

# Circular Product Design Strategies, Principles and Guidelines for the Metal Sector



## About this progress report

This progress report is a structured account of the development of a comprehensive framework for Circular Product Design (CPD) strategies, principles, and guidelines within the metals sector. Addressing the environmental and strategic imperatives of transitioning to a circular economy, the report aligns design decisions with supply chain strategies and lifecycle thinking through a hierarchical model integrated into the broader CircularMetal initiative. By systematically categorizing over 200 actionable guidelines, the framework provides designers, engineers, and policymakers with a practical, decision-support tool to embed circularity into product development processes. It acknowledges the complexities and trade-offs inherent in circular design and emphasizes the importance of interdisciplinary collaboration and systems thinking. This work offers a significant contribution to advancing net-zero targets, resource efficiency, and systemic innovation, equipping stakeholders to drive impactful change toward a truly circular metal economy.



For environmental reasons, this progress report should not be printed because it contains numerous photographs and was originally meant to be a digital edition.

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## List of key terms

**Circular Economy (CE):** Refers to an economic system where waste and pollution are designed out, and resources are kept in use for as long as possible.

**Closed-loop system (CLS):** Refers to a system in which unused or recaptured value is reused for the same or similar business purposes.

**Life cycle data (LCD):** Refers to information about a product or material from its creation to its disposal. This includes data on the raw secondary materials used to create the product, data on the manufacturing process, data on the use and disposal of the product, and data on the recycling or reuse of the product. In the context of CE, life cycle data can be used to assess the environmental impact of a product or material throughout its entire life cycle. This information can then be used to improve the design of products and materials to reduce their environmental impact.

**Net-zero emission:** Refers to a situation where the total amount of greenhouse gas emissions released into the atmosphere is balanced by the amount that is removed. This can be achieved through a variety of means, including planting trees, which absorb carbon dioxide from the atmosphere, and using technology to capture and store carbon dioxide emissions.

**Open-loop system:** Refers to a system in which the value created by one business is reused by other businesses to generate new value.

**Product Life Cycle:** Refers to a series of stages that a product goes through during its lifetime. The cycle begins when a product is first introduced and ends when the product is recycled. Between the first and final life cycles, a product may undergo multiple life cycles in which it is reused, refurbished, or remanufactured.

**Product lifetime** Refers to the length of time that a product remains on the market across several product life cycles.

**Eco-design strategy Wheel:** The Eco-design Strategy wheel is a tool that helps you consider all stages in a product's lifecycle, suggesting sustainable design strategies at each stage.

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## Introduction

The transition from a linear economy (LE) to a circular economy (CE) is becoming increasingly critical as global resource consumption continues to accelerate. Traditional product design, which prioritizes cost-efficiency and short-term performance, has contributed significantly to resource depletion, environmental degradation, and waste generation. As industries seek sustainable alternatives, circular product design (CPD) emerges as a key approach to extending product lifespans, optimizing resource use, and minimizing environmental impact. However, despite the growing recognition of CPD's importance, many industries lack structured and comprehensive guidelines to implement circular design strategies effectively.

This report aims to address this gap by providing a systematic framework for circular product design, focusing on clear and actionable design guidelines. These guidelines are structured around seven overarching strategies: **reducing material impact, reducing manufacturing impact, reducing distribution impact, reducing use impact, optimizing product lifespan, remanufacturing and reuse, and optimizing end-of-life processes**. By following these strategies, designers can create products that contribute to a more circular system, reducing waste and improving resource efficiency across the entire product lifecycle.

Building on existing research in eco-design, mechanical design, and sustainability-focused product development, this report refines and systematizes key principles into an accessible hierarchy. It aligns with established frameworks, such as the **Circular Design Strategy Wheel**. Additionally, it acknowledges the challenges of implementing circular design principles, including trade-offs between material efficiency and durability, technological feasibility, and industry adoption barriers.

The findings presented here are particularly relevant to industries reliant on finite raw materials, such as metals, where circularity is not just an environmental goal but also an economic and strategic necessity. By adopting the proposed guidelines, businesses, designers, and policymakers can work toward a more resilient and sustainable economy—one that prioritizes long-term value creation over short-term consumption.

*In the following sections, this report will outline the hierarchical structure of circular product design guidelines. Through this approach, it seeks to provide a practical roadmap for advancing circular product design in industrial and consumer goods sectors.*

## Background / Context

The UKRI Interdisciplinary Centre for Circular Metals is affiliated with several universities, including Brunel University London and Loughborough University. These two universities are responsible for Work Package 3 (WP3) of the CircularMetal research programme, which consists of three research teams for the following research aspects:

- Circular business model (CBM) innovation (WP3.1)
- Circular supply chain (CSC) design (WP3.2)
- Circular product design (WP3.3)

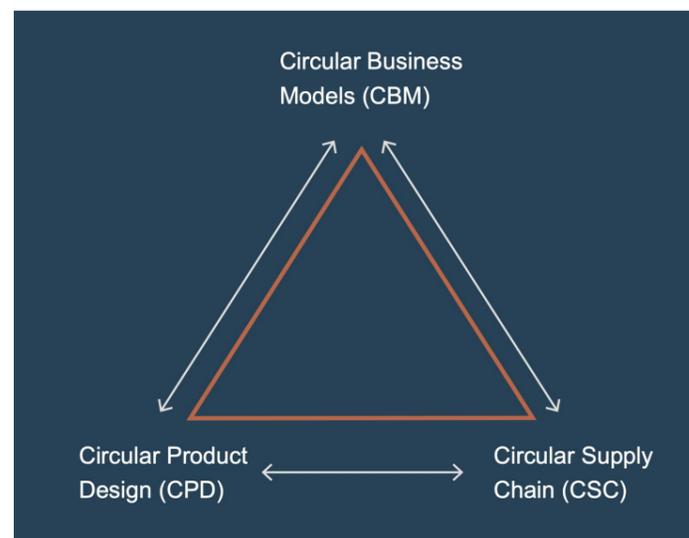


Figure 1: Schematic depicting the alignment between circular business models, product design and supply chain.

The transition to a circular economy is becoming increasingly vital for sustainable resource management, particularly in industries reliant on metals. The **Interdisciplinary Centre for Circular Metals** (CircularMetal) is a research initiative dedicated to achieving full metal circulation by addressing economic, environmental, technological, and societal challenges. A collaboration between Brunel University London, The University of Warwick, University College London, and Loughborough University, the programme focuses on **steel and aluminium**, the most widely used and economically significant metals.

CircularMetal's research aims to **identify gaps in metal circularity** and develop **pathways, policies, and regulations** to bridge them. The programme explores **circular product design, innovative business models, and advanced alloy processing technologies** to create a more sustainable and resilient metals industry. In addition, it actively engages with **academia, industry, policymakers, and the public** to maximise impact.

By integrating insights from CircularMetal, this report aligns its **design guidelines** with the programme's strategies, ensuring a **comprehensive approach to circularity**. This interdisciplinary effort plays a crucial role in helping the UK achieve its **net-zero carbon emissions target by 2050**, supporting industrial growth, and fostering a **secondary metals industry** that prioritises **reuse, remanufacture, and recycling**.

## Research Approach

The research adopted a futures-oriented approach to envision a preferable future for a Circular Metal Economy (CME) in the UK by 2050. The methodology included several stages, with experts from academia, business, and government providing their insights to form visions and snapshots of this future. These steps included stakeholder interviews, data analysis, internal workshops, expert validation, and co-design workshops.

Key elements of the approach included:

1. **Stakeholder Engagement:** Interviews with 30 experts from a diverse range of fields, from metallurgy to policymaking, were conducted to define initial visions.
2. **Identification of Common Themes:** The data collected from the interviews was analyzed to identify common themes and points of agreement and disagreement among experts.
3. **Development of Visions and Snapshots:** Based on the identified themes, eight visions and 36 snapshots were initially developed, which were refined through further workshops and surveys.
4. **Refinement through Workshops:** The findings were validated and refined through multiple workshops, including a co-design workshop where experts assessed and proposed changes to the visions, identified barriers and opportunities, and explored them through multiple lenses: social, technological, ecological, economic, and political.

## Framework for Strategies, Principles, and Guidelines

The Circular Metal Project organises its approach using a structured framework (figure 2) that includes strategies, principles, and guidelines, starting with the seven overarching design strategies. Each strategy has product design guidelines associated, which have been tailored to the metal sector. A total of 229 circular product design guidelines were collected and systematised.

They are structured in the following format:

1. Overarching design strategy
2. Circular product design strategy
3. Circular product design principles
4. Circular product design guidelines

### Difference Between Circular Design Strategy, Principle, Guideline, and Consideration

#### 1. Overarching Strategy

The seven overarching circular design strategies are aligned with the five product lifecycle phases, spanning from reduce material impact to optimise end of life.

#### 2. Circular Design Strategy

A **circular design strategy** defines the general direction for how a product, material, or process should be designed to support a circular economy.

**Example: Design for Dematerialization** – This strategy focuses on reducing metal usage by either using alternative materials or optimizing the structure to require less metal.

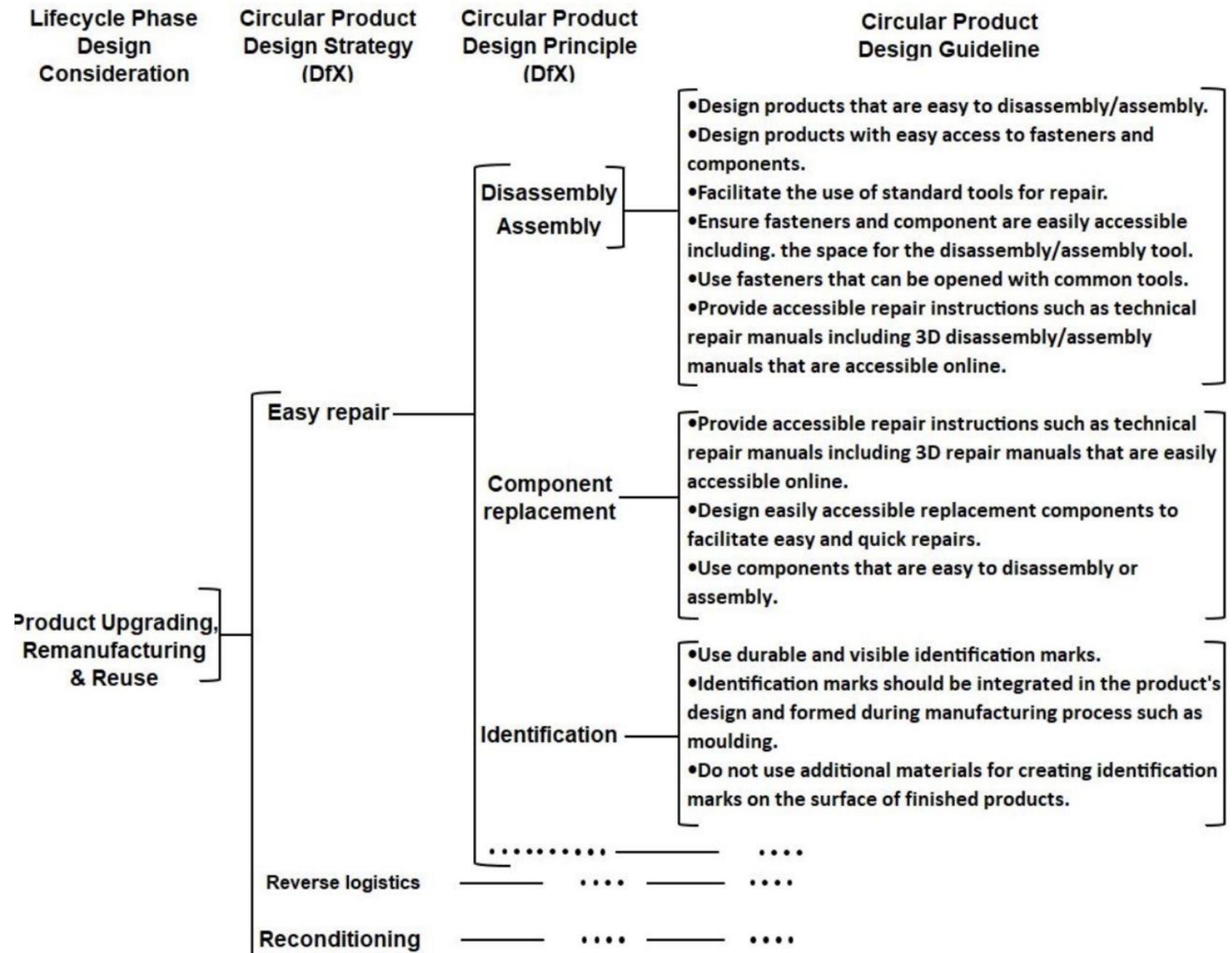


Figure 2: Tabulated Format of the Hierarchy for the strategies, principles and guidelines.

**3. Circular Design Principle**

A **circular design principle** is a more specific concept within a strategy that outlines what should be achieved to fulfill that strategy. It often acts as a guiding rule or design philosophy to implement the strategy.

*Example: Design for Metal Replacement – This principle supports the "Design for Dematerialization" strategy by suggesting that one way to reduce metal usage is to replace metals with alternative materials.*

**4. Circular Design Guideline**

A **circular design guideline** provides specific instructions or best practices to implement the principle. It serves as a practical recommendation to translate the principle into real-world design actions for designers, engineers, or manufacturers.

**Example Guidelines for Metal Replacement:**

- Replace metal components with materials that have similar or superior performance.
- Use digital solutions to replace physical metal products (e.g., switching from a traditional metal drum kit to an electronic version).

**5. Design Consideration For Metals**

A **design consideration** refers to external factors, constraints, or challenges that must be taken into account when implementing a circular design strategy. These can include technical, economic, environmental, regulatory, or social factors that might impact the feasibility or effectiveness of the design approach.

**Example Considerations for Metal Replacement:**

- *Performance trade-offs – Are the alternative materials as strong, durable, or cost-effective?*  
*Recyclability & environmental impact – Are the replacement materials truly more sustainable in the long term?*

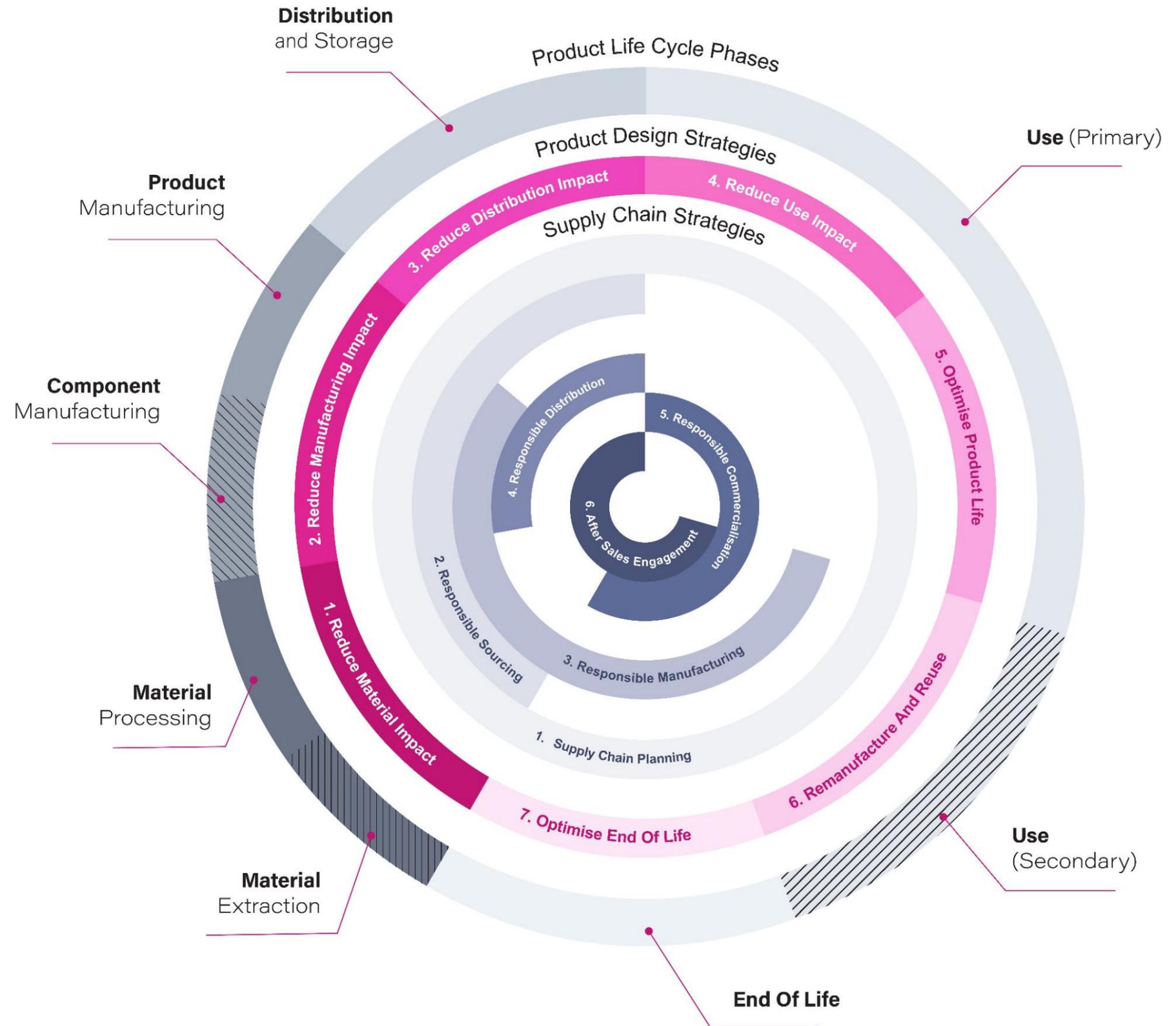


Figure 3: Schematic depicting the integration of circular product design with circular supply chain strategies.

## Integrated congruent framework

The congruent framework (figure 3) integrates circular design strategies (green) with circular supply chain strategies (blue) to the whole lifecycle of a product (red), starting at material extraction.

The informational graphic identifies the interaction of the highest overarching strategies. Within each of the overarching strategies is a combination of 500 circular product design and supply chain strategies that have corresponding strategies, principles and guidelines.

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The strategies, principles and guidelines are formatted in the following format:

### OVERARCHING DESIGN STRATEGY (LIFECYCLE PHASE DESIGN CONSIDERATION)

Description of the overarching design strategy.

#### Circular product design strategy

Description of the circular product design strategy.

#### Circular product design principles

#### Circular product design guidelines

- Design guidelines considerations

## Justification For Hierarchical Framework

The hierarchical structure for strategies, principles, and guidelines is designed to provide clear, systematic, and actionable frameworks for the metals industry to integrate circular economy principles effectively. This is achieved through:

1. **Clarity and Focus:** By creating a clear and logical structure, stakeholders are better equipped to prioritize and execute circular economy practices, making it easier to navigate the complexity of the metals industry and its transition toward circularity.
2. **Alignment and Consistency:** By categorizing different components into clear levels (strategies, principles, guidelines), the approach ensures everyone is working toward the same overarching goal, which is vital for coherence and effective collaboration.
3. **Efficient Decision-Making:** The hierarchical structure simplifies the decision-making process by providing a roadmap of actions that stakeholders can follow. The distinction between broader strategies and specific guidelines helps industry leaders and researchers make decisions more effectively.
4. **Adaptability and Scalability:** The hierarchical model can be adapted for use by large corporations, SMEs, or academic institutions, each applying the principles and guidelines most relevant to their specific situation while still contributing to the common vision of circular metal systems.
5. **Collaboration Across Sectors:** The hierarchical framework facilitates a shared understanding of the goals, strategies, and actions required to transition to a circular metal economy. The clear structure helps ensure that all parties — whether they're working on theory or practice — can contribute to the same overarching vision.
6. **Measurement and Evaluation:** The hierarchical nature of strategies and guidelines enables stakeholders to assess how well they are advancing in various aspects of the circular economy, identifying where improvements are needed or where more efforts should be focused.
7. **Long-Term Vision and Continuity:** The hierarchical structure ensures that there is a pathway from vision to action, with strategies providing the long-term goals and guidelines offering the concrete steps to achieve them over time.

In summary, the creation of a hierarchical structure in the article supports that the metals industry and academia can better understand, implement, and evaluate circular economy strategies in a systematic, collaborative, and scalable manner.

The next section *in this report* will outline the hierarchical structure of circular product design guidelines.

## Strategy guidelines

In the transition towards a circular economy, designing metal products with sustainability in mind is essential. This report outlines key **Overarching circular design strategies, Circular Design Strategies, Circular Design Principles, Circular Design Guidelines, and Design Considerations for Metals** to create a more sustainable and resilient metals industry.

The following chapter will outline the strategies, principles and guidelines in accordance with the seven overarching circular product design strategies, outlined as:

1. Reduce Material Impact
2. Reduce Manufacturing Impact
3. Reduce Distribution and Storage Impact
4. Reduce Use Impact
5. Optimise Product Lifespan
6. Remanufacture and Reuse
7. Optimise End Of Life

The seven overarching design strategies align with a product's lifecycle from material extraction to the products end of life.

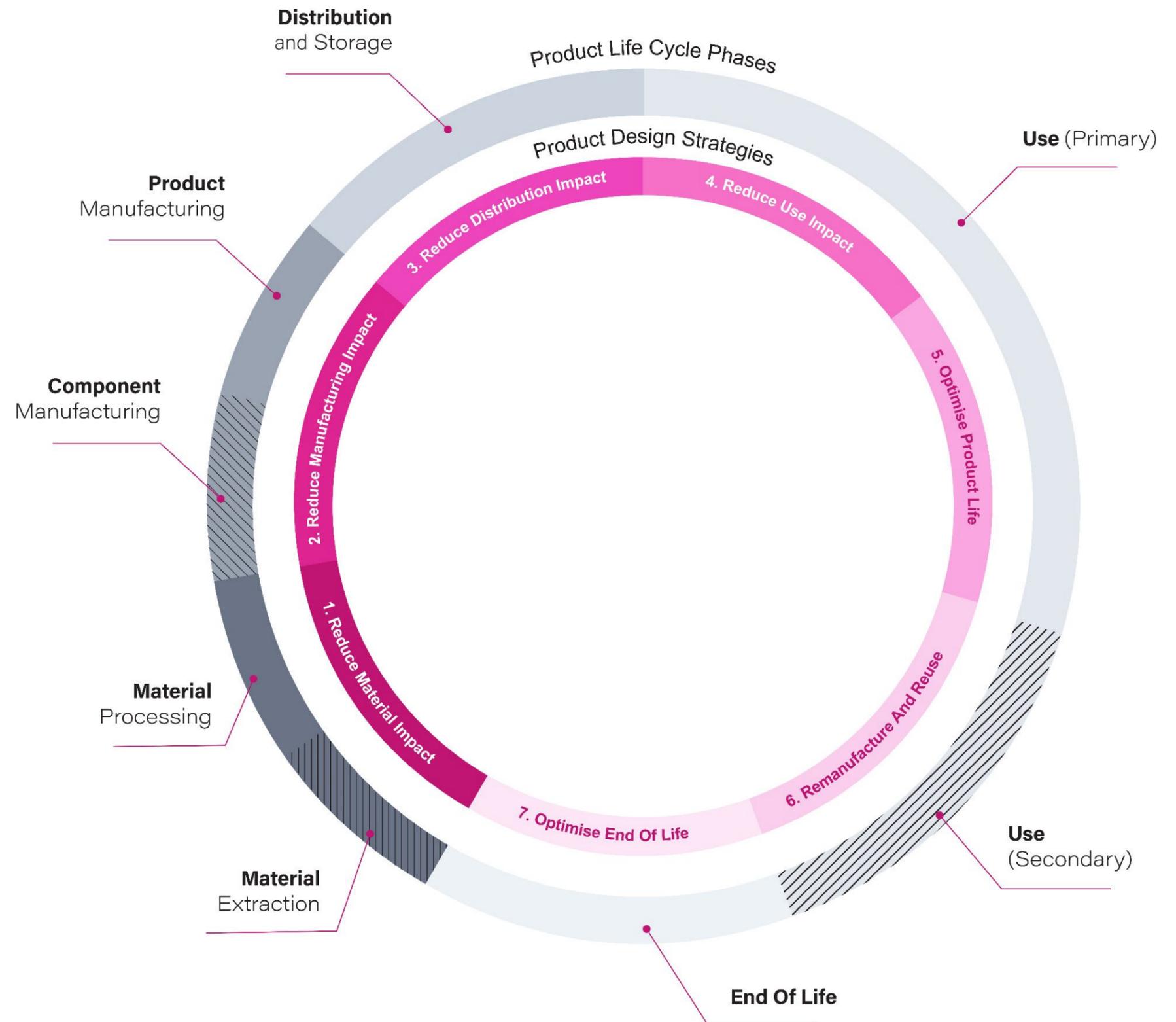
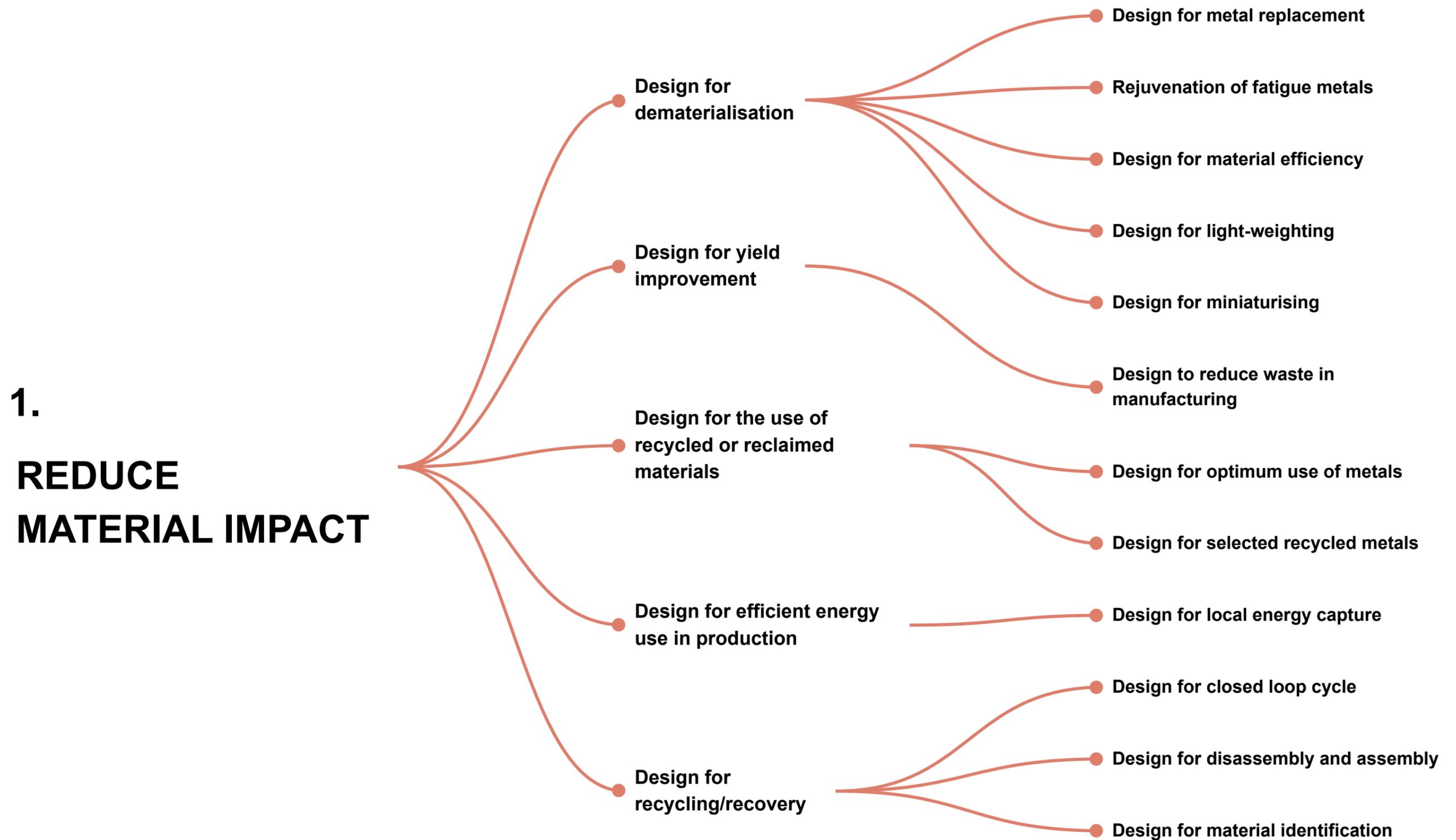


Figure 4: Schematic depicting the circular product design strategies, highlighting the seven overarching strategies guidelines

The graphic below illustrated the strategies and principles associated to the overarching circular design strategy.



# 1. REDUCE MATERIAL IMPACT

This overarching design strategy is associated with the material extraction and processing phase of a product's lifecycle. It focuses on designing to reduce the raw material input to minimise waste and resource depletion by prioritizing material purity.

## Design for Dematerialisation

Design for dematerialisation aims to reduce the reliance on raw materials by substituting metals with alternative materials or digital solutions. This strategy helps decrease resource extraction, minimise waste, and lower environmental impact.

## Design for Metal Replacement

Develop products that replace metals with digital alternatives (e.g., replacing a physical drum kit with an electronic drum kit).

- *The replacement product should not have a greater environmental or ecological impact than the physical material product that is replaced.*

## Rejuvenation of fatigue metals

Include design features in products to facilitate access to metal rejuvenation devices.

- Design features should enable metal treatment devices to be attached to products that cannot be disassembled for rejuvenation of fatigue metals. E.g. rails on metal I-beams on bridges or metal bridges to attach metal rejuvenation devices.
- Integrate design standards into the design of the products that are developed by metal health services.
- Consideration should be given to the design features, including the size, and mass of metal components or products to facilitate easy access to metal health service facilities.
- Clear instructions should be provided for the fatigue metal rejuvenation process to prevent damage to parts of components or products by metal rejuvenation devices.

## Design for material efficiency

Design products to use materials with high-performance characteristics.

- Use high-strength or high-performance multi-principal element alloys (multicomponent and high entropy alloys) including Cantor alloys to design long-lasting products for slowing material resource loops in a circular economy.
- Use high-performance multi-principal element alloys (multicomponent and high entropy alloys) to design efficient thermal, and and corrosion-resistant applications.
- Use refractory multi-principal element alloys (multicomponent and high entropy alloys) to design components or products with a high specific strength requirement at elevated temperatures.

Minimise material input.

- Use less material without compromising longevity of product.
- Design products to use a common grade or small range of metal/alloys for multiple components of a whole metal product.
- Avoid the use of multiple grades of the same metal/metal alloys to manufacture multiple components for a single and whole metal product if possible. This is to facilitate the recycling and use of a small range or grade of metals/alloys for the fostering of a closed-loop of material resources.
- Select manufacturing processes of the product that reduces left-overs or discarded materials during production.

Use light-weighting designs.

- Use optimised geometry to reduce material content whilst retaining strength and structural stiffness.
- Consideration should be given to design requirements such as formability, stackability buckling strength and panel growth suppression.

## Minimise material waste in machining, 3D printing or additive manufacturing process, and forging.

For machining, consider the following:

- Use optimised material block/billet geometry by cutting the billet to near product shape to reduce material input.
- Care must be taken to prevent unwanted cuts on billets to prevent crack initiators or stress concentration points on the finished components or products. Crack initiators or stress concentration points can cause components or product to become defective or damage before their expected lifespan.

- Adopt the use of forging (e.g., cold forming), casting to produce optimised block/billet for machining as a prerequisite for milling and turning, especially for CNC machining.
- Use integrated vacuum systems to collect swarf from machining processes such as milling, turning, and drilling for recycling purpose.
- Store swarf in segregated storage according to material grades or range of material grades, and types for easy recycling.
- Use swarf to replace other materials in components, e.g. Replacement of copper in brake pads. Consideration should be given to the scale of component to substitute for reduced or increased performance.
- Prevent swarf from contamination (oil, grease, moisture, etc.) to enable easy recycling. If contaminated, decontaminate swarf as necessary.
- Utilise hot briquetting to prevent yield loss on swarf and contamination (oil, grease, moisture, etc.) to enable easy recycling.

For cutting in fabrication, consider the following:

- Use remnant of sheet metals or materials to manufacture other components/products instead of recycling them.
- Adopt optimisation of sheet metal cutting to reduce unusable leftover material.

For Metal 3D printing, use the appropriate methods in the following for the correct application to save energy and material resources

- Consider the use of directed energy deposition (DED) 3D printing for applications which require mechanical properties that are as good as cast or wrought material. There are three types of DED: Laser, Arc and Electron beam.
- **Laser DED:** is faster than other types of 3D printing manufacturing processes, uses low heat input for powder feedstock, precise material deposition and melt and generally used for smaller parts. It can be scaled up to produce much larger components.

- **Arc** : is better for large builds and may use existing robotics and power supply
- **Electron beam DED (EB-DED)**: enables the manufacturing of large parts faster than other 3D printing processes.
- DED 3D printing does not use support structures in the manufacturing process/printing of components.
- DED 3D printing produces low build resolution which requires secondary process for good finish.
- Consider the use of selective laser melting (SLM) for precision, durable, lightweight 3D parts that have complex structures, geometries and thin walls especially for aerospace applications.
- Consideration should be given to the strength of material that is used for 3D parts regarding its application.

#### Forging

- Utilise precision forging to reduce material input.

#### Design for light-weighting

##### Select lightweight materials or metal alloys.

- Use light-weight high performance multi-principal element alloys.

##### Use light-weight designs.

- Use optimised geometry to reduce material content whilst retaining strength and structural stiffness.
- Consideration should be given to design requirements such as loading due to stacking, fatigue bending, buckling strength and panel growth suppression.

##### Use honeycomb panels or ribbed design such as in I-beams to improve strength of structures and weight reduction.

- Optimise the cross-sectional areas and perform finite element analysis to ensure that the I-beam design meets the loading requirement for bending and shear stress, buckling, impact and structural stiffness.
- Ensure yielding is within the permitted loading of the structure.
- Use only engineering adhesives that permits recovery and recycling of honeycomb structure materials at the product's end of life.
- Adopt complex geometrical shapes to increase structural stiffness for honeycomb Structures.
- Use flexible honeycomb panels for curved geometry where possible.

##### Design miniaturised components or products. See *Design for miniaturising*.

- Reduce the size of product without compromising key design features such as durability and performance. Trade-offs can be made where necessary.

#### Design for miniaturising

##### Reduce the size of components through the use of design optimisation.

- Optimise the geometry to reduce the size of components or products whilst retaining previous or improved performance level or efficiency.
- The reduction of geometrical size should not diminish the performance of the component or product requirement.
- Trade-offs including reduced lifespan or structural should only be made were the benefits of such optimisation of geometry is absolutely necessary.
- Avoid designing sharp corners or edges to reduce or eliminate stress concentrations on the optimised geometry or structure.

##### Select high strength materials or metal alloys.

- Use light-weight high performance multi-principal element alloys.
- Ensure that the material strength meet the component or product's performance requirement.

#### Design for yield improvement

Optimising material and energy efficiency throughout the production process to maximise resource utilisation.

##### Design to reduce waste in manufacturing

- Use modelling and simulation to test product performance, optimise material use (material reduction) and address any undesired findings.
- Identify and eliminate waste in the design and production stages.

#### Design for the use of recycled or reclaimed materials

This strategy promotes using secondary raw materials to reduce virgin resource use, lower environmental impact, and support circular supply chains.

#### Design for optimum use of metals

##### Use remnants of metals after cuttings in fabrication to make other components or products.

- Print or make markings of components or products on sheet metals for multiple products to optimally use sheet metals.
- Use leftovers of metal, including metal tubes or bars to make other metal components or products.
- Segregate the remnants of sheet metals after cutting in fabrication to enable the recycling of materials according to their grades or types.

#### Design for selected recycled metals

##### Use recycled or reclaimed metals with the appropriate material property for new products.

- Consider the material properties and application of the component/product when using reclaimed materials for manufacturing new components/products
- Select metals that after recycling can retain/recover their original performance characteristics.

##### Design components or products with compatible recycled materials within the product or sub-assembly.

- Use compatible materials for fasteners and components to be joined to prevent corrosion and potential loss of materials.
- Make sure that these different components can be easily separated to facilitate recycling at the product's end of life.

## Design for recycling / recovery

Design for recycling/recovery strategy ensures products are made for easy disassembly and material separation, enabling efficient reclamation and reintegration into circular manufacturing systems.

## Design for closed loop cycle

**Use materials that will be easily recycled from a wide range of components or products.**

- Use multi-principal element alloy for different components in a product to enable easy recycling.

## Design for disassembly and assembly

**Reduce and facilitate the easy operations of disassembly/assembly.**

**Overall architecture of product:**

- Prioritise the disassembly of toxic and dangerous components or materials.
- Prioritise the disassembly of components or materials with higher economic value.
- Prioritise the disassembly of more easily damageable components.

**Adopt modular structures:**

- Divide the product into easily separable and easy-to-handle sub-assemblies.
- Minimise hierarchically dependent connections among components.

**Shape of components and parts:**

- Avoid difficult-to-handle components

- Design measures to minimize the probability and the damage related to the falling out of assembly parts during the handling (e.g., due to a poor grip or poorly design housing).
- Design components which present the simplest possible external geometry.
- Design components which present symmetry axis or, if not possible, exaggerate asymmetrical features.
- Design final components by minimizing the number of assembly parts.

**Shape and accessibility of joints:**

- Avoid joint systems that require simultaneous interventions for opening.
- Minimise the overall number of fasteners.
- Minimise the overall number of different fastener types .
- Ensure fasteners and component are easily accessible including the space for the disassembly tools.
- Ensure fasteners are easily identified.

**Use reversible joint systems.**

- Use a two-way snap-fit joining mechanisms.
- Use fasteners that can be opened with common or standard tools.
- Use fasteners that can be opened with special tools, when opening could be dangerous (e.g., for users).
- Use fasteners that can be automatically removed under certain conditions, e.g., specific temperature.

**Use permanent joint systems that can be easily separated.**

- Avoid the use of rivets to join components.
- Avoid the use of adhesives to form permanent joints.
- Where the use of adhesive is required, use easily removable adhesives that are without toxic chemicals.

**Protect fasteners from corrosion and wear.**

- Use fasteners that are made of materials which are compatible with the materials of component to be joined together. Protect fasteners from corrosion if its material is different from component materials.
- Use protective layers on fasteners that are exposed to elements which can cause potential material degradation.

**Facilitate easy access or reach to components.**

- All components should be easily accessible for humans/robots and maintenance equipment/tools.

**Facilitate the use of standard tools or equipment.**

- Foster the use of standard tools for disassembly/ assembly by using standard fasteners in the design of the components.

**Facilitate access to disassembly and assembly instructions.**

- Provide easily accessible online repair instructions including 3D disassembly and assembly manuals or technical documentation.

**Facilitate access to specialist tools disassembly and assembly tasks.**

- Provide specialist tools or information to access specialist tools which are required for replacing components.

**Facilitate the use of virtual reality or augmented reality tools to support remote disassembly and assembly tasks.**

- Provide easy access or information to access VR or AR tools and their relevant software applications for training, disassembly and assembly tasks.

## Design for material identification

**Provide durable material identification on products or materials to aid sorting process.**

- Use standardized labelling of products and components on recyclability, incompatibility, and/or toxicity so that they can be easily identified from recyclables and waste streams.

**Provide validated and traceable material information.**

- Provide information of non-recyclable materials that are assembled with recyclable materials.
- facilitate the use of material or digital product passport to easily identify the materials of components or products.
- Provide information of non-recyclable materials that are assembled with recyclable materials.

**Use available technology to sort material types (e.g., AI imaging sorting technology).**

- Utilise an integrated x-ray defraction, video, magnetic sorting and eddy-current separation system with artificial intelligence technology to enable the separation of recovered materials by types or grades during recycling.

**Use standardized coding and marking of materials to facilitate identification.**

- Consider the use of international and local standards on the use of identification marks or codes.

- Use component identification marks or labels such as barcode or QR codes to provide online product/material information.

**Eliminate the use of labels which are incompatible with end-of-life treatment.**

- Avoid using labels that are permanently attached to the component and could contaminate metal recycling. These labels should not be placed on the component.

**Place identification marks in visible locations.**

- Identification marks or codes are to be easily visible and readable with human eyes and optical recognition devices in an easily accessible location on the component or product.

**Place identification elements in locations where they are not subjected to continuous contact to prevent wear.**

- Contact with identification marks, labels or codes must be prevented to avoid unnecessary wear and identification issues.
- Identification marks are not to be placed in positions that can come in contact with moving parts.

**Use durable identification design such which are made during the component's manufacturing processes.**

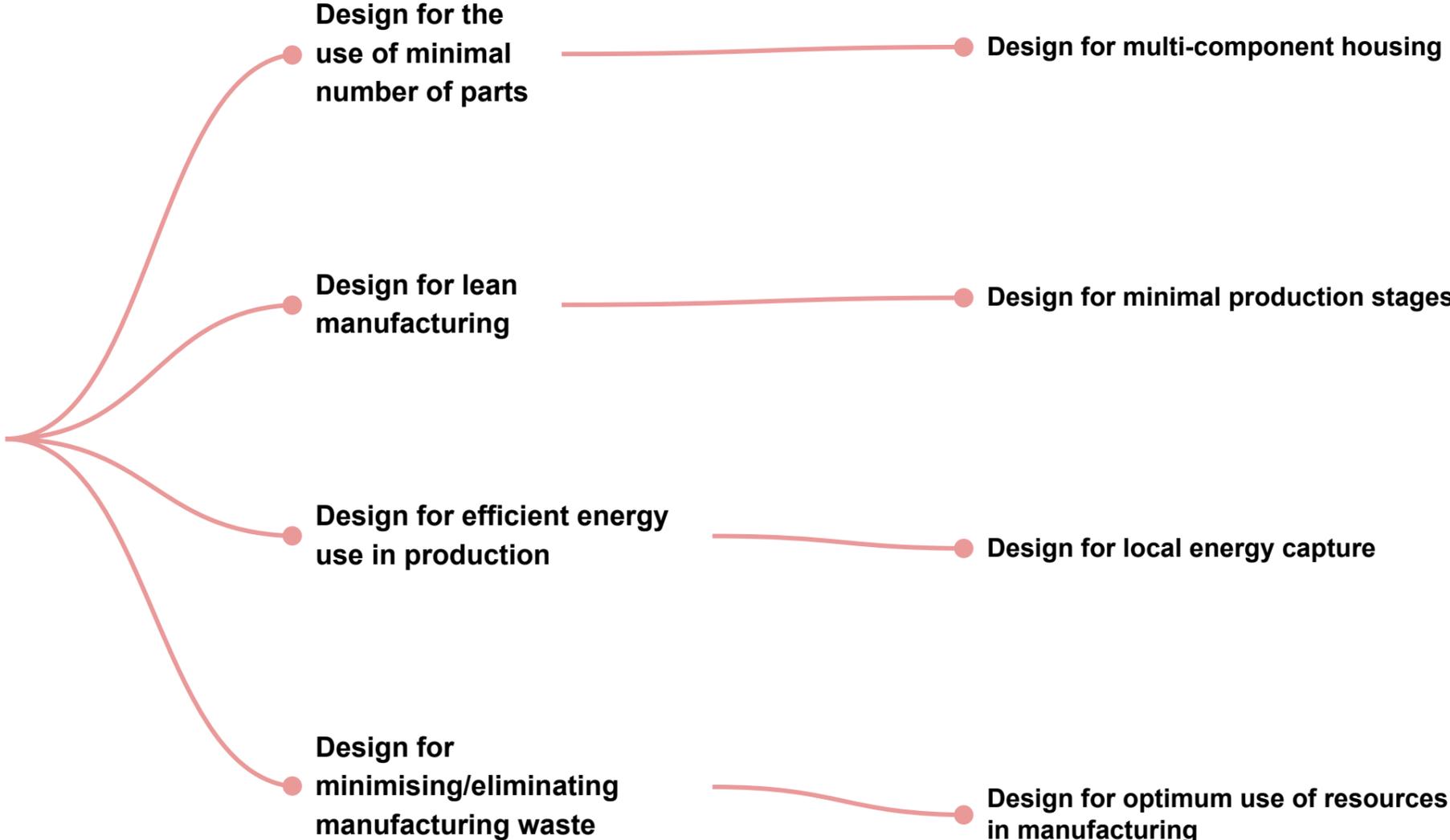
- Integrate the identification marks into the design of the components or products.
- The identification marks are to be made during manufacturing process such as casting, moulding, forging, rolling, pressing, CNC machining, friction stir processing or 3D printing of the component.
- Friction stir processing must not be used on aerospace components or on components where minute changes in material properties can initiate catastrophic damage to the component.

**Avoid using additional materials for marking or codification of components after the initial manufacturing processes.**

- Adding materials on components especially at high temperatures which can cause localised changes in material properties should be avoided.

The graphic below illustrated the strategies and principles associated to the overarching circular design strategy.

# 2. REDUCE MANUFACTURING IMPACT



## 2. REDUCE MANUFACTURING IMPACT

This overarching design strategy is associated with the manufacturing lifecycle phase. Design recommendations are given to reduce the impact of the manufacturing processes and including efficient use of energy, optimised layout of manufacturing equipment and sequencing of manufacturing processes.

### Design for the use of minimal number of parts

This strategy aims to simplify products by reducing the number of components, which streamlines manufacturing, eases maintenance and disassembly, and enhances recyclability.

### Design for multi-component housing

Use multi-components housing designs to reduce number of parts or materials.

- Design components for multi-functionality, e.g., a motor with pulleys on its shaft that operates a fuel and water pump on a system.

### Design for lean manufacturing

This strategy focuses on minimizing waste throughout the production process by designing products that are easy to manufacture efficiently, require fewer resources, and reduce time, cost, and energy across the value chain.

### Design for minimal production stages

Adopt lean manufacturing practices to create an efficient production workflow and continuous product development.

- Obtain feedback from stakeholders including product users and those concerned with manufacturing processes to improve the design of products and manufacturing processes.
- Identify the performance requirement of user, custodians/guardians (replacement terminology for consumers in a circular economy) to determine design specification of products or components which would eliminate material waste in the design of components or products.

- Facilitate the regular implementation of lead product design development including the use of advanced materials and manufacturing process optimisation.

### Design for efficient energy use in production

This strategy involves designing products and selecting manufacturing processes that minimize energy consumption, supporting lower carbon emissions and more sustainable production practices.

### Design for local energy capture

Design systems that can harness renewable energy from the manufacturing process.

- Identify any source of energy that is a by-product of the manufacturing process that may be applied to the manufacturing or other operations.
- Convert heat energy generated from manufacturing process to produce building heating or electricity, e.g., hot gases or radiant heat to generate steam for steam powered (steam turbine) electricity generators.

### Design for minimising/eliminating manufacturing waste

This strategy focuses on maximizing material and process efficiency during manufacturing by minimizing resource inputs, reducing waste, and selecting processes that support sustainable use of materials and energy.

### Design for optimum use of resources in manufacturing

Design a simple manufacturing system with clearly defined elements of the system for easy monitoring and improvement through waste elimination.

- Use monitoring systems to identify and eliminate/minimise waste in the manufacturing process.

Minimise material waste in machining, 3D printing or additive manufacturing process, and forging.

For machining, consider the following:

- Use optimised material block/billet geometry by cutting the billet to near product shape to reduce material input.
- Care must be taken to prevent unwanted cuts on billets to prevent crack initiators or stress concentration points on the finished components or products. Crack initiators or stress concentration points can cause components or product to become defective or damage before their expected lifespan.
- Adopt the use of forging (e.g., cold forming), casting to produce optimised block/billet for machining as a prerequisite for milling and turning, especially for CNC machining.
- Use integrated vacuum systems to collect swarf from machining processes such as milling, turning and drilling.
- Store swarf in segregated storage according to material grades or range of material grades and types for easy recycling.
- Use swarf to replace other materials in components, e.g. Replacement of copper in brake pads. Consideration should be given to the scale of component to substitute for reduced or increased performance.
- Prevent swarf from contamination (oil, grease, moisture, etc.) to enable easy recycling. If contaminated, decontaminate swarf as necessary.
- Utilise hot briquetting to prevent yield loss on swarf and contamination (oil, grease, moisture, etc.) to enable easy recycling.

For cutting in fabrication, consider the following:

- Use remnant of sheet metals or materials to manufacture other components/products.
- Adopt optimisation of sheet metal cutting to reduce unusable material residue.

For Metal 3D printing, use the appropriate methods in the following for the correct application to save energy and material resources.

- Consider the use of directed energy deposition (DED) 3D printing for applications which require mechanical properties that are as good as cast or wrought material. There are three types of DED: Laser, Arc and Electron beam.

**Laser DED:**

- Is faster than other types of 3D printing manufacturing processes, uses low heat input for powder feedstock, precise material deposition and melt and generally used for smaller parts. It can be scaled up to produce much larger components.

**Arc:**

- Is better for large builds and may use existing robotics and power supply.

**Electron beam DED (EB-DED):**

- Enables the manufacturing of large parts faster than other 3D printing processes.
- DED 3D printing does not use support structures in the manufacturing process/printing of components.
- DED 3D printing produces low build resolution which requires secondary process for good finish.
- Consider the use of selective laser melting (SLM) for precision, durable, lightweight 3D parts that have complex structures, geometries and thin walls especially for aerospace applications.
- Consideration should be given to the strength of material that is used for 3D parts regarding its application.

**Forging:**

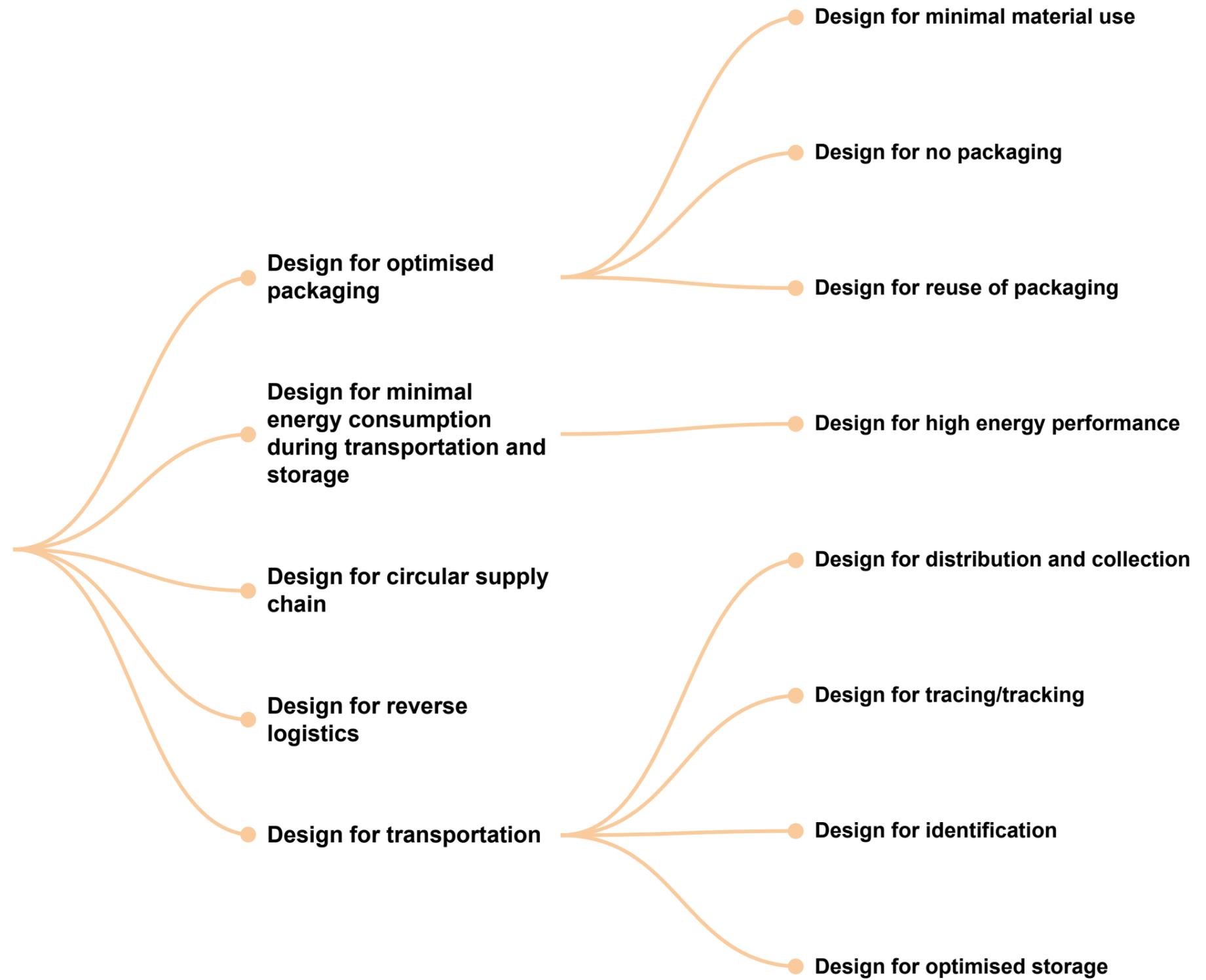
- Utilise precision forging to reduce material input.

**Adopt simulation systems to optimise manufacturing processes.**

- Utilise computer modelling simulation tools such as Tecnomatix, Simul8, FlexSim, AnyLogic, etc., for virtual testing of manufacturing operations and process optimisation such as component production and assembly.

The graphic below illustrated the strategies and principles associated to the overarching circular design strategy.

### 3. REDUCE DISTRIBUTION IMPACT



### 3. REDUCE DISTRIBUTION IMPACT

This overarching design strategy is associated with the distribution lifecycle phase. It focuses on reducing the impact of distribution, collection, and storage. The design recommendations include durability, energy-efficient transportation, and reverse logistics.

#### Design for optimised packaging

This strategy focuses on minimizing the material, volume, and environmental impact of packaging and logistics while ensuring product protection and functionality throughout the supply chain.

#### Design for minimal material use

**Design the packaging to be part (or to become a part) of the product.**

- Integrate the packaging design to be a feature of the component or product.

**Apply materials only where absolutely necessary.**

- Consider the use of skeletal frames to reduce material input in packaging.

**Design the packaging to be collapsible for easy and efficient transportation and storage.**

- Consider the use of hinged panels/sections of packaging for optimised storage and high capacity transportation.

**Use ribbed design for structural stiffness.**

- Consider the use of honeycomb structures.

**Use multi-component or multi-product packaging.**

- Design packaging with adjustable mechanisms which can be used hold multiple products in the packaging.

#### Design for no packaging

**Design product housing or components to avoid the use of packaging.**

- Design product housing/casing with features of packaging to avoid the use of separate packaging.

#### Design for reuse of packaging

**Design durable packaging.**

- Design durable packaging which can be easily repaired and maintained.
- The performance of materials must meet the requirement for the defined service life of components.
- Use high performance multi-principal element alloy.
- Consideration should be given to the strength of materials when selecting the choice of materials for components.
- Perform fracture analysis where it is determined that significant loading of the component would occur in the service life of component, especially for fatigue loading.
- Due consideration should be given to fatigue loading of components which requires less load than static loading to cause failure of components.
- Consider the various types of failure which would accelerate other types of failure, e.g., fracture resulting from stress-corrosion on a loaded beam and include preventive or mitigating measures in the design of components.
- Use optimised design instead of over-specification if avoidable.
- Avoid using metal additive manufacturing for components which are to be loaded in tension where shear forces are greatest.
- Use metal additive manufacturing for components which are primarily loaded in compression or does not experience tension loading above their yield strength.
- Avoid using 3D printing for components which are to be loaded in tension where shear forces are greatest.
- Use 3D printing for components which are primarily loaded in compression or does not experience tension loading above their yield strength.

**Design packaging with integrated tracking/tracing technology, e.g., satellite tracking for shipping containers.**

- Utilised tracking/tracing data to be stored in a secure, accessible database for all relevant parties that are concerned with the packaging.

**Design packaging with rust or corrosion prevention measure.**

- Make sure that the metal used in the design of the packaging is not susceptible to rust or corrosion.

**Design packaging with durable identification to enable tracking/tracing.**

- Identification marks should be positioned in a safe location that is visible, readable with sensors and where there is very little or no contact can be easily made with the identification marks.

**Design packaging for easy maintenance or repair.**

- Facilitate disassembly and assembly.

**Design packaging which can be easily cleaned.**

- Design packaging that can be easily cleaned with water without the water being trapped in it.
- Use skeleton frame or include drain holes at the bottom of packaging to aid draining of water used during cleaning or washing of packaging.

#### Design for minimal energy consumption during transportation and storage

This strategy aims to reduce the energy required to move and store products by optimising their size, weight, shape, and packaging. It supports circularity by lowering carbon emissions, improving logistics efficiency, and reducing the overall environmental footprint of distribution.

#### Design for high energy performance

**Use light-weight metals.**

The use of light-weight metals must not compromise the performance requirement of the component or products.

**Use ribbed design to reduce the mass of packaging and products.**

Use aluminium honeycomb sandwich structure for large packaging to minimise the mass of the packaging and retention of structural rigidity.

**Select lowest-impact transportation systems.**

Consider the use of electric vehicles or rail transportation for large volumes of products.

**Design compactable products with high storage density.**

**Design products for on-site assembly.**

Facilitate design for disassembly and assembly.

**Decentralise activities to reduce transportation volumes.**

Facilitate distributed manufacturing including 3D printing or additive manufacturing for localised production to reduce transportation volumes.

**Where local resources are available, prefer local raw materials and energy sources.**

**Prefer local suppliers along the whole supply chain if possible.**

### Design for circular supply chain

This strategy focuses on enabling and enhancing closed-loop supply systems through product and system design. It ensures that materials and components can be efficiently recovered, reused, remanufactured, or recycled, supporting material circularity across the entire value chain.

**Facilitate reverse logistics with identifiable, traceable/trackable materials or products.**

- Every stakeholder in the supply chain should be considered and design parameters which relates to them included in the design of the component/product.

### Design for reverse logistics

This strategy involves designing products and packaging to facilitate efficient return, recovery, and reintegration of materials or components after use.

**Facilitate easy transportation of components including the collection and distribution of components.**

- Every element in the reverse logistics network should be considered and design parameters which relates to them included in the design of the component/product.

### Design for transportation

This strategy focuses on optimising product and packaging design to improve transport efficiency throughout the supply chain. It aims to reduce energy use, costs, and emissions by minimising volume and weight, enhancing stackability, and using modular or collapsible designs.

### Design for distribution and collection

**Facilitate easy collection and distribution of components or products.**

- Design components or products to be easily disassembled/assembled, collapsible, stackable, modular, trackable/traceable, and identifiable.

**Facilitate the use of modular design to reduce component or product size for easy transportation.**

### Design for tracing/tracking

**Integrate tracking or tracing technologies in the design of components or products to determine their location in support of reverse logistic.**

- Use tracking technologies such as GPS for tracking high value components or products such as shipping containers to support supply or reverse logistics, and auditing purpose.
- Adopt the use of sensors to monitor the state of components or products.
- Adopt the use of digital passport for component or material identification.

**Use standardized coding and marking of metal components to facilitate their identification.**

- Consider the use of international and local standards on the use of identification marks or codes.

**Design packaging with rust or corrosion prevention measure.**

- Make sure that the metal used in the design of the packaging is not susceptible to rust or corrosion.

**Design packaging with durable identification to enable tracking/tracing.**

- Identification marks should be positioned in a safe location that is visible, readable with sensors and where there is very little or no contact can be easily made with the identification marks.

### Design for identification

**Use standardized coding and marking of materials to facilitate identification.**

- Consider the use of international and local standards on the use of identification marks or codes.
- Use component identification marks or labels such as barcode or QR codes to provide online product information.
- Adopt the use of digital passport for component or material identification.

**Eliminate the use of labels which are incompatible with end-of-life treatment.**

- Avoid using labels that are permanently attached to the component and are potential contaminants metal in recycling. These labels should not be placed on the component.

**Place identification marks in visible locations.**

- Identification labels, marks or codes are to be easily visible and readable with human eyes and optical recognition devices in an easily accessible location on the component or product.

**Place identification elements in locations where they are not subjected to continuous contact to prevent wear.**

- Contact with identification marks, labels or codes must be prevented to avoid unnecessary wear and identification issues.
- Identification marks are not to be placed in positions that can come in contact with moving parts.

**Use durable identification design such which are made during the component's manufacturing processes.**

- Integrate the identification marks into the design of the components or products.
- The identification marks are to be made during manufacturing process such as casting, moulding, forging, rolling, pressing, CNC machining, friction stir processing or 3D printing of the component.
- Friction stir processing must not be used on aerospace components or on components where minute changes in material properties can initiate catastrophic damage to the component.

**Avoid using additional materials for marking or codification of components after the initial manufacturing processes.**

- Adding materials on components especially at high temperatures can cause localised changes in material properties.

### Design for optimised storage

**Design high capacity with minimal storage space requirement.**

- Design stackable or collapsible products to enable optimised storage and reduced transport carbon footprint
- Use interlocking mechanisms to enable easy collapsing, stacking, and securing products for storage and transportation
- Where packaging is designed for short life, design them for easy compression for collection after use.

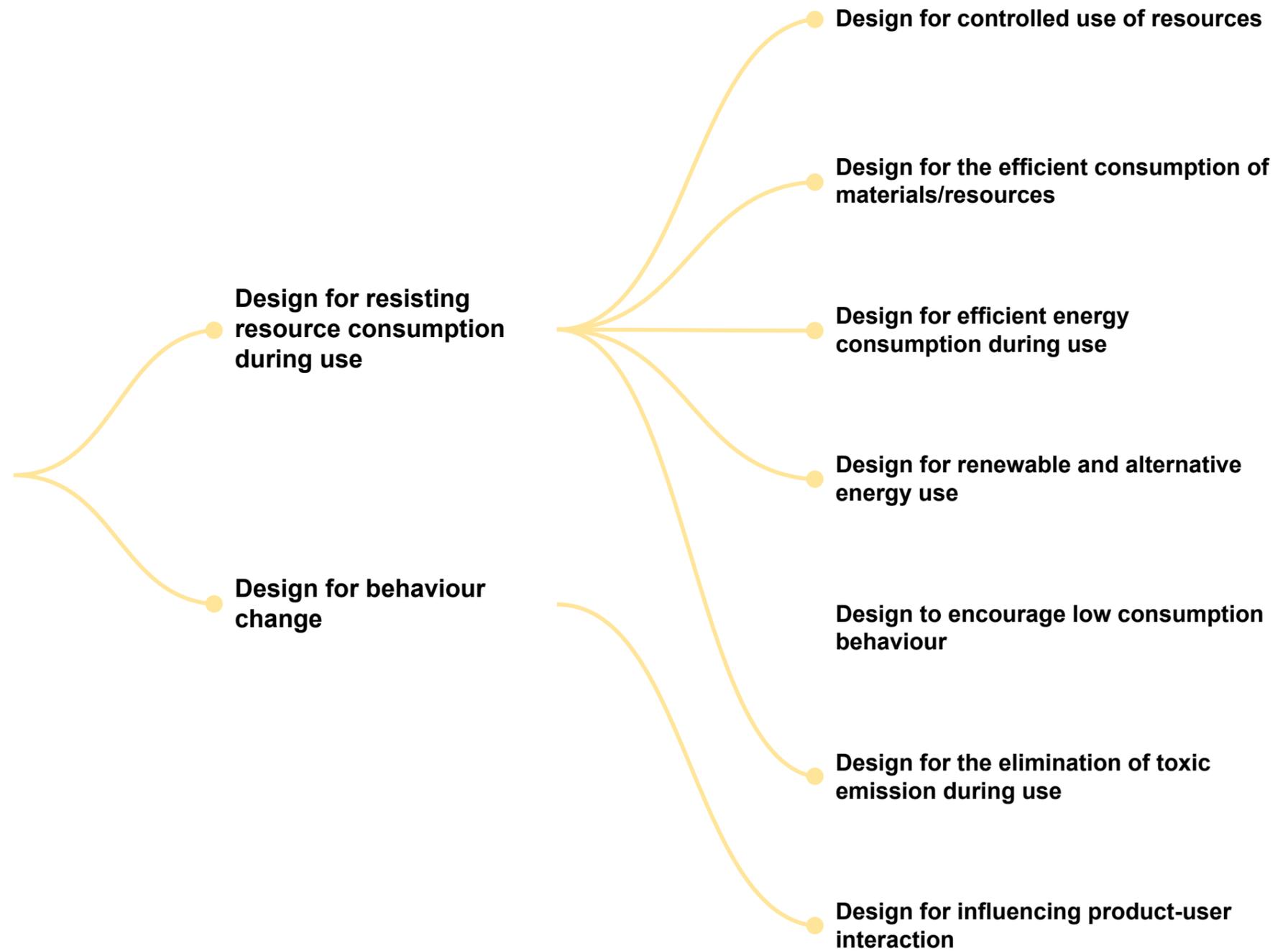
**Use modular design to aid transportation of packaging, e.g., male-female unit for large shipping containers.**

- Facilitate disassembly and assembly of modular products for easy and high volume storage. *See Design for modularity.*

The graphic below illustrated the strategies and principles associated to the overarching circular design strategy.

# 4.

## REDUCE USE IMPACT



## 4. REDUCE USE IMPACT

This overarching design strategy is associated with the use phase of the product lifecycle. It focuses on minimising the products impact when it is being used. Design recommendations include controlled use of consumables, influencing product-user interaction, energy efficiency, and behavioural change.

### Design for resisting resource consumption during use

This strategy aims to minimise the ongoing use of resources, such as water, energy, and consumables throughout a product's operational life. It focuses on integrating energy-efficient technologies, durable components, and intelligent control systems that reduce unnecessary consumption.

#### Design for controlled use of resources

**Design mechanisms that will control the use of necessary resource in different conditions.**

- Use sensors to adjust resource consumption according to different conditions.

**Integrate sensors into the design of products to cease operation when the product is not required to be in operation.**

- Various aspects such as completion of task, conditions of operation, etc., when determining the parameters of operation.

**Use physical indicators or digital sensors on products to show or notify when the required resource reaches its limit, e.g., volume marks on kettles.**

- The physical indicators or digital sensors on products should be durable and reliable to last for the products lifespan.

#### Design for the efficient consumption of materials/resources

**Design products that can be used in a cascade approach.**

- Multi-purpose use should be considered in the design of components or products to extended their useful lifespan and prevent or delay physical obsolescence.

**Reduce resource consumption in product's default state.**

- Optimise the design of components to use minimal material content.
- Consideration should be given to safety factors or FOS when optimising the design of components.

### Design for efficient energy consumption during use

**Use highly efficient engines, energy conversion and transmission systems.**

- Use passive energy systems.
- Use energy recovery systems.
- Use energy saving systems.
- Use sensors to adapt energy consumption in relation to contextual conditions.
- Equip the product with intelligent power-off function.
- Set product default state at minimum energy consumption.

### Design for renewable and alternative energy use

**Use renewable energy sources.**

- Use local energy sources such as wind, solar, geothermal, and hydroelectric.
- Convert hot gases from manufacturing processes into steam powered energy source.

**Design products to use human power instead of electric or fuel powered engine, e.g., push mower.**

- Consideration should be given to the mass of the product to ensure users of vary strength can use the product.
- Design the product to be used and maintained easily.

### Design to encourage low consumption behaviour

**Use sensor warning system to conserve energy.**

### Design for the elimination of toxic emission during use

**Avoid materials that emit toxic or harmful substances during the use phase.**

**Design products that do not consume toxic and harmful materials in the use phase.**

**Select energy resources that reduce dangerous emissions during usage.**

### Design for behaviour change

This strategy focuses on influencing user habits and choices to encourage more sustainable actions during a product's use phase. By embedding prompts, feedback mechanisms, and intuitive interfaces, designers can guide users toward reduced energy use, better maintenance, and responsible disposal. Design for behaviour change empowers users to actively participate in circular outcomes, making sustainability a shared responsibility between the product and its user.

### Design for influencing product-user interaction

**Design products that can compel users to adopt predetermined behaviour or behavioural change to achieve a desired outcome.**

- Include preliminary action/s in the function of a product which are to be performed before the final action is done in a process. E.g., utilising an ignition key release mechanism which requires the driver to move the gear stick on a vehicle from forward drive to park position for the ignition key to be released from the ignition switch.

**Design products that provide users with useful information to adopt a desired behaviour or behavioural change.**

- Consider the integration of information display system on products to foster the reduction of resource consumption. E.g., home energy usage meter or heating system with digital display meters to inform users of their energy consumption.

**Design products that can make it harder for people to perform an undesired behaviour.**

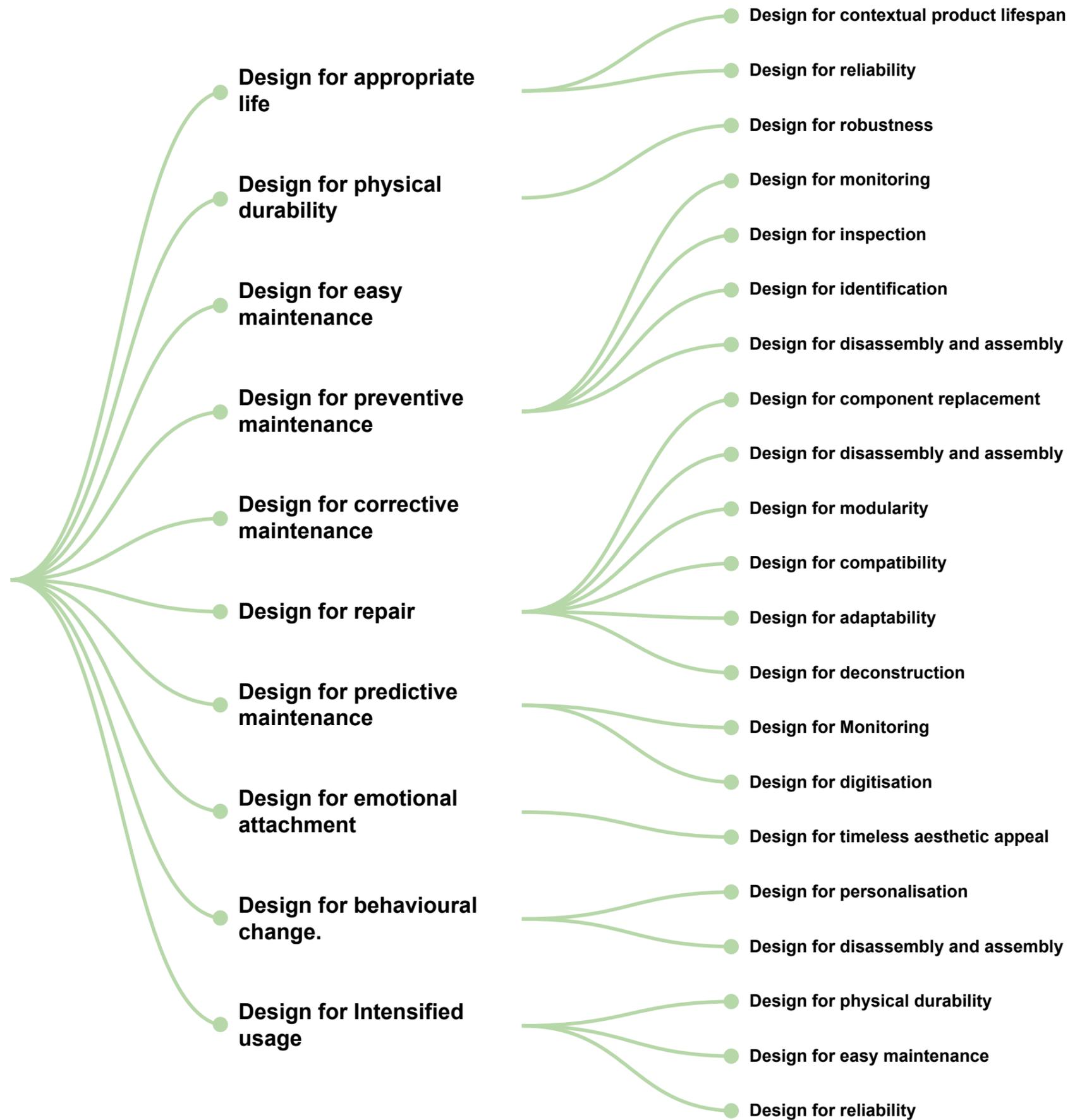
- Eliminate product functionality or access to functions in order to deter people from behaving undesirably. E.g., the Apple music application that is mirrored by Android auto or Apple CarPlay has its search function disable on vehicle infotainment system to prevent drivers from searching for songs whilst driving.

**Design products that can make people not want to perform an undesired behaviour.**

- Integrate warning device or system to warn product users of their actions which would waste material or energy resources. E.g., a refrigerator which warns users that its door is needed to be closed after a brief opening period with an alarm that sounds very loud and annoying until the door is closed to prevent high energy usage.

The graphic below illustrated the strategies and principles associated to the overarching circular design strategy.

# 5. OPTIMISE PRODUCT LIFE



## 5. OPTIMISE PRODUCT LIFE

This overarching design strategy is also associated with the product's use phase. It focuses on extending the lifespan. This design strategy places emphasis on durability and maintenance to extend the product lifespan, including associated software upgrades.

### Design for appropriate lifespan

This strategy involves aligning a product's durability and performance with its intended use and user needs, neither under- nor over-engineering its longevity. By considering factors such as expected usage patterns, upgradeability, and contextual obsolescence, designers can avoid unnecessary resource use while ensuring the product remains functional and valuable throughout its lifecycle.

### Design for contextual product lifespan

#### Design lifespan of components according to their scheduled duration.

- Do not over-design component or product with a factor of safety that exceeds its relevant duration of use.

#### Use durable materials according to the product performance requirement and lifespan.

- Select materials with the properties that are suitable to meet the component's or product's requirement regarding duration, conditions in use, and loading conditions.

#### Avoid selecting durable materials for temporary products or components.

- Strength of materials should be relative to the application for which the component or product is used.

### Design for reliability

#### Reduce overall number of components.

- Consider designing components with multiple functions.

#### Make parts and connections physically robust.

- Consideration should be given to joint or connection design for rigidity, assembly and disassembly.

- Identify and mitigate the various loading conditions that would cause failure including corrosion, shock/impact, humidity, mechanical bending, compression, tension, vibration (random and harmonic), and temperature.
- Implement mitigating features into the design of components or products and manufacturing processes to prevent early obsolescence.
- Eliminate the effect of the failure induced loads in the design of components or products and manufacturing processes if possible.
- Identify the environments associated with the products including manufacturing, storage, transportation and operational (user) environment to determine their respective effect on the performance of the product.
- Perform reliability testing such as quantitative accelerated life testing (QALT) or highly accelerated life tests (HALT) to identify unforeseen or undetermined failure modes for validation of the reliability of the design.

### Design for physical durability

This strategy focuses on enhancing a product's ability to withstand mechanical stress, environmental exposure, and wear over time. By selecting robust materials, reinforcing high-stress components, and ensuring structural integrity, products can maintain functionality and safety over extended periods of use.

### Design for robustness

#### Design durable products

- The product specification should be fully and clearly defined to meet all performance requirements.
- The performance of materials must meet the requirement for the defined service life of components including for all loading conditions.
- Use high performance multi-principal element alloy.
- Consideration should be given to the strength of materials when selecting the choice of materials for components.
- Perform fracture analysis to determine where significant loading of the component would occur in the service life of component, especially for fatigue loading and utilise failure mitigation design measures.
- Due consideration should be given to fatigue loading of components which requires less load than static loading to cause failure of components. This should be done to employ failure mitigation design measures.

- Consider the various types of failure which would accelerate other types of failure such as fracture which occur due to corrosion or rust induced crack or stress concentration on a loaded beam. Provide preventive or mitigating measures in the design of components.
- Use optimised design instead of over-design if possible.
- Avoid using metal additive manufacturing for components which are to be loaded in tension where shear forces are greatest.
- Use metal additive manufacturing for components which are primarily loaded in compression or does not experience tension loading above their yield strength.
- Avoid using 3D printing for components which are to be loaded in tension where shear forces are greatest.
- Use 3D printing for components which are primarily loaded in compression or does not experience tension loading above their yield strength.

### Design for easy maintenance

Creating products that are easy to repair, service, or upgrade with minimal effort and cost. This includes using durable, accessible parts and modular designs to extend product life and reduce waste.

#### Facilitate monitoring, inspection, repair, servicing including replacement of components.

- Circular design strategies and principles related to design for maintenance are to be adopted in the design of components/products.

### Design for preventive maintenance

Designing products to proactively reduce wear and prevent breakdowns through regular upkeep. This includes features like wear indicators, accessible components, and easy-to-follow maintenance schedules, ensuring longevity and minimizing downtime.

### Design for monitoring

#### Equip products with diagnostic and/or auto-diagnostic systems to forecast malfunctions.

- Use sensors to monitor performance, degradation of components and adverse operating conditions to prevent failure of components or products.

- Use monitoring technologies to determine the state of components material property (e.g., use strain gauge sensor on metal beams on a bridge to inform of cycle loading and the induced stress for the fostering stress relieving treatment.)
- Integrate predictive maintenance monitoring or telemetry technologies in the design of products to provide useful maintenance data or information for the facilitation of proactive maintenance tasks.
- Utilise video technology to aid visual monitoring of components.

### Design for inspection

#### Design simple methods of inspection and evaluation of components.

- Specify inspection timeframe and triggers for inspection.
- Clearly define the components that are to be inspected and what to look for during the inspection.
- Provide criteria that are simple to understand for the evaluation of components.
- Define how the evaluation of performance or state of components are to be done against the reference evaluation criteria.
- Define how the inspection is to be carried out including the sequence of the inspection.
- Specify specialist equipment that are required for inspection.
- Provide current/updated inspection instructions as necessary.

### Design for identification

#### Use standardized coding and marking of materials to facilitate identification of components.

- Consider the use of international and local standards on the use of identification marks or codes.
- Use component identification marks or labels such as barcode or QR codes to provide online repair information.
- Adopt the use of digital passport for component or material identification.

#### Eliminate the use of labels which are incompatible with end-of-life treatment.

- Avoid using labels that are permanently attached to the component and could contaminate metal recycling. These labels should not be placed on the component.

#### Place identification marks in visible locations.

- Identification marks or codes are to be easily visible and readable with human eyes and optical recognition devices in an easily accessible location on the component or product.

#### Place identification elements in locations where they are not subjected to continuous contact to prevent wear.

- Contact with identification marks, labels or codes must be prevented to avoid unnecessary wear and identification issues.
- Identification marks are not to be placed in positions that can come in contact with moving parts.

#### Use durable identification design such which are made during the component's manufacturing processes.

- Integrate the identification marks into the design of the components or products.
- The identification marks are to be made during manufacturing process such as casting, moulding, forging, rolling, pressing, CNC machining, friction stir processing or 3D printing of the component.
- Friction stir processing must not be used on aerospace components or on components where minute changes in material properties can initiate catastrophic damage to the component.

#### Avoid using additional materials for marking or codification of components after the initial manufacturing processes.

- Adding materials on components especially at high temperatures can cause localised changes in material properties.

### Design for disassembly and assembly

See *design for disassembly and assembly*.

### Design for corrective maintenance

Designing products with features that make repairs easy after a failure occurs. This includes accessible parts, clear diagnostics, and simple repair processes to quickly restore function and minimize disruption.

#### Facilitate easy repair, replacement, extended use of components.

### Design for repair

Designing products to be easily disassembled and repaired with accessible parts, tools, and clear instructions. This approach prioritizes durability and modularity, enabling straightforward fixes and extending product life.

### Design for component replacement

#### Facilitate the replacement of all components.

- Provide easy access to replacement parts including the necessary information to obtain the parts.
- Facilitate the easy identification of components. See Design for identification.

#### Facilitate easy disassembly and assembly of all components.

- Include *design for disassembly and assembly* in the design of components.
- use standard fasteners and tool for disassembly and assembly of components.

#### Use standard components to facilitate the substitution of faulty components.

- Avoid the use of bespoke components as replacement parts.

#### Design low-maintenance products.

- Robustness and reliability of components are key elements to be considered among other factors which could potentially foster frequent maintenance.

#### Simplify access for assembly and disassembly of components.

- Components should be easily accessible including space for tools and persons doing the replacement of components.

#### Facilitate easy cleaning.

- Provide easy access for cleaning.
- Specify the types of cleaning material, agents, or substance to be used for cleaning components to avoid abrasion, corrosion, or rust.
- Specify clearly defined condition or timeframe for cleaning to be done.
- Make components easily accessible for cleaning including the space for cleaning tools or person doing the cleaning.
- Specify the maximum temperature for cleaning fluids where high temperature or hot cleaning is required.
- Define the maximum pressure for jet wash where it is required to avoid damage being caused to components during cleaning.

**Design components or products for easy onsite maintenance using standard tools.**

- Components are to be easily disassembled and assembled.

**Facilitate access to repair or maintenance instructions.**

- Provide easily accessible online repair instructions including 3D repair manuals or technical documentation.

**Facilitate access to specialist tools.**

- Provide specialist tools or information to access specialist tools which are required for replacing components.

**Facilitate the use of virtual reality or augmented reality tools to support remote repair tasks.**

- Provide easy access or information to access VR or AR tools and their relevant software applications for training and repair tasks.

**Design for disassembly and assembly**

See *Design for disassembly and assembly*.

**Design for modularity****Adopt modular designs.**

- Design assemblies to enable faster repairs.
- Modular systems should be designed with the considerations of handling and transportation.
- Consideration should be given to structural integrity when adopting modular designs.
- Standard interfaces are to be used in the design of the assembly modules.
- The design of modular systems should not foster the creation of unnecessary number of parts or sub-assemblies.
- Ensure that the modular units do not increase packaging.

**Design for compatibility****Adopt platform based designs.**

- Components are to be designed to integrate into existing and future systems or products without causing failure or reduced performance.
- A common standard should be adopted for all platform based design, especially at interfaces of components or assembly modules.

Facilitate design for disassembly and assembly. See *Design for disassembly and assembly*.

**Design for adaptability****Include flexibility in the design of components.**

- Design components or systems with anticipation of changes in future performance requirement.
- Design components or systems with anticipation of changes in future legislation.
- Design components that can be used for other functions or with different systems after minimal modification.
- Design standards must be maintained to prevent or delay physical obsolescence.

Facilitate design for disassembly and assembly. See *Design for disassembly and assembly*.

**Design for deconstruction****Facilitate the use of mechanical fasteners.**

- See also *Design for disassembly and assembly*.
- Ensure fasteners and component are accessible.
- Fasteners must be easily accessible including the space for the deconstruction equipment or tool.
- Fasteners must be easily identified.
- Minimize the number of different types of fasteners.
- Minimize the number of fasteners if possible without compromising joint strength.
- Protect fasteners from corrosion and wear.
- Use fasteners which are made of a materials that are compatible with the components which are required to be joined or assembled.

**Facilitate safe handling of components.**

- Design measures to minimize the probability of damage occurring to components due to it being dropped during the handling.
- Include equipment handling points in the design of components.

**Use mechanical methods of separating components from permanently attached materials such as concrete.**

- Avoid the use of chemical or thermal methods of separating metal components from other types of materials that are permanently joined to them to prevent unwanted changes in material properties of the metal components.

**Design for predictive maintenance**

Designing products with built-in sensors or data systems that monitor performance and predict when maintenance is needed. This approach helps identify potential issues before they cause failure, reducing downtime and optimizing resource use.

**Design for Monitoring**

Facilitate monitoring of components or systems. See *Design for monitoring*.

**Design for digitisation****Integrate digital data management and communication technologies with sensors to facilitate automated and remote monitoring of components.**

- Use reliable and durable sensors to collect data on component's performance, structural status and other useful data.
- The integrated digital data management and communication technologies should be able to reliably acquire useful data from the sensors, transmit and store the data securely.
- Utilise maintenance data analytical or processing software application to process and interpret the collected data into useful maintenance information.

**Design for emotional attachment**

Creating products that foster a strong personal connection by appealing to users' emotions, values, or memories. This can involve thoughtful aesthetics, meaningful functionality, or long-lasting quality that encourages loyalty and care, extending the product's lifespan.

**Design for timeless aesthetic appeal****Use classic designs that appeals to individuals' cultural and physical changes.**

Facilitate easy repair. See *Design for repair*.

## Design for behavioural change.

Designing products or systems that encourage users to adopt new behaviors or habits, often by making the desired actions easier, more rewarding, or more intuitive. This approach leverages psychology and design principles to nudge users toward positive, sustainable changes.

## Design for personalisation

**Enable and facilitate personalisation or customisation without compromising product upgrade or reuse.**

- Personalisation of components or product should not require the use of bespoke replacement parts which could potential hinder repair or upgrade.

**Enable and facilitate refurbishment or reconditioning.**

- Design products to resist damage and wear (corrosive, rust, abrasive wear).

## Design for disassembly and assembly

See *Design for disassembly and assembly*.

## Design for intensified usage.

Designing products to withstand frequent or heavy use without compromising performance or durability. This includes selecting robust materials, reinforcing high-stress areas, and ensuring ease of maintenance to support long-term, intensive use.

## Design for physical durability

Facilitate design for durability. See *Design for physical durability*.

## Design for easy maintenance

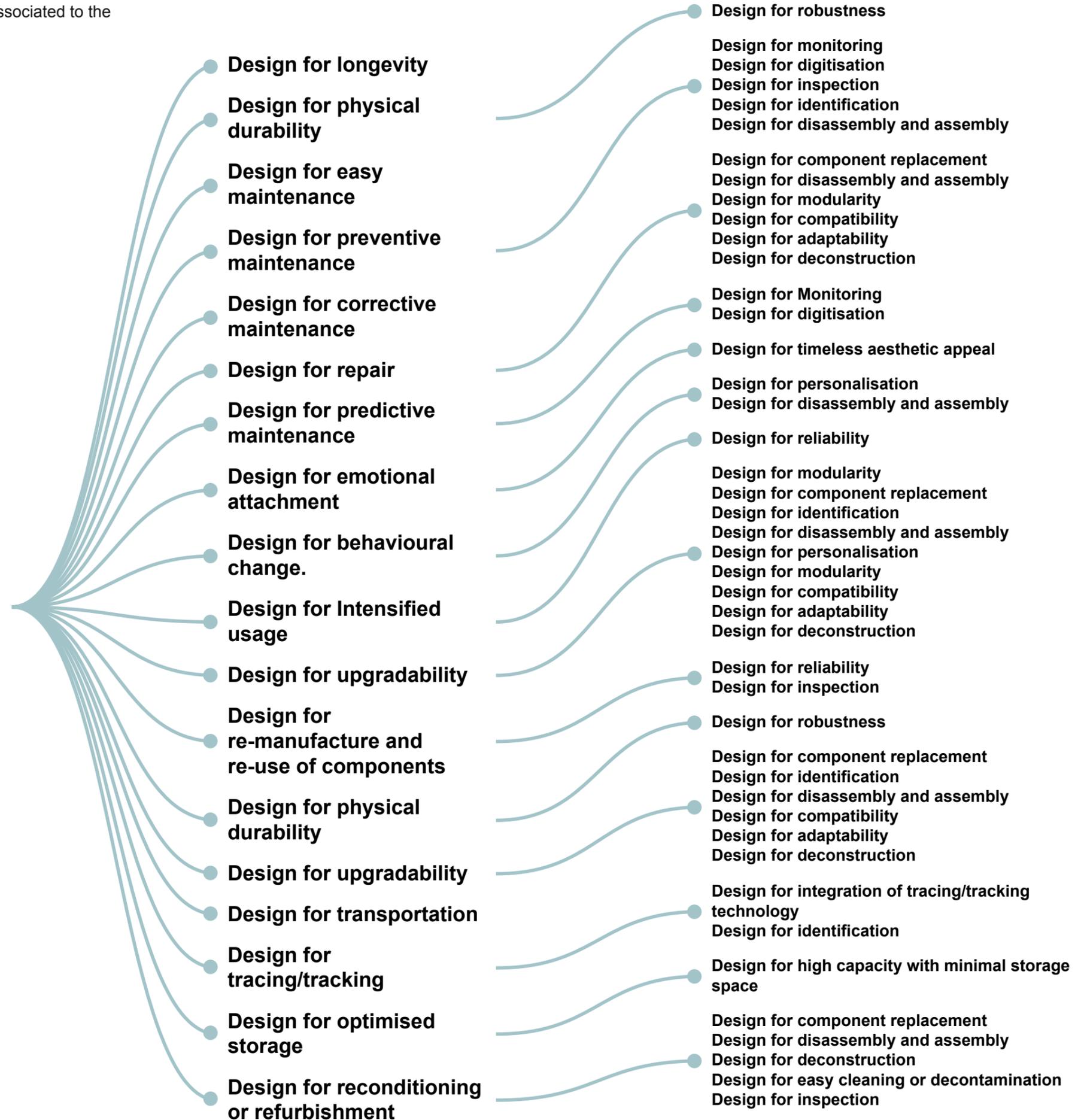
Facilitate easy maintenance. See *Design for easy maintenance*.

## Design for reliability

Facilitate reliable design. See *Design for reliability*.

The graphic below illustrated the strategies and principles associated to the overarching circular design strategy.

# 6. REMANUFACTURE AND REUSE



## 6. REMANUFACTURE AND REUSE

These overarching design strategies are also associated with the product's use phase. They focus on using parts from defective units to create new ones, repairing damaged products to a like-new state, and reusing products over multiple lifecycles, respectively.

### Design for longevity

Creating products that last longer through durable materials, timeless aesthetics, and the ability to be maintained, repaired, or upgraded. This approach reduces the need for replacement, supporting sustainability through extended product lifecycles.

**Facilitate long-life of components or products by utilising circular design strategies and principles such as design for attachment, disassembly/assembly, standardisation, compatibility, upgradability, durability, easy maintenance, and repair.**

### Design for physical durability

This strategy focuses on enhancing a product's ability to withstand mechanical stress, environmental exposure, and wear over time. By selecting robust materials, reinforcing high-stress components, and ensuring structural integrity, products can maintain functionality and safety over extended periods of use.

### Design for robustness

#### Design durable products

- The product specification should be fully and clearly defined to meet all performance requirements.
- The performance of materials must meet the requirement for the defined service life of components including for all loading conditions.
- Use high performance multi-principal element alloy.
- Consideration should be given to the strength of materials when selecting the choice of materials for components.
- Perform fracture analysis to determine where significant loading of the component would occur in the service life of component, especially for fatigue loading and utilise failure mitigation design measures.

- Consider the various types of failure which would accelerate other types of failure such as fracture which occur due to corrosion or rust induced crack or stress concentration on a loaded beam. Provide preventive or mitigating measures in the design of components.
- Use optimised design instead of over-design if possible.
- Avoid using metal additive manufacturing for components which are to be loaded in tension where shear forces are greatest.
- Use metal additive manufacturing for components which are primarily loaded in compression or does not experience tension loading above their yield strength.
- Avoid using 3D printing for components which are to be loaded in tension where shear forces are greatest.
- Use 3D printing for components which are primarily loaded in compression or does not experience tension loading above their yield strength.

### Design for easy maintenance

Creating products that are easy to repair, service, or upgrade with minimal effort and cost. This includes using durable, accessible parts and modular designs to extend product life and reduce waste.

#### Facilitate monitoring, inspection, repair, servicing including replacement of components.

- Circular design strategies and principles related to design for maintenance are to be adopted in the design of components/products.

### Design for preventive maintenance

Designing products to proactively reduce wear and prevent breakdowns through regular upkeep. This includes features like wear indicators, accessible components, and easy-to-follow maintenance schedules, ensuring longevity and minimizing downtime.

### Design for monitoring

#### Equip products with diagnostic and/or auto-diagnostic systems to forecast malfunctions.

- Use sensors to monitor performance, degradation of components and adverse operating conditions to prevent failure of components or products.

- Use monitoring technologies to determine the state of components material property (e.g., use strain gauge sensor on metal beams on a bridge to inform of cycle loading and the induced stress for the fostering stress relieving treatment.)
- Integrate predictive maintenance monitoring or telemetry technologies in the design of products to provide useful maintenance data or information for the facilitation of proactive maintenance tasks.
- Utilise video technology to aid visual monitoring of components.

### Design for digitisation

#### Integrate digital data management and communication technologies with sensors to facilitate automated and remote monitoring of components.

- Use reliable and durable sensors to collect data on component's performance, structural status and other useful data.
- The integrated digital data management and communication technologies should be able to reliably acquire useful data from the sensors, transmit and store the data securely.
- Utilise maintenance data analytical or processing software application to process and interpret the collected data into useful maintenance information.

### Design for inspection

#### Design simple methods of inspection and evaluation of components.

- Specify inspection timeframe and triggers for inspection.
- Clearly define the components that are to be inspected and what to look for during the inspection.
- Provide criteria that are simple to understand for the evaluation of components.
- Define how the evaluation of performance or state of components are to be done against the reference evaluation criteria.
- Define how the inspection is to be carried out including the sequence of the inspection.
- Specify specialist equipment that are required for inspection.
- Provide current/updated inspection instructions as necessary.

## Design for identification

### Use standardized coding and marking of materials to facilitate identification of components.

- Consider the use of international and local standards on the use of identification marks or codes.
- Use component identification marks or labels such as barcode or QR codes to provide online repair information.
- Adopt the use of digital passport for component or material identification.

### Eliminate the use of labels which are incompatible with end-of-life treatment.

- Avoid using labels that are permanently attached to the component and could contaminate metal recycling. These labels should not be placed on the component.

### Place identification marks in visible locations.

- Identification marks or codes are to be easily visible and readable with human eyes and optical recognition devices in an easily accessible location on the component or product.

### Place identification elements in locations where they are not subjected to continuous contact to prevent wear.

- Contact with identification marks, labels or codes must be prevented to avoid unnecessary wear and identification issues.
- Identification marks are not to be placed in positions that can come in contact with moving parts.

### Use durable identification design such which are made during the component's manufacturing processes.

- Integrate the identification marks into the design of the components or products.
- The identification marks are to be made during manufacturing process such as casting, moulding, forging, rolling, pressing, CNC machining, friction stir processing or 3D printing of the component.
- Friction stir processing must not be used on aerospace components or on components where minute changes in material properties can initiate catastrophic damage to the component.

### Avoid using additional materials for marking or codification of components after the initial manufacturing processes.

- Adding materials on components especially at high temperatures can cause localised changes in material properties.

## Design for disassembly and assembly

See *Design for disassembly and assembly*.

## Design for corrective maintenance

Designing products with features that make repairs easy after a failure occurs. This includes accessible parts, clear diagnostics, and simple repair processes to quickly restore function and minimize disruption.

### Facilitate easy repair, replacement, extended use of components.

## Design for repair

See *Design for repair* under overarching circular design strategy 5.

## Design for predictive maintenance

See *Design for predictive maintenance* under overarching circular design strategy 5.

## Design for emotional attachment

See *Design for emotional attachment* under overarching circular design strategy 5.

## Design for behavioural change.

See *Design for behavioural change* under overarching circular design strategy 5.

## Design for intensified usage.

Designing products to withstand frequent or heavy use without compromising performance or durability. This includes selecting robust materials, reinforcing high-stress areas, and ensuring ease of maintenance to support long-term, intensive use.

Facilitate design for durability. See *Design for physical durability*. Facilitate easy maintenance. See *Design for easy maintenance*. Facilitate reliable design. See *Design for reliability*.

## Design for reliability

### Reduce overall number of components.

- Consider designing components with multiple functions.

### Make parts and connections physically robust.

- Consideration should be given to joint or connection design for rigidity, assembly and disassembly.
- Identify and mitigate the various loading conditions that would cause failure including corrosion, shock/impact, humidity, mechanical bending, compression, tension, vibration (random and harmonic), and temperature.
- Implement mitigating features into the design of components or products and manufacturing processes to prevent early obsolescence.
- Eliminate the effect of the failure induced loads in the design of components or products and manufacturing processes if possible.
- Identify the environments associated with the products including manufacturing, storage, transportation and operational (user) environment to determine their respective effect on the performance of the product.
- Perform reliability testing such as quantitative accelerated life testing (QALT) or highly accelerated life tests (HALT) to identify unforeseen or undetermined failure modes and validation of design.
- Avoid creating many parts within a component to reduce the level of reliability risk.

## Design for upgradability

Designing products so components can be easily replaced or enhanced over time. This allows users to improve performance or adapt to new needs without discarding the whole product, reducing waste and extending usability.

### Facilitate hardware upgrading (to prevent economic, technological, and social obsolescence)

- Provide a defined set of criteria for upgrading products including levels of wear (friction, corrosive, rust, abrasive, thermal), upgradable functions, fatigue loading cycle, critical crack length, upgrade timeframe (predefined operational hours with respect to various operational environment).
- Facilitate software upgrading where it is require to enhance the performance of components that are being upgraded to prevent economic and technological obsolescence.

### Design components or products for easy onsite upgrading using standard tools.

- Components are to be easily disassembled and assembled.

### Facilitate access to upgrading instructions.

- Provide easily accessible upgrading instructions including 3D upgrading manuals or technical documentation.

### Facilitate access to specialist tools.

- Provide specialist tools or information to access specialist tools that are required for upgrading tasks.

### Design durable components or products that can be upgraded.

- Use standard components that are easily replaceable and reproducible.
- Identify components that are most likely to fail easily or are most likely to require upgrade and optimise their design to meet durability requirement.
- Define upgrade-assist components and add appropriate specifications to such components to meet reliability requirement.
- Design on-site upgradeable and adaptable products.
- Design complementary tools and documentation for product upgrading and adaptation.
- Design components or products with specifications or an estimate of future performance requirements for upward compatibility.

### Design new components that are backward compatible with older systems to resist or prevent economic, technological.

- The performance requirement for components that are designed for backward and upward compatibility must not adverse affect the performance of the system or product in which they are used.

## Design for modularity

### Design modular and dynamically configurable products to facilitate their adaptability to changing environments.

See also *Design for modularity*.

### Design modular and dynamically configurable products to facilitate their adaptability to individuals' cultural and physical changes.

See also *Design for modularity*.

## Design for component replacement

Facilitate the replacement of all components. See *Design for component replacement*.

## Design for identification

Facilitate the design of durable identification marks or codes. See *Design for identification*.

## Design for disassembly and assembly

Reduce and facilitate the easy operations of disassembly and assembly. See *Design for disassembly and assembly*.

## Design for personalisation

### Enable and facilitate personalisation or customisation without compromising product upgrade or reuse.

See *Design for personalisation*.

## Design for modularity

Adopt modular designs. See *Design for modularity*.

## Design for compatibility

Adopt platform based designs. See *Design for compatibility*.

## Design for adaptability

Include flexibility in the design of components. See *Design for adaptability*.

## Design for deconstruction

Facilitate the easy and safe deconstruction of infrastructures. See *Design for deconstruction*.

See also *Design for disassembly and assembly*.

## Design for re-manufacture and re-use of components

Creating products so parts can be recovered, refurbished, and reassembled into new products. This involves using standardized, durable components and reversible assembly methods to retain value and reduce the need for virgin materials.

## Design for reliability

### Reduce overall number of components.

- Consider designing components with multiple functions.

### Make parts and connections physically robust.

- Consideration should be given to joint or connection design for rigidity, assembly and disassembly.
- Identify and mitigate the various loading conditions that would cause failure including corrosion, shock/impact, humidity, mechanical bending, compression, tension, vibration (random and harmonic), and temperature.
- Implement mitigating features into the design of components or products and manufacturing processes to prevent early obsolescence.
- Eliminate the effect of the failure induced loads in the design of components or products and manufacturing processes if possible.
- Identify the environments associated with the products including manufacturing, storage, transportation and operational (user) environment to determine their respective effect on the performance of the product.
- Perform reliability testing such as quantitative accelerated life testing (QALT) or highly accelerated life tests (HALT) to identify unforeseen or undetermined failure modes and validation of design.

### Design for inspection

#### Design simple methods of inspection and evaluation of components.

- Specify inspection timeframe and triggers for inspection.
- Clearly define the components that are to be inspected and what to look for during the inspection.
- Provide criteria that are simple to understand for the evaluation of components.
- Define how the evaluation of performance or state of components are to be done against the reference evaluation criteria.
- Define how the inspection is to be carried out including the sequence of the inspection.
- Specify specialist equipment that are required for inspection.
- Provide current/updated inspection instructions as necessary.
- Provide easily accessible online inspection instructions and evaluation guidance.

### Design for physical durability

#### Design for robustness

Facilitate design durable products. See design for robustness.

### Design for upgradability

Creating products with modular parts that can be easily replaced or improved over time. This extends product life, adapts to changing user needs, and reduces waste by avoiding full replacement.

### Design for component replacement

See relevant circular design guidelines in *Design for components replacement*.

### Design for identification

Facilitate the design of durable identification marks or codes. See *Design for identification*.

### Design for disassembly and assembly

Reduce and facilitate the easy operations of disassembly and assembly. See *Design for disassembly and assembly*.

### Design for compatibility

Adopt platform based standardised designs. See *Design for compatibility*.

### Design for adaptability

Include flexibility in the design of components. See *Design for adaptability*.

### Design for deconstruction

Facilitate the easy and safe deconstruction of infrastructures. See *Design for deconstruction*. See also *Design for disassembly and assembly*.

### Design for reverse logistics

Facilitate easy transportation of components including the collection and distribution of components.

### Design for transportation

Facilitate easy collection and distribution including using the relevant circular design strategies and principles such as design for disassembly/assembly, collapsibility, stackability, optimised storage, modularity, tracking/tracing, and identification in the design of the component.

### Design for tracing/tracking

#### Design for integration of tracing/tracking technology

##### Use tracing technologies to determine the location of components products to support reverse logistics.

- Use tracking technologies such as GPS for tracking high value components or products such as shipping containers and maintaining and for auditing purpose.
- Adopt the use of sensors to monitor the state of components or products.
- Adopt the use of digital passport for component or material identification.

##### Use standardized coding and marking of metal components to facilitate their identification.

- Consider the use of international and local standards on the use of identification marks or codes.

### Design for identification

Facilitate the design of durable identification marks or codes. See *Design for identification*.

### Design for optimised storage

Designing products and systems to minimize space requirements during use, transport, or storage. This includes stackable, collapsible, or modular features that improve efficiency and reduce environmental and logistical costs.

### Design for high capacity with minimal storage space

#### Design stackable products to enable optimised storage and reduced transport carbon footprint.

Use interlocking mechanisms to enable easy collapsing, stacking, and securing products for storage and transportation.

Where packaging is designed for short life, design them for easy compression for collection after use.

#### Use modular designs

- Facilitate disassembly and assembly of modular products for easy and high volume storage. See *Design for modularity*.

### Design for reconditioning or refurbishment

Creating products so they can be restored to good working condition after use. This involves using durable components, modular designs, and easy disassembly to enable cleaning, repair, and part replacement, extending the product's lifecycle.

#### Facilitate cleaning or decontamination, disassembly/assembly, replacement of component.

- Avoid the use of bespoke component and use standard component as replacement parts.
- Make replacement parts accessible.
- Provide instructions for local and user reconditioning tasks.
- facilitate the use of standard fasteners and tools for easy disassembly or assembly.
- Avoid the use of adhesive for joining components to enable easy disassembly or assembly and prevention of damage to parts during assembly.

### **Design for component replacement**

See relevant circular design guidelines in *Design for components replacement*.

### **Design for disassembly and assembly**

Reduce and facilitate the easy operations of disassembly and assembly. See *Design for disassembly and assembly*.

### **Design for deconstruction**

Facilitate the easy and safe deconstruction of infrastructures. See *Design for deconstruction*.

See also *Design for disassembly and assembly*.

### **Design for easy cleaning or decontamination**

Facilitate easy cleaning of components.

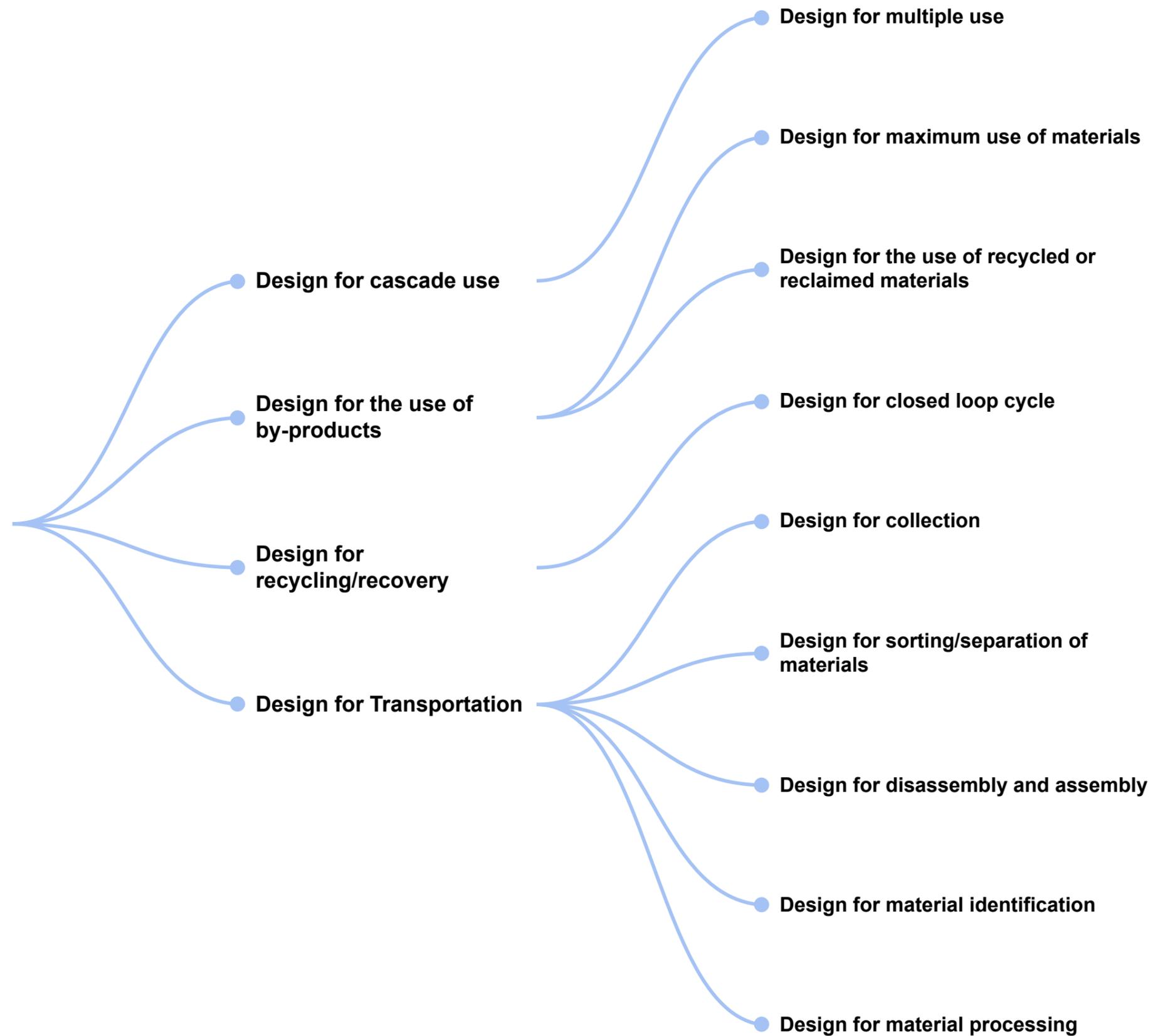
- Specify the types of cleaning material, agents, or substance to be used for cleaning components.
- Specify the types of cleaning material, agents, or substance that would cause unwanted abrasion on protective material layer.
- Specify the types of cleaning material, agents, or substance that would not degrade protective material layer and initiates rust or corrosion on components.
- Specify clearly defined condition or timeframe for components to be cleaned or decontaminated.
- Make components easily accessible for cleaning including the space for cleaning tools or equipment.
- Specify the maximum temperature for cleaning fluids where hot cleaning is required.
- Define the maximum pressure for jet wash where it is required to avoid damage being caused to components during cleaning or decontamination.

### **Design for inspection**

Design simple methods of inspection and evaluation of components. See *Design for inspection*.

The graphic below illustrated the strategies and principles associated to the overarching circular design strategy.

# 7. OPTIMISE END OF LIFE



## 7. OPTIMISE END OF LIFE

This overarching design strategy is associated with the product's end-of-life/ lifecycle phase. It focuses on enabling closed-loop recycling at the end of a products usefulness or life.

### Design for cascade use

Designing products so their components or materials can serve multiple functions over time, typically in lower-grade applications after initial use. This maximizes resource value and delays disposal by enabling sequential lifecycles.

### Design for multiple use

Design components or products that can be utilised for different functions or multiple purpose.

Facilitate recycling of materials in components with lower mechanical requirements.

Facilitate recycling of materials in components with lower aesthetical requirements.

Facilitate the recovery of metals during energy recovery from materials in the combustion process in incinerators.

### Design for the use of by-products

Creating products or systems that incorporate waste or residual materials from other processes. This turns by-products into valuable inputs, reducing resource consumption and supporting circular material flows.

### Design for maximum use of materials

Use remnants of sheet metals after cuttings in fabrication to make other components or products.

- Print or make markings of components or products on sheet metals for multiple product to optimally use the sheet metals.
- Segregate the remnants of sheet metals after cutting in fabrication to enable the recycling of materials according to their grades or types.

### Design for the use of recycled or reclaimed materials

Use recycled or reclaimed materials with the appropriate material property for new products.

- Consider the material properties and application of the component/product when using reclaimed materials for manufacturing new components/products.
- Select metals that after recycling can retain/recover their original performance characteristics.
- Avoid contamination with copper or aerospace grade aluminium alloys.
- Avoid the use of metal matrix composites (MMC) materials to prevent contamination of recyclable metals.
- Adopt geometrical solutions like ribbing to increase structural stiffness instead of using reinforcing fibres or metal matrix composites (MMC).

Design components or products with compatible materials (that could be recycled together) within the product or sub-assembly.

- Use compatible materials for fasteners and the components which are to be joined.

### Design for recycling/recovery

Designing products so materials can be easily separated, identified, and processed at end-of-life. This includes using recyclable materials, minimizing material mixing, and enabling efficient disassembly to support high-quality material recovery.

### Design for closed loop cycle

Use materials that will be easily recycled from a wide range of components or products.

- Use multi-principal element alloy for different components in a product to enable easy recycling.

Provide information for recycling or recirculating metals or metal components.

- Provide user with information about the recycling or recirculating modalities of the product or its parts.

### Design for Transportation

Creating products and packaging to optimize space, weight, and protection during transit. This includes stackability, flat-pack formats, and durable materials to reduce emissions, costs, and damage across the supply chain.

### Design for collection

Design components that are easily compressible and collapsible for applications that do not require high structural strength to meet their performance requirement.

- Avoid the use of ribbed design where it may provide high structural strength that can prevent compression of products.

Design products whose volume can be reduced by disassembly.

Facilitate *Design for disassembly*.

Facilitate the easy handling of components or products.

- Consider the handling requirement of robots and human in the design of the components or products.

Protect fasteners from corrosion and wear.

### Design for sorting/separation of materials

Facilitate the sorting of metals in waste streams or mixed-metal collection using circular design strategies and principles such as design for material identification and disassembly.

- Consider how relevant sorting technologies can be used to facilitate the design of the components with features that can enable their utilisation for sorting or separation by material types or grades of a type of material or metal alloys.

### Design for disassembly and assembly

Facilitate *Design for disassembly*.

### Design for material identification

#### Provide durable material identification on products or materials to aid sorting process

- Use standardized labelling of products and components on recyclability, incompatibility, and/or toxicity so that they can be easily identified from recyclables and waste streams.

#### Provide validated and traceable material information

- Provide information of non-recyclable materials that are assembled with recyclable materials.

#### Use available technology to sort material types (e.g., AI imaging sorting technology)

- Utilise an integrated x-ray defraction, video, magnetic sorting and eddy-current separation system with artificial intelligence technology to enable the separation of recovered materials by types or grades during recycling.

#### Use standardized coding and marking of materials to facilitate identification.

- Consider the use of international and local standards on the use of identification marks or codes.
- Use component identification marks or labels such as barcode or QR codes to provide online product/material information.
- Adopt the use of digital passport for component or material identification.

#### Eliminate the use of labels which are incompatible with end-of-life treatment.

- Avoid using labels that are permanently attached to the component and could contaminate metal recycling. These labels should not be placed on the component.

#### Place identification marks in visible locations.

- Identification marks or codes are to be easily visible and readable with human eyes and optical recognition devices in an easily accessible location on the component or product.

#### Place identification elements in locations where they are not subjected to continuous contact to prevent wear.

- Contact with identification marks, labels or codes must be prevented to avoid unnecessary wear and identification issues.
- Identification marks are not to be placed in positions that can come in contact with moving parts.

#### Use durable identification design such which are made during the component's manufacturing processes.

- Integrate the identification marks into the design of the components or products.
- The identification marks are to be made during manufacturing process such as casting, moulding, forging, rolling, pressing, CNC machining, friction stir processing or 3D printing of the component.
- Friction stir processing must not be used on aerospace components or on components where minute changes in material properties can initiate catastrophic damage to the component.

#### Avoid using additional materials for marking or codification of components after the initial manufacturing processes.

- Avoid the practice of adding materials on components especially at high temperatures which can cause localised changes in material properties.

### Design for material processing

#### Facilitate cleaning of components or materials.

- Avoid the use of unnecessary coating finishing.
- Avoid the use of irremovable coating materials.
- Enable the removal of coating materials.
- Avoid the use adhesives or choose adhesives which are compatible with materials that are recyclable.

### Conclusion

The transition to a circular economy represents not only an environmental imperative but also a strategic opportunity for industries. This report has presented a comprehensive and structured framework of circular product design (CPD) strategies, principles, and guidelines tailored to the unique challenges and opportunities within the metals sector. By integrating the hierarchical model with the broader CircularMetal initiative, the report aligns design decisions with supply chain strategies and lifecycle thinking, integrating systems-level innovation.

Through the systematic categorisation of over 200 actionable guidelines, this framework provides designers, engineers, and policymakers with a practical roadmap to embed circularity into product development processes. The hierarchical approach enhances clarity, supports decision-making, and enables more consistent implementation across diverse contexts—from industrial manufacturing to academic research. It also establishes a foundation for measurement, evaluation, and continuous improvement.

Crucially, the guidelines acknowledge the complexities and trade-offs inherent in circular design—whether in material substitution, modular design, or end-of-life recovery—and provide tools to navigate them. This reinforces the necessity of interdisciplinary collaboration and systems thinking in the pursuit of circularity.

As industries move toward net-zero targets and resource efficiency becomes a competitive differentiator, the implementation of well-defined, evidence-based design guidelines will be essential. The framework outlined in this report represents a significant step in that direction, equipping stakeholders to take informed, impactful action toward a circular metal economy.

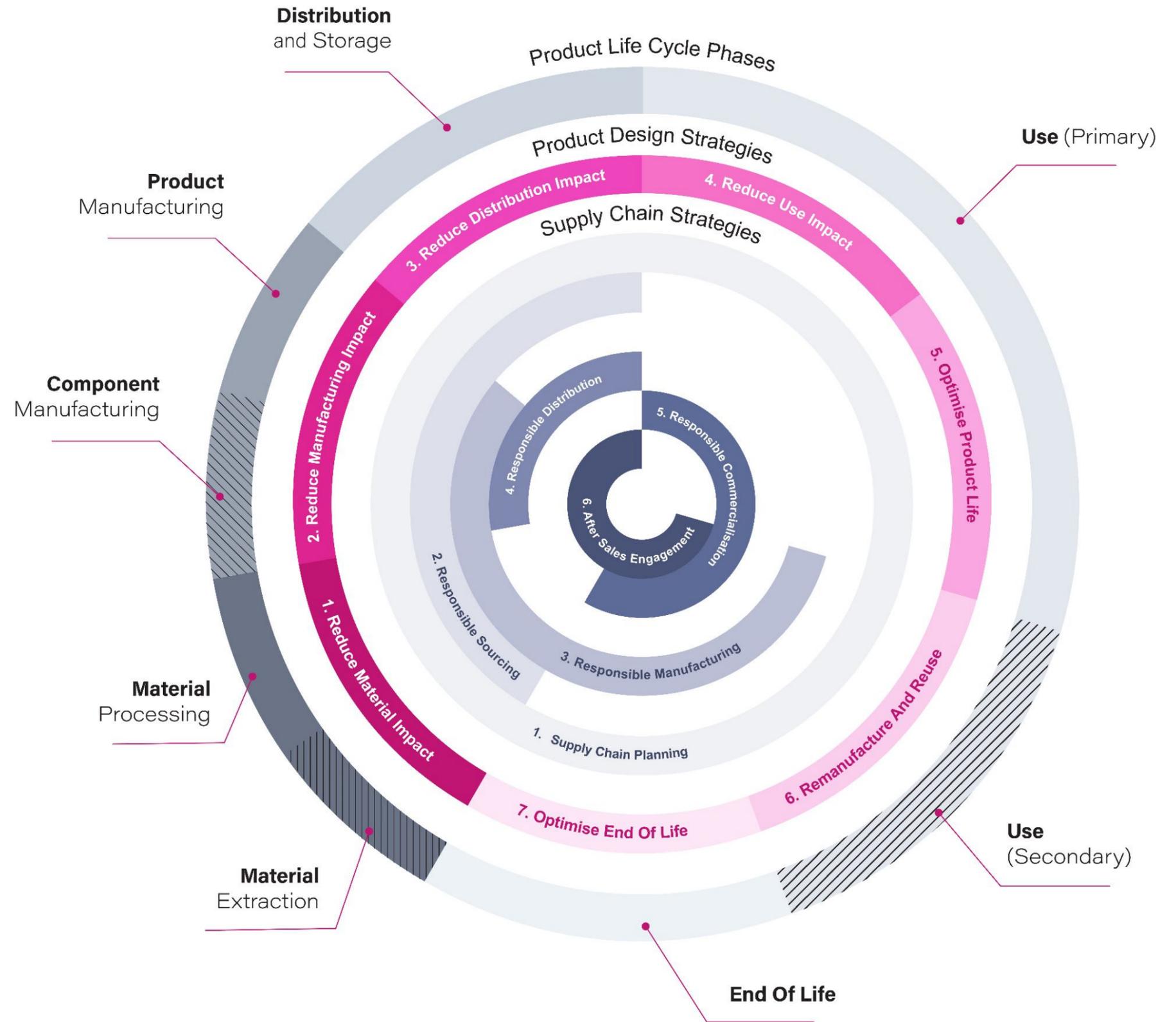


Figure 5: Schematic depicting the integration of circular product design with circular supply chain strategies.

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