Guidelines for circular product design and development

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Author: Sasha Shahbazi.

CIRCit NORDEN

1. Circular economy

Apart from niche markets for high quality, high durability products, a major portion of the world's products has been designed with a mentality of make, use - more and more briefly - and discard, which depletes the planet's resources (linear economy). A circular economy (CE), on the other hand, contrasts with the entrenched, intensive linear economic approach by aiming at "closing material flow loop in the whole economic system via design and business model strategies to minimize resource input and waste, emission, and energy consumption and also to keep products, components and materials at their highest utility and value, at all times". CE is a concept currently promoted by the EU; it is viewed as an operationalization for businesses to implement the concept of sustainable development. CE represents a systemic shift that builds long-term resilience, generates business and economic opportunities, and provides environmental and societal benefits. In practice, CE aims to minimize waste, extend product lifespan, facilitate circular strategies (repair, reuse, remanufacturing, etc.) and ease recycling of the rest. There are also risks involved in the CE approach, for instance when we aim to repair and remanufacture, we have to be cautious what parts are taken out and how the waste is managed. There is a danger of generating waste streams in a new way, including emissions caused by product movements or unsafe disposal/reuse of hazardous components. Another downside might be the life extension of products that are no longer energy or water efficient. While extending the products' life, the balance between products being produced, reused, repaired, remanufactured and recycled will be disrupted, and the flows and rates are unclear.

2. Who can use this guideline

This guideline aims to support a variety of functions within a manufacturing company, such as product development, product ownership, research and development, marketing, those working with sustainable development and the circular economy within the company, environmental coordination/management, general management, and whoever is interested in rethinking the linear manufacturing process.

Whether we are trying to extend the service life of our products or trying to ensure that when their service life ends, they can be repaired, remanufactured, or recycled more easily, we must consider who will perform such activities and what incentives, if any, they will have to do so. To implement a circular innovation, a few aspects need to be considered: (1) researchers: product design, technology and system; (2) entrepreneurs: appropriate business model; (3) the general public: the general public must be open to the new product; and (4) government: the product must be compliant with regulations.

3. Using the design guideline in product development

A generic product development process is used here to clarify where this guideline can be applied. Companies have different product development processes, and they differ base on companies, product type and categories, production system, and market plans, etc. This generic product development process consists of six phases that can be changed in length and prerequisites. Industrial design, purchasing, marketing, engineering and manufacturing are the main actors to make the changes.

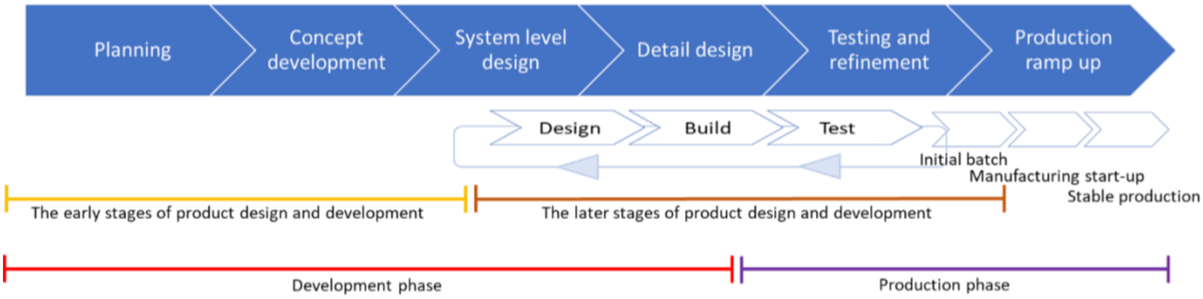


Figure 1 – Generic product development process by Ulrich and Eppinger, 2008

In the early stages of the product development process, decisions on environmental and circularity aspects such as materials, energy, waste minimization, zero toxic waste and emissions, reduction of other environmental effects, exclusion of hazardous material and nonrenewable natural sources, etc. must be made; otherwise, once the design concept is established, improving the circularity performance means time-consuming iterations. If you want the product to be easy to reuse, repair, remanufacture or recycle, you have to think about that in an early design phase. When designing a product for circularity, the first point is to decide which circular strategy you are aiming for. Therefore, this guideline should be used within concept development, system-level design and detail design phases.

There are points to consider when using these circularity guidelines:

- There is not a clear line between design for each of the circular strategies; hence, although different guidelines are formulated for each circular strategy, the design guidelines overlap with each other to some extent, and similar design guidelines might be applied to several circular strategies. For instance, “make exchanging of faulty components easily accessible” is a common guideline among many of the circularity strategies.
- There can be similarities between circular strategies. However, the main focus area differs. For example, “design for repair and maintenance” and “design for reuse” share similar design guidelines; the former has more focus on exchangeability of parts and the latter more focus on durability of parts, even though both share several similar guidelines.
- Although there is no clear line between circular strategies and they might share some common design guidelines, the same design guideline might slightly differ at the core and fulfillment levels. For example, “use durable and robust components and materials” is a common design guideline among “design for repair and maintenance” and “design for reuse”. However, in “design for reuse”, it is important that all components have the same durability, while in “design for repair”, it is not vital that all components have the same lifespan because faulty parts are designed to be removed and replaced.
- A design guideline may simultaneously (positively and/or negatively) affect several circularity strategies or other design guidelines, although the nature and intensity might differ among them. For instance, “design using recyclable and secondary (recycled) materials” influences “design for recycling” and “design for remanufacturing”, although the effect on the latter is less. Additionally, “design using recyclable and secondary (recycled) materials” influences both “make it easy to clean the product and components” and “use durable and robust components and materials”.
- Some design guidelines are generally applicable for several circular strategies, such as “focus mainly on functionality and quality performance” or “focus to fulfill the customer’s requirements and value creation”, which both are the core part of any

circularity strategy. However, both are more related to a "rethink" strategy than to the other strategies.

- Facilitating end-of-life collection and transportation should be considered for a majority of circular strategies.
- You will probably find more design guidelines during the design process and analysis of a specific product concept. As a result, it is recommended to first use the guideline comprehensively as a whole and then refer to specific design guidelines if needed.
- Designers usually consider several circular strategies simultaneously, as they are interconnected; e.g., design for remanufacturing with ease of dismantling while faulty parts should be easily recyclable (design for recycling). Hence, design for recycling should be considered under any circumstances, as one product eventually fails completely after several lifecycles; recycling is its final fate.
- Think about consistency and dependencies between the circular strategies. It is important to have a broad overview of all the circular strategies and guidelines in mind when designing, so one activity does not make any other circularity activities too difficult or expensive to carry out. The changes in design can be both major and minor, although the product's function must be the same.

4. Overall picture of circular strategies

Within the framework of the CIRCit project, the following "circular strategy scanner" is used in the development of this guideline, where different strategies and dependencies are mapped to enhance the understating of a circular economy and minimize confusion about various strategies.

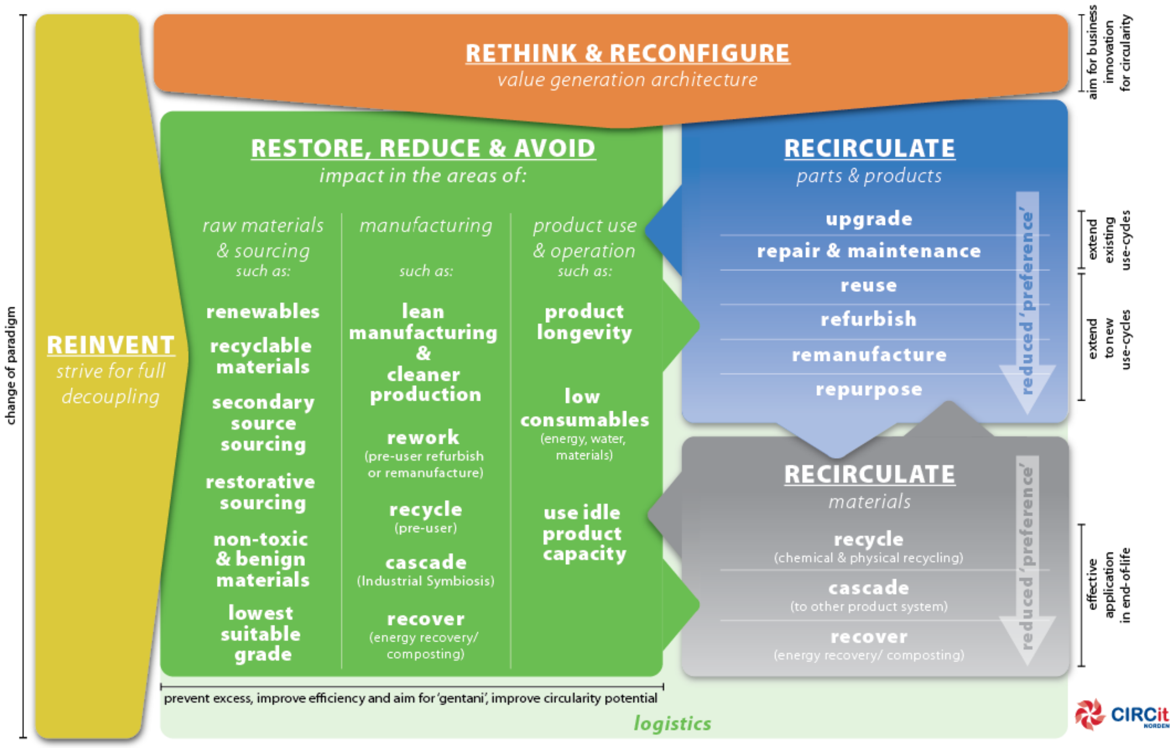


Figure 2 – Circular Strategy Scanner

5. Design guidelines for circular strategies

5.1 Rethink

5.1.1 Definition

There are several strategies to consider when designing and developing a circular product. The first strategy, which affects the rest, is to “think in circles”. It is crucial to have a holistic view about other circular strategy options and think in systems around the product rather than about the product itself. This strategy enables smarter business concepts through business model innovation for circularity. Think about function and value delivery/proposition to market and how a customer or user can use, interact and experience the products. This strategy includes making product use more intensive by rethinking how to deliver the function and/or value proposition, e.g., performance or access-based models and sharing. Consider combinations of product and services and cooperation with different partners for different lifecycle segments. The rethink strategy does not mean large and radical technological or product changes (although technology can evolve) but rather behavioral changes and the rethinking of the operating system.

Companies always must think about their business model before deciding to design for repair, reuse or remanufacturing or for any other circular strategy. Manufacturing activities are driven by business interests and the need to return investors’ investment, generate profit and maintain cashflow. Rethinking can increase the value of their brand, attract new customers, and increase the loyalty of their existing customer base. The rethink strategy is the design of products for new forms of business value creation where innovative companies are increasingly understanding the design of products for service-life extension and service-life intensification.

Selection of the right business model is vital to create and maintain value over time and to keep the revenue coming in. The key feature is to fulfill the customer's real needs optimally. Clarify customer value with the product. Business model and product design can influence each other. Try to establish the business model by the start of the design of the product. There are five main business models and product service systems. Going from the first to the last, reliance on the product as the core component decreases, and the need of a client is formulated in more-abstract terms.

1) **The classic long-life model:** high-quality durable products with a long lifespan and with a high price point, i.e., sell more, sell faster.
2) **The hybrid model:** repeatedly selling cheap consumable products with a short lifespan that only function together with high-quality durable products.
3) **The gap exploiter model:** this model is the same as previous ones, although it concerns a function in between that provides repair services or refurbished units.
    a. Product-related service: the provider not only sells a product but also offers services that are needed during the use phase of the product, such as a maintenance contract, a financing scheme or the supply of consumables; the provider also offers a take-back agreement when the product reaches its end of life.
    b. Advice and consultancy: the provider gives advice on its most efficient use of the sold product, the organizational structure of the team using the sold product or optimizing the logistics in a factory where the sold product is used as a production unit.
4) **The access model:** providing access to a product for a limited period of time or fixed number of cycles rather than selling the product, while product ownership remains with the access provider. Service provider sells functions instead of products.

a. Product lease: The provider retains ownership and is also often responsible for maintenance, repair and control. The lessee pays a regular fee for the use of the product with unlimited and individual access to the leased product. Leased products are often sold to the customers after the contract is completed.
b. Product renting or sharing: The provider retains ownership and is also often responsible for maintenance, repair and control. The user pays for the use of the product. However, the user does not have unlimited and individual access; the same product is sequentially used by different users at other times.
c. Product pooling: This technique greatly resembles product renting or sharing. However, here, there is a simultaneous use of the product.

5) **The performance model:** providing the performance and service where users are exclusively interested in the quality of service, not the product providing it. It is, therefore, the provider's responsibility and decision to select machinery or products deployed to carry out the required task and fulfill the function that the customer is buying.
    a. Activity management/outsourcing: a part of an activity of a company is outsourced to a third party—for example, the outsourcing of catering and office cleaning that is now a commonplace in most companies.
    b. Pay per service unit: For example, the pay per print in which the copier producer takes over all activities that are needed to keep a copying function in an office available (i.e., paper and toner supply, maintenance, repair and replacement of the copier when appropriate).
    c. Functional result. Here, the provider agrees with the client on the delivery of a result, and the provider is, in principle, completely free concerning how to deliver the result. Typical examples of this form of PSS are companies that offer to deliver a specified 'pleasant climate' in offices rather than gas or cooling equipment.

5.1.2 Design guidelines for rethinking

Things to consider when designing for rethinking include the following:

- Focus mainly on functionality and quality performance.
    - Products designed with a rethink strategy (particularly product service system) are not usually fashion-affected products, although those designed for "product lease" and "product-related service" must also fulfill aesthetic features.
    - Products designed for the "performance model" and to some extent for the "access model" are mainly functionality focused; hence, age, make and model are less important as long as the quality-performance is delivered.
- Think about activity supports in the operational stage.
    - Think about activity support in the operational stage of the product/service to make the system run as efficiently as possible (also see 5.3.3).
        - Since the product will be used over a longer term, product safety during the entire use phase is crucial.
        - Since the product lifecycle has been increased in this circular strategy, the product should be designed with no use of toxic materials and more use of renewables and recyclable materials. However, this approach should not reduce the lifespan of the product.
        - As the product function, availability and service is the main value proposition, supplying replacement materials, maintenance services, repair, control of post-use on a regular basis are necessary for continuous and increased product use. These factors not only prolong the physical lifetime of the product but also increase the economic lifetime of the product.

        - Education and guidance about the product/service usage is essential, e.g., how-to-use manuals and procedures for more-efficient and effective use of equipment and optimal operation.
        - Think about all necessary infrastructures such as technologies, devices and spatial layouts to offer the service/product.
        - Think about core aspects that make the product/service keep running; e.g., ensure repair and maintenance (see section 5.6) and upgradability (see section 5.5).
        - Ensure reduced environmental impact and resource consumption during the use phase, e.g., less energy consumption, green logistics (see 5.4), using local services (technicians) or the service being built near major consumer centers.
    - Low consumption of energy, water and materials during product use and operation
        - How much and what types of energy will be required?
        - Consider energy-efficient technologies. Use components that use little energy.
        - Use rechargeable batteries.
        - Consider clean energy technologies. Use (if possible) wind power, water-based renewable energy, solar energy, potential energy, or tidal power, etc.
        - If the product should be moved, reduce the weight to reduce the energy consumption.
        - Isolate the product to retain warmth or cold.
        - Help users to save, e.g., default double-side printing and marking the least amount of material/liquids to use.
        - How much and what kind of consumables will be required?
        - Reduce the use of consumables.
    - Have an environmental overview of partners involved in the service offer
    - Think about the common consumption factors: including money and cost of product/service, time and duration, space taken, availability of technology or material, skills required to provide/use the product/service, information, access and availability, customer responsibility towards the product/service, convenience and comfort, risk and safety, and, finally, perception and image of the product/service.
    - Ensure that at the end of the use phase, when the product can no longer provide its original functionality, there is incentive for product and materials to be reused, recycled or remanufactured.
    - Think about take-back systems after the product or service is obsolete.
    - Consider what lifecycle stage of the product is dominant from an environmental perspective; for example, if it is energy-consuming in the use phase, then reduce the energy consumption. Otherwise, if it is not energy intensive during the use phase, focus on lifespan extension.
- Focus on fulfilling the customer’s requirements and value creation.
    - Place a strong focus on how to fulfill the customer’s requirements or create customer value; e.g., develop a close relationship with the customer to understand their requirements and hence adjust personalized services and develop capabilities accordingly.
    - Design the product to be used individually with individual access.
    - Think about the current system that would be replaced, and find the substitutions and changes, e.g., how a customer would behave. For example, consider number of usages and the duration of each. This analysis can be done with customer segmentation or survey methods.
    - In product development, the detailed and complete development process is defined in the early stages of development. On the other hand, in service development (rethink), the service design cycle is continuously repeated and improved to be able to adapt to various human factors and requirements that influence overall service development. Consequently, the focus is on a wide range of development, from business strategy to detailed design.
- Try to use digitalization, ICT and IoT solutions.
    - Since quality-performance and function in the product use phase is mainly delivered in this circular strategy, product control and monitoring become extra vital. Therefore, online monitoring using digitalization, ICT and IoT facilitate obtaining better knowledge and learning more about product performance through its lifecycle, particularly the use phase. Consequently, it would be possible to discover latent design errors and improve the product accordingly.

    - In the case of product sharing and renting, use a logging system to monitor user behavior and performance, e.g., a user using the product incorrectly or incautiously, so the offending user can be consulted. This approach is also consistent with the rebound effect of a product service system, in which customers care less about a product not being owned or overuse environment-friendly products. With such a control, damage during the use phase is reduced, and overall safety and lifetime is improved. The drawback here is that the user might feel monitored and less trusted.
    - Consumers should be informed about the effective used of the product to ensure adequate performance. Guide customers to use the product effectively and optimally via information sharing and online guidance.
    - ICT technologies should also enable communication between those involved in the business. When using ICT technologies and IoT, consider the following:
        - Possibility to create personal profile
        - Fast login for customer
        - Easy and secure access
        - System integrity
        - Personalization and customization for different users/profiles
        - System to be ready for the next customer as soon as possible
        - Clear and friendly user interface
        - Automatically saving of data on the server
- Make it easy to inspect the product and components.
    - Since products are used over a longer lifespan and more intensely, accurate inspection is essential. Design should enable ease of accurate inspection, early identification and verification of component conditions and product functionality.
- Make it easy to clean the product and components.
    - The surfaces to be cleaned should be smooth and wear resistant.
    - Make it easy to clean. All product components should withstand the same cleaning process, liquid and chemicals, and temperatures, detergents and cleaning tools.
    - Avoiding making areas where dirt might collect and are hard to clean properly; e.g., avoid small holes, nooks, grooves, sharp edges and thresholds that capture dirt. This approach can make a product appear newer for a longer time.
    - As product function, availability and service is the main value proposition, providing clean product to each customer is necessary for continuous and increased product use. This approach also prolongs the physical lifetime of the product.
- Make exchange of faulty components easily accessible.
    - As product function, availability and service is the main value proposition, providing a fully functional product to each customer is necessary for continuous and increased product use. Hence, components to be exchanged or parts that are subject to stress, wear, corrosion, stain, breaking or failing easily should be marked, easy to recognize and easy to access.
- Use durable and robust components and material.
    - Since products are used over a longer and more intensified lifespan, products should be made of durable and robust components and materials to last throughout more than one lifecycle. This approach not only reduces long-term resource consumption and maintenance costs but also results in a longer service interval.
    - Since the product has a longer lifespan, it is necessary to ensure that the components have almost the same lifespan.
- Make spare parts and exchanging components easily available.
    - Since products in this strategy are designed to be used over a longer lifespan and more intensely by several customers, the likelihood of breakdown and a requirement for repair is much higher. Therefore, this strategy is only viable if components of products are easily found on the market and preferably provided inexpensively.
- Provide manuals and documentation.

    - Since products in this strategy are designed to be used over a longer lifespan and more intensely, it is a good idea to provide manuals and documentation to customers on how to efficiently use the product with adequate performance.
- Design for reduced energy consumption and usage of renewable energy.
    - If the use stage of the product lifecycle is dominant from an environmental perspective, design the product for reduced energy consumption, usage of renewable and clean energy.
    - Use idle product capacity.
    - Use historical data for improvements for better scheduling of downtime.
    - Make a stand-by function that can also be turned off.

Rethink and reconfiguration strategy is consistent with and related to other strategies. Think about design for upgradability (see 5.5) to enable coping with future customer requirements or technological changes. Think about design for repair and maintenance (see 5.6) to retain product availability and functionality. Periodic and condition-based maintenance are vital. Consider ease of maintenance and modularity. Think about design for reuse (see 5.7) to extend the product use phase. Durability and robustness are the keys here to reduce long-term resource consumption and maintenance costs. Think about design for recyclability (see 5.11) for exchanging components and the product itself after several lifecycles.

5.1.3 Example of rethink

- Car sharing services (e.g., Drive Now, Sunfleet, Green Mobility, Zipcar, and Blablacar)
- Clothing rental and subscriptions (e.g., Rent the Runway, Vigga, and Mud Jeans)
- Performance contracts (Rolls Royce – Power by the Hour)
- Bike sharing services (e.g., Bycyklen in Copenhagen, EU Bikes in Stockholm, Santander Cycles in London, and many other services in cities around the world). There are many bike-sharing companies all over the world where the bicycles are used by many people. These bikes are designed with some interesting aspects to be used for a longer time (life extension) and under heavy duty (life intensification). Therefore, features such as robustness, simplicity and fewer components, lightweight and same types of materials, and standard parts for replaceability and repairability are considered in their design.

Figure 3 – Rethink: Bike sharing services

5.2 Reinvent

5.2.1 Definition

This strategy enables smarter business concepts through striving for full decoupling, meaning the service provided by the material can be dematerialized. The reinvent strategy makes physical products redundant by offering the same function or combined functions, usually enabled by radically different products, technology or both. This strategy can also be a means of moving from a product-based to a service-based economy in which, instead of consumers paying to own a product, they pay to use a maintainable and upgradable service. This strategy includes reinventing current solutions through new meaning (e.g., iTunes: replacing the

Walkman as a portable music player, buying music with a click and organizing personal playlists) or new solutions based on a new meaning (e.g., Spotify: listening to playlists readymade by fans and experts to match your current mood, discovering new music and sharing it with others). The current reinvent strategies have often been focused on the use of digital technologies, particularly advances in information and communications technologies (ICTs), to provide a wide variety of services such as music in the form of online streaming platforms, letters and communications in the form of email, and news in the form of online news aggregators. However, the complete material decoupling and resource impact in a reinvent strategy depend critically on producer responsibility and improvements in the energy required to operate the business (digital devices), efficient and effective production of the necessary equipment to run the business, and development of end-of-life management practices such as a proper takeback and recovery systems (reuse, repair, remanufacture or recycle); otherwise, they add to current circularity problems (e.g., waste from electrical and electronic equipment). Although the reinvent strategy is elusive, it has substantial scope and effect in a circular economy. Enabling a reinvent strategy requires infrastructures, investments, incentives, viable business models, competent and efficient operation and a high degree of convergence to create market drivers and systems.

5.2.2 Generic (design/innovation) guidelines for reinvent

Since this strategy is based on radical innovation in products and technology, generic guidance is presented here to not only increase the likelihood of survival in the case of external innovations and technological discontinuities but also enable internal innovation and configuration to come up with radical out-of-the-box ideas for changes.

- Focus mainly on functionality and quality performance.
  - Functionality and quality performance are the main drivers of this strategy, although the solutions are usually innovative, radical and out-of-the-box.
  - Think about the current system that would be replaced; find the substitutions and changes. How would customers behave?
- Focus on fulfilling the customer's requirements and value creation.
  - Place a strong focus on how to fulfill the customer's requirements or create customer value.
  - Think about the current system that would be replaced; find the substitutions and changes. How would customers behave—for example, number of usages, duration of each, skills and knowledge required, etc.
- Try to use digitalization, ICT and IoT solutions.
  - The current reinvent strategies have often been focused on the use of digital technologies, particularly advances in information and communications technologies (ICTs), to provide a wide variety of services; hence, dematerialization in this strategy is usually dependent on online monitoring and machine learning using digitalization, ICT technologies and IoT.
- Think about boundary management.
  - Build and exploit cooperative networks, relationships and interorganizational collaboration to create and adjust innovation focus and to reap the benefits of external innovators and influence, explore the boundaries, new paradigms and upstream innovations and boost the position in the market.
  - Keep focusing on the core business and strategy but also invest in supplier relationships to increase the likelihood of influence by new entrants' innovations.
  - Increase the innovation rate and strengthen the competitive position through mergers and acquisition to reduce uncertainty, increase financial capabilities and acquire innovators or set up joint ventures.
- Think about incumbent configuration.
  - Fostering innovation through proper management of organization and employees via a high level of autonomy and mobility, involvement, decentralization, and interfunctional collaboration combined with informal and organic organizational structures helps to successfully face radical change. This approach includes looking for internal interpreters who

can bring new perspective to the field and rethink their own role in the industry. Recognize employees who think like innovators, those who are contrarian and challenge popular opinion and those who harness underappreciated trends. Company leaders should create frequent opportunities for rethinking and reinventing, demonstrate an appetite and avoid premature judgments for unconventional new ideas and alternatives, celebrate smart failures, assign time and money for innovation and ideas and hire and promote for creativity.
    - Continuously work on current businesses and technologies while maintaining a search for long-term efficiency and incrementally realigning activities and internal configurations. Identify core competencies and strategic assets of the organization and the world around it. Take a systemic view, and ensure the entire team is on board and all the pieces come together in one coherent system.
- Think about complementary capabilities.
    - Leveraging specialized technologies facilitates product development and supply chain efficiency
    - Privileged access to distribution channels to prevent threats by new entrants
    - Leveraging complementary technologies via being ready to embrace opportunities and new technologies
    - Evaluating the chance of a changing value proposition in terms of market, value chain, revenue mechanism, cost structure, and position in the value network
    - Becoming customer-oriented with a focus on both current and potential customers in the future via understanding the latent and unexpressed requirements

5.2.3 Example of reinvent

- Music and video streaming services negate the need for data carriers such as CDs and DVDs.
- Multifunctional devices such as smart phones combine the functionality of multiple devices (camera, GPS, phone, calculator, alarm clock, sound system, and computer) in a single device.
- The ‘bring-your-own’ movement facilitates replacing such single use items as coffee cups and utensils with durable reusables.

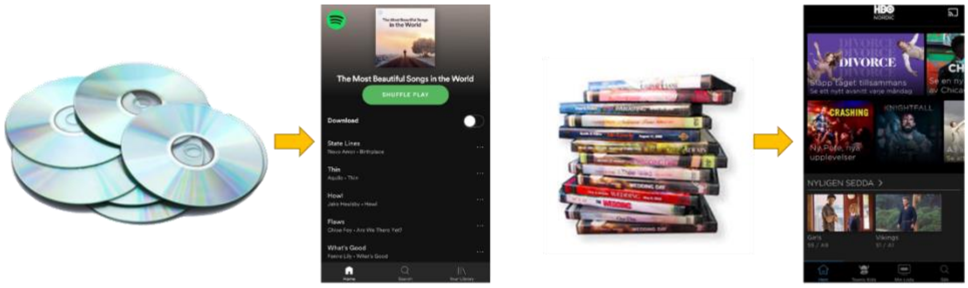


Figure 4 – Reinvent: Music and video stream services

5.3 Restore, reduce and avoid

This strategy aims to improve circularity potential, effectiveness and efficiency (Gentani) in the sourcing process, product manufacturing, product use and operation, and logistics.

5.3.1 Guidelines for raw materials and sourcing

To improve circularity, efficiency and effectiveness in sourcing processes, the following points can be considered:

- Design using renewable materials.
    - Reduce the use of materials of which there are only limited quantities such as tin and precious metals, and use more renewable and bio-based materials, especially in sectors such as packaging, textiles, chemicals and construction.
- Design using recyclable and secondary (recycled) materials.
    - Choose materials that are easy to recycle.

  - Consider the recycling rate of materials.
  - Use economically recyclable material.
  - Use materials for which only one recycling method/process is needed with no separation.
  - Design out the loss of value through impurities in recycling parts, e.g., different colored glasses.
  - Avoid composite materials such as laminates.
  - Select fewer material types and increase material homogeneity in products or use materials that are compatible or are easy to separate to increase recycling possibilities.
  - Metal alloys that contain fewer additives are easier to recycle because elements retain their properties, which is much more difficult for materials such as plastics. Additionally, in the case of metals, the process of recycling saves much energy compared to primary production, which is not true for plastics.
  - Use unplated metals and low-alloy metals for recycling purposes.
  - Avoid additives and coatings to obtain an easily recyclable material.
  - Use materials that already have recycling market.
  - Select materials with the most efficient recycling technologies.
  - Technically well-known and economical recycling processes enable cleaning of impure materials during recycling.
  - Design taking into consideration the secondary use of the materials once recycled.
  - Reduce the use of virgin raw materials.
  - Increase the use of recovered/recycled material.
  - Industrial symbiosis (one's byproduct or waste as a primary input material for another) and restorative sourcing (use of materials previously designated as waste, such as re-mining from landfill or using ocean plastics) are enablers.
- Consider toxicity and other environmental aspects of materials.
  - Think about chemicals that compose the specified materials. Are they safe for humans and the environment?
  - Indicate the existence of toxic or harmful materials.
  - Eliminate toxic and hazardous materials such as PCBs, flame retardants, mercury and cadmium.
  - Use materials that do not contain substances from hazardous chemicals lists.
  - Use materials that do not threaten biodiversity; e.g., choose wood eco-labeled forestry or fiber products that were not cultivated with pesticides.
  - Choose materials that have less environmental impact.
  - Select quality, strong, robust and durable materials that do not degenerate during multiple lifecycles to withstand lifecycles with different applications.
  - Avoid materials that might lose strength, become brittle or become discolored.
  - Use components and materials with verified reliability.
  - Think about "appropriate fit" and optimize the use of quality the materials where the lowest adequate level of material quality is suitable for the application without influencing the quality.
  - Think about strategic materials and characteristics such as monopolies, conflicts, rarity, and cost, etc. Think about how to handle them. Perhaps substitute alternatives or employ new technical solutions.
  - Reduce the use of materials that cause high emissions in production such as chrome and nickel.
  - Think about the means of transportation that is used to procure them.
  - Think about the energy and resources required to extract materials. Choose materials with high energy efficiency in their extraction processes.
  - Select lightweight materials for less energy consumption in transportation.
- Use durable and robust components and materials.
  - To extend the product's lifespan, choose durable and robust components and materials with a long lifespan.
  - Choose the correct material for the right job.
  - Estimate product behavior in the use phase, i.e., components' strength and stiffness.
  - Select quality, strong, robust and durable materials and components that do not degenerate during multiple lifecycles.
  - Avoid materials that might lose strength, become brittle or become discolored.

- Minimize the number of different incompatible or dissimilar materials.
  - Use as few materials as possible; i.e., minimize the number of different incompatible or dissimilar materials. Homogeneity of products with similar materials is vital for end-of-life management.
  - While selecting correct and compatible materials and avoiding multimaterials and composites, consider also the durability of materials. Find a balance!

5.3.1.1 Example of raw materials and sourcing

- Columbia Shoe makes a sneaker with 40% recycled materials. The fabric and laces are built with recycled polyester, while the midsole is made from reground EVA foam. The rubber in the outsole is also recycled.
- Kalundborg Symbiosis in Denmark is based on public-private partnerships, with exchanges of energy, water and materials in closed loops. Kalundborg Symbiosis has made all the partnerships successful through shared values including trust, confidentiality, openness, equality and cooperation. It has also had economic advantages, including minimized costs for waste management, minimized costs for resource purchases and increased income from byproduct sales, in addition to environmental benefits in the form of resource saving in groundwater, surface water, natural gypsum and oil.

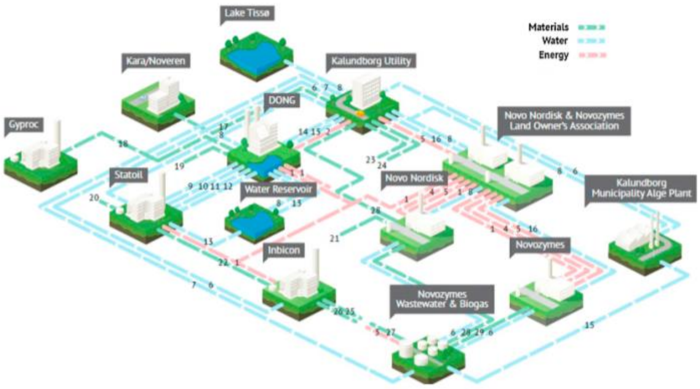


Figure 5 – Raw materials and sourcing: Kalundborg Symbiosis in Denmark

5.3.2 Guidelines for product manufacturing

To improve circularity, efficiency and effectiveness in product manufacturing, the following points can be considered.

- Favor cleaner production, processes, machines and equipment.
  - Favor manufacturing processes, machines and equipment that use less energy and materials.
  - Favor manufacturing processes, machines and equipment that discharge less to air and water.
  - Favor manufacturing processes, machines and equipment that generate less waste.
  - Select production technologies with good and ergonomic working environments.
  - Avoid processes that have been listed by authorities.
  - Select machines and equipment that require less-frequent maintenance and cleaning.
  - Use prevention and condition-based maintenance to avoid machine breakdowns that lead to scrap generation.
  - Select production processes with high production quality and reduced production deviation, scrap and waste.
  - Manufacture the product with proper tolerances and less welding and grinding.
  - Minimize turning and milling.
  - Avoid secondary finishes and coatings.
  - Select a surface treatment that reduces the total environmental impact during the entire lifecycle.
- Consider toxicity and other environmental aspects of materials.
  - Choose auxiliary materials and chemicals that have fewer environmental impacts.

    - Think about "appropriate fit" and optimizing the use of the quality of the materials where the lowest adequate level of material quality is suitable for the application without influencing the quality.
    - Reduce material consumption (see 5.3.1) and waste generation in production.
    - How much and what types of auxiliary material are needed? Reduce the use of auxiliary material.
    - Select auxiliary material that can be fully recovered and recycled.
    - Use materials that do not require extra surface treatment, and avoid cyanide and hexavalent chromium.
    - Eliminate toxic and hazardous material.
    - Use processes with fewer types of chemical consumption.
    - Use durable chemicals in manufacturing processes that do not required frequent changing.
    - Reduce human contact with chemicals to a minimum.
    - Solvent-free paint has fewer environmental effects.
    - Avoid cyanide and hexavalent chromium.
- Design using recyclable and secondary (recycled) materials.
    - Choose auxiliary materials that are easy to recycle.
    - Consider the recycling rate of auxiliary materials.
    - Use economically recyclable material.
    - Use auxiliary materials for which only one recycling method/process is needed.
    - Avoid composite materials.
    - Select fewer material types and increase material homogeneity or use materials that are compatible or are easy to separate to increase recycling possibilities.
    - Use auxiliary materials that already have recycling market.
    - Reduce the use of virgin raw materials.
    - Increase the use of recovered/recycled material.
    - Industrial symbiosis (one's byproduct or waste as a primary input material for another) and restorative sourcing (use of materials previously designated as waste, such as re-mining from landfill or using ocean plastics) are enablers.
- Treat production (pre-consumer) wastes appropriately.
    - Think about how much waste and what types are generated.
    - Think about what segment and fractions will be used for generated waste.
    - Increase waste segregation for higher homogeneity of waste to facilitate pre-consumer recycling.
    - What can be done with the generated waste? Find other uses for manufacturing wastes, either internally, or at other facilities (industrial symbiosis).
- Design for reduced energy consumption and usage of renewable energy.
    - Consider energy recovery or recovery of biological nutrients.
    - Use renewable energy.
    - Select production processes with high energy efficiency to reduce energy consumption.

5.3.2.1 Example of product manufacturing

In 2000, Adnams PLC introduced a new set of company values and developed corporate social responsibility. Consequently, Adnams set a new innovative and sustainable production system. In 2001, state-of-the-art fermenting vessels were installed. In 2006-2007, its 100-year-old brewing system was completely replaced with the most efficient system available on the market. The new technology recycles 100% of the heat used to provide energy for the next brew. In general, their new equipment saves an average of 30% a year on gas and water consumption each year. This saving is compounded by computerization of the processes, in which human activities, flows of materials inside the brewery and waste inefficiencies have been significantly reduced.

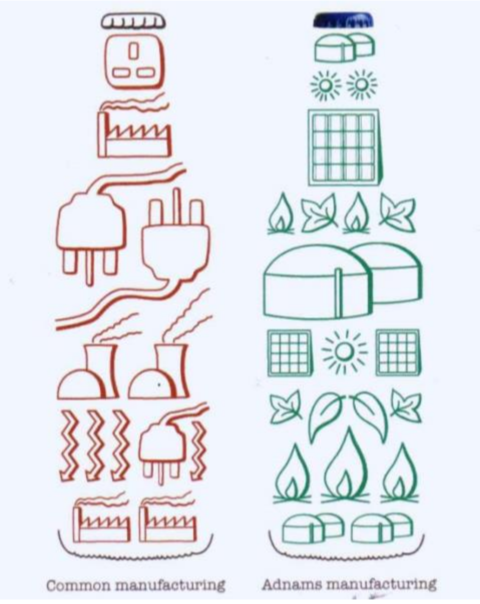


Figure 6 – Product manufacturing: Adnams PLC (source: http://www.brief-cases.com)

5.3.3 Guidelines for product use and operation

To improve circularity, efficiency and effectiveness in product use, the following points can be considered:

- Think about activity supports in the operational stage.
  - What will be the technical lifetime?
  - What will be the aesthetic lifetime of the product? Aesthetic lifespan should not be shorter than the technical lifecycle of product.
  - Reuse components and products.
  - Clear instructions for users to prevent misuse.
  - How much maintenance, cleaning and repair are required?
  - Design for as minimal as possible maintenance.
  - Mark the product parts that require maintenance.
  - Place parts exposed to wear together; ensure that they are visible and easily accessible.
  - Design for ease of repair and maintenance (see 5.6) by users themselves and for good reliability.
  - Design a safe product with fewer environmental effects.
  - Enable components or function upgrading (see 5.5) in addition to aesthetic feature upgrading. Use modular design for upgrading.
  - The ability to change exterior appearance can be a means of giving a product longevity. An example is mobile phones for which you can change the covers.
  - Promote use of the product under the intended conditions to avoid breakdowns.
  - Optimize the functional requirement, quality and strength without oversizing.
  - Avoid placing parts in a way that exposes them to wear.
  - Making the product timeless may be a means of having it accepted for a long time.
  - Age and wear that give the product a "patina" might add extra value.
  - As the product function, availability and service is the main value proposition, supplying replacement materials, maintenance services, repair, and control in post-use on a regular basis are necessary for continuous and increased product use. These factors not only prolong the physical lifetime of the product but also increase the economic lifetime of the product.
  - Since the product lifecycle is increased in this circular strategy, the product should be designed with no use of toxic materials and more use of renewables and recyclable materials. However, this approach should not reduce the lifespan of the product.
  - Since the product has a longer lifespan, it is necessary to ensure that the components have almost the same lifespan.

   - Ensure that at the end of the use phase, when the product can no longer provide its original functionality, there is incentive for the product and materials to be reused, recycled or remanufactured.
   - Consider which lifecycle stage of the product is dominant from an environmental perspective; for example, if it is energy-consuming in the use phase, then reduce the energy consumption. Otherwise, if it is not energy intensive during the use phase, focus on lifespan extension.
   - Use historical data for improvements to obtain insight into the possibilities for pooled or shared use (product life intensification).
   - Maximize the product life intensification through upgrading and even timeless design.
   - Design for low consumption of energy, water and materials during product use and operation.
     - How much and what types of energy will be required?
     - Consider energy-efficient technologies. Use components that use little energy.
     - Use rechargeable batteries.
     - Consider clean energy technologies. If possible, use wind power, water-based renewable energy, solar energy, potential energy, or tidal power, etc.
     - If the product should be moved, reduce the weight to reduce energy consumption.
     - Isolate the product to retain warmth or cold.
     - Help users to save, e.g., by default double-side printing and marking the least amount of material/liquids to use.
     - How much and what kind of consumables will be required?
     - Reduce the use of consumables.
   - Think about activity support in the operational stage of the product/service to make the system runs as efficiently as possible (also see 5.3.3).
     - Since the product will be used over a longer term, product safety during the entire use phase is crucial.
     - Education and guidance about the product/service usage is essential, e.g., how-to-use manuals and procedures for more-efficient and effective use of equipment and optimal operation.
     - Think about all necessary infrastructures such as technologies, devices and spatial layouts to offer the service/product.
     - Think about core aspects that make the product/service keep running; e.g., ensure repair and maintenance (see section 5.6) and upgradability (see section 5.5).
     - Ensure reduced environmental impact and resource consumption during the use phase, e.g., less energy consumption, green logistics (see 5.4), use of local services (technicians) or building the service location near major consumer centers.
   - Think about take-back systems after the product or service is obsolete.
   - Have an environmental overview of partners involved in the service offering.
   - Think about the common consumption factors: cost of the product/service, time and duration, space taken, availability of technology or material, skills required to provide/use the product/service, information, access and availability, customer responsibility towards the product/service, convenience and comfort, risk and safety, and, finally, perception and image of the product/service.
- Design using recyclable and secondary (recycled) materials.
   - Choose consumable materials that are easy to recycle.
   - Consider the recycling rate of consumable materials.
   - Use economically recyclable material.
   - Use consumable materials that require only one recycling method/process.
   - Avoid composite materials.
   - Select fewer material types and increase material homogeneity, or use materials that are compatible or are easy to separate to increase recycling possibilities.
   - Use consumable materials that already have recycling market.
   - Reduce the use of virgin consumable materials.
   - Increase the use of recovered/recycled material as consumable materials.

    - Industrial symbiosis (one's byproduct or waste as a primary input material for another) and restorative sourcing (use of materials previously designated as waste, such as re-mining from landfill or using ocean plastics) are enablers.
- Use durable and robust components and materials.
    - Increase high product integrity, durability and robustness.
    - Product should be made of durable and robust components and materials to last throughout more than one lifecycle. This approach not only reduces long-term resource consumption and maintenance costs but also results in a longer service interval.
- Make it easy to clean the product and components.
    - The surfaces to be cleaned should be smooth and wear resistant.
    - Reshape the interior surfaces to make them easier to clean.
    - Make it easy to clean. All product components should withstand the same cleaning process, liquid and chemicals, and temperatures, detergents and cleaning tools.
    - Avoiding making areas where dirt might collect and are hard to clean properly; e.g., avoid small holes, nooks, grooves, sharp edges and thresholds that capture dirt. This approach can make the product appear newer for a longer time.
    - Most products can use some basic cleaning and maintenance every now and then.
- Design for reduced energy consumption and usage of renewable energy.
    - If the use stage of the product lifecycle is dominant from an environmental perspective, design the product with reduced energy consumption, usage of renewable and clean energy.
    - Use idle product capacity.
    - Use historical data for improvements for better scheduling of downtime.
    - Make a stand-by function that can also be turned off.
- Focus on fulfilling the customer's requirements and value creation.
    - Place a strong focus on how to fulfill the customer's requirements or create customer value; e.g., develop a close relationship with the customer to understand their requirements and hence adjust personalized services and develop capabilities accordingly.
    - Design the product to be used individually with individual access.
    - Think about the current system that would be replaced; find the substitutions and changes and how a customer would behave. For example, examine number of usages and the duration of each, etc. This activity can be done with customer segmentation or survey methods.
    - In product development, the detailed and complete development process is defined at the early stages of development. On the other hand, in service development (rethink), the service design cycle is continuously repeated and improved to be able to adapt to various human factors and requirements that influence overall service development. Consequently, the focus is on a wide range of development, from business strategy to detailed design.
    - Create maximum function with minimum environmental impact; consider which function you will create, not which product.
- Consider timeless design, emotional attachment and compatibility.
    - Employ timeless design to avoid outdated fashion.
    - Simplicity and functionality often help a product remain attractive for a longer time.
    - Compatibility and adaptability can be a means of giving a product longevity in the information technology field, e.g., the USB or flash drive.
    - The ability to change appearance, i.e., the exterior, can be a means of giving a product longevity. An example is mobile phones where you can change the covers.
    - Think about product attachment and trust between customers/users and products.
    - Think about the effect time and fashion will have on your product and about how specific is the function your product is aiming to fulfill.
    - In addition to emotional attachment, reliability is also crucial; even if it is not the latest functional model, users still prefer to utilize it instead of replacing it.
- Try to use digitalization, ICT and IoT solutions.
    - Since quality-performance and function in the product use phase are mainly delivered in this circular strategy, product control and monitoring become extra vital. Therefore, online monitoring using digitalization, ICT technologies and IoT facilitate obtaining better knowledge

and learning more about the product performance through its lifecycle. Consequently, it would be possible to discover latent design errors and improve the product accordingly.

- In the case of product sharing and renting, use a logging system to monitor user behavior and performance, e.g., to detect whether the user is using the product incorrectly or incautiously, so the offending user can be consulted. This approach is also consistent with the rebound effect of a product service system in which the customer cares less about a product not being owned or overuse of environment-friendly products. With such control, damage during the use phase is reduced, and overall safety and lifetime improved. The drawback here is that the user might feel monitored and less trusted.
- Consumers should be informed about the effective use of the product to ensure adequate performance. Guide customers to use the product effectively and optimally via information sharing and online guidance.
- ICT technologies should also enable communication between those involved in the business. When using ICT technologies and IoT, consider the following:
    - Possibility to create personal profile
    - Fast login for customer
    - Easy and secure access
    - System integrity
    - Personalization and customization for different users/profiles
    - System to be ready for the next customer as soon as possible
    - Clear and friendly user interface
    - Automatically save data on the server.

5.3.3.1 Example of product use and operation

Finlayson is a Finnish brand for textile manufacturing; they make their products with high quality and durable materials to ensure product lifecycle extension. To facilitate the lifespan extension of their products, a series of educational videos and manuals is published to educate consumers on how to take care of their products by washing, drying, pulling, ironing, storing and picking up textiles. Finlayson also has a tack-back system in place and uses recycled materials such as plastic bottles.

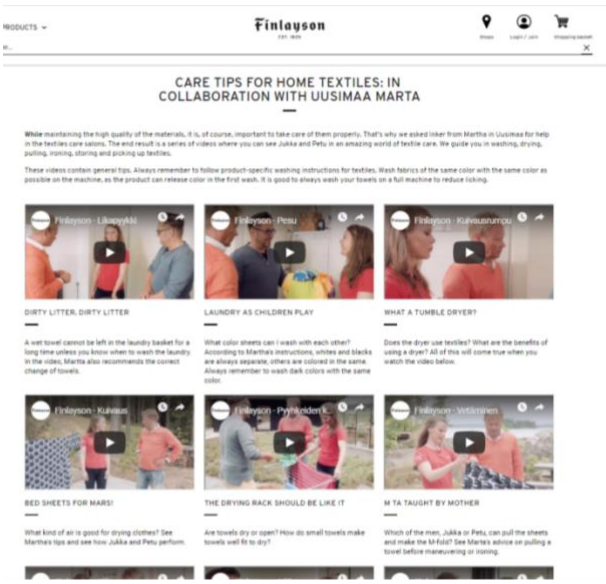


Figure 7 – Product use and operation: Finlayson (source: https://www.finlayson.fi/)

5.4 Logistics and packaging

To improve circularity, efficiency and effectiveness in logistics, the following points can be considered:

5.4.1 Design guidelines for logistics and packaging

- Design for reduced energy consumption and usage of renewable energy.
  - Plan the most energy-efficient shipping with minimum environmental effect.
  - Which means of transport will be used? Boats and trains are better than trucks.
  - Can the product be designed for effective loading and transport?
  - Combine forward with return logistics.
  - Incentivize eco-friendly driving and transport.
  - Reduce freight volumes.
  - Reduce emissions from transport.
  - Choose local suppliers, and transport larger quantities at a time.
  - Reduce the volume of transportation via stackable and foldable products.
  - Consider transporting products in compacted modules; assembly can be done at customers or retailer.
  - Minimize weight of components.
- Design using renewable materials.
  - Use more renewable and bio-based materials for packaging.
- Design using recyclable and secondary (recycled) materials.
  - Choose packaging materials that are easy to recycle.
  - Consider the packaging recycling rate.
  - Use economically recyclable material.
  - Use packaging for which only one recycling method/process is needed.
  - Avoid composite materials.
  - Select fewer material types, increase material homogeneity in packaging, or use materials that are compatible or are easy to separate to increase recycling possibilities.
  - Use packaging materials that already have recycling market.
  - Select materials with the most efficient recycling technologies.
- Use durable and robust components and materials.
  - Choose the correct material for the right job.
  - Estimate packaging strength and stiffness.
  - Select quality, strong, robust and durable packaging materials with a long lifespan that do not degrade during multiple transportation.
  - Avoid materials that might lose strength, become brittle or become discolored.
- Consider toxicity and other environmental aspects of materials.
  - What kind of transport packaging, bulk packaging and retail packaging will be used (volume, weight, materials, and reusability)?
  - Choose packaging materials that have fewer environmental impacts.
  - Eliminate, reduce, reuse or recycle (transit) packaging.
  - Eliminate toxic and dangerous packaging material.
  - Use standardized packaging.
  - Avoid high-quality materials such as aluminum and PVC in packaging.
  - Instead of packaging goods for branding purposes, use high-quality products.
  - Think about “appropriate fit” and optimizing the use of the quality of the materials where the lowest adequate level of material quality is suitable for the application without influencing the quality.
  - Reduce material consumption in packaging.
  - Eliminate toxic and hazardous material.

5.4.1.1 Example of logistics and packaging

Garçon Wines designs and produces an innovative 10-count corrugated case and flat wine bottles that will significantly cut carbon emissions and logistics costs from the supply chain of wine. The bottle is not only made from recycled PET but also designed in a flat bottle that, compared to an average round glass bottle, is approximately 55% spatially smaller. In their innovative space-saving package design, eight flat bottles pack vertically with two lying horizontally in the airspace around the bottlenecks, eliminating almost all unused airspace.

Therefore, a pallet loaded with 10 flat bottle cases could carry 1,040 bottles of wine, whereas a standard pallet with 6 round, glass bottles cases which would carry just 456 bottles of wine.

Figure 8 – Logistics and packaging: Garçon Wines flat bottle case [Source: https://www.garconwines.com]

5.5 Upgrade

5.5.1 Definition

With the current increased pace of change due to new breakthroughs and innovations in products, technologies, advanced composites and materials and production methods and behavioral changes in producers and consumers, innovation cycle time has been dramatically reduced, leading to increased launches of new products into the market and higher obsolescence of old products. Therefore, the products are usually disposed of before their actual functional lives are over. This situation calls for the creation of technological and market mechanisms for upgrading. In the upgrade strategy, the product is still functional, but new changes, evolution and new features are added to extend the lifecycle of products. The strategy therefore extends product value through enhancing the function of an existing product to even beyond its original design condition and reducing value loss from continued use of parts and products. The design method for product upgradability includes predicting the product performance and functions that will be required at the time of upgrade. Hence, the upgrade occurs (1) for technological change for a better performance or (2) to modify the structure of the product for a new solution or function.

5.5.2 Design guidelines for upgrade

To design for product upgradability, the following points can be considered.

- Focus mainly on functionality and quality performance.
  - Consider future product performance (e.g., operation speed) and future product functions (e.g., new features).
  - Roughly estimate the price of each generation.
  - Think about the (possibly adverse) dependencies and effect of the upgrade on other product components. There is a possibility that an upgrade to a product may require additional changes in the physical product due to mutual dependencies, e.g., installation of an additional cooling fan when upgrading a CPU in a laptop.
  - Predict how many lifecycles the product is supposed to live; i.e., estimate the number of product upgrades and the time of upgrade for each generation.
  - Consider a disposal plan for the exchanged component. Ensure that at the end of the use phase, when the product can no longer provide its original functionality, there is incentive for products and materials to be recycled (see 5.11).
- Focus on fulfilling the customer’s requirements and value creation.

- Design for customization and flexibility. Key feature of a product is that it fulfills the customer's needs optimally. Try to meet the customer's real needs in each upgrade. This approach is vital for products to be used in product service systems.
  - Future trends including technological trends, customer requirement and demand trends, trends of competitors, the company's policy, future business models, legal and legislations need to be considered.
  - Consider whether customers execute the upgrade and exchange the components or whether the manufacturer collects the product, upgrade it and delivers it back.
- Use durable and robust components and materials.
  - Durable life vs. value life: durable life is a measure of the duration until the product is nonfunctional. Value life is a measure of the duration until the product value perceived by customers drops. Hence, customers usually discard a product, especially technological items, when its perceived value has decreased with time to less than the perceived durable life, i.e., the value life is shorter than the durable life. Therefore, the design should aim to extend the value life of the product.
  - The platform (components that do not change throughout all generations of a product) should be designed to be durable, robust and reliable for several lifecycles, so it can withstand several upgrades.
  - The modules (components that will possibly be changed from one product generation to another) need to be robust and durable, although they might be changed in each upgrade. This approach might reduce the need for an upgrade.
  - Parts that wear out earlier should be able to be replaced easily in time, either preventively or in an upgrade procedure.
  - Parts that are subject to stress, wear, corrode, stain, break or fail easily should be avoided or minimized or be made particularly resistant and durable.
  - Estimate durable life and value life to ease upgrading.
  - The lifespan of the different parts should be recognizable; obvious (warning) signs or indicators for wear are ideal for exchange in each upgrade.
  - The ability to change appearance, i.e., the exterior, can be a means of giving a product longevity. An example is mobile phones for which you can change the covers.
  - Durability of parts and the product itself should match its economic and stylistic/aesthetic lifespan.
  - Select quality, strong, robust and durable materials and components that do not degenerate during the multiple lifecycles.
  - Avoid materials that might lose strength, become brittle or become discolored.
- Make it easy to dismantle the product nondestructively.
  - Determine parts and components that do not change throughout all generations of a product (platform) and parts and components that will possibly be changed from one product generation to another (modules).
  - Make a component database for future upgrades. The designer might not know an exact value of performance in the next generations but should estimate a certain range in which required upgrade performance resides. The range should then be converted into a set of components of the same kind but different in performance. Hence, when the product is upgraded, the right component with most appropriate performance is selected.
  - Due to the difficulty of predicting future trends with regards to function and performance, plausibility of component changes should be evaluated. Components with low plausibility of change in the future should be isolated, since this upgrade function may not be required in the next generation. Conversely, components with high plausibility of change in the future should be designed modularly to ease upgrade operation.
  - Standardize constructions and joints.
  - Robustness and wear resistance of product parts and joints are important. They must not break during disassembly and upgrading, since they are to be reused again.
  - A proper take-back system for (faulty and good condition) components is necessary.
  - Avoid a requirement for glue and adhesives, ideally avoiding the need for any tools.

    - Make the product easy to open and dismount nondestructively, together with ease of access and reachable direction.
    - Those parts that will not continue the journey to the next new lifecycle have to be designed for recycling (see 5.11).
    - No critical security conditions should appear during the dismantling and maintenance.
- Make exchanging of faulty components easily accessible.
    - In the case of physical upgrade, the exchangeable components should be marked, easy to recognize and easy to access (preferably from one side) and replace.
    - Ensure that the parts that need to be upgraded are easy to access and easy to dismount.
- Design in modular construction.
    - Make the modularity of products for upgrade to be user oriented to help with adapting the product to new users.
    - A simple modular structure and design of the product makes it easy to self-upgrade and change modules without damage.
    - Divide the product into different modules, and place all the parts that need to be exchanged or upgraded into one single module, thus lowering the effort needed to upgrade the product.
    - Avoid cross-dependences between modules; otherwise, we might be forced to update a working module simply as a consequence of updating an outdated one.
    - Make a "kit" with all the elements required for an upgrade.
- Provide manuals and documentation.
    - Include good documentation for upgrading, particularly if customers themselves execute the upgrade. The documentation should be understandable for all users, for example including signs on how to open the product and exchange components and documenting the effect of the upgrade. In addition, provide a link to where the data about the product are to be found.
- Try to use digitalization, ICT and IoT solutions.
    - Constantly collecting data about usage behavior and product performance through its lifecycle will help discover latent design errors, improve the product accordingly and add additional customer demands to the next upgrade. Taking customer feedback into account is important to maximize customer satisfaction for each upgrade.
    - Consumers should be informed about the upgrade of the product (particularly software upgrades).

5.5.3 Example of upgrading

Fischer Lighting has integrated new LED technologies into old lighting solutions, in which the latest LED technology can be directly installed into existing fixtures without any additional changes. In addition, the design makes it possible for future LED technology to be installed similarly to almost every type of existing fixture on the market today. Through this innovative design for installing new LED technology, the energy usage is decreased significantly, and the life expectancy of the existing lighting solution is extended. Due to lower maintenance costs, the amount of waste produced is also reduced in the long term, as is the total cost of ownership. This solution is vital, as LED technology has been developed fast, but nonupgradeable solutions on the market require changing the whole technology even when the end-of-life has not yet been reached.

Figure 9 – Upgrading: New LED solutions on the existing fixture, reference: https://www.fischer-lighting.com/english/

5.6 Repair and maintenance

5.6.1 Definition

Correct, replace or fix faulty components of a defective product to return it to its original *functionality* to the *same user* to extend the lifespan of a product and hence reduce the need for new resources, avoiding waste and producing fewer emissions. When the product was not functioning, a *warranty* for the replaced or fixed components may be issued (less than the one for a newly manufactured equivalent). Partial disassembly is envisioned. The easy and quick repair of a product means saving time and money and should be done easily with nondestructive dismantling. Since some energy and resources are used for the actual repair, reuse is better than repair, but repair is better than remanufacturing. There are three main approaches to repair a product, but there is even also a combination of these three in which some parts in a product might be repaired by the customer and some by third parties because of special tools or safety issues.

(1) Industrial repair by companies: for many companies, repair and maintenance services are a core part of their revenue streams. Hence, some products are intentionally difficult for consumers to repair themselves, which has negative effects on a circular economy. This option is good when (a) the hazardous product can cause direct harm to the user in case of nonprofessional repair, i.e., hazardous equipment; (b) products whose operation and maintenance can be dangerous or lead to safety concerns, e.g., large products; (c) the structure of the product is too complex to be repaired by customers; (d) products are hard to repair for a consumer because of a high risk of damaging the product or making a repair that can lead to a future failure; (e) products that need special tools; and (f) warranty issues.
(2) Repair by third party: third party earns money through this option. The manufacturing company might receive revenue from selling spare parts. This approach also saves much environmental impact from a product traveling to the factory to be repaired; it would be repaired very close by in local repair shops. Many professional services are often expensive and more B2B-driven.
(3) Domestic repair: customers invest their own time and costs for spare parts and tools. The manufacturing company might obtain revenue from selling spare parts, tools and updates and upgrades. Design for repair by the customers is the right approach if a company wants to contribute to a circular economy, as much of the environmental impact from service engineers traveling to correct problems is saved. However, all concerns about safety and warranties must be solved.

Unfortunately, for some products, repair is not an option. Despite the huge possibilities of keeping valuable products in use for longer, there is a powerful monetary motivation for a business model that designs a product to not be repairable but instead for selling spare parts, services and upgrades. Is it broken? Please buy a new one! The company will sell product updates, both for soft- and hardware, and decrease its need for growth by only selling more new products. In addition, the customer will see that paying for a service and repair can be cheaper than regularly buying new products. The risk however arises that the consumer begins to distrust such products because they fail so easily. However, broken/dysfunctional products are occasionally not repaired due to evolution or new features of new models (outdated product). Hence, the old product is condemned to end up in the waste stream unless it is repaired and re-sold or sold broken for a lower price; then, the new buyer saves money and repairs it herself. Occasionally, there is a tradeoff that needs to be investigated case-by-case to find the optimum life span. For instance, by keeping energy-using products in use for a longer time, we are at the same time preventing new and more energy-efficient products from entering our homes, and we will use more energy than we would with new products.

5.6.2 Design guidelines for Repair

Reparability should be considered in design decisions during the product's development process with considerations of level of technical expertise and the number, type and specialized tools required. The faster is the repair, the lower cost for repair, i.e., more efficiency with shorter service time. Things to consider when designing for repair include the following:

- Use durable and robust components and materials.
    - Although it is desirable to have product's components be as robust and durable as possible, in design for repair and maintenance, not all parts have to be equally durable, robust and reliable as long as the ones that wear out earlier can be replaced easily in time, either preventively or in a repair procedure.
    - On the other hand, it is generally desirable to have product's components robust and durable to minimize the repair and maintenance. It is better if products are designed and developed with longer service intervals.
    - Choose durable and robust components and materials with a long lifespan, so only the parts that wear out earlier are replaced.
    - Predict how many lifecycles the product is supposed to live. Make it strong enough to withstand these circumstances for the duration of the supposed lifetime.
    - The lifespan of the different parts should be recognizable; obvious (warning) signs or indicators for wear are ideal.
    - Do not combine parts that have different lifespans. They should be easily separable.
    - All parts should be able to withstand the same cleaning materials, chemicals and processes.
    - Heavily stained surfaces should withstand mechanical cleaning.
    - Select quality, strong, robust and durable materials and components that do not degenerate during the multiple lifecycles.
    - Avoid materials that might lose strength, become brittle or become discolored.
- Make it easy to inspect the product and components.
    - Inspection points and testing components should be marked and easily accessed.
    - Manuals for testing and inspection should be available.
    - The product must be safe to inspect and not include hazardous materials.
    - The condition of a product and its components must be easy to determine to know whether it is useful to repair, i.e., ease of identification and verification.
    - Data for materials, load limits, tolerances and adjustments, etc. must be clear and available.
    - Product parts must be standardized to ease conducting the inspection and across different models/products.
- Make exchanges of faulty components easily accessible.

    - Components to be cleaned or parts which are subject to stress, wear, corrode, stain, break or fail easily should be marked, easy to recognizable and easy to access (preferably from one side) and replaced.
- Make it easy to dismantle the product nondestructively.
    - Standardize construction and joints.
    - Design easy access to gripping and breaking points.
    - Design ease of change and service. Spare part availability is also vital.
    - Robustness and wear resistance of product parts and joints are important. They must not break during disassembly, since they are to be reused at least one more time.
    - A proper take-back system for (faulty and good condition) components is necessary.
    - Avoid a requirement for glue and adhesives, ideally avoiding the need for any tools.
    - Design the product to be easy to open and dismount nondestructively, together with ease of access and reachable directions.
    - No critical security conditions should appear during the dismantling and maintenance.
    - Those parts that will not continue the journey to the next new lifecycle have to be designed for recycling (see 5.11).
- Design standardized components across different products and models.
    - Use standard components and lubricants in general and across different products and models. Compatibility and exchangeability of components is required across other models and products, e.g., the same type and size of screws.
    - Require fewer joining parts and detachable/resolvable joints.
- Design standardized tools required cross different products and models.
    - Fewer and simple tools should be used.
    - Compatibility and adaptability of tools is required; e.g., require the same type and size of screwdriver across other models and products, which requires less time, effort and confusion when dismantling. Using a single type of tool not only helps achieve a lower number of parts but also eliminates the risk of selecting the wrong screw during reassembly.
    - Use sturdy heads that are usable multiple times such as hex or Allen geometry or even Torx, and do not provide lifting forces at loss and tightening.
    - Prefer a clearance fit.
- Design in modular construction.
    - Make it possible to modernize and upgrade the product by simple replacement of modules by the end-user without damaging the product. It might also be a good means of placing parts that are supposed to be replaced in a module, such as batteries or wear parts.
    - Modularity of products for reuse should be user oriented to help with adapting the product to new users. It might thus become a driving force for reuse.
- Provide manuals and documentation.
    - Include with the product information on how it can be repaired by customers themselves. The documentation should be understandable for every amateur user, for example, by including signs on the product itself and user repair manuals. In addition, provide a link to where the data about the product are to be found.
- Make spare parts and exchange components easily available.
    - Repair and maintenance are only viable if components of products are easily found on the market and preferably provided inexpensively.
- Use joints and connectors that can be easily opened and closed multiple times.
    - Reversible fasteners that can be reused are good.
    - Mark where fasteners are located to ease dismantling.
    - Use inseparable joints and connectors for components made of the same material or compatible material.
    - In generally, minimize the number of connectors and joints.
    - Make it easy to disassemble the product with as few ordinary tools as possible. Use fastening devices that can be easily opened and closed multiple times.

- Latches, snaps and clips are normally preferred to screws and bolts for time efficiency reasons. Prioritize latches, snaps, clips and bolts and screws over welding, rivets, folding, staples, and gluing, all of which make a joint more difficult to demount.
- Snap fasteners and latching are good for disassembly.
  - There are normal snap fasteners that are integrated into the details and are usually made of plastics.
  - There are snap fasteners that are pressed into place.
  - Occasionally, Velcro can be a suitable fastener.
- Screws are normally good for disassembly.
  - Use one type and size so that you can use one single tool.
  - Ensure that access is possible with a tool (screwdriver). If there is a nut, you must also have access to the back side.
  - Use screws that are often made with heads that combine two systems. This approach enables disassembly with tools in a different system than the one the assembling factory uses. Examples include hex head cross drive, slotted internal Torx, and hex head internal Torx.
- Adhesives and glues are generally not preferred if the product must be dismantled for remanufacturing.
  - If adhesive is to be used, the best alternative is a water-based adhesive.
  - Breakpoints can be good for glued joints that must be broken. This approach provides controlled damage.

- Try to use digitalization, ICT and IoT solutions.
  - IoT and digitalization enable design for repair and maintenance. Therefore, online monitoring using ICT technologies and IoT facilitates obtaining better knowledge and learning more about product performance through its lifecycle. It would thus enable condition-based maintenance and preventive maintenance to understand what components are going to fail when, so repair and maintenance can be planned with minimum effect on product performance.

5.6.3 Example of Repair

- Fairphone is a company that provides smartphones made for repair by the customers themselves. The products should last longer than common phones, with up to a 4-to-5-year planned lifespan. The product is designed for modular assemblies of the main functions. Every assembly can be exchanged in a very short time. The design also eases remanufacturing and recycling.

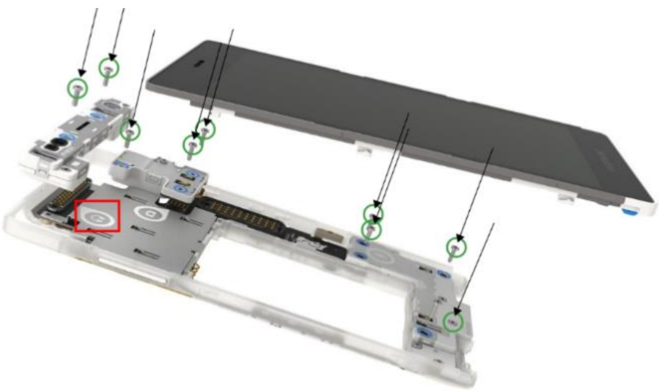


Figure 10 – Repair: A Fairphone in an opened view [Source: Fairphone]

Features for ease of repair include the following: nondestructive disassembly, opening without tools, one black and same size of screws, one mounting direction, modules that are easy to replace, documentation and signs in the form of pictograms on the modules.

- 3Temp designs and produces coffee machines that are made for easy repair by the customers themselves and for online performance tracking. On the top of the machine, the brewing tube is set as a module that can be simply opened via only two screws. The cover has a hinge; it is thus possible to open the tube and obtain access to the important parts very easily. The brewing tube is the “heart” of the machine, containing most of the vital parts of the coffee machine. The design also eases remanufacturing. Features for ease of repair include nondestructive disassembly, opening with one tool, using only a few screws, easy access to functional modules, modules that are easy to replace, and signs in the form of pictograms on the modules for disassembly.

Figure 11 – Repair: 3Temp coffee machine designed for easy access and maintenance with one tool

5.7 Reuse

5.7.1 Definition

Reuse of a (discarded) product involves a product that is still in good condition and fulfills its *original function* to keep the product functional and attractive to as many *different* users as possible, and for as long as possible, to extend and intensify the use of a product by preventing it from becoming obsolete and then waste. Reuse is implemented relatively easily and may involve a minimum amount of cleaning and repackaging. No *warranties* are provided, and no disassembly is envisioned.

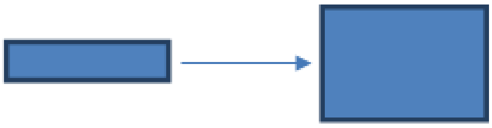
Reuse redistributes used products and extends the service life of the existing products, which reduces the number of products that had to be produced in the first place and (1) saves all the resources and values place into extraction and production of a new product including energy, work, time and material, (2) reduces the waste stream, and (3) saves time, resource and energy used in repairing, remanufacturing, or recycling the old ones.

Reuse might not always be good. For instance, a washing machine working great for 20 years, might not be as energy/water efficient as new ones on market. It is important to critically evaluate whether reusing a product or another circular strategy option would be more appropriate. The reused product should still be functional, efficient, and attractive. We might reuse preowned products perhaps because it is cheaper, has vintage design, or is better than new ones.

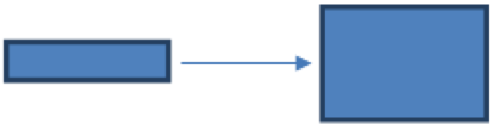
Reuse happens in two ways:

(1) Service-life extension of product: bring it back after its first life or extend it. A service-life extension is the simple redistribution of existing, preowned products to new users. Users exchange products between them based on their needs, without the business model of the company that manufactured that product necessarily changing from its linear economic model. Examples include selling secondhand products on Ebay and Blocket.

(2a) Service-life intensification and service economy: shared use of a single product by different consecutive users within short periods of time. It is a centralized model around the activities of companies, in which a company is responsible for the production, maintenance, repair and management of a product. The customer pays a fee to access and use this product. Examples include leasing, carpools and city bikes.



(2b) Service-life intensification and sharing economy: shared use of a single product by different consecutive users within short periods of time. The sharing economy is a decentralized model that often happens outside of the influence of companies without the company managing the product or making it accessible to one user or another. It might even benefit companies other than the original manufacturers. Examples include Air BNB and Uber.



However, points that can be argued include the difference between a service and sharing economy and whether for example Uber is a share or service.

5.7.2 Design guidelines for Reuse

There are many reasons for a product to become obsolete; obsolescence can result from technical obsolescence, fashion changes, social expectations, new innovative technologies and many other reasons. Design for reuse must therefore consider not only the wear and tear (aging) that makes products eventually fail but also the social and even emotional reasons that lead users not to discard their products. From a technical perspective, products are more likely to stay in use longer, and even pass on from one generation to another, if they are built to last with good manufacturing quality and the right choice of materials. A majority of products found in the market were not designed to be durable and robust nor to be used by more than one user (intensification) or last long (extension). However, products can often be reused even when they were not originally designed to be, given the correct mindset, such as buildings.

Products must be designed and manufactured to be durable and robust and last for a very long time by being easy to maintain and clean, by being resistant to wear and tear, or being resistant to changes in technology and fashion to extend their life. The design should consider the following:

- Think about activity supports in the operational stage.
  - As the product function, availability and service is the main value proposition, supplying replacement materials, maintenance services, repair, control in post-use on a regular basis are necessary for continuous and increased product use.
  - Provide periodic and condition-based maintenance based on monitoring the use phase via ICT technologies to retain product availability and functionality.
  - Consider which lifecycle stage of the product is dominant from an environmental perspective; for example, if it is energy-consuming in the use phase, then reduce the energy consumption. Otherwise, if it is not energy intensive during the use phase, focus on lifespan extension.
  - Since the product is reused and the lifecycle is increased, the product should be designed with no use of toxic materials and with the use of renewable and recyclable materials.
  - Ensure that at the end of the use phase, when the product can no longer provide its original functionality, there is incentive for products and materials to be recycled (see 5.11).

- Use durable and robust components and materials.
  - In designing for reuse, since the product has a longer lifespan, it is necessary to ensure that all components have almost the same lifespan and the same durability. Otherwise, parts that wear out earlier should be able to be replaced easily in time, either preventively or in a repair procedure.
  - Choose durable and robust components and materials with a long lifespan.
  - Choose the right material for the right job.
  - Parts that are subject to stress, wear, corrode, stain, break or fail easily should be avoided, minimized or made particularly resistant and durable.
  - Predict how many lifecycles the product is supposed to live. Make it strong enough to withstand these circumstances for the duration of the predicted lifetime.
  - The lifespan of the different parts should be recognizable; obvious (warning) signs or indicators for wear are ideal.
  - All parts should be able to withstand the same cleaning materials, chemicals and processes.
  - All parts should be able to withstand the same temperature.
  - Heavily stained surfaces should withstand mechanical cleaning.
  - Durability of parts and the product itself should match its economic and stylistic/aesthetic lifespan.
  - Estimate product behavior in its use phase, i.e., components’ strength and stiffness.
  - Select quality, strong, robust and durable materials and components that do not degenerate during multiple lifecycles.
  - Avoid materials that might lose strength, become brittle or become discolored.
- Make it easy to clean the product and components.
  - The surfaces to be cleaned should be smooth and wear resistant.
  - Reshape the interior surface to make it easier to clean.
  - Make it easy to clean. All product components should withstand the same cleaning process, liquid and chemicals, and temperatures, detergents and cleaning tools.
  - Make heavily stained surfaces able to withstand mechanical cleaning.
  - Avoid making areas where dirt might collect and are hard to clean properly; e.g., avoid small holes, nooks, grooves, sharp edges and thresholds that capture dirt. This approach can make the product appear newer for a longer time.
  - Avoid unnecessary coating procedures.
  - Avoid nonremovable coating materials. Make it easy to remove the coating materials.
  - Prioritize dyeing internal polymers over surface painting.
  - Most products can use some basic cleaning and maintenance every now and then.
- Make it easy to inspect the product and components.
  - Accurate inspection for reuse is essential to keep the product functional. Design should enable early identification of stress, wear or breakdown.
  - Inspection points and testing components should be marked and easily accessed.
  - Manuals for testing and inspection should be available for the user.
  - The product must be safe to inspect and not include hazardous materials.
  - Data for materials, load limits, tolerances and adjustments, etc. must be clear and available.
- Consider timeless design, emotional attachment and compatibility.
  - Employ timeless design to avoid outdated fashion.
  - Simplicity and functionality often help a product remain attractive for a longer time.
  - Compatibility and adaptability can be a means of giving a product longevity in the information technologies field, e.g., the USB or flash drive.
  - The ability to change appearance, i.e., the exterior, can be a means of giving a product longevity. An example is mobile phones for which you can change the covers.
  - Think about product attachment and trust between customers/users and products.
  - Think about the effect time and fashion will have on your product and about how specific is the function your product is aiming to fulfill.
  - In addition to emotional attachment, reliability is also crucial; even if it is not the latest functional model, users still prefer to utilize rather than replace it.

- Try to use digitalization, ICT and IoT solutions.
    - Since quality-performance and the function of the product in the use phase are delivered in multiple lifecycles, product control and monitoring become particularly vital. Therefore, online monitoring using ICT technologies and IoT facilitates obtaining better knowledge and learning more about the product's performance through its lifecycle. Consequently, enable condition-based maintenance and preventive maintenance to understand what components are going to fail when so that repair and maintenance can be planned with minimum effect on product performance.
    - In the case of product sharing and renting, use a logging system to monitor user behavior and performance, e.g., a user using the product incorrectly or incautiously, so that the offending user can be consulted. This approach is also consistent with the rebound effect of a product service system in which customers care less about a product not being owned or overuse environment-friendly products. With such control, damage during the use phase is reduced and overall safety and lifetime improved. The drawback here, however, is that the user might feel monitored and less trusted.
    - IoT can be used to support the optimization and efficiency of product operation. This approach includes education with how-to-use manuals.

Products with this design might be more expensive, as they usually require more material and more energy to be produced in the first place; therefore, they become less competitive. Moreover, repairs cost a great deal, which can also become a barrier. However, the disadvantage in the production stage of such products and the extra product cost will be worth it in the long term, as they will save the company much time and resources repairing its hundreds or even thousands of products and as the number of reuse cycles grows. The more reuse cycles a product can go through, the higher its environmental advantage over a nonreusable alternative. Occasionally, to reuse, the product has to be transported and then has to be cleaned. However, the environmental effect of transportation is much less than making a new product from virgin materials.

5.7.3 Example Reuse

Ope AS, a Norwegian company, makes office interior furniture that optimizes people's environment in open-plan offices in terms of variety and flexibility. Its designs are modular and consist of modules that can be built and taken apart according to need. Like LEGO, you can build and rebuild variations from the same basic components, redecorating cost and waste free. Depending on the room and requirements, the shape and function of the furniture is decided by the owner, allowing for different possibilities, whether to create simple storage units for the home, room dividers in an office environment or sculptural structures in public spaces. The main feature and enabling of their design lie with the Ope™ connector, with which the product can be reconfigured and rebuilt as needs change to accommodate a different or expanded purpose to provide everyone from individuals, interior designers and architects with the freedom to define and redefine spaces through their furnishing.

Figure 12 – Reuse: modular office furniture, resource: https://opework.com/

5.8 Refurbish

5.8.1 Definition

Refurbishing comprises repairing a returned product after a certain period of use to satisfactory mechanical specifications and operating condition within the bounds of what is considered acceptable by rebuilding or repairing major components that are close to failure, even when there are no reported or apparent faults in those components. The main difference from remanufacturing is that refurbishment is usually less rigorous, less costly, involves less disassembly and reassembly and involves a lower production volume. Refurbishing is a process where products are returned to some central facility, visually inspected, and functionally tested, and necessary repairs (including assembly and disassembly) are performed for the purpose of resale or redistribution. The device might be cosmetically enhanced, and protective coating might be applied. In the disassembly, products' components are kept together and, after cleaning, inspecting and replacing of the severely worn or broken parts with new parts, the products are reassembled with most of its original parts to reach its original condition. Refurbishment can happen via different business models:

(1) Original equipment manufacturer (OEM): products arriving from service centers, trade-ins from retailers or end-of-lease contracts.
(2) Contracted centers: are contracted to refurbish products on behalf of OEMs. In other words, the OEM maintains ownership of the products but does not perform the actual remanufacturing itself.
(3) Independent centers: OEM has little or no contact with the product, and they buy or collect cores for their processes.

5.8.2 Design guidelines for Refurbishment

Refurbishment and remanufacturing share things to consider when designing for refurbishment:

- Investigate current and upcoming laws and regulations
    - Refurbished products need to comply with applicable laws and regulations, e.g., hazardous material or chemicals that were not forbidden in the first lifecycle.
    - Do not incorporate any chemicals that might be banned later. REACH is a regulation with a list of banned materials and a list of materials to be banned.
- Use durable and robust components and materials.
    - Since the product lifecycle is increased with refurbishment, the product should be designed with no use of toxic materials and more use of renewables and recyclable materials. However, this approach should not reduce the lifespan of the product. Try to choose materials that are already less harmful from the start.

    - All parts having the same durability and lifespan (if possible) is optimal. Make it easy and time-efficient to replace components that wear or can easily break.
    - Parts that are subject to stress, wear, corrode, stain, break or fail easily should be avoided, minimized or made particularly resistant and durable.
    - Predict how many lifecycles the product is supposed to live. Use quality, strong and robust materials to make the product strong enough to withstand these circumstances.
    - Use materials that, after many lifecycles, can be recycled.
    - The lifespan of the different parts should be recognizable; obvious (warning) signs or indicators for wear are ideal.
    - All parts should be able to withstand the same conditions, e.g., cleaning materials, chemicals, processes, temperature and mechanical cleaning in both refurbishment phase and use phase.
    - Avoid materials that might lose strength, become brittle or become discolored.
    - Use materials, parts and components that will be available in the future. Keep in mind the second use of a refurbished product.
    - Make the core parts robust enough that can be used repeatedly.
    - Make it possible and easy to upgrade the product (see 5.5).
    - Occasionally, it might be appropriate to leave room for new screw holes that will be needed by the refurbishment.
    - Make heavily stained surfaces able to withstand mechanical cleaning.
    - Select quality, strong, robust and durable materials and components that do not degenerate during multiple lifecycles.
    - Avoid materials that might lose strength, become brittle or become discolored.
- Make it easy to clean the product and components.
    - The surfaces to be cleaned should be smooth and wear resistant.
    - Reshape the interior surface to make it easier to clean.
    - Make it easy to clean. All product components should withstand the same cleaning process, liquid and chemicals, and temperatures, detergents and cleaning tools.
    - Make heavily stained surfaces able to withstand mechanical cleaning.
    - Avoid making areas where dirt might collect and are hard to clean properly; e.g., avoid small holes, nooks, grooves, sharp edges and thresholds that capture dirt. This approach can make the product appear newer for a longer time.
    - Avoid unnecessary coating procedures.
    - Avoid nonremovable coating materials. Make it easy to remove the coating materials.
    - Prioritize dyeing internal polymers over surface painting.
- Make it easy to inspect the product and components.
    - Inspection points and testing components should be marked and easily accessed.
    - Manuals for testing and inspection should be available.
    - The product must be safe to inspect and not include hazardous materials.
    - Make identification and verification of faulty components easy.
    - Data for materials, load limits, tolerances and adjustments, etc. must be clear and available.
    - Product parts must be standardized to ease conducting the inspection and across different models/products.
    - Ensure that it is possible to easily validate the product, that is, to measure to determine whether it is in condition to be given a new life.
    - It is good if an initial first rough assessment can be made without costs for cleaning, disassembly, etc. to decide whether the actual item can be refurbished.
- Make exchange and faulty components easily accessible.
    - Make disassembly points, gripping points and breaking points accessible, preferably from one side.
    - Components to be cleaned or parts that are subject to stress, wear, corrode, stain, break or fail easily should be marked, easy to recognize and easy to access (preferably from one side) and replace.
- Make it easy to dismantle the product nondestructively.
    - Standardize construction and joints.

    - Use a single type of tool to achieve a lower number of parts and to eliminate risk.
    - Robustness and wear resistance of product parts and joints are important. They should not break during disassembly.
    - Avoid a requirement for glue and adhesives, ideally avoiding the need for any tools.
    - Note which parts of a product may need to be disassembled. Make these parts easy to disassemble.
    - Design for ease of access to gripping and breaking points.
    - Make products easy to open and dismount nondestructively.
    - No critical security conditions should appear during refurbishment.
    - Those parts that will not continue the journey to the next new lifecycle have to be designed for recycling (see 5.11).
- Design standardized components across different products and models.
    - Include fewer joining parts and detachable/resolvable joints.
    - Use standard components and lubricants.
    - Compatibility and exchangeability of components should be required across other models and products, e.g., the same type and size of screws.
- Design standardized tools required across different products and models.
    - Compatibility and adaptability of tools is required, e.g., the same type and size of screwdriver across other models and products.
    - Use sturdy heads that are usable multiple times such as hex or Allen geometry or even Torx, and do not provide lifting forces at loss and tightening.
    - Prefer a clearance fit.
    - Make it easy to disassemble the product with as few ordinary tools as possible. Latches, snaps and clips are normally preferred over screws and bolts. Welding, rivets, folding, staples, and gluing make a joint more difficult to demount.
    - If you are using screws, design the fastening element so that it is easy to open. Use screw types that are easy to open by hand, such as Torx or Hex socket.
    - Use the same type and size of joining element (screws) to make it possible to use only one tool, i.e., fewer and simple tools.
    - Make threads short, and include the thread in the body of the product.
    - Use fastening devices that can be easily opened and closed multiple times, e.g., snap fasteners.
    - Use standardized elements and measures to facilitate future upgrading and exchange of parts (see 5.5).
- Design in modular construction.
    - Divide product into different modules, and put all the parts that need to be exchanged or upgraded into one single module, thus lowering the effort needed to refurbish the product.
    - Avoid cross-dependences between modules; otherwise, we might be forced to update a working module simply as a consequence of updating an outdated one.
    - Make a "kit" with all the elements required for an update.
    - Design simple modular structures and design the product for changing modules without damage.
- Provide manuals and documentation.
    - Provide with the product understandable information such as the content of materials and some tips about refurbishment. In addition, provide a link to where the data about the product are to be found.
- Use joints and connectors that can be easily opened and closed multiple times.
    - Reversible fasteners that can be reused are good.
    - Mark where fasteners are located to ease dismantling.
    - Use inseparable joints and connectors for components made of the same or compatible material.
    - Generally, minimize the number of connectors and joints.
    - Make it easy to disassemble the product with as few ordinary tools as possible. Use fastening devices that can be easily opened and closed multiple times.

- Latches, snaps and clips are normally preferred over screws and bolts for time efficiency reasons. Prioritize latches, snaps, clips and bolts and screws over welding, rivets, folding, staples, and gluing, all of which make a joint more difficult to demount.
- Snap fasteners and latching are good for disassembly.
  - There are normal snap fasteners that are integrated into the details and are usually made of plastics.
  - There are snap fasteners that are pressed into place.
  - Occasionally, Velcro can be a suitable fastener.
- Screws are normally good for disassembly.
  - Use one type and a size so that you can use one single tool.
  - Ensure that you have access with a tool (screwdriver). If there is a nut, you must also have access to the backside.
  - Use screws that are often made with heads that combine two systems. This approach enables disassembly with tools in a different system than the one the assembling factory uses. Examples include hex head cross drive, slotted internal Torx, and hex head internal Torx.
- Adhesives and glues are generally not preferred if the product must be dismantled for remanufacturing.
  - If adhesive is to be used, the best alternative is a water-based adhesive.
  - Breakpoints can be good for glued joints that must be broken. This approach provides controlled damage.

- Make spare parts and exchange components easily available.
  - The refurbishing of a product becomes much easier if components and spare parts are available and easy to find on the market.
  - Compatibility and exchangeability of components is required across other models and products.
- Try to use digitalization, ICT and IoT solutions.
  - Obtain valuable information back regarding the quality of your products, how your customers are using them, and why they break or otherwise stop working as intended.
  - Create a system for identification of the individual product, or even of components within the product, by for example RFID, barcode, tag or QR code. Create a system to save important traceable data regarding the product.
  - Mark parts with the types of material. For plastics, use existing systems.
  - Design a structural means of diagnosing the old and worn out component to make it easy to understand what must be done to the product to give it a second life.
  - Create a system to keep track of your products and to know where they are at the end of their service life.

5.8.3 Example Refurbishment

Inrego is a company that provides repaired, remanufactured and refurbished IT equipment in Sweden. With their lifecycle management business model, they not only extend the lifecycle of laptops, TVs and smartphones through repair but also reintroduce them to a second or third lifecycle through remanufacturing and refurbishment. Their refurbishment process includes cleaning, easy repairs, fixing the aesthetic features such as polishing and removing scratches and adjusting the product to the new customer, e.g., reprinting the keyboard language to the targeted market.

Figure 13 – Refurbishment: reprinting laptop's keyboard language

5.9 Remanufacture

5.9.1 Definition

Remanufacturing means collecting and returning used products, disassembling, sorting, cleaning, inspection, repairing and reconditioning, assembly, testing and finally combining and upgrading them with new parts to make a product that both looks and performs *as-new condition* and selling them as new. The remanufactured product might have *equivalent or higher performance and functionality* and might be used by *the same or a new user*. *Full warranties* and guaranties are given in remanufacturing. Remanufactured products are sold with the same functionality but to a different or the same user. Remanufacturing takes place in an industrial environment.

Remanufacturing aims at keeping the product in use for a longer time and retains added value as much as possible; resource (material and energy) consumption in transportation and production of the new product is saved, and new resource extraction is avoided. Some companies sell the remanufactured components as spare parts, which in some cases may be a faster source of delivering parts than providing new replacements. The main driver for many companies is profitability, as the cost to produce through remanufacturing is lower due to reduced cost for materials, components, energy and labor. The other drivers are competitiveness and policy. The price of the used product prior to remanufacturing can be 0–20% of the new price, and the remanufactured product retails at 40–60% of the new price. In addition, energy and material savings range between 30 and 90%. Therefore, remanufacturing provides companies 2-5 times more economic advantage compared to brand new ones. Remanufacturing is a very good option for highly material intensive, very expensive and very specialized products and for those whose environmental impacts related to the production of a new product are considerable.

There are also barriers for remanufacturing that include the following: (1) much/enough of the same kind of product is required to be able to run a manufacturing facility, and the collection and transportation of those products over great distances might not be environmentally and economically beneficial; (2) consumers might mistrust remanufactured products, thinking they are no longer "new"; (3) infrastructure is required for product collection; (4) the fear that sales of the company's new products will decrease, and the loss of these sales will be greater than the profit from the selling of remanufactured products, known as market cannibalization; (5) it can be difficult to track the products; (6) insecurity about the quality of the products or components that are coming back for remanufacturing; (7) legal aspects, regulations and standards might be problems that require adjusting your products and offerings to meet the new demands such as chemicals; and (8) keeping old products in use has the risk of preventing new, more energy-efficient products from entering the market.

Remanufacturing can happen via different business models:

(1) Original equipment manufacturer (OEM): products arriving from service centers, trade-ins from retailers or end-of-lease contracts
(2) Contracted remanufacturers: are contracted to remanufacture products on behalf of OEMs. In other words, the OEM maintains ownership of the products but does not perform the actual remanufacturing itself.
(3) Independent remanufacturer: the OEM has little or no contact with the product, and it buys or collects cores for its processes.

5.9.2 Design guidelines for Remanufacturing

Designing for remanufacturing involves considering design for disassembly aspects such as speed of disassembly, cost, etc. during product development stages. Things to consider when designing for remanufacturing include the following:

- Investigate current and upcoming laws and regulations.
    - Remanufactured products need to comply with applicable laws and regulations, e.g., hazardous material or chemicals that were not forbidden in the first lifecycle.
    - Be aware of chemicals and additives that can be present in materials. Do not incorporate any chemicals that now or later are harmful and might be banned. REACH is a regulation with a list of banned materials and a list of materials to be banned.
- Use durable and robust components and materials.
    - All parts having the same durability and lifespan (if possible) is optimal. Make it easy and time-efficient to replace components that wear or can easily break.
    - Choose durable and robust components and materials with a long lifespan.
    - Choose the right material for the right job.
    - Parts that are subject to stress, wear, corrode, stain, break or fail easily should be avoided, minimized or made particularly resistant and durable.
    - Predict how many lifecycles the product is supposed to live. Use quality, strong and robust materials to make the product strong enough to withstand these circumstances.
    - All products, even those designed for remanufacturing, in the end become so worn out that they cannot be used further. Select materials that then can be recycled into new materials after many lifecycles (see 5.11).
    - The lifespan of the different parts should be recognizable; obvious (warning) signs or indicators for wear are ideal.
    - Use "overabundance" in an area that may need to be processed in remanufacturing. For example, provide a tabletop a thick surface layer (veneers) that is possible to grind.
    - Ensure that all parts are able to withstand the same condition in the use phase.
    - All parts should be able to withstand the same cleaning materials, chemicals, processes, temperature and mechanical cleaning in the remanufacturing phase.
    - Try to choose materials that are already less harmful from the start.
    - Avoid materials that might lose strength, become brittle or become discolored.
    - Design for fewer parts.
    - Use materials, parts and components that will be available in the future. Keep in mind the second use of a remanufactured product.
    - Make the core parts robust enough that they can be used repeatedly.
    - Make it possible and easy to upgrade the product, for example by exchanging whole components or by updating software (see 5.5).
    - Add some extra material on surfaces supposed to be machined during remanufacturing. It may also help if you include reference points for the coming machining.
    - Occasionally, it might be appropriate to leave room for new screw holes that will be needed in remanufacturing.
    - Select a surface treatment that is resistant to the desired number of lifecycles.

    - Select a surface treatment that can be removed if it must be renewed.
    - Select quality, strong, robust and durable materials and components that do not degenerate during multiple lifecycles.
    - Avoid materials that might lose strength, become brittle or become discolored.
- Make exchange and faulty components easily accessible.
    - Make disassembly, gripping and breaking points accessible, preferably from one side.
    - Components to be cleaned or parts that are subject to stress, wear, corrode, stain, break or fail easily should be marked, easy to recognize and easy to access (preferably from one side) and replaced.
- Make it easy to clean the product and components.
    - The surfaces to be cleaned should be smooth and wear resistant.
    - Reshape the interior surface to make it easier to clean.
    - Make it easy to clean. All product components should withstand the same cleaning process, liquid and chemicals, and temperatures, detergents and cleaning tools.
    - Make heavily stained surfaces able to withstand mechanical cleaning.
    - Avoiding making areas where dirt might collect and are hard to clean properly; e.g., avoid small holes, nooks, grooves, sharp edges and thresholds that capture dirt. This approach can make the product appear newer for a longer time.
    - Avoid unnecessary coating procedures.
    - Avoid nonremovable coating materials. Make it easy to remove the coating materials.
    - Prioritize dyeing internal polymers over surface painting.
- Make it easy to dismantle the product nondestructively.
    - Standardize constructions and joints.
    - Using a single type of tool to achieve a lower number of parts and to eliminate risk.
    - Robustness and the wear resistance of product parts and joints are important. They should not break during disassembly.
    - Avoid a requirement for glue and adhesives, ideally avoiding the need for any tools.
    - Make the product easy to open and dismount nondestructively.
    - Note which parts of a product may need to be disassembled. Make these parts easy to disassemble.
    - No critical security conditions should appear during remanufacturing.
    - Those parts that will not continue the journey to the next new lifecycle have to be designed for recycling (see 5.11).
- Use joints and connectors that can be easily opened and closed multiple times.
    - Reversible fasteners that can be reused are good.
    - Mark where fasteners are located to ease dismantling.
    - Use inseparable joints and connectors for components made of the same or compatible material.
    - Generally, minimize the number of connectors and joints.
    - Make it easy to disassemble the product with as few ordinary tools as possible. Use fastening devices that can be easily opened and closed multiple times.
    - Latches, snaps and clips are normally preferred over screws and bolts for time efficiency reasons. Prioritize latches, snaps, clips and bolts and screws over welding, rivets, folding, staples, and gluing, all of which make a joint more difficult to demount.
    - Snap fasteners and latching are good for disassembly.
        - There are normal snap fasteners that are integrated into the details and are usually made of plastics.
        - There are snap fasteners that are pressed into place.
        - Occasionally, Velcro can be a suitable fastener.
    - Screws are normally good for disassembly.
        - Use one type and a size allowing the use of one single tool.
        - Ensure that you have access with a tool (screwdriver). If there is a nut, you must also have access to the backside.
        - Use screws that are often made with heads that combine two systems. This approach enables disassembly with tools in a different system than the one the assembling factory

uses. Examples include hex head cross drive, slotted internal Torx, and hex head internal Torx.
  - Adhesives and glues are generally not preferred if the product must be dismantled for remanufacturing.
    - If adhesive is to be used, the best alternative is a water-based adhesive.
    - Breakpoints can be good for glued joints that must be broken. This approach provides controlled damage.
- Make it easy to inspect the product and components.
  - Inspection points and testing components should be marked and easily accessed.
  - Manuals for testing and inspection should be available.
  - The product must be safe to inspect and not include hazardous materials.
  - Design for ease of identification and verification of faulty components.
  - Data for materials, load limits, tolerances and adjustments, etc. must be clear and available.
  - Product parts must be standardized to ease conducting the inspection and across different models/products.
  - Add indications that show you how large the wear is. For example, many tires have a rubber bar in the pattern that makes it possible see when it is worn out.
  - It is good if an initial first rough assessment can be made without costs for cleaning, disassembly, etc. to decide whether the product can be remanufactured.
- Design standardized components across different products and models.
  - Use fewer joining parts, connectors and detachable/resolvable joints.
  - Use standard components and lubricants.
  - Compatibility and exchangeability of components is required across other models and products, e.g., the same type and size of screws.
- Design standardized tools required across different products and models.
  - Compatibility and adaptability of tools is required, e.g., the same type and size of screwdriver across other models and products.
  - Use sturdy heads that are usable multiple times such as hex or Allen geometry or even Torx, and do not provide lifting forces at loss and tightening.
  - Prefer a clearance fit.
  - Make it easy to disassemble the product with as few ordinary tools as possible. Latches, snaps and clips are normally preferred over screws and bolts. Welding, rivets, folding, staples, and gluing all make a joint more difficult to demount.
  - If you are using screws, design the fastening element so that it is easy to open. Use screw types that are easy to open by hand, such as Torx or Hex socket.
  - Use the same type and size of joining element (screws) to make it possible to use only one tool, i.e., fewer and simple tools.
  - Make threads short, and include the thread in the body of the product.
  - Use fastening devices that can be easily opened and closed multiple times, e.g., snap fasteners and latches.
  - Use standardized elements and measures to facilitate the future upgrading and exchange of parts.
- Make spare parts and exchange components easily available.
  - The remanufacturing of a product becomes much easier if components and spare parts are available and easy to find on the market.
- Try to use digitalization, ICT and IoT solutions.
  - Obtain valuable information back regarding the quality of your products, how your customers are using them, and the reasons they break or otherwise stop working as intended.
  - Create a system for identification of the individual product, or even components within the product, by for example RFID, barcode, tag or QR code. Create a system to save important traceable data regarding the product.
  - Mark parts with the types of material. For plastics, use existing systems.
  - Design a structural means of diagnosing the old and worn out component to make it easy to understand what must be done to the product to give it a second life.

    - Create a system to keep track of your products to know where they are at the end of their service life.
- Design in modular construction.
    - Divide the product into different modules, and place all the parts that need to be exchanged or upgraded into one single module, thus lowering the effort needed to upgrade the product.
    - Avoid cross-dependences between modules; otherwise, we might be forced to update a working module simply because of updating an outdated one.
    - Make a "kit" with all the elements required for an update.
    - Simplify the modular structure and design the product for changing modules without damage while remanufacturing.
- Provide manuals and documentation.
    - Provide with the product understandable information such as the content of materials and procedures for remanufacturing or signs on how to open the product and exchange components. In addition, provide a link to where the data about the product are to be found.

5.9.3 Example of remanufacturing

Canon has remanufactured its printers through retrieving used products from the market, remanufacturing them and then reselling them with the same high quality and guarantee as original products. This approach reduces product greenhouse gas emissions associated with raw materials, parts and manufacturing by more than 80% compared to a newly manufactured product.

Figure 14 – Remanufacturing: Canon copy machines

5.10 Repurpose

5.10.1 Definition

Repurpose means extending a product lifecycle to new use cycles by using a product (discarded/not in use) or its parts for different functions.

5.10.2 Design guidelines for Repurpose

- Use durable and robust components and materials.
    - Since the product will be used for two different purposes (not necessarily at the same time), select quality, strong, robust and durable materials that do not degenerate during both lifecycles and withstand different applications.
    - Avoid materials that might lose strength, become brittle or become discolored.
    - Determine both the technical and aesthetic lifetimes of the product for each purpose (lifecycle with different function).
    - Determine how much maintenance, cleaning and repair are required for each purpose (lifecycle with different function).
    - Promote use of the product under the intended conditions to avoid breakdown so the product can move to the next lifecycle with a different function.

  - Since the product lifecycle is increased with repurposing, the product should be designed with no use of toxic materials and more use of renewables and recyclable materials.
- Make it easy to dismantle the product nondestructively.
  - In case the product needs to be dismantled or separated into different parts for a new lifecycle, ease of disconnecting the components is vital.
  - Those parts that will not continue the journey to the next new lifecycle have to be designed for recycling (see 5.11).
- Provide manuals and documentation.
  - Provide with the product information such as the content of materials and the process for the repurposing. Document how to use the same product for the new purpose after its first lifecycle. Perhaps some parts need to be discarded; how should those parts be managed? In addition, provide a link to where the data about the product are to be found.

5.10.3 Example for Repurpose

The Sprout company makes eco-friendly pencils that are available in a variety of colors and to give new life at the end of the pencil's functional usability. The pencil is produced with sustainable materials such a cedar casing, clay and carbon-based graphite, but what makes it unique is the end of the pencil where you would expect an eraser to be, but there is a biodegradable capsule that holds plants seeds. Hence, once you have sharpened your way through that much-awaited manuscript or copious to-do list, your pencil brings new life in the form of plants. The seeds packed into the pencil range from colorful flowers to herbs and even vegetables, and buyers can select their preference.

Figure 15 – Repurpose: Sprout making sustainable pencil into plants (source: https://inhabitat.com/sustainable-pencil-stubs-sprout-into-plants/)

5.11 Recycle

5.11.1 Definition

Recycling means any recovery operation by which waste material is reprocessed into products, materials or substances whether for their original or other purposes. Since every product finally reaches its end-of-life, if we do not have recycling systems in place, the material is then lost and the waste stream increases. However, not only recycling destroy the energy and value that were placed into the product but also additional energy and resources for the recycling process are required; even more additional energy and resources are required to transform the recycled materials back into a new product. This approach makes recycling the last circular strategy option for the circular economy. Hence, reuse, repair, or remanufacturing are generally better alternatives, as they retain the materials, embedded energy, and value of our existing products.

Recycling is challenged by the variety of materials used in the products (multimaterial) and by products' complexity, which require advance recycling technology for material separation.

Moreover, a low volume and concentration of materials are economically unfeasible. Typical recycling steps include the following:

(1) Transportation of the product, which costs and requires energy.
(2) Extract the parts that can be reused. The easier it is to remove the decent quality working components and the higher the value of the part in the overall product, the higher the likelihood that they will actually be removed and reused or remanufactured.
(3) Separate those parts that are already of a decent quality.
(4) Feed the rest into the deeper recycling process.
(5) Shred everything.
(6) Classify it. Classifying divides this output into a material mix that can be processed in the following sorting phase. The output is mostly classified by particle size. At the end of the process, there will be at least two different classes, which are distinguished on at least one dimension.
(7) Sort: The above could happen by density, with a magnetic or electric field, or by using other physical or mechanical characteristics of the material we want to separate. The chosen mechanism depends on the material mix.
(8) Extract suitable materials out of the process. Materials that are lower cost to obtain from primary sources (mining) make the recycling process less valuable.
(9) Restart this process, from step five, for as long as it is economically feasible. In most cases, the separation of smaller parts requires a different machine from the one used previously. Certain processes will be more expensive because increasingly complex machines and processes are needed to sort and separate the shredded materials.
(10) Burn or dispose of the rest.

5.11.2 Design guidelines for Recycling

Things to consider when designing for recycling include the following:

- Design using recyclable and secondary (recycled) materials.
  - Choose materials that are easy to recycle.
  - Consider the recycling rate of materials.
  - Use economically recyclable material.
  - Use materials for which only one recycling method/process is needed, with no separation.
  - Design out the loss of value through impurities in recycling parts, e.g., different colored glasses.
  - Avoid composite materials such as laminates.
  - Select fewer material types and increase material homogeneity in the product, or use materials that are compatible or are easy to separate to increase recycling possibilities.
  - Metal alloys that contain fewer additives are easier to recycle because elements retain their properties, which is much more difficult for materials such as plastics. Additionally, the process of recycling, in the case of metals, saves much energy compared to primary production, which is not true for plastics.
  - Use unplated and low-alloy metals for recycling purposes.
  - Avoid additives and coatings to obtain easily recyclable materials.
  - Use materials that already have recycling market.
  - Select materials with the most efficient recycling technologies.
  - Technically well-known and economical recycling processes enable cleaning of impure materials during recycling.
  - Design taking into consideration the secondary use of the materials once recycled.
- Consider toxicity and other environmental aspects of materials.
  - Choose materials and chemical that have fewer environmental impacts.
  - Indicate the existence of toxic or harmful materials.
  - Select materials that can be fully recovered and recycled.
  - Eliminate toxic and hazardous materials.

- Think about chemicals that compose the specified materials. Are they safe for humans and the environment?
    - Use materials that do not contain substances from hazardous chemicals lists.
    - Reduce human contact with chemicals to as little as possible.
- Minimize the number of different incompatible or dissimilar materials.
    - Use as few materials as possible; i.e., minimize the number of different incompatible or dissimilar materials. Homogeneity of products with similar materials is vital for recycling.
    - Integrate functions to reduce the overall number of materials and components.
    - Use one kind of material (if possible) or compatible materials for each component to facilitate shredding, regeneration and recycling.
    - Facilitate the separation of incompatible materials.
    - Avoid molding and fusing incompatible materials.
    - While selecting correct and compatible materials and avoiding multimaterials and composites, consider also the durability of materials. Find a balance!
    - For joining, use the same or compatible materials as in the components (to be joined).
- Make it easy to identify the materials and relevant information.
    - Create a system for identification of the individual components within a product by for example RFID, barcode, tag or QR code. Create a system to save important traceable data regarding the product.
    - Codify different materials to facilitate their identification.
    - Use standardized material identification systems.
    - Avoid using additional materials for marking or codification.
    - Codify polymers with a laser.
    - Mark parts with the types of material. For plastics, use existing systems.
    - Provide additional information about the product regarding material content, the material's age, number of times recycled, additives used, and a guide to component separation and process for the recycling. Provide a link to where the data about the product are to be found.
- Make it easy to dismantle the product nondestructively.
    - Design for ease of disconnecting the components via standardized parts to extract single materials.
    - Screws, rivets or glue almost always add an additional material.
    - Employ a simple design with standardized pieces that can be dismantled easily.
    - The joint technique is very important; the density and conductivity of the materials make it possible to sort them later. When it is not possible to design it out of one material, you may have a choice of what the other material is.
    - Design out the special parts that are not recyclable.
    - Arrange and facilitate dismantling the components with lower mechanical requirements for recycling.
- Provide manuals and documentation.
    - Provide with the product information such as the content of materials, how to dismantle it and what material segments and fractions should be discarded for recycling. In addition, provide a link to where the data about the product are to be found.
- Design in modular construction.
    - Design via modular structure either easy dismantling or complete recycling of a product without dismantling being needed. Modules that are easy to dismantle will help make the recycling process economically feasible.
    - Locate unrecyclable components and materials in one module to be easily removed.
    - Put materials and components with a certain recycling method/process in one module while striving to place only one material in each module.

5.11.3 Example for recycling

- These glasses frames are only made by a 3D printer as monoframes considering all the functions of common made glasses. Moreover, due to the design, they are even more durable. The elastic material allows a flexible hinge and clips at the temples. In addition, the frame is much more durable without brittle components. The glasses are made from a similar material and are also stress resistant. The plastic material is not ideal but is good for recycling, and the lenses are made of a similar material. The initial idea was to create a product which is specially made for 3D printing and not to try to copy a common design for production in a 3D printer. Hence, there are no steel parts within a plastic frame and no joining connections that can break. This product is an example of a new approach to thinking of design by using new technologies and using only one or two materials that can be recycled easily. Features for ease of recycling include the following: using similar materials (frame and glasses), only one material for the frame (which is good for common recycling processes), and no need for dismantling.

Figure 16 – Recycling: 3D-printed glasses frame as a monoframe [Source: Projekt Samsen]

- The Kickpack football table product is developed and made from only cardboard and some pieces of wood. This example is ideal for design recycling due to the usage of only a few materials that are very good to recycle. The initial idea is that using cardboard only for packaging is a waste of a good and durable material (cardboard). Cardboard and wood of course are not as durable as steel and plastics, but you can fix them by taping or can easily replace broken parts. You can also move them into the paper recycling stream in case of damage. Features for ease of recycling include the following: using similar materials (cardboard and wood), minimum use of screws, glues and rivet connections, and simple destruction and disposal by hand without any complexity and dismantling structure.

Figure 17 – Recycling: The soccer table made of cardboard and wood [Source: KICKPACK Company]

5.12 Cascade

5.12.1 Definition

Cascading means that product materials are reused to extend resource timelines. The cascading can occur in different ways. For instance, a metal piece can be melted and gain a resource quality close to the original, or a plastic piece can be melted to a lower quality material than its initial application. However, in cascading, a new application usually has a lower demand for resource quality. In both cases, it is important to consider the cascading process early in the design process.

In a cascade strategy, a material starts its lifetime at the highest quality possible, and the quality of the material naturally declines over time. Every step of the cascade has a certain lifetime. In accordance with the cascading strategy, the resource should be used in a new application before the quality is too low. However, quality decline is not necessarily the result of natural processes over time. A decline in quality can also occur due to the production or the consumption of the product. However, the parameters to evaluate material quality are highly product dependent.

5.12.2 Design guidelines for cascading

- Design using recyclable and secondary (recycled) materials.
  - The purer the material used, the better and easier the cascading process will be. Hence, avoid mixing resources, and avoid composite materials or, when necessary, choose easily cascadable ones.
  - Avoid additives and coatings to obtain an easily cascadable material.
  - While selecting correct materials and avoiding multimaterials and composites, consider also the durability of materials.
  - Think about “appropriate fit” and optimizing the use of the quality of the materials, where the lowest adequate level of material quality is fulfilled for accomplishing the job. In other words, the quality of the resource should fit certain applications. For instance, using newly harvested high-quality wood directly as paper fibers would not be an appropriate fit; however, using newly harvested high-quality wood for a table would be.
  - The level of material quality in a product is very much dependent on the utilization time of the individual product. For instance, a product such as a napkin does not need to be durable for a longer time; therefore resource quality should be fitted according to the utilization time. Hence, avoid selecting durable materials for temporary products or components.
  - Avoid using scarce resources.
  - Choose materials that are easy to recycle.
  - Consider the recycling rate of materials.
  - Use economically recyclable materials.
  - Use materials for which only one recycling method/process is needed, with no separation.
  - Select fewer material types and increase material homogeneity in the product, or use materials that are compatible or are easy to separate to increase recycling possibilities.
  - Use unplated metals and low-alloy metals for recycling purposes.
  - Use materials that already have recycling market.
  - Select materials with the most efficient recycling technologies.
  - Technically well-known and economical recycling processes enable cleaning of impure materials during recycling.
  - Design taking into consideration the secondary use of the materials once recycled.
- Consider toxicity and other environmental aspects of materials.
  - Choose materials and chemical that have fewer environmental impacts.
  - Indicate the existence of toxic or harmful materials.
  - Select material that can be fully recovered and recycled.
  - Eliminate toxic and hazardous materials.
  - Think about chemicals that compose the specified materials. Are they safe for humans and the environment?
  - Use materials that do not contain substances from hazardous chemicals lists.
  - Reduce human contact with chemicals to as little as possible.
- Design in modular construction.
  - Design via a modular structure for either easy dismantling or complete recycling of a product without dismantling being needed. Modules that are easy to dismantle will help in making the recycling process economically feasible.
  - Locate unrecyclable components and materials in one module to be easily removed.
  - Put materials and components with a certain recycling method/process in one module while striving to place only one material in each module.
- Minimize the number of different incompatible or dissimilar materials.

- Use as few materials as possible; i.e., minimize the number of different incompatible or dissimilar materials. Homogeneity of a product with similar materials is vital for recycling.
    - Integrate functions to reduce the overall number of materials and components.
    - Use one kind of material (if possible) or compatible materials for each component to facilitate shredding, regeneration and recycling.
    - Facilitate the separation of incompatible materials.
    - Avoid molding and fusing incompatible materials.
    - While selecting correct and compatible materials and avoiding multimaterials and composites, consider also the durability of materials. Find a balance!
    - For joining, use the same or compatible materials as in the components (to be joined).
- Make it easy to dismantle the product nondestructively.
    - Ease of disconnecting the components via standardized parts to extract single materials is important.
    - Screws, rivets or glue almost always add an additional material.
    - Use a simple design with standardized pieces to be dismantled easily.
    - The joint technique is very important; the density and conductivity of the materials makes it possible to sort them later. When it is not possible to design it out of one material, you may have a choice of what the other material is.
    - Design out the special parts that are not recyclable.
    - Arrange and facilitate dismantling the components with lower mechanical requirements for recycling.
- Provide manuals and documentation.
    - Provide with the product information such as the content of materials, how to dismantle it and what material segments and fractions should be discarded for recycling. In addition, provide a link to where the data about the product are to be found.
- Make it easy to identify the materials and relevant information.
    - Create a system for identification of the individual components within a product by for example RFID, barcode, tag or QR code. Create a system to save important traceable data regarding the product.
    - Codify different materials to facilitate their identification.
    - Use standardized material identification systems.
    - Avoid using additional materials for marking or codification.
    - Codify polymers with a laser.
    - Mark parts with the types of material. For plastics, use existing systems.
    - Provide additional information about the product regarding material content, the material's age, number of times recycled, additives used, guide to component separation and process for recycling. Provide a link to where the data about the product are to be found.

5.12.3 Example for Cascading

The EcoXpac company, which produces molded pulp solutions for packaging in particular for Carlsberg Breweries, has an innovative Green Fiber Bottle concept for beer bottles. The concept of the Green Fiber Bottle is to create a sustainable, fully biodegradable beer bottle made from renewable and sustainable sourced paper fiber. Its fibers are provided from a well-managed source with trees replanted at the same rate that they are harvested. The Green Fiber Bottle could thus be randomly discarded to environmentally and nonharmfully biodegrade in nature or enter a recycle system along with other paper-based products.

Figure 18 Cascading: The Green Fiber Bottle [Source: https://www.carlsberggroup.com]

5.13 Recover

5.13.1 Definition

This strategy means energy recovery via incinerating materials with characteristics that no longer satisfy any application whatsoever. This recovery must happen only after materials have been recycled more than once. The main problem in the recovering strategy is toxic smoke emitted by some materials and additives.

5.13.2 Design guidelines for recovery

- Consider toxicity and other environmental aspects of materials.
  - Select materials that degrade in the expected end-of-life environment.
  - Avoid combining nondegradable materials with products that are going to be composted.
  - Facilitate the separation of nondegradable materials.
  - Select high-energy materials (embedded energy) for products that are going to be incinerated.
  - Avoid materials and additives that emit dangerous substances during incineration.
  - Facilitate the separation of materials that might compromise the efficiency of combustion (with a low energy value).
  - Reduce the use of materials that cause high emissions in production such chrome and nickel.
  - Think about the means of transportation that is used to procure them.
  - Select lightweight materials for less energy consumption in transportation.
- Design using renewable materials.
  - Reduce the use of materials of which there are only limited quantities such as tin, , and precious metals, and use more renewable and biobased materials, especially in sectors such as packaging, textiles, chemicals and construction.

5.13.3 Example for recovery

Domestic waste and nonhazardous commercial wastes of similar composition are delivered to the Spittelau waste incineration plant where waste is converted into ash, flue gas and heat.

Figure 19 – Cascading: The Green Fiber Bottle [Source: https://www.carlsberggroup.com]

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