, ensure good **Accessibility** to cutting points [117] and consider the impact of using power-intensive processes like welding. Like all the design choices in this paper, the entire machine and product lifecycle should be considered.







3.4.5.2.1 Adhesives

Adhesives present particular challenges during the **Disassembly** process, as separation currently relies on mechanical cutting and thermal degradation (even using knives and wires where there is complex geometry), with large amounts of residue still detrimental to the **Reuse**, **Repurpose** or **Recycle** of components [118]. When adhesives are necessary, several novel alternatives [119] are identified in the literature. However, these techniques must meet several of the key requirements outlined below.

- The disbonding process must minimise:
 - Residue
 - Energy input (as excessive input would negate environmental benefits)
 - Hazardous by-products
 - Damage to component
- The adhesive must:
 - Be capable of withstanding the machine's operating conditions
 - Provide adequate bond strength and resistance to oscillatory stress
 - Be economically feasible through the entire lifecycle (this does not necessarily mean cheap)
 - Allow short separation and curing time
 - Offer a relatively sustainable process
 - Provide suitable permeability (application dependent)
 - Ensure optical transparency (application dependent)

Disbonding requires a trigger, for which there are six main types – each with corresponding drawbacks outlined in Table 15 (not an exhaustive list).

Table 15 - Disbonding types

Disbonding Type	Description	
Pressure [120]	<ul style="list-style-type: none"> If the required pressure is too high it could damage components; if it is too low the adhesive could disbond during operation 	
Reversible chemical reaction	<ul style="list-style-type: none"> Potentially harmful emissions 	
Heat	<ul style="list-style-type: none"> Often with expandable additives in the priming layer or the adhesive itself Disbonding temperature needs to be high enough to avoid initiation during the curing (assembly) process or the operation of the machine Potentially harmful emissions when thermal decomposition occurs 	
Electrical current	<ul style="list-style-type: none"> Potential difference between substrates drives ion conduction which leads to the polarisation, and therefore delamination, of the boundary layer Requires components made from conductive materials 	
Magnetic field	<ul style="list-style-type: none"> Embedded iron oxide particles act like nano magnets that heat up when a magnetic field is applied Conductive or magnetic substrates can cause electromagnetic shielding, preventing the heating mechanism from occurring 	
Radiation	<ul style="list-style-type: none"> For example, reversible phase change induced via UV light Full adhesive layer needs full and easy access to a light source 	

Although there are drawbacks to using permanent joints at EoL, it is important not to forget the benefits they offer during other stages of the machine's lifecycle.

4 Monitoring Interventions

Expected developments for the IoT (Internet of Things) will connect physical components and machines via the internet. These devices gather and share data to optimise operations, improve efficiency (e.g. having machines order the bearing that needs replacing as soon as any issue is detected) and enable remote control.

This section discusses two ways in which **Digital Monitoring** is used to collect and analyse data from sensors, enabling **Energy Efficient** design and reduced downtime (thereby increasing machine utilisation) by moving to condition-dependent maintenance. The key is that the data is both real-time, so that potential issues are noticed earlier, and recorded, so that emerging trends can be identified.

4.1 Predictive Maintenance

Predictive maintenance is the use of data to predict equipment failures and prevent unexpected failures. This is beneficial from a machine **Lifespan Extension** perspective as 82% of failures occur randomly rather than due to age [121]. Additionally, Magnus Firth from Renewable Parts highlighted the greater difficulty during EoL projects (e.g. **Refurbishment**) if the machine has not been well maintained. **Digital Monitoring** not only protects critical high-value components but also allows third parties and second-life users to understand the condition of the machine at EoL. Failure may be imminent following unusual changes in:

- Temperature
- Humidity
- Strain, deflection and vibration
- Velocity
- Acoustics
- Current
- Particulate count in fluids
- Pressure
- Fluid flow rate

Monitoring these variables can provide critical insights into specific aspects of a components condition, such as:

- Shaft alignment and bearing wear
- Excessive dynamic loading on components
- Status of rotor balance
- Excessive friction between components (e.g. metal in lubricants can indicate that gears are grinding)
- Condition of components, such as seals, in hydraulic systems
- Lubricant condition
- Filter condition
- Energy consumption spikes can also indicate an impending failure in an energy-intensive mechanical (e.g. pump) or electrical component (e.g. motor)

The following improvements have been demonstrated:

- 30-50% reduction in unexpected downtime [122] [123]
- 20-30% reduction in maintenance costs
- Machine service lives [124] extended by 20-40%

An additional example of improvement was highlighted by MTT, who are using the data they have collected on common failure modes (sources: metrology data and service reports) to determine the characteristics for effective donor machines.

4.2 Energy Monitoring

As outlined above, energy monitoring can form part of a good predictive maintenance plan, but it also plays an important role in **Energy Efficient** design, as highlighted in Section 3.4.2. Current transducers [125] can be used in both single- and three-phase power supplies and can be fitted to machines to record data at the machine or circuit level.

An increased awareness of energy consumption during **Operation** was also highlighted by Dr. Faiz Iqbal from the University of Lincoln, epitomised by a factory example where the company began monitoring energy consumption (amongst other metrics). Almost immediately, they identified that a single machine was responsible for the majority of the facility's total energy consumption – which was then rectified with machine replacement.

Another example involved multiple conveyor systems, one of which required unplanned maintenance. In this instance, operators left the remaining conveyors running whilst one was repaired. Energy consumption monitoring tools would have highlighted the costs to operators and management, likely prompting the simple step of shutting down unused machines.

As a caveat to the above, there may be cases where the downtime required for the **Repair** of a specific machine may be unknown, and the restart of remaining machines in the production line is energy intensive and time consuming. This may make operators reluctant to shut down machines upstream or downstream. However, an increase in **Digital Monitoring** has been shown to reduce diagnosis time, which would help alleviate such concerns.

Other benefits of **Digital Monitoring** include:

- Digital records (e.g. DPPs) will assist during the **Identification** stage at EoL
- When **Configurable** and monitored, a machine's process parameters can be optimized to attain **Energy Efficient** operation, reduce wear or improved function [126]

4.3 Section Conclusion

Industry experience has shown that **Digital Monitoring** can be implemented even on existing machinery, so from a design

perspective only a few key considerations need to be kept in mind.

- Ensure **Accessibility** to consumable and critical components (e.g. line of sight access for a sensor)
- Enable **Accessibility** and **Modularity** so sensors can be upgraded easily in the future.
- Use data insights from machines in **Operation** to inform better design – e.g. are certain designs consistently failing faster than intended?

Future trends with research potential include:

- Growing demand for digital **Modularity**, as seen in the design of MTT's sensor toolkit [127]
- Wider adoption of energy monitoring to identify savings
- Increased use of machine learning to analyse large datasets
- Development of more sophisticated models to filter and process raw data, and determine which data should be retained for analysis [128]
- Rising adoption due to reduced TCoO is expected, though uptake still needs encouragement (as of 2017, 30% of facilities used predictive maintenance, but 51% had no plans [129])

For continued adoption of **Digital Monitoring** in UK manufacturing, key enablers include:

- Adequate data centre infrastructure
- Continued development in machine learning models
- Roll out of 5G networks and other key communications technologies [130]
- Adoption and improvement in digital twins and analysis software [131]

5 Paper Conclusions

The evidence in this paper points to one key conclusion: machine components play a supporting role, and the material and energy waste associated with scrapping many of these components is negligible compared to the impact of machine failure, improving machine efficiency or improving function.

This is expanded into design and policy recommendations, as well as further detail

on specific categories of components, in the following sub-sections.

5.1 Conclusions Regarding Specific Components

Table 16 below summarises the key conclusions drawn from this paper and Paper 1, specific to each component category.

Table 16 – Key conclusions for each type of component

Component Types	Conclusions
IEM	Digital Modularity and Standardisation are key to forward and backward compatibility as the technology for digital control systems and the IoT continues to develop.
SOTS	Configurability in the design of these higher-value components, with the necessary Modularity for Disassembly , can increase circularity through Reuse or Repurpose of individual components and machines.
Bespoke	For more bespoke components, there is some evidence that Lifespan Extension is feasible, but practices are yet to be fully studied and codified. There are few guarantees they will be recirculated; therefore, it is not worth redesigning these components with a second service life in mind. Material Application is currently a more realistic option that can be best pursued by reconsidering Material Selection .
COTS	Typically considered to be consumable/scrapable with no Residual Life , the integration of COTS into the full machine design should prioritise the machine's function (in accordance with the conclusions in Paper 1), without significant concern for enhancing individual component Durability (which is already high e.g. bearings). Higher-value designs may begin to utilise the novel and expensive versions of these components, such as magnetic or air bearings [132] – at that point they become SOTS (because these are specialised, not common) and therefore the respective conclusions apply. When considering the design around these components (e.g. bearing housings, shaft loading etc) researchers should look at what data and conclusions can be obtained from Digital Monitoring . This will deliver improvements for machines currently in service and those yet to be designed. These economic benefits can fund more expensive up-front designs, designed with sustainability and circularity in mind. The prevalence of COTS components also means some kind of circular supply chain for the collection, sorting and recycling of these common components is more feasible than the other types of components.

5.2 Recommendations for Industry, Academia, and Government

Table 17 below shows a prioritised set of policy recommendations for industry, academia and government.

Table 17 – Policy recommendations for industry, academia, and government

#	Applicable	Recommendation
1	Academia & Government	Quantify and communicate the economic and environmental costs of poor selection and maintenance practices for key components like motors, pumps and pneumatic systems.
2	Academia & Government	Conduct horizon scanning to identify EoL technologies (e.g. new methods of recycling) and material technologies close to commercialisation (e.g. plastic compatibilisers and additives in plastics) to improve recycling rates.
3	Academia & Industry	Support the commercialisation and implementation of research into DfD (Design for Disassembly) to enable machine upgrades for more Energy Efficient Operation and to increase circularity during service and at EoL.
4	Academia, Government & Industry	Assess the feasibility of organising recycling supply chains for prevalent, low-cost off-the-shelf components, including Collection from businesses and scrap merchants.
5	Academia & Government	Strengthen machine design education for young engineers to ensure good execution of established design practices. This will be essential to improving the sustainability and circularity of future machines, as much of the desired design characteristics discussed (e.g. Modularity), will come about via good execution of established machine design practices. Resources like Roymech.co.uk [133], which provides material data and design calculators, can play a key role in disseminating these practices.
6	Academia & Industry	Undertake further research into the feasibility of redesigning common or highly consumable machine components to improve sustainability and circularity (e.g. bearings that are recyclable, more efficient pump designs).

5.3 Specific Design Recommendations

Similarly to Paper 1, there is a set of design factors to consider (some of which reconfirm the findings in Paper 1) that should be prioritised in the order as follows

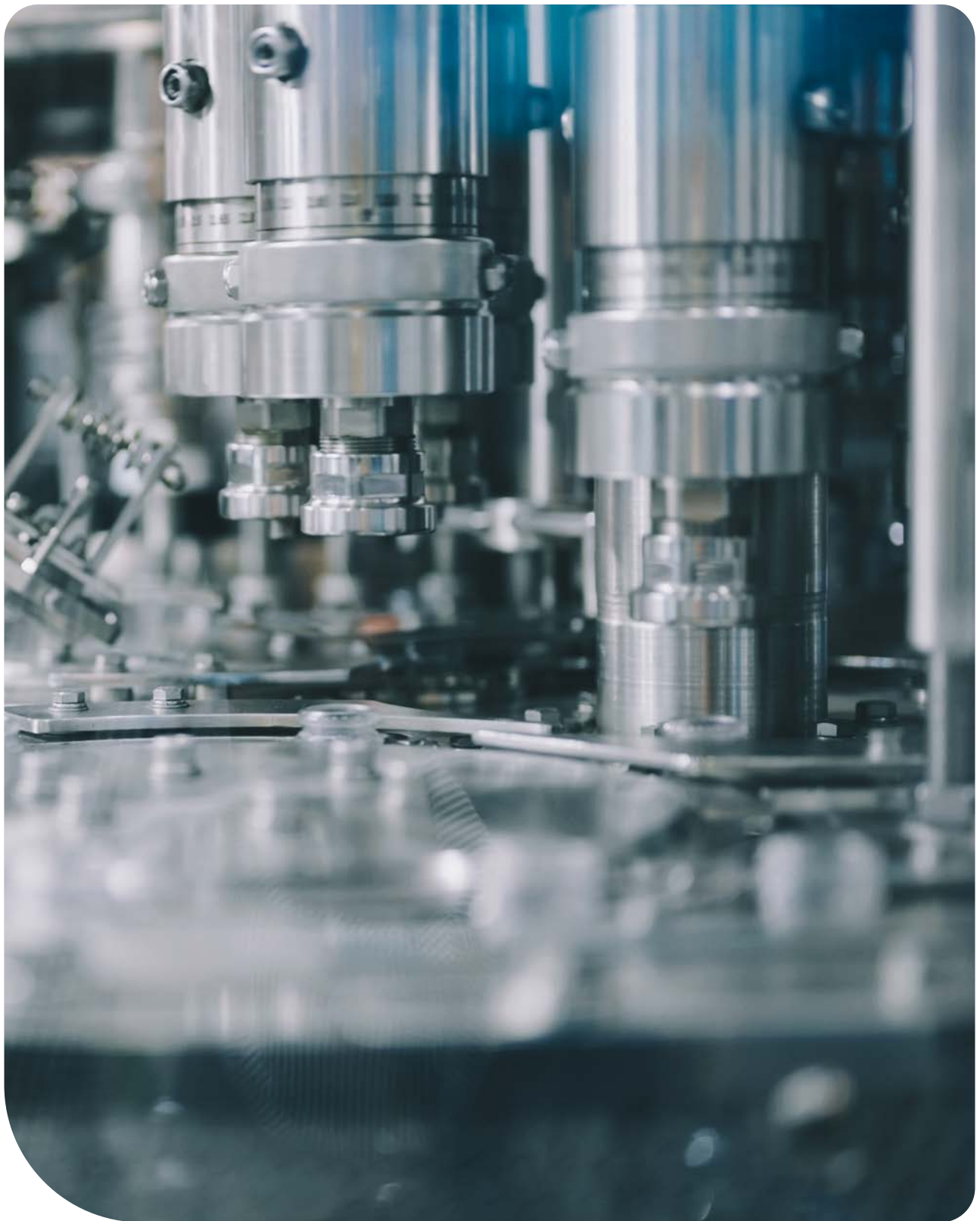
1. Treat component-specific recommendations as secondary to those discussed in Paper 1.
2. Reduce energy consumption in high-consumption components (e.g. motors and pneumatics), as these have an outsized impact on sustainability.
3. Integrate **Digital Monitoring** to apply strategies higher up the waste hierarchy (preventing and predicting failure) – this can deliver a significant increase in circularity, economic benefits and data to inform future designs.
4. Futureproof control components (IEMs) through **Standardisation** (e.g. using process orchestration layers to enable interchangeability) and high **Configurability** to reduce the likelihood of machine obsolescence.
5. Ensure effective execution of established machine design practices – this is low cost, will reduce failures and enable the desired **Modularity, Standardisation** and **Accessibility**.
6. Select consumable components with feasible EoL waste streams.
7. Reconsider material selection and surface treatments to enhance **Durability** in components – but avoid assuming a second life and ensure treatment choices do not come at the expense of recyclability.
8. Consider novel alternatives to disassembly.

6 Final Notes

As part of this research, several EoL/waste companies were approached, ranging from machine disposal services and recycling facilities to scrap merchants. Some companies, due to the specific nature of their work, simply didn't have answers to machines-related questions. Others were unwilling to respond out of concern about potential journalism, particularly given the rise of anti-business environmental activism across the UK. Had insight been attained from these types of companies and facilities, answers to the following enquiries would have been valuable for informing additional design and policy recommendations:

- What elements of machine design are adding costs to **Lifespan Extension** or **Material Application** at EoL?
 - Are there factors causing difficulty with shredding, sorting or processing (e.g. machine or component size/shape, selection of certain materials, presence of chemicals like lubricants)
- What is happening in the UK at EoL to common machine components?
- In what EoL technology areas (e.g. sorting and processing) could R&D best enable an increase in sustainability and circularity?

Should any companies that handle machines at EoL wish to contribute please contact max.wade@the-mtc.org and mark.libby@the-mtc.org.



7 Contributors

Thank you to those from MTC, our industry network and academia who contributed to this paper – the names below include those who assisted with Paper 1 and Paper 2.

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