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Digital Twin

A Lever for Reducing the Industry's Impact on the Environment?

Solutions INDUSTRIE DU FUTUR

Published in March 2023, the first contribution from the "Digital Twin" Technical Committee aimed to enlighten and guide manufacturers in their thinking by delivering a definition of the digital twin and detailing numerous industrial use cases.

THE DIGITAL TWIN

A LEVER FOR REDUCING THE INDUSTRY'S IMPACT ON THE ENVIRONMENT?

Mapping industrial opportunities in a circular economy context

Today, the industry must face up to the challenge of climate change and work towards a more sustainable future. In this document, we explore the potential of the Digital Twin to foster sustainable development[1] and a circular economy[2].

Our previous brochure provided a definition of the Digital Twin and detailed 23 use cases, some of which featured a leaf-shaped icon. This indicated that the use case could contribute to reducing the environmental impact of industrial activities. This brochure details these various scenarios where the Digital Twin can reduce environmental impact such as:

- reducing energy consumption in production,
- limiting greenhouse gas emissions during procurement and delivery,
- reducing the consumption of raw materials through increased reuse and recycling.

This document is aimed at anyone wishing to lower the environmental impact of their company's production, particularly SMEs, and who is considering implementing a Digital Twin.

The Digital Twin can then complement a product Ecodesign approach, which is now integrated into the strategy of 75% of French companies, and generalized to the entire product portfolio for 21% of them[3].

The Digital Twin can also provide the means to quantify greenhouse gas emissions, plan sustainability initiatives and ensure compliance with sustainability standards of industrial companies.

It is important to emphasize here that the vision of the Digital Twin as a means of significantly reducing, in many situations, the environmental impact of industrial activities must be qualified. Indeed:

1. Firstly, the environmental impact reductions presented in this document must be validated by a Life Cycle Assessment, on a case-by-case basis.
2. Once this study has been carried out, the expected impact reductions have to be balanced against the direct environmental impacts of the Digital Twin technology. This is particularly important when it relies on massive data collection and artificial intelligence, greedy in computing and communication resources. This crucial question is addressed in chapter 4: "Considering the environmental impact of the Digital Twin itself".

Note: societal aspects, which complement environmental aspects as classic pillars of sustainable development, are briefly discussed at the end of this document.

[1] "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs." Brundtland Report, Our Common Future, G.H. Brundtland, World Commission on Environment and Development, 1987.
[2] The concept of the circular economy is presented in the following chapter.
[3] From ADEME: "Gagnez en performance avec l'Ecodesign."

CONTENTS

01

CONTRIBUTION OF THE DIGITAL TWIN TO THE CIRCULAR ECONOMY

1.1 THE CIRCULAR ECONOMY AS A LEVER TO REDUCE ENVIRONMENTAL IMPACTS

According to the French Ministry of Ecological Transition,

"The circular economy consists in producing goods and services in a sustainable manner by limiting the amount of waste. It is about moving from a throwaway society to a more circular economic model"[4]

The implementation of circularity in the economy is a powerful way for reducing its environmental impact.

This document aims at giving examples of use cases where the Digital Twin can support this Circular Economy approach, and thus bring potential reductions of the environmental impact of the industry.

The figure opposite represents a simplified view of the different life cycle stages of a product in a circular economy (other representations of this cycle exist, and are broadly equivalent).

These steps are defined on the following double page.

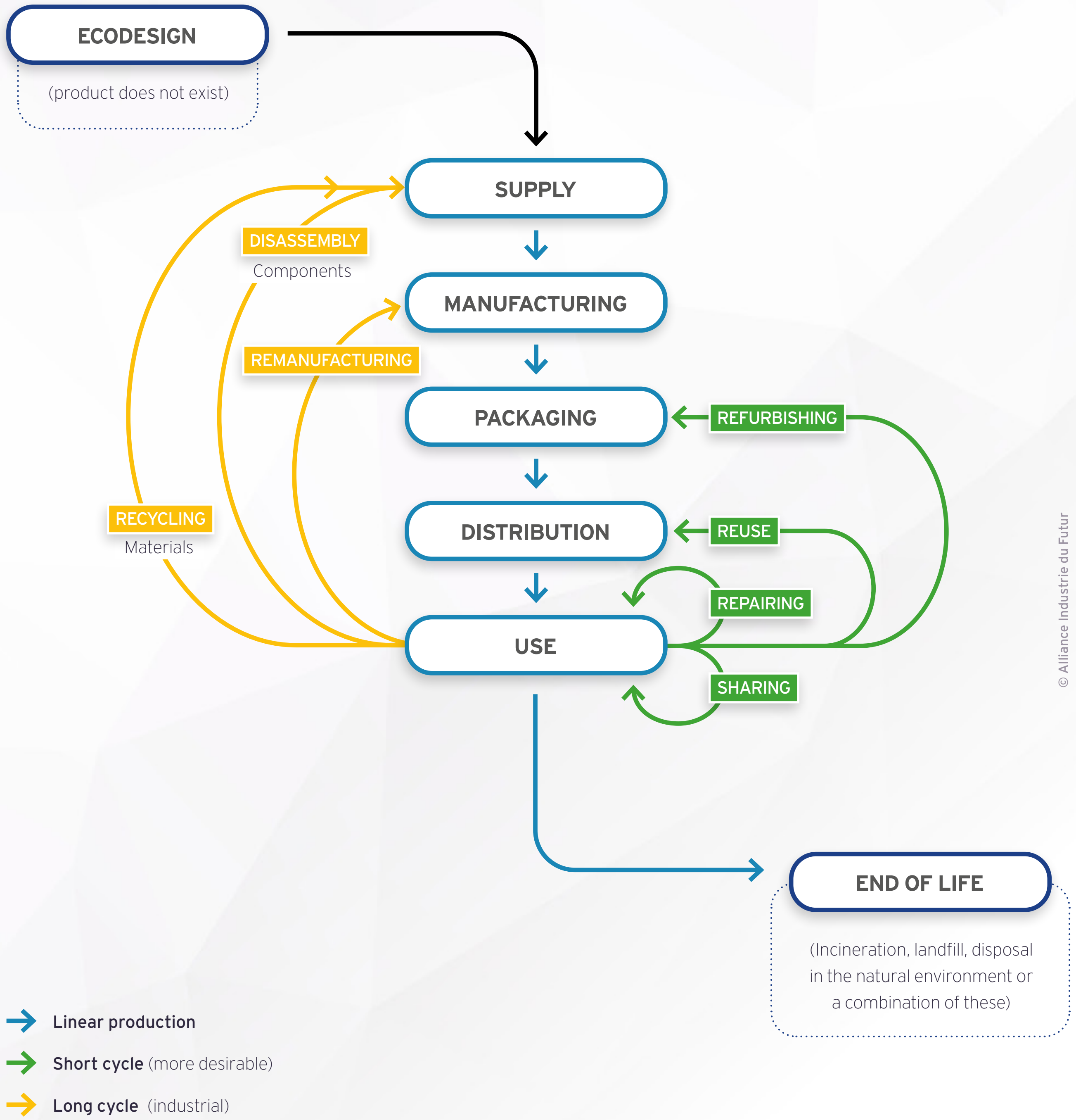
The very essence of the Circular Economy is to preserve the created value for as long as possible, in order to minimize material and energy losses. Contrary to the linear model and simple recycling, the idea is to set up value conservation loops at every stage of the life cycle, as shown in the diagram opposite.

The shorter and smaller the loop, the more value is retained, with recycling being the final lever to be activated.

It should be noted that circularity is not an end in itself, but a lever toward a sustainable economy by reducing resource and energy requirements. It is the flows into and out of the economy that matter for the environment, and the objective is to reduce these flows. Circularity is a means to achieve this by decreasing inputs and outputs, assuming the size of the economy is kept unchanged.

[4] https://www.ecologie.gouv.fr/leconomie-circulaire

Life cycle in a circular economy



STAGE DEFINITIONS

Disassembly
The process of dismantling a product to facilitate repair, reuse, remanufacturing or recycling of all or part of the product.

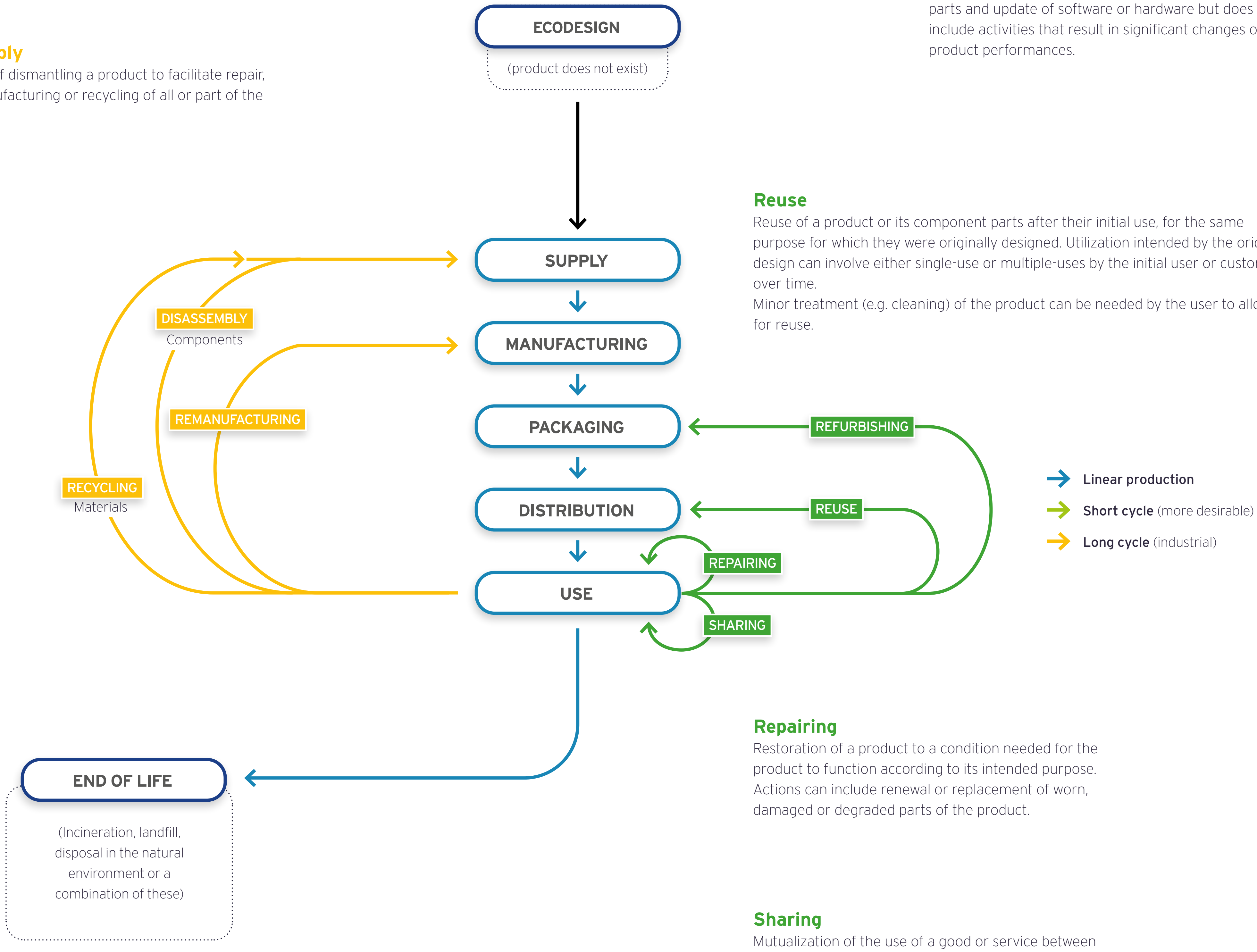
Remanufacturing[5]
The industrial process by which an item is returned to a like-new condition from both a quality and performance perspective.
The item can be previously been sold, leased, used, worn, remanufactured, or be a non-functional product or part.
A like-new condition can also be described as "same-as-when-new" or "better-than-when-new".

Recycling
Activities to obtain recovered resources for use in a process or a product, excluding energy recovery.
Activities to obtain recovered resources include recovery, collection, transport, sorting, cleaning and re-processing.
Recycling does not include reuse.

End-of-life (of a product)
Point in time when a product is taken out of use and its resources are either recovered for processing or it is disposed of.
"Taken out of use" refers to when the product is no longer usable or ceases to exist in its current form.
Disposal can be by incineration, deposit to landfill or the natural environment, or a combination thereof.

Ecodesign
Design and development based on a life cycle perspective aimed at supporting sustainable development.

Refurbishing
Process by which an item, during its expected service life, is restored to a useful condition for the same purpose and with at least similar quality and performance characteristics. Refurbishing does not include restoration after the expected service life. Refurbishing can include activities such as repair, rework, replacement of worn parts and update of software or hardware but does not include activities that result in significant changes of product performances.



Reuse
Reuse of a product or its component parts after their initial use, for the same purpose for which they were originally designed. Utilization intended by the original design can involve either single-use or multiple-uses by the initial user or customer over time.
Minor treatment (e.g. cleaning) of the product can be needed by the user to allow for reuse.

Repairing
Restoration of a product to a condition needed for the product to function according to its intended purpose.
Actions can include renewal or replacement of worn, damaged or degraded parts of the product.

Sharing
Mutualization of the use of a good or service between individuals or legal entities.

[5] All definitions, with the exception of Sharing and Disassembling, are taken from: ISO 59004:2024 - Circular economy - Vocabulary, principles and guidance for implementation, May 2024.

1.2 | *ADEME'S 7 PILLARS*

ADEME, the French Environment and Energy Management Agency, has defined seven fundamental pillars, represented in the chart opposite, for implementing an effective circular economy.

It is through the prism of these seven pillars that the Digital Twin's use cases are examined in this document, with an additional breakdown for the "Ecodesign" pillar.

Pillar 1: Sustainable extraction, exploitation and purchasing aims to use renewable resources or recycled materials to save resources. Scenarios where the Digital Twin can be used to reduce the environmental impact of procurement will be described here.

Pillar 2: Ecodesign involves integrating environmental impacts throughout the life cycle, right from the design stage. Here, Ecodesign is considered in its broadest sense, encompassing not only the Ecodesign of products and services, but also all the actions a manufacturer can take to reduce the impact of its operations:

- Product Ecodesign.
- Reducing the impact of production, by reducing resource consumption (e.g. energy, water, materials) or by reducing waste and pollution.
- Reducing the impact of industrial facilities (equipment, machines, buildings), from manufacturing or construction to their end-of-life.
- Reducing the impact of industrial tool maintenance.
- Reducing the impact of deliveries, i.e. the transport of products from the factory to warehouses or stores.
- Compliance with environmental regulations: the aim here is not to directly reduce the impact of production activities, but to help manufacturers comply with current and future environmental regulations.

Pillar 3: Industrial and territorial ecology creates synergies between players in the same region to pool resources.

Pillar 4: Economy of functionality favors use over possession by offering service solutions rather than goods. Here, we will discuss facilitating reuse and repurposing thanks to the Digital Twin.

Pillar 5: Responsible consumption aims to help lifestyles evolve towards sober consumption. We will see how the Digital Twin can help reduce the impact of product use in certain situations.

Pillar 6: Extending useful life through better repair and reuse of products.

Pillar 7: Recycling and waste management must be optimized, at the end of life, through better material and energy recovery.

WASTE MANAGEMENT

Recycling (materials and organic)

ECONOMIC ACTORS' OFFER

Sustainable extraction, exploitation and purchasing

Ecodesign (of products and processes)

Industrial and territorial ecology

Economy of functionality

CONSUMER DEMAND AND BEHAVIOR

Responsible consumption

- Purchasing
- Collaborative consumption
- Use

Extending useful life

- Repair
- Reuse

02

PRESENTATION OF THE "IMPACT REDUCTION OPPORTUNITY" SHEETS

2.1 CATEGORIES OF ENVIRONMENTAL INDICATORS FOR INDUSTRIAL MONITORING

The environmental footprint is generally assessed through a multiplicity of indicators. Some methods, such as PEF[6] *(Product Environmental Footprint)* standardize indicators with a high level of precision, particularly in the context of product Life Cycle Assessments.
In this document, we group these indicators into ten categories:

GHG emissions
(unit : kg eq. CO_2)

Reflects the increase in the average atmospheric concentration of various substances commonly known as greenhouse gases (GHG_s), such as carbon dioxide (CO_2), methane (CH_4) or nitrogen dioxide (NO_2).
This increase is the cause of global warming.

Water
(unit : m³)

Expresses consumption of water resources (fresh or sea).

Material
(unit : kg)

Expresses the consumption of raw materials needed for the industrial process (such as iron, copper, lead, zinc, rare earths, crude oil, coal, etc.).
It is also possible to use indicators reflecting the depletion of natural resources, in line with the PEF[7] method:

- The depletion of non-renewable energy resources (coal, gas, oil, uranium) is considered by an indicator expressed in Megajoules (MJ).
- The depletion of non-mineral resources (copper, lithium, rare earths, sand, etc.) is expressed in kilograms of antimony equivalent (kg Sb eq).
  A value greater than 1 for a resource indicates consumption of a scarcer resource than antimony.

Transport
(unit : km)

It corresponds to the kilometers traveled to transport components, people, products and production equipment. Transport can result in the consumption of fossil fuels, leading to greenhouse gas emissions.

Energy
(unit : kWh)

This category of indicators relates to fossil or non-fossil energy consumption linked to the production, transport and use of products and production equipment.
This energy consumption can cause greenhouse gas emissions and lead to the depletion of fossil fuels (gas, oil, coal, etc.). In the case of a reduction in electricity consumption, the actual reduction of the impact on the environmental will largely depend on the energy mix of the concerned area.

Service life
(unit : months)

Corresponds to the actual or estimated lifetime of the product. A short lifespan indicates rapid functional obsolescence, while a long lifespan means less consumption of materials and energy in the production of the object to be replaced. Reuse, repair and Refurbishing, for example, are ways of increasing product life.

Waste
(unit : kg)

This corresponds to the quantity of material lost during product production because of the production process (e.g. offcuts) or quality problems (non-conforming parts).

Pollution
(unit : kg)

This category of indicators considers all waste and pollution resulting from product production and use (toxic gases, polluted water, plastic waste, etc.), which can have a negative impact on human health and biodiversity.

- **Human health:** for example, emissions of fine solid particles (dust) into the air, leading to heart and lung disease in humans, or carcinogenic effects.
- **Loss of biodiversity:** e.g. ocean acidification, freshwater eutrophication or marine eutrophication..

For further information, please refer to the PEF[8] indicators.

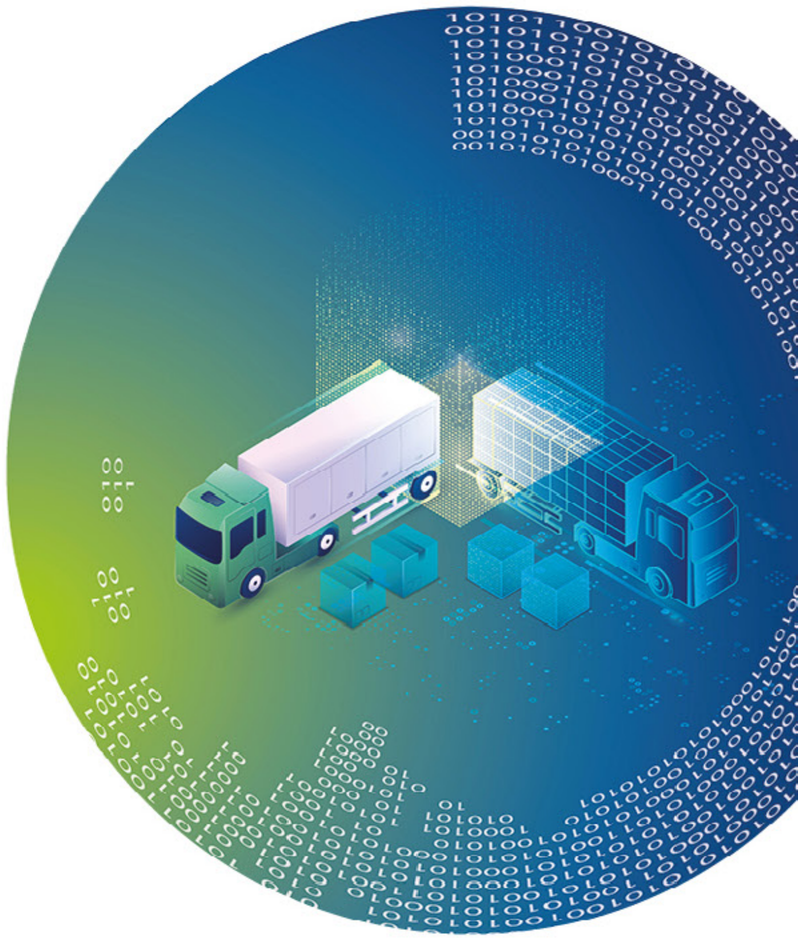
Recycling
(units : % or kg of recycled or recyclable material)

This category of indicators measures:

- the quantity of recycled material used in the manufacture of the product.
- the quantity of recyclable material in the product at end-of-life.

Land artificialization
(unit : m²)

This category of indicators considers the occupation and changes in land use (arable land and urban areas) over time, and measures the risk of biodiversity loss linked to these changes in land use, by quantifying the loss of territories favorable to biodiversity.



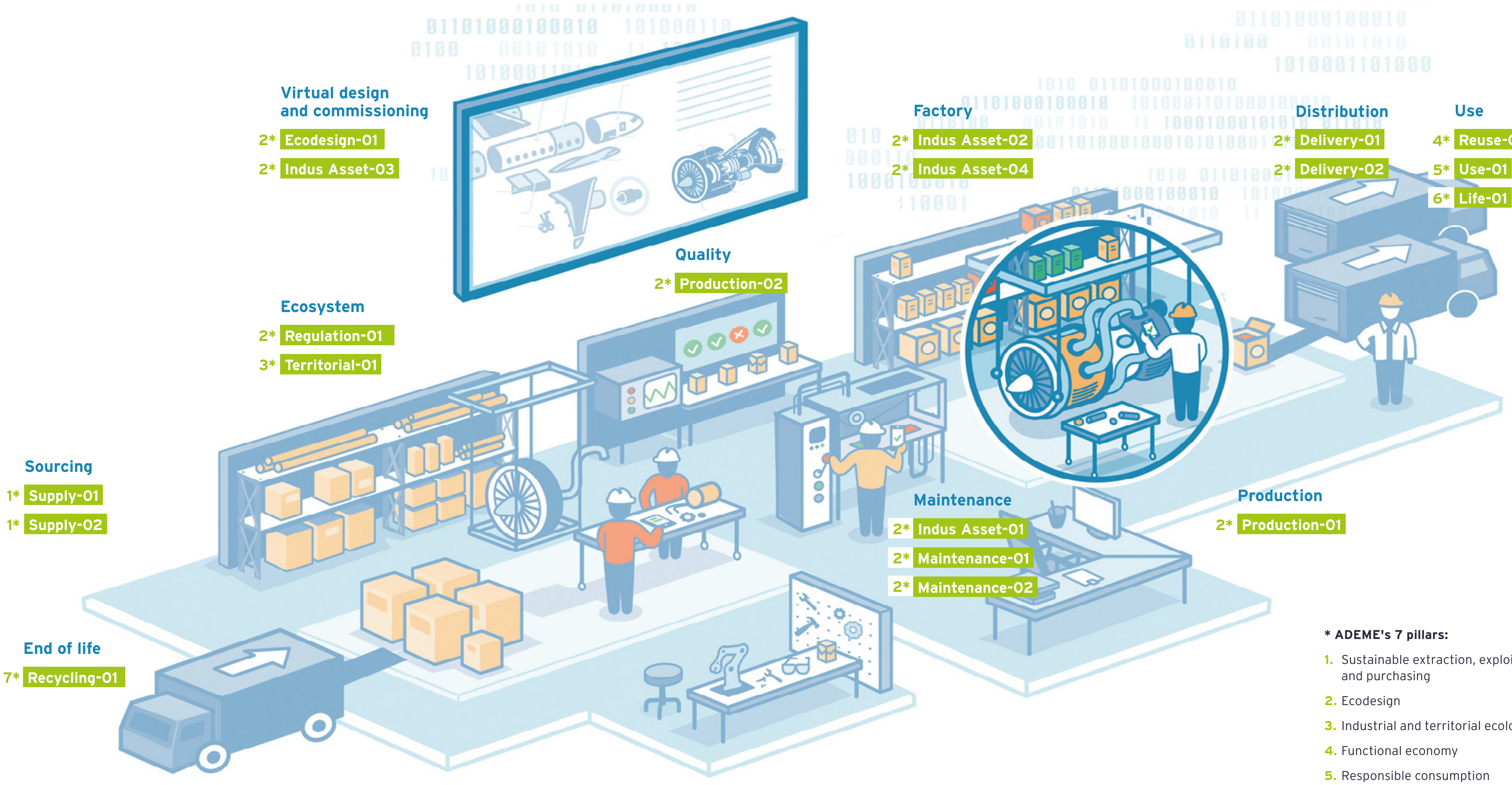
For more details related to the indicators that can be measured in each of these categories, and how they are calculated, please refer to ISO standard 59020[9]

[6] Find out more: https://eplca.jrc.ec.europa.eu/EnvironmentalFootprint.html
[7] Find out more: https://eplca.jrc.ec.europa.eu/permalink/PEFCR_guidance_v6.3-2.pdf, page 49
[8] Find out more: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32021H2279, page 29
[9] Find out more about ISO 59020: www.iso.org/standard/80650.html

2.2 | *OPPORTUNITIES FOR IMPACT REDUCTION MAPPED ACCORDING TO THE DIFFERENT USE CASES FOR THE DIGITAL TWIN*

The diagram below shows the various opportunities for reducing environmental impact, positioned in an industrial context and in relation to the seven ADEME pillars.

It should be compared with the mapping of Digital Twin use cases presented in our first Digital Twin brochure.

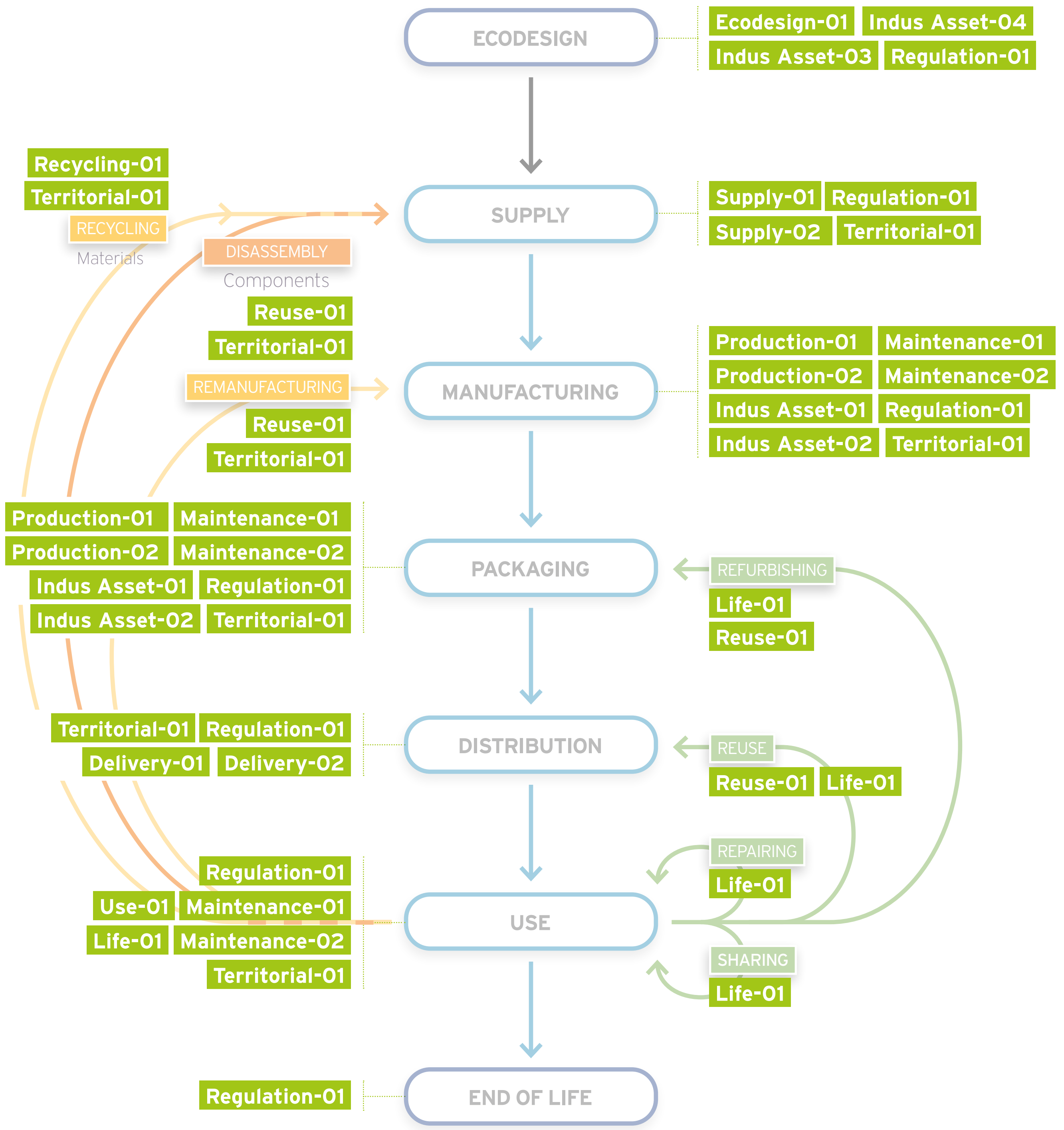


*** ADEME's 7 pillars:**

1. Sustainable extraction, exploitation and purchasing
2. Ecodesign
3. Industrial and territorial ecology
4. Functional economy
5. Responsible consumption
6. Extending useful life
7. Recycling

2.3 | *MAPPING IMPACT REDUCTIONS ACCORDING TO THE CIRCULAR ECONOMY SCHEME*

The diagram below shows the various opportunities for reducing environmental impact, positioned according to their contribution to the circular economy.



03

IMPACT REDUCTION OPPORTUNITIES

Instructions for opportunities

1 **Title:** the acronym, for example [Supply-01], allows to reference the opportunity in the various indexes at the end of the document.

2 **Description of the opportunity:** this section explains in detail how the Digital Twin may enable impact reduction. Indeed, deploying a Digital Twin does not necessarily mean reducing impact; it is necessary to have this objective in mind from the outset of the deployment project to be able to achieve it.

3 **List of Environmental Impact Indicators:** which indicators should be monitored? What can be improved?

4 **Industrial examples:** description of industrial use cases guiding in the project deployment. They aim to present issues frequently encountered in the industrial world.

A **Pillar** corresponding to the opportunity

B **List of use cases** relating to this opportunity, as described in the brochure "Digital Twin, Leveraging the Digital Transformation of the Industry".

C **List of Circular Economy stages** related to this opportunity.

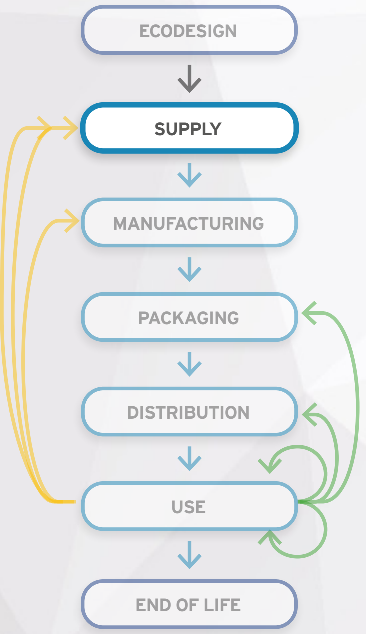
D **"See also" section** linking to other impact reduction opportunities.

PILLAR 1

SUSTAINABLE EXTRACTION, EXPLOITATION AND PURCHASING: REDUCING THE IMPACT OF PROCUREMENT

USE CASE

CIRCULAR ECONOMY DIAGRAM



SEE ALSO

Delivery-01

[SUPPLY-01] REDUCING THE ENVIRONMENTAL IMPACT OF THE SUPPLY CHAIN

DESCRIPTION

The Digital Twin reflects the different options considered for the supply network: possible suppliers of the various components, warehouse locations, possible means of transport.
In addition:

- Estimations of the impact of manufacturing the components, such as the carbon footprint, are collected from suppliers and integrated into the Digital Twin data model.
- The Digital Twin is capable of calculating the environmental impact, or at least the carbon footprint, of the main possible routes between depots per unit transported (e.g. kilogram or unit component).
- Cost and possibly component quality criteria are also taken into account.

A multi-criteria optimization algorithm is then used to find the right compromise between cost control, quality of components supplied, delivery times and environmental impact criteria. Users can compare different supply chain configurations and choose the one that suits them best. Ultimately, the environmental impact of component supply, including manufacturing and transport, can be reduced as much as possible.

Finally, another algorithm allows to optimize the supply network to meet future orders within the required lead times. This enables the right sizing of stocks, and therefore of the warehouses housing them, thus reducing energy consumption linked to heating or cooling buildings.

ENVIRONMENTAL IMPACT INDICATORS

Greenhouse gas emissions from the product supply chain, broken down into the impact of component manufacturing and transporting.

Quantities of pollutants emitted during component manufacture and transport.

Estimates of the distances covered for the routing of components according to the supply chain considered.

Quantities of recycled materials integrated into the various components of the supply chain.

INDUSTRIAL EXAMPLES

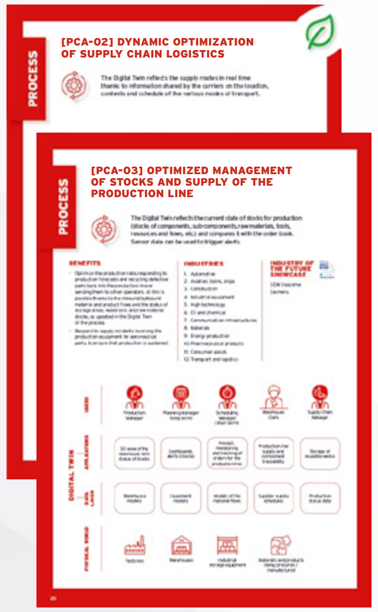
This situation of impact reduction potentially applies to all industrial players dependent on a supply chain.

Major customers responsible for assembling complex systems and using a large number of sourced components (carmakers, aircraft manufacturers, etc.) have the greatest opportunity to reduce their impact.

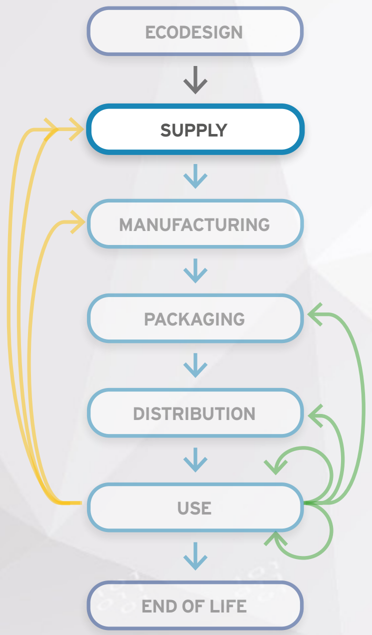
PILLAR 1

SUSTAINABLE EXTRACTION, EXPLOITATION AND PURCHASING: REDUCING THE IMPACT OF PROCUREMENT

USE CASE



CIRCULAR ECONOMY DIAGRAM



SEE ALSO

Delivery-02

[SUPPLY-02] REDUCING THE ENVIRONMENTAL IMPACT OF COMPONENT TRANSPORT

DESCRIPTION

In contrast to the previous case, it is assumed here that the characteristics of the supply chain have been determined: suppliers, warehouses and vehicle fleets are known. The Digital Twin of the supply logistics network reflects all the suppliers warehouses, the factories to be supplied, as well as the various possible routes for delivery of each type of component, whether by land, sea, air or rail. Route profiles and the weight of goods to be delivered are also taken into account.

Depending on the degree of transparency accepted by suppliers and transporters, additional information can be used to refine the calculation of the impact of transport, such as the transport capacity of vehicles or their nominal fuel or electricity consumption.

Based on the components required from the purchase orders, an optimization algorithm seeks to establish the best compromise between transport costs, minimization of environmental impact and lead times. The result is a set of component orders to selected suppliers.

Once orders have been placed, and if carriers allow, the manufacturer has full visibility of current deliveries and can request route changes according to various criteria, some of which relate to environmental impact.

It is also possible to obtain a detailed view of material consumption. An integration that gives suppliers visibility over the state of the ordering party's inventories can facilitate volume deliveries adapted to demand. This reduces the amount of stock required, and therefore the space needed for storage.

Knowing the state of stocks, as well as the fill rate of transport resources through the Digital Twin of the distribution/procurement process can also facilitate the pooling of containers.

ENVIRONMENTAL IMPACT INDICATORS

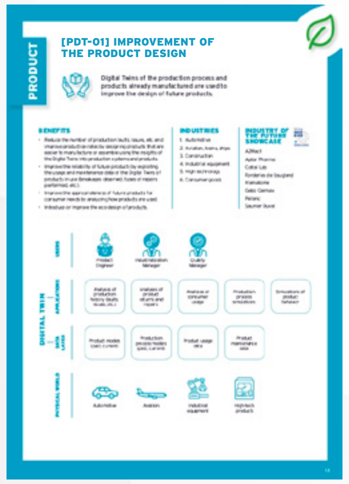
Distances traveled to transport components.

Greenhouse gas emissions linked to the transport and storage of components

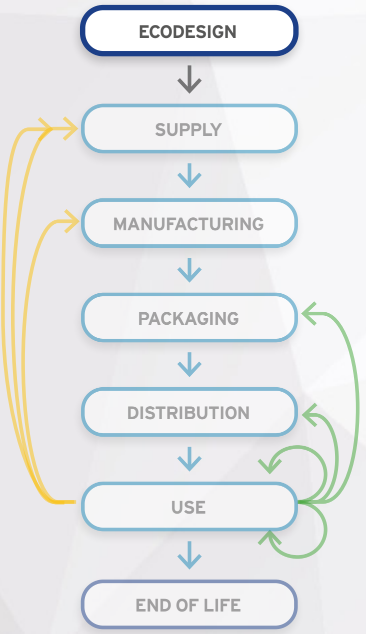
INDUSTRIAL EXAMPLES

This impact reduction situation applies to industrial players dependent on a supply chain and with different options to select components and routing.

USE CASE



CIRCULAR ECONOMY DIAGRAM



[ECODESIGN-01] EXTENDING PRODUCT LIFE AND REDUCING THE IMPACT OF USE THROUGH ECODESIGN

DESCRIPTION

By exploiting usage and maintenance data from the Digital Twins of products in use, it is possible to reduce the environmental impact of new product versions and product lines at the design phase, as illustrated in the two scenarios below.

Extended product life

Data on parts breakdowns, types of repairs carried out and other anomalies observed during the product's life are used to build reports on the most frequent breakdowns, and to better understand their causes. These findings can then be taken into account when designing new products to increase their lifespan.

In addition, the simulation of product behavior (friction, wear, areas subject to high mechanical stress, etc.) can be combined with test data from prototypes. This makes it possible to prevent and anticipate breakage or failure, depending on the materials chosen and the product geometry.

All these findings can then be taken into account in the design of new products to increase their robustness.

Reducing the environmental impact of product use

Product usage data such as, in the case of an automobile, fuel or electricity consumption, driving style or speed, provide a better understanding of how products are used and their impact on the environment.

These findings can be used to develop new products that are better suited to their intended use, with a view to reducing their environmental impact in use and extending their lifespan. Simulations of the product's behavior in operation can also be used to anticipate energy consumption and modify the design accordingly. Similarly, with a view to resilience, it is possible to improve the robustness of parts in the event of accidents or natural disasters.

ENVIRONMENTAL IMPACT INDICATORS

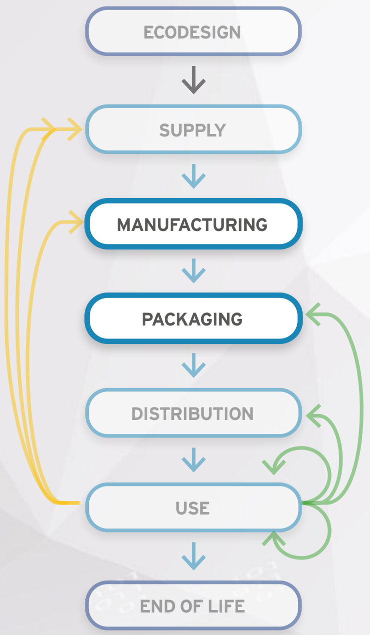
- **Actual or estimated lifespan** of the product or parts.
- **Energy consumption** of product in use.
- **Greenhouse gas emissions** of product in use.
- **Quantities of pollutants** emitted by product in use.
- **Water consumption** of product in use.

INDUSTRIAL EXAMPLES

- **The scenario of extending lifespan through ecodesign** potentially applies to all types of manufactured products for which usage and maintenance data can be recovered. This includes: industrial equipment (industrial machinery, electrical power equipment, heavy vehicles), household appliances, high-tech, vehicles, etc.
- **The scenario for reducing the environmental impact of the product in use** concerns, for example, the reduction of the consumption of future vehicle models (cars, airplanes, etc.), but also of other everyday objects (hot water tanks, refrigerators, etc.).

USE CASE

CIRCULAR ECONOMY DIAGRAM



[PRODUCTION-01] REDUCING THE ENERGY AND RESOURCE CONSUMPTION OF A PRODUCTION LINE

DESCRIPTION

Reducing energy consumption through sensors network and predictive models

Data collected by sensors or from other sources, coupled with simulations where appropriate, can be used to reduce energy consumption or the consumption of natural resources, such as water or raw materials, thanks to:

- **Energy dashboard:** real-time monitoring of production, including alerts on energy consumption (equipment shutdown, consumption peaks, etc.).
- **Computation of the energy consumption** of various production units, by product and product family, for analysis and regulatory compliance purposes (greenhouse gas emissions, environmental product declaration, etc.).
- **Simulation** of different manufacturing options, based on collected data and flow models, to choose the right compromise between output and energy consumption.
- **Prediction** of energy consumption according to planned production, available equipment and human resources, and other influential parameters such as the weather. This makes it possible to adjust production to meet the load curve contracted with the energy supplier.

Scheduling operations to reduce energy consumption

Thanks to knowledge of the order book and a detailed model of the production line stored in a Digital Twin, it is possible to calculate a **schedule**. In addition to optimizing operations and ensuring that production rates are respected, the scheduling calculation can be configured to achieve other objectives, such as **chaining heating operations** to avoid energy-intensive temperature rises; **grouping parts** from different orders in a single heating or additive (3D) printing operation; and taking advantage of hourly pricing for operations that consume a lot of energy.

ENVIRONMENTAL IMPACT INDICATORS

- **Energy consumption** of the production process; energy consumption attributable to each product category, batch or physical product.
- **Raw material consumption** of the production process.
- **Water consumption** of the production process.

INDUSTRIAL EXAMPLES

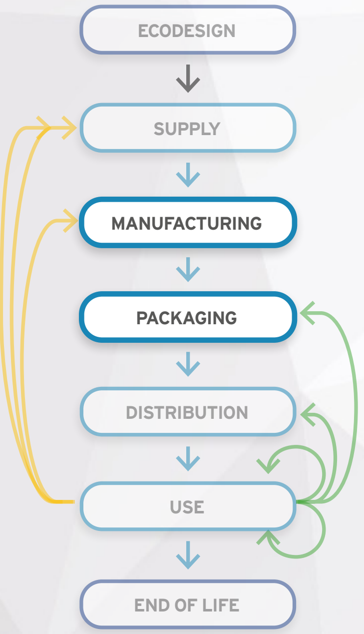
- **Industrial processes consuming energy,** which can be instrumented to retrieve production data, notably heavy industrial plants (steelworks, cement plants, etc.).
- **Industrial processes including heat or surface treatments,** with multiple parts processed in the same furnace / treatment bath, possibly with recurring temperature increases.

PILLAR 2

ECODESIGN / REDUCING THE IMPACT OF PRODUCTION

USE CASE

CIRCULAR ECONOMY DIAGRAM



[PRODUCTION-02] REDUCING THE MATERIAL AND ENERGY FOOTPRINT OF PRODUCTION BY REDUCING THE SCRAP RATE

DESCRIPTION

Defects can occur in industrial processes even when all production parameters are within the recommended tolerances. This is the case for certain complex processes involving chemical or biological reactions, particularly during the ramp-up phase.

The production data stored in a Digital Twin can then be used to build a model to relate measured data to the quality obtained, using statistical or machine learning (AI) techniques. Measured data can come from machines (IIoT data, images, etc.), the environment (temperature, humidity, etc.) or raw material characteristics (supplier, expiration date, etc.). Added to this are adjustments made during production (oven temperatures, fermentation times, etc.).

Once the model has been built, it is possible to predict final quality, based on current production data. In the event of an incurable defect, production will be stopped, thus avoiding unnecessary consumption of energy and raw materials.

In a more advanced configuration, the model proposes recommendations where possible (prescriptive model). New settings are then proposed, aimed at avoiding the quality defect initially predicted.

ENVIRONMENTAL IMPACT INDICATORS

Quantities of various materials consumed, that cannot be recycled due to quality problems.

Material consumption required to obtain a product of the expected quality.

Energy consumption required to obtain a product of the expected quality.

Water consumption required to obtain a product of the expected quality.

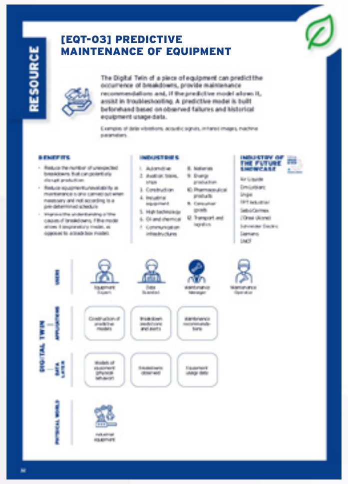
INDUSTRIAL EXAMPLES

- **Production of composite materials (aeronautics, wind energy):** avoid air bubbles and delamination defects.
- **Vaccine production:** ensuring that the batch meets quality requirements.
- **Production of tires and elastomers:** avoid defects such as bubbles, obtain the desired geometric characteristics of the tire.
- **Metallurgy:** avoid bubbles, cracks and other manufacturing defects.
- **Additive manufacturing:** reduce the number of trials before obtaining a defect-free part by using thermal images captured during printing.

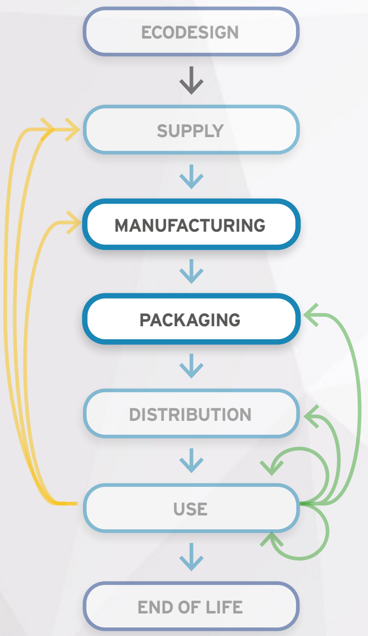
PILLAR 2

ECODESIGN / REDUCING THE IMPACT OF INDUSTRIAL FACILITIES AND EQUIPMENT

USE CASE



CIRCULAR ECONOMY DIAGRAM



[INDUS ASSET-01] INCREASING THE LIFESPAN OF EQUIPMENT AND ITS COMPONENTS

DESCRIPTION

Sensors installed on industrial equipment, along with an IIoT platform, enable the collection, storage, and visualization of machine usage data in a Digital Twin. Machine learning algorithms are then used to build predictive models based on historical data and observed incidents or breakdowns.

Compared with preventive maintenance, which follows a pre-established schedule, predictive maintenance aims to avoid both unforeseen breakdowns and unnecessary maintenance operations.

This prolongs the life of the equipment by preventing fatal breakdowns, and also avoids the premature replacement of certain wearing parts.

Predictive maintenance favors a "product-as-a-service" marketing model: a manufacturer of industrial equipment (robot, CNC machine, etc.) sells time spent using its equipment rather than the machine itself, and takes responsibility for keeping the equipment running. It relies on a predictive maintenance model using its customers' usage data and its own expertise.

The business model is based on the ability to minimize the number of failures.

ENVIRONMENTAL IMPACT INDICATORS

Average equipment life. Complementary indicators such as Mean Time Between Failures (MTBF) or Overall Equipment Efficiency (OEE) are commonly used in the industry.

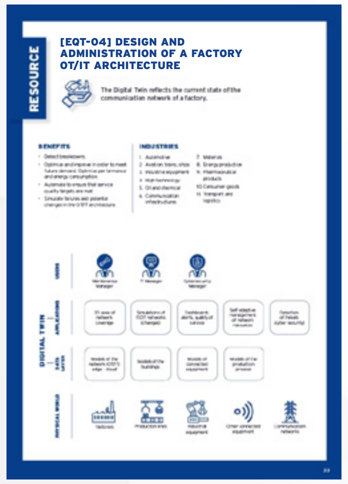
INDUSTRIAL EXAMPLES

- **Rotating machines, motorized equipment:** the Digital Twin's predictive model detects abnormal equipment vibrations, heralding a forthcoming breakdown. It can also use other parameters such as temperature or recorded noise.
- **All types of failure-prone equipment and systems** for which usage data and maintenance data can be retrieved.

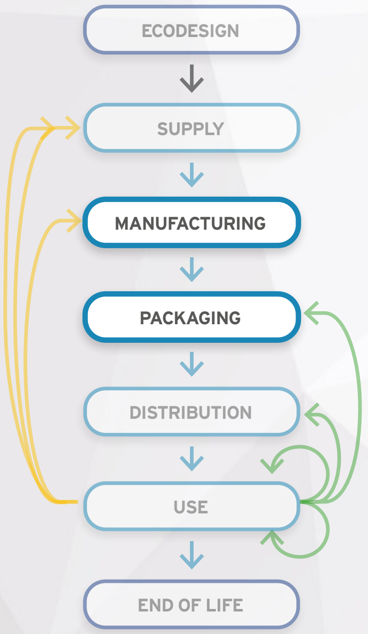
PILLAR 2

ECODESIGN / REDUCING THE IMPACT OF INDUSTRIAL FACILITIES AND EQUIPMENT

USE CASE



CIRCULAR ECONOMY DIAGRAM



[INDUS ASSET-02] OPTIMIZATION AND DYNAMIC ADAPTATION OF THE IT/OT ENVIRONMENT

DESCRIPTION

The Digital Twin of the IT/OT infrastructure reflects the model and current state of a plant's communications network and IT equipment. Network topology and network status data, server data, and operator information make it possible to observe and model changes in the load and performance of the IT/OT system based on the number of terminals, devices and connected objects, the volume of information processed, and the frequency of messages.

During the design phase, the modeling of the IT/OT infrastructure (levels 1-2 of the ISA-95 standard) and the simulation of the behavior of the system and local networks, according to changes in data load and processing load facilitate decision-making.

This concerns the choice of network equipment, connected devices and sensors, as well as their configuration. This makes it possible to adjust the number of routers, reduce or fine-tune transmission power, increase battery life, and reduce energy consumption and the number of devices according to the needs of higher-level applications (i.e. 3-4 ISA-95 level).

It is also possible to optimize the architecture (centralized or distributed) according to the amount of data to be transferred and the types of analysis and calculations to be carried out.

For example, if data volumes are large, it may be appropriate to use edge computing to limit data transfer.

During the deployment and operational phases, network performance and congestion problems can be detected and remedied automatically or more rapidly, and IT/OT equipment can be better sized based on observation of the infrastructure in use. This eliminates the need for a repair technician to travel and saves time thanks to remote maintenance of complex IIoT equipment or systems.

Generally speaking, the IT/OT Digital Twin enables IT/OT systems to be continuously observed, optimized, adapted and remotely maintained. These analyses help to reduce the environmental impact of the initial and operational infrastructure.

ENVIRONMENTAL IMPACT INDICATORS

Energy consumption for the manufacturing and operation of connectivity (sensors, networks), computing, and storage (edge and cloud) infrastructure.

Consumption of resources (particularly copper and rare earths) in the manufacture of IoT and IT equipment (servers, networks, etc.).

INDUSTRIAL EXAMPLES

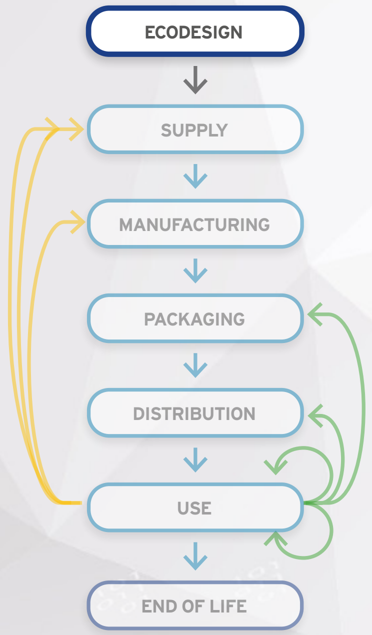
- **Wireless or cellular network** (private 5G) for an industrial site.
- **IIoT infrastructure for optimal** monitoring and operation of a connected factory, nuclear power plant, airport, train...

PILLAR 2

ECODESIGN / REDUCING THE IMPACT OF INDUSTRIAL FACILITIES AND EQUIPMENT

USE CASE

CIRCULAR ECONOMY DIAGRAM



[INDUS ASSET-03] REDUCING ENVIRONMENTAL IMPACT WHEN (RE-)DESIGNING OR RECONFIGURING A PRODUCTION LINE

DESCRIPTION

Using the data collected by the Digital Twin and their analysis, it is possible to:

- Carry out various simulations of a production line: simulation of the line's energy consumption in operation, simulation of equipment, flows and line layouts.
- Identify possible improvements affecting energy consumption and the environmental impact of the production system: carbon footprint, water use, pollution...
- Reduce flows, travel and waste, and choose the most appropriate equipment.

Depending on the scheduling methods or management rules chosen, it is possible to simulate the impact of a new production line architecture in nominal use, for example by replaying a "typical" year. On an existing system, it may be necessary to define which equipment will be in operation according to external constraints (e.g. demand for power load shedding), with a view to a reconfigurable production system.

In a "Manufacturing as a Service" context, it is possible to check with the customer, thanks to the Digital Twin, that the system is behaving as it should, thus avoiding product updating and/or remanufacturing operations, and contributing to the controlled consumption of resources (energy, materials, etc.).

ENVIRONMENTAL IMPACT INDICATORS

Production line energy consumption.

Greenhouse gas emissions from the production line.

Production line materials consumption.

Production line water consumption.

Production line pollutant emissions.

Quantity of recycled materials used in production and recyclable materials produced.

INDUSTRIAL EXAMPLES

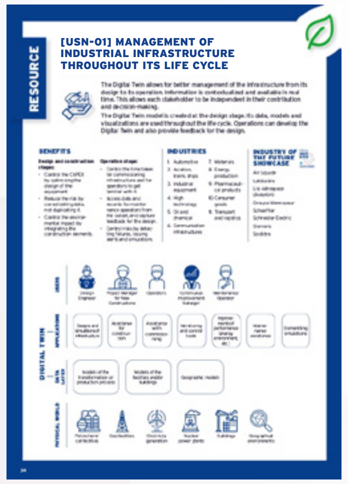
This scenario applies to a wide range of industrial production systems, including:

- **Configurable assembly lines:** automotive industry.
- **Batch production:** modular pharmaceutical production.

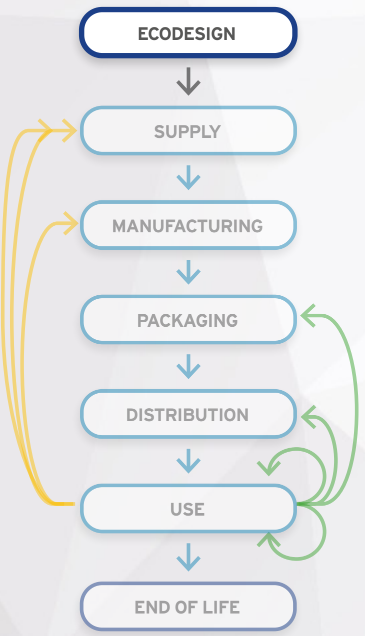
PILLAR 2

ECODESIGN / REDUCING THE IMPACT OF INDUSTRIAL FACILITIES AND EQUIPMENT

USE CASE



CIRCULAR ECONOMY DIAGRAM



[INDUS ASSET-04] ECO-RESPONSIBLE CHOICES WHEN DESIGNING A PLANT

DESCRIPTION

The plant's Digital Twin, developed from the site design stage, can help with design choices, including:

- **Optimized design of the infrastructure shell.**
  By adjusting the exposure and orientation of the building's windows, it is possible to optimize the use of natural light and improve thermal comfort. Similarly, by adapting the infrastructure to its environment, the aim is to minimize the impact on surrounding ecosystems.
- **A choice of ecodesigned materials and equipment, with low environmental impact and low maintenance requirements.**
  For example, the Digital Twin can be used to simulate the environmental performance of different building materials, taking into account their durability, recyclability and energy efficiency.
- **A choice of different equipment and plant configurations to minimize the movement of raw materials and finished products.**
  An optimized layout can reduce energy consumption and CO2 emissions associated with in-plant transport.
- **Optimization of lighting, ventilation and heating systems.**
  The Digital Twin can be used to simulate the performance of plant lighting, ventilation and heating systems, taking into account factors such as the outside temperature, humidity and occupancy rates.

In addition, a life cycle assessment of the building, starting from the design phase, and an update at the various stages of the infrastructure life cycle, are particularly relevant. A Digital Twin maintained throughout the building's life cycle will help reduce energy and water consumption.

It can also facilitate building maintenance and renovation by simulating proposed changes prior to their physical implementation, enabling stakeholders to visualize and approve the envisaged changes.

ENVIRONMENTAL IMPACT INDICATORS

- **Energy consumption** related to plant construction and operation.
- **Greenhouse gas emissions** linked to plant construction and operation.
- **Quantities of materials** used during construction.
- **Water consumption** during construction and operation.
- **Pollutant emissions** during construction and operation.
- **Quantities or proportions of recycled materials** used during construction.
- **Changes in land use** following the construction of the factory and its developments.

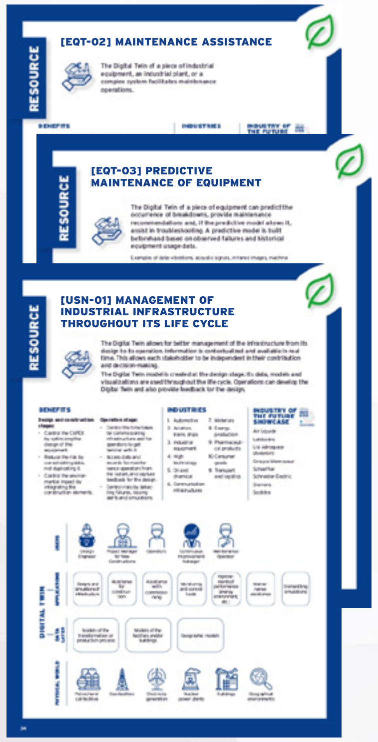
INDUSTRIAL EXAMPLES

- **Construction or renovation of an industrial site** (building, power plant, farm, wind farm, etc.).
- **Construction or renovation of an infrastructure** (rail, road, airport, etc.).

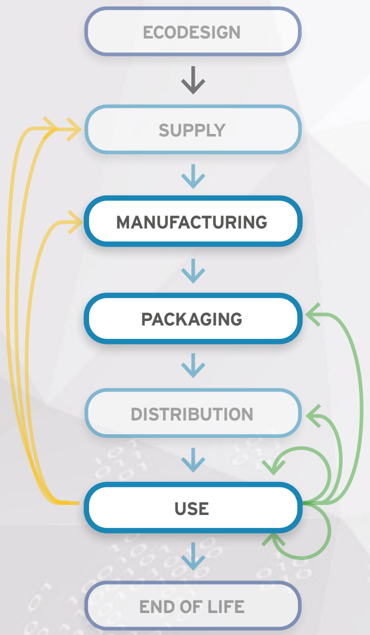
PILLAR 2

ECODESIGN / REDUCING THE IMPACT OF MAINTENANCE

USE CASE



CIRCULAR ECONOMY DIAGRAM



[MAINTENANCE-01] REDUCED ENERGY CONSUMPTION AND ENVIRONMENTAL IMPACT OF MAINTENANCE OPERATOR TRAVEL

DESCRIPTION

A Digital Twin collects and processes operating data from industrial equipment, and displays it remotely to enable continuous monitoring and remote maintenance.

A maintenance expert has access to the Digital Twin, which reflects the exact status and configuration of the equipment being monitored. He/she can then remotely guide an operator to carry out the necessary maintenance operations on site.

This makes the best use of the time of the experts, who are sometimes few in number, and avoids the environmental impact of their travel.

In the case of complex equipment or installations, it is sometimes essential to send out experts. A predictive maintenance application, based on operating data from the Digital Twin, reduces the number of trips required compared with preventive maintenance. This is because parts are only changed when the application deems it necessary (see [Maintenance-02] Reduced consumption of spare parts thanks to predictive maintenance).

Predictive maintenance also makes it possible to anticipate or prevent breakdowns, thus reducing the need for emergency trips.

ENVIRONMENTAL IMPACT INDICATORS

- **Distances traveled** by maintenance experts.
- **Greenhouse gas emissions** linked to maintenance expert travel.
- **Quantities of pollutants** emitted as a result of maintenance expert travel.

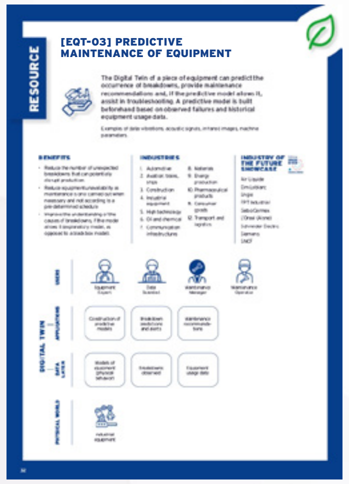
INDUSTRIAL EXAMPLES

- **Complex industrial facilities** (refineries, gas production, chemical industry).
- **Sophisticated or specific industrial equipment** requiring maintenance.
- **Consumer equipment:** elevators, escalators, air conditioning, ventilation, boilers, heat pumps...
- **Computer servers,** network equipment...

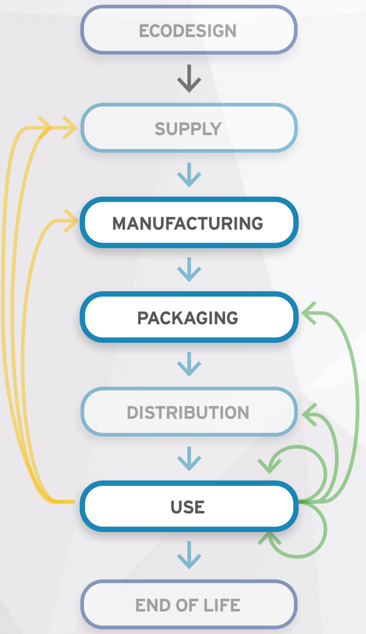
PILLAR 2

ECODESIGN / REDUCING THE IMPACT OF MAINTENANCE

USE CASE



CIRCULAR ECONOMY DIAGRAM



SEE ALSO

Indus Asset-01

[MAINTENANCE-02] REDUCED CONSUMPTION OF SPARE PARTS THANKS TO PREDICTIVE MAINTENANCE

DESCRIPTION

The building of a predictive failure model as described in "[Indus Asset-01] Increasing the lifespan of equipment and its components" makes it possible to determine the situations in which a maintenance activity is necessary in order to avoid a predicted failure.

Predictive maintenance makes it possible to avoid unnecessary maintenance activities, often resulting from preventive maintenance. In this way, premature replacement of wearing parts can be avoided, as would be the case if the maintenance schedule were followed.

ENVIRONMENTAL IMPACT INDICATORS

Service life of the various parts in the equipment and of the equipment itself. In particular, we can compare the number of spare parts installed per category of equipment according to predictive and preventive maintenance requirements.

INDUSTRIAL EXAMPLES

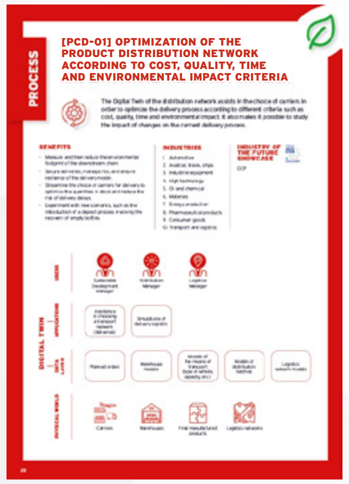
Predictive maintenance potentially applies to all types of equipment and systems for which usage and maintenance data can be retrieved. For example:

- **Rotary machines, motorized equipment...**
- **Complex industrial plants** (refineries, gas production, chemical industry).
- **Sophisticated or specific industrial equipment** requiring maintenance.
- **Consumer equipment:** elevators, escalators, air conditioning, ventilation, boilers, heat pumps...
- **Computer servers,** network equipment...

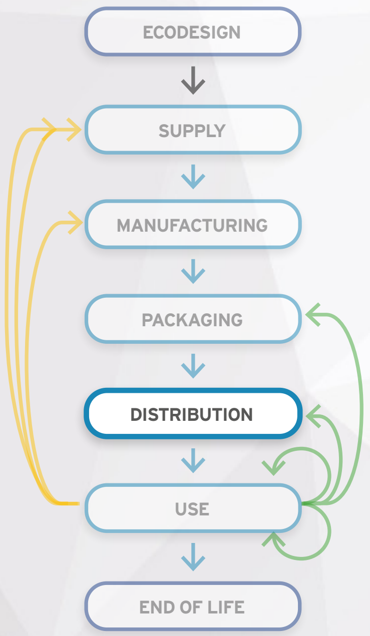
PILLAR 2

ECODESIGN / REDUCING THE IMPACT OF DELIVERIES

USE CASE



CIRCULAR ECONOMY DIAGRAM



SEE ALSO

Supply-01

[DELIVERY-01] REDUCING THE ENVIRONMENTAL IMPACT OF THE DISTRIBUTION NETWORK

DESCRIPTION

The Digital Twin of the distribution network can help in the choice of means of transport and carriers to optimize the delivery process according to criteria of cost, quality, lead times and environmental impact.

The relative importance of each of these criteria can be adjusted.

The Digital Twin can also be used to study the impact of changes to the current delivery process, by simulating alternative processes.

It can be used to estimate environmental impact according to the means used: rail freight, air freight, sea freight, etc.

Depending on the means of transport used, it is thus possible to estimate the carbon impact of its use and the consumption of resources necessary for its operation.

ENVIRONMENTAL IMPACT INDICATORS

Product delivery distances.

Greenhouse gas emissions related to product delivery.

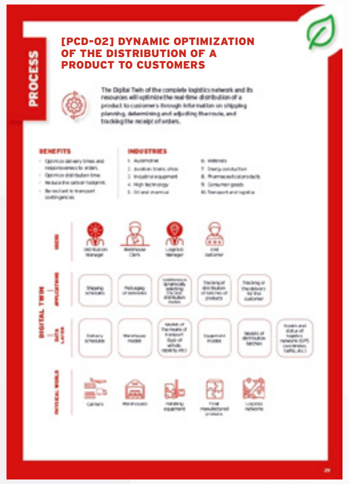
INDUSTRIAL EXAMPLES

This situation of reduced impact potentially applies to all industrial players managing their product distribution chain. It also applies to logistics service providers involved in optimizing the distribution chain (so-called 3PL service providers or higher).

PILLAR 2

ECODESIGN / REDUCING THE IMPACT OF DELIVERIES

USE CASE



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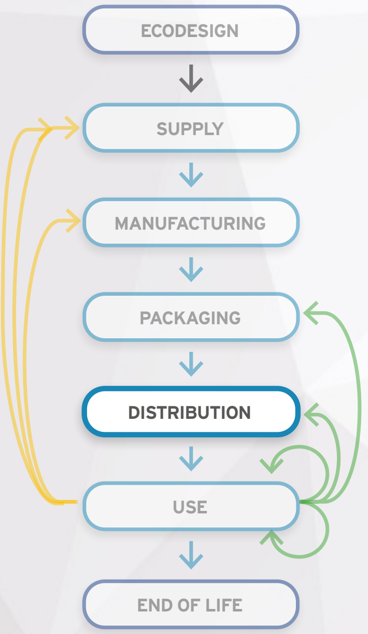


SEE ALSO

Supply-02

[DELIVERY-02] REDUCING THE ENVIRONMENTAL IMPACT OF PRODUCT DISTRIBUTION

DESCRIPTION

The Digital Twin of the logistics network allows for real-time optimization of product distribution using information related to shipping planning and geolocation. It determines and adjusts the route, and tracks the receipt of orders.

Here are a few examples of distribution optimization:

- Information on traffic conditions, planned roadworks or road closures can be used to adapt routes, or even to change delivery means.
- Knowing the position/presence of certain customers for a delivery can help avoid unnecessary travel.
- Depending on the number of deliveries scheduled for a given day, the Digital Twin can anticipate the charging requirements of the electric vehicles needed for the delivery, and optimize the tour accordingly. Energy mix data can be taken into account to favor recharging periods during which the mix is predominantly renewable.

ENVIRONMENTAL IMPACT INDICATORS

- **Product delivery distances.**
- **Greenhouse gas emissions** related to product delivery

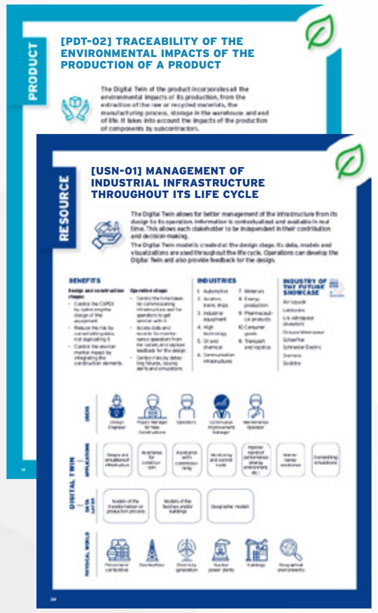
INDUSTRIAL EXAMPLES

- **Optimization of the routes** of a fleet of transport vehicles, possibly of different types (ships, planes, trucks, trains, drones, etc.).
- **Optimization of last-mile logistics** (e.g. delivery by bicycle).
- **Optimization of reverse logistics:** taking into account the return of returnable or recyclable packaging.

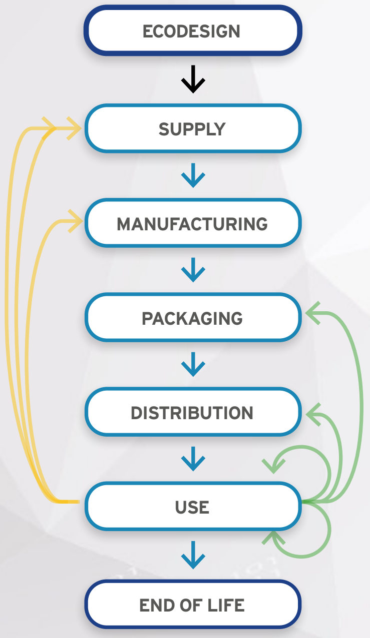
PILLAR 2

ECODESIGN / COMPLIANCE WITH ENVIRONMENTAL REGULATIONS

USE CASE



CIRCULAR ECONOMY DIAGRAM



[REGULATION-01] COMPLIANCE WITH ENVIRONMENTAL REGULATIONS THANKS TO TRACEABILITY

DESCRIPTION

The traceability of components and materials used in the manufacture of a product is a regulatory imperative in many sectors, such as aeronautics, automotive, agri-food, pharmaceutical and chemical industries:

- The Digital Twin of the Manufactured Product allows to identify the origin of all components or materials, thanks to a hierarchy that accurately reflects the product as manufactured or assembled (*as-built* product view). This tree, known as the product or material genealogy, associates a serial or batch number with each of its nodes, enabling the supplier to be queried in the event of a defect in an external component.
- When worn or faulty parts are replaced, the genealogy is updated. Thus, it reflects the composition of the product throughout its life and the repairs it has undergone (*as-maintained view*).

More recently, the European Union's digital product passport regulation project aims to promote the circular economy. In addition to component tracking and information on ease of repair or reuse, it includes new traceability requirements: consumption of energy, water and other resources, use of recycled materials, environmental impact of the product throughout its life cycle, etc.

For certain categories of objects, such as electric vehicle batteries, the passport information must be specific to the physical object produced, and not just to its conceptual model. In this case, the Digital Twin of each physical product will have to integrate, in addition to the genealogy, the environmental impact information described above.

Finally, the Digital Twin of a plant can help companies to avoid possible breaches of legislation, which can be damaging (fines, reputation, production stoppage...), and also help to be better prepared for inspections.

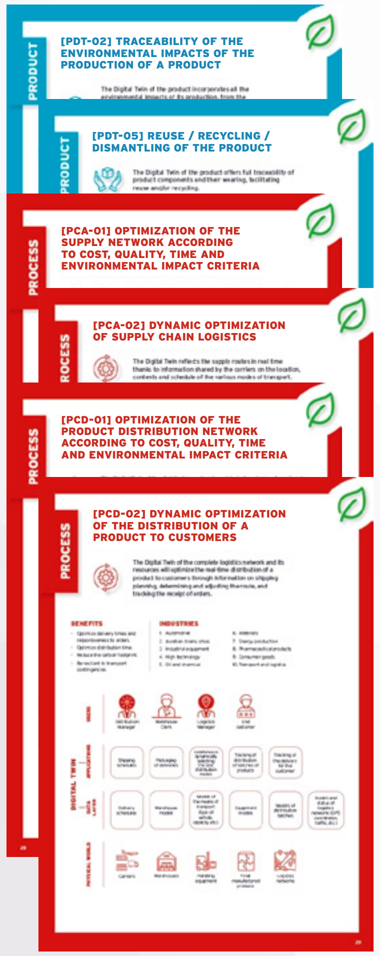
ENVIRONMENTAL IMPACT INDICATORS

- **Nature and quantity of each raw or processed material** consumed during production (steel plates, copper tubes, water, oils, etc.).
- **Quantity of greenhouse gases** emitted during production, use and end-of-life.
- **Waste and pollution** resulting from production, use and end-of-life.
- **Nature and quantity of recycled materials** used during product manufacturing.
- **Nature and quantity of recyclable materials** in the product at end-of-life.
- **Energy consumed** during production, use and end-of-life.

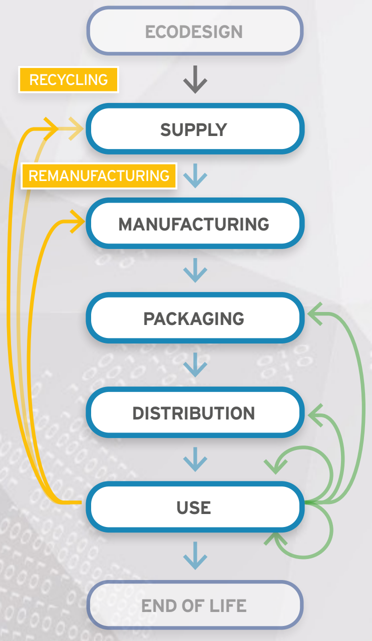
INDUSTRIAL EXAMPLES

- **Aerospace, automotive:** compliance with traceability regulations for aircraft or vehicle parts.
- **Pharmaceutical and food industries:** compliance with regulations on the traceability of ingredients and active principles used.
- **Products containing chemical substances:** compliance with regulations on hazardous substances (e.g. EU REACH regulation).
- **Potentially all industries:** creation and updating of the European digital product passport.

USE CASE



CIRCULAR ECONOMY DIAGRAM



[TERRITORIAL-01] OPTIMIZING A REGION'S RESOURCES

DESCRIPTION

According to ADEME[10], , "Industrial and Territorial Ecology (ITE) is an economic model that aims to optimize resources. [...] Its aim is to optimize a territory's resources, including energy, water, raw materials, waste, equipment and skills. [...] This systemic approach is inspired by the way natural ecosystems function."
The Digital Twin offers a means of monitoring and managing complex systems involving numerous interdependencies along a value chain, throughout a product's life cycle. It enables intra- and inter-company collaboration and synergies (exchange of flows, e.g. valorization of co-products; pooling of goods, resources or services, etc.).
In concrete terms, it's a set of Digital Twins interacting with each other that could support a territory and its economic system. Thus, the combination of Digital Twins addressing some of the use cases in our first brochure would be relevant for implementing an industrial and territorial ecology to:

- Track components and raw materials traded in the region and measure environmental impact [PDT-02].
- Facilitate recycling and reuse through traceability of the various components and their state of use [PDT-05].
- Optimize the regional supply chain (choice of suppliers for each component, factories, etc.) according to criteria of cost, quality, deadlines and environmental impact [PCA-01].
- Optimize supply routes and reduce their carbon and environmental footprint [PCA-02].
- Optimize the choice of carriers in the region to optimize the delivery process in terms of cost, quality, deadlines and environmental impact [PCD-01].
- Define distribution routes and reduce their carbon and environmental footprint [PCD-02].

ENVIRONMENTAL IMPACT INDICATORS

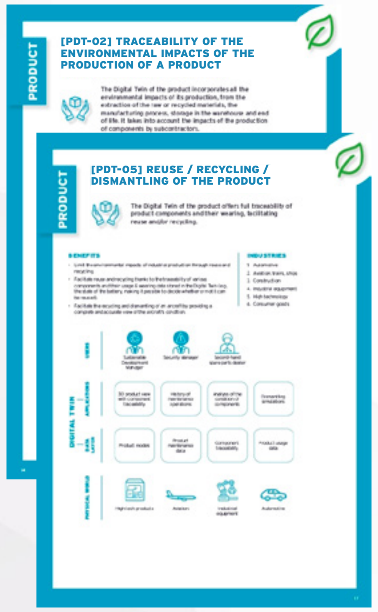
- **Quantity of greenhouse gases** emitted by all the region's industrial players.
- **Nature and quantity of virgin materials** consumed in the manufacture of local products.
- **Freshwater and seawater consumption** by local industrial players.
- **Distances traveled** to supply the region's industrial players and deliver their products.
- **Waste and pollution** resulting from the production, use and end-of-life of the products of the region's industrial players.
- **Nature and quantity of recycled materials** used in the manufacture of local products.
- **Energy consumption** of local industrial players.

INDUSTRIAL EXAMPLES

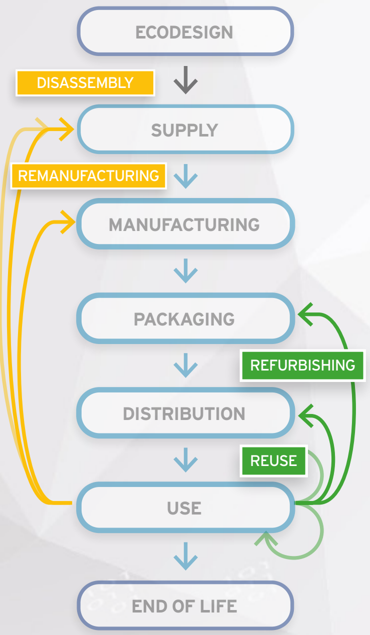
Kalundborg, Denmark, is a pioneering city[11] in the implementation of industrial and territorial ecology.
The various companies in the area have signed agreements to exchange water, energy and resources, in a circular approach: waste from one company becomes resources or energy for others.

[10] https://economie-circulaire.ademe.fr/ecologie-industrielle-territoriale-enjeux
[11] https://www.symbiosis.dk/en/

USE CASE



CIRCULAR ECONOMY DIAGRAM



SEE ALSO

Recycling-01

[REUSE-01] FACILITATING THE REUSE OF COMPONENTS THROUGH TRACEABILITY

DESCRIPTION

The Digital Twin facilitates reuse thanks to the traceability of the various components and materials that make up the product. Detailed knowledge of the product's composition makes it possible to determine what can be refurbished, what can be reused in other products, whether of the same type or not, and what must be recycled or destroyed.
High-risk components and materials (hazardous materials, pollutants, etc.) are identified, ensuring the safety of people and the environment.
Sorting is also made easier: for example, different plastics used in the product can be recycled in different ways.

The Digital Twin ensures traceability of installed or replaced components, and reflects their state of wear. This facilitates disassembly or dismantling. Recoverable or reusable parts are identified according to their condition, facilitating the circular economy.

ENVIRONMENTAL IMPACT INDICATORS

- **Nature and quantity of materials** or components that can be reused or recycled at the end of the product's life.
- **Increased lifespan** of product components.

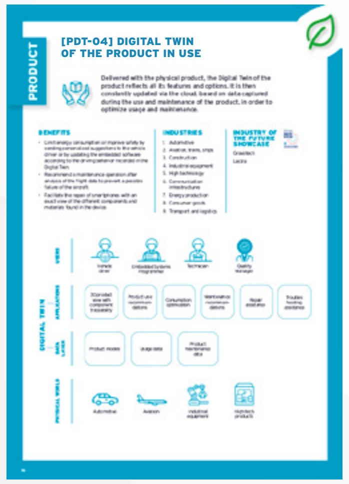
INDUSTRIAL EXAMPLES

- **Recovering parts** from end-of-life vehicles in a scrapyard.
- **Recovery of battery components** according to their condition (pack, modules, cells).
- **Aircraft dismantling.**
- **Construction of new vehicles, electronic equipment,** etc., thanks to the recovery of components from end-of-life products.

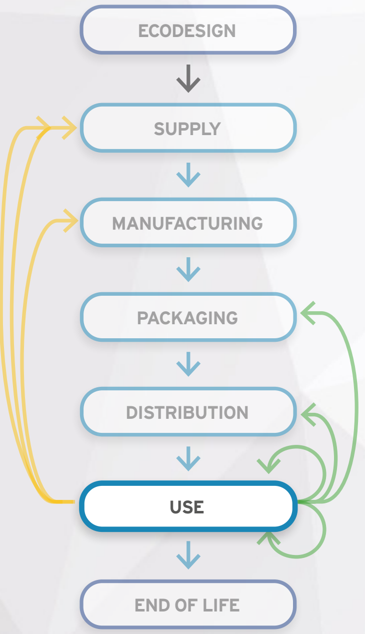
PILLAR 5

RESPONSIBLE CONSUMPTION: REDUCING THE IMPACT OF PRODUCT USE

USE CASE



CIRCULAR ECONOMY DIAGRAM



[USE-01] REDUCING THE IMPACT OF PRODUCT IN USE

DESCRIPTION

Delivered with the physical product, the Digital Twin of the product reflects all its features and options. Subsequently, its status is constantly updated according to data captured during product use and maintenance and transmitted to the cloud.

These data are analyzed, for example by an artificial intelligence algorithm, to optimize product use and maintenance according to the user's specific habits and context of use, which cannot be taken into account at the design stage.

Optimizing the product use according to user behavior and context can then take the form of direct actions on the equipment, recommendations to the consumer (to save energy, for example), on-board software updates, maintenance recommendations, etc.

ENVIRONMENTAL IMPACT INDICATORS

Quantities of greenhouse gases emitted during product use.

Nature and quantity of materials consumed during product use (e.g. printer ink).

Consumption of water resources when using the product.

Distances covered when using a vehicle.

Waste and pollution resulting from the use of the product.

Energy consumption when using the product.

INDUSTRIAL EXAMPLES

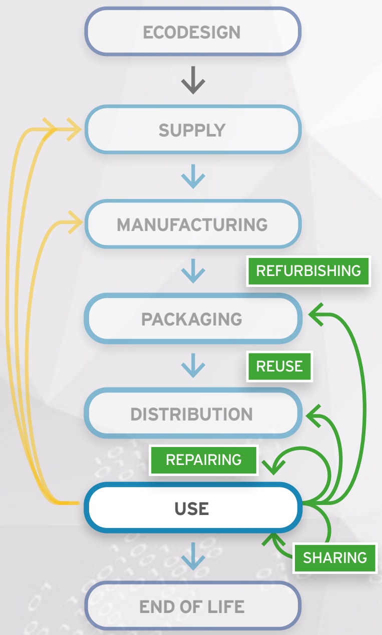
- **Limit energy consumption** by sending personalized suggestions to a vehicle driver or product user, or by updating on-board software, based on driving or usage behavior recorded in the Digital Twin (speed reduction, trajectory change, responsible use, etc.).
- **Recommendation of a maintenance operation** to avoid a future breakdown after analysis of flight data in the case of an aircraft, operating and status data in the case of a machine tool, etc.
- **Precise control of domestic hot water heating equipment.** The Digital Twin precisely determines the time required to bring the water up to temperature, starting from a given state.
Sensors can be used to automatically determine, at different times of the day, the preferred temperature setting for the hot water cylinder to meet user expectations while limiting energy consumption.

PILLAR 6

EXTENDING USEFUL LIFE

USE CASE

CIRCULAR ECONOMY DIAGRAM



SEE ALSO

Reuse-01

[LIFE-01] EXTENDED PRODUCT USEFUL LIFE

DESCRIPTION

The Digital Twin of the product and its sub-systems provides information on the status of the product and its components. This information allows to anticipate breakdowns thanks to predictive maintenance, and to plan the replacement of defective components, if possible with second-hand components (see impact reduction situation [MAINTENANCE-02] "Reduced consumption of spare parts thanks to predictive maintenance"). This increases the product's lifespan.

Moreover, the knowledge of a product's usage metrics allows proposing usage adjustments to limit wear (e.g. speed reduction, responsible driving for a vehicle).

Finally, knowledge of the Digital Twin's components and a design that facilitates disassembly help increase the product's lifespan. This promotes repairability and reuse.

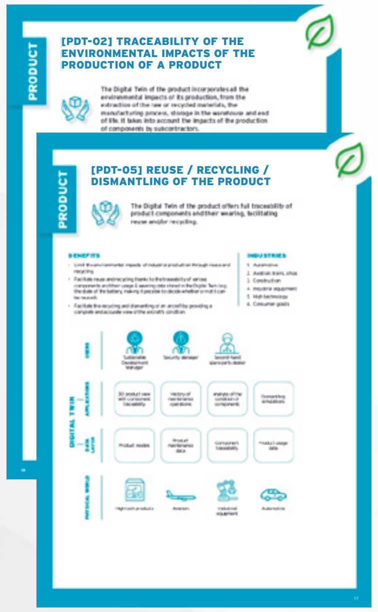
ENVIRONMENTAL IMPACT INDICATORS

Lifespan of the product or industrial equipment considered.

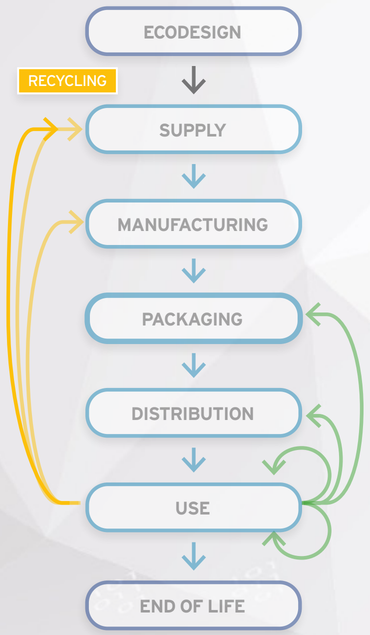
INDUSTRIAL EXAMPLES

- **Extending a product's lifespan,** in line with the shift to an economy of use or functionality, where the product is rented or integrated into a service, rather than purchased. The manufacturer's interest is to keep the product in production as long as possible.
- **Maintaining industrial equipment** (vehicles, machine tools, etc.) in operational condition for a longer period.

USE CASE



CIRCULAR ECONOMY DIAGRAM



SEE ALSO

Reuse-01

[RECYCLING-01] FACILITATING RECYCLING THROUGH TRACEABILITY

DESCRIPTION

The product's Digital Twin, created at the manufacturing stage and updated after repairs, collects data on the nature and quantity of the materials and components making up the product. It also includes information to facilitate recycling, such as disassembly instructions.

All this information from the Digital Twin can be used to generate regulatory documents such as the Digital Product Passport. It can also be used during product dismantling to sort and recycle materials that can be recycled. Today, the main obstacles to the use of recycled materials lie in a lack of knowledge about the resources available and their quality, as well as the difficulties involved in extracting them.

ENVIRONMENTAL IMPACT INDICATORS

Nature and quantity of different materials that can be extracted from the product at end-of-life for reuse.

Nature and quantity of different materials that can be extracted from the product at end-of-life for recycling.

INDUSTRIAL EXAMPLES

- **Regulatory requirement to recycle** certain products or to incorporate a minimum rate of recycled materials during production. For example, the European Union has set a target of collecting 73% of portable batteries from household appliances by 2030, and envisions minimum recycling rates of 16% for cobalt, 85% for lead and 6% for lithium and nickel[12].
- **Setting up industrial processes using recycled materials.** In the steel industry, for example, efforts will be made to minimize the use of virgin ore while maintaining the quality of the steel.

[12] https://www.europarl.europa.eu/news/en/press-room/20221205IPR60614/batteries-deal-on-new-eu-rules-for-design-production-and-waste-treatment

19 OPPORTUNITIES TO REDUCE IMPACT

04

CONSIDERING THE ENVIRONMENTAL IMPACT OF THE DIGITAL TWIN ITSELF

4.1 | IMPACT OF THE DIGITAL TWIN THROUGHOUT ITS LIFE CYCLE

Interfaced and synchronized with the physical world, Digital Twins potentially store massive volumes of data, can perform resource intensive artificial intelligence processing and/or digital simulation, and offer sophisticated user interfaces (virtual or augmented reality) as well as high-level services.
They are often integrated into **cloud infrastructures** to facilitate deployment and collaborative operation.

Cloud architectures rely on large data centers and data transmission networks. These are responsible for almost **1% of the world's annual energy-related greenhouse gas emissions** according to the International Energy Agency[13], and are responsible for the emission of around 330 million tonnes of CO2 equivalent in 2020, including emissions induced by the IT equipment manufacturing.

During the design and development of a Digital Twin, the impact reduction that it can enable must therefore be balanced with the environmental impact of the supporting digital infrastructures throughout its life cycle, from design to use and end of life.

The Life Cycle Assessment of the Digital Twin can be based on ADEME's[14] guidelines for the environmental assessment of digital services, which suggest dividing the inventory of equipment and infrastructures required for the service into three tiers: networks, terminals and data centers.

To limit the computing and storage loads imposed on servers and the volumes of data exchanged, it is advisable to implement software Ecodesign best practices[15].

Environmental impact indicators for the digital twin

- **Volume of greenhouse gas emissions** linked to data transfers and processing.
- **Resources needed** to manufacture IT equipment (servers, network, etc.).
- **Water consumption** for cooling data centers during development and use. Water consumption for IT equipment manufacturing.
- **Energy for building and operating** the digital infrastructure: network, computing and storage.
- **Service life** of Digital Twin infrastructure.

[13] www.iea.org/energy-system/buildings/data-centres-and-data-transmission-networks
[14] https://librairie.ademe.fr/industrie-et-production-durable/6022-referentiel-par-categorie-de-produit-rcp-des-services-numeriques.html
[15] https://github.com/cnumr/best-practices

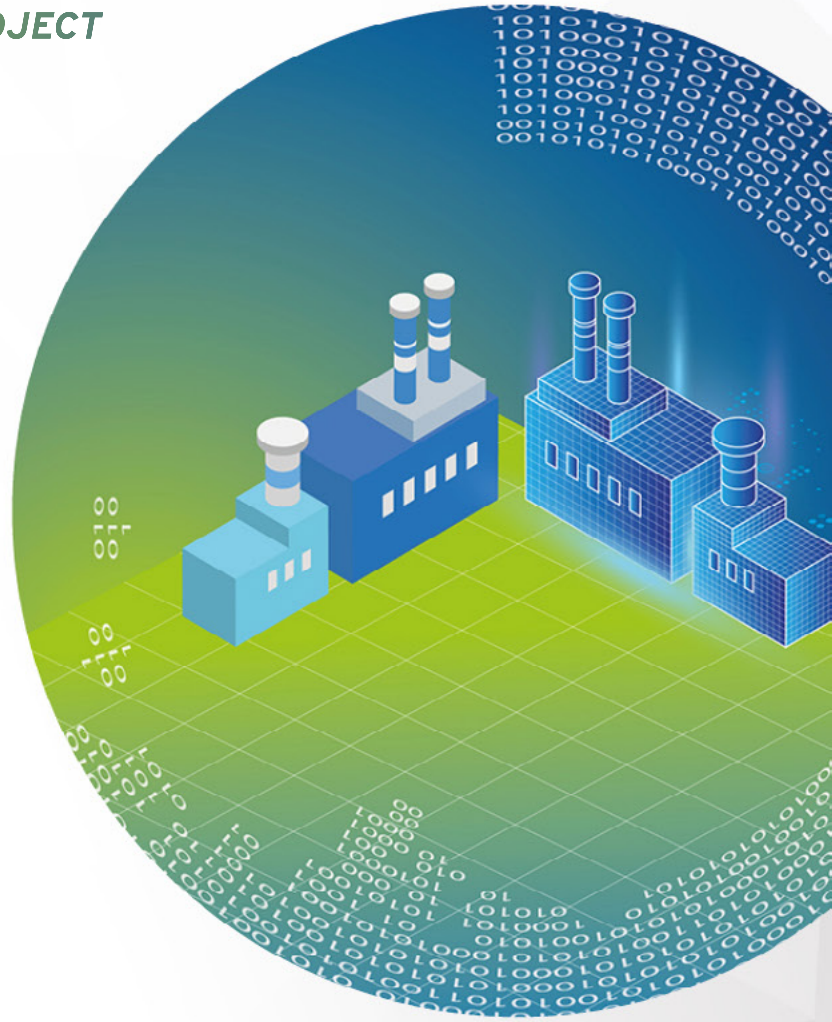
4.2 | CONSEQUENTIAL IMPACT OF THE DIGITAL TWIN PROJECT

Strictly speaking, the Life Cycle Assessment of the Digital Twin should be completed by an analysis of the project's indirect impact. In particular, **"rebound effects"** can occur. For example:

- Reducing energy consumption in production (cf. [Production-01]) may enable to produce at lower cost and use the money saved to bring new products to market, with additional impacts. Conversely, if the money saved is invested in thermal insulation of the building, the overall impact is beneficial for the same level of heating.
- The use of a Digital Twin for the development of new products or processes can facilitate Ecodesign. However, the Digital Twin can also reduce time to market, which could lead to increased consumption of goods and a greater environmental impact.

A so-called "consequential" Life Cycle Assessment makes it possible to take such situations into account, by comparing the environmental impacts before and after the introduction of the Digital Twin.

The ITU L1480 standard, which aims to estimate the carbon emissions avoided for a given digital service, can help with this analysis[16].



[16] Cf. https://hellofuture.orange.com/en/recommendation-l-1480-quantifies-all-usage-related-co2-impacts-including-the-rebound-effect/

05

EXTENDING THE CONVERSATION TO THE SOCIETAL DIMENSION OF INDUSTRIAL ACTIVITIES

We have seen that the Digital Twin can help reduce the environmental impact of industrial activities, with the reservations expressed in the previous chapter. This is in line with the objective of respecting planetary boundaries[17].
This concept has been extended in Kate Raworth's "doughnut theory[18]": in addition to the ecological ceiling, we need to be above the social foundation of the doughnut, which ensures human well-being.

The Digital Twin could also contribute to this objective in an industrial context, while itself raising social issues.

5.1 | *SOCIETAL BENEFITS*

Potential societal benefits of the Digital Twin include[19] :

For operators in industrial environments:

- Improved safety, with detection of risky situations, for example using cameras and AI.
- Improved workstation ergonomics, taking into account the mental and physical fatigue induced by the type of operation, the posture of operators engaged in production or logistics processes, and repetitive actions in order to reduce musculoskeletal disorders in particular.
- Learning and training through simulation of operations at the workstation in an immersive environment (Digital Twin coupled with a Virtual Reality device).

At the territorial level, the Digital Twin can be used to:

- Guide urban planning policies by assessing the environmental impact of industrial developments (bio-diversity, water management, land artificialization, etc.).
- Prepare for operations on sensitive sites or requiring role-playing (fire, defense, etc.).

The doughnut theory

5.2 | *HUMAN IMPACTS OF THE DIGITAL TWIN*

The introduction of Digital Twin technology requires a significant amount of time to get to grips with its power and complexity, and may necessitate adaptations of workstations. These changes may also give rise to resistance, for example if the Digital Twin seems to contradict or replace the operator's expertise, or if it is accompanied, in safety and ergonomic applications, by the introduction of cameras.

Compliance with privacy protection regulations such as GDPR is also a point of attention. All this therefore requires upstream vigilance and reflection, followed by support and training.

[17] https://www.stockholmresilience.org/research/planetary-boundaries.html
[18] https://doughnuteconomics.org/about-doughnut-economics
[19] Pater, J., & Stadnicka, D. (2021). Towards digital twins development and implementation to support sustainability-systematic literature review. Management and Production Engineering Review, 13(3), 63-73. Greco, A., Caterino, M., Fera, M., & Gerbino, S. (2020). Digital Twin for Monitoring Ergonomics during Manufacturing Production. Applied Sciences, 10(21), 7758. Bilberg, A., & Malik, A. A. (2019). Digital twin driven human-robot collaborative assembly. CIRP Annals, 68(1),Romero, D., & Stahre, J. (2021). Towards the Resilient Operator 5.0: The Future of Work in Smart Resilient Manufacturing Systems. Procedia CIRP, 104, 1089-1094.

CONCLUSION

This document has presented the potential for reducing the environmental impact of industrial activities thanks to the Digital Twin.

The Digital Twin can thus be a lever for implementing the circular economy and achieving sustainable development goals.

By collecting, linking and processing a coherent set of manufacturing and product usage data, it can help estimate and reduce the impact of these activities. In this way, the use of a Digital Twin, particularly in Ecodesign, helps link field information, modeling and simulation to create and compare different manufacturing and usage scenarios.

The Digital Twin can help reduce environmental impact by:

- reducing energy consumption in production and use,
- reducing greenhouse gas emissions through Ecodesign, longer product life and optimized sourcing and delivery,
- reducing the consumption of raw materials through design, recycling and reuse.

However, it is essential to take into account the impact of the Digital Twin itself, particularly that of infrastructures such as data centers and communication networks. At the start of an implementation project, a consequential Life Cycle Assessment is therefore necessary to assess the expected benefits in relation to the impact of the Digital Twin itself.

The Digital Twin can also facilitate compliance with various environmental regulations such as :

- the Digital Product Passport (discussed in [Regulation-01]),
- the CSRD[20] (Corporate Sustainability Reporting Directive),
- ESRS[21] (European Sustainability Reporting Standards)
- REACH[22], IED[23] (Industrial Emissions Directive) or SEVESO[24] regulations, related to the traceability of hazardous substances.

The Digital Twin also provides capabilities potentially eligible for the European taxonomy[25], such as predictive maintenance.

The Digital Twin can also help develop new business models based on use and sharing rather than individual possession. The challenge is then for the manufacturer to keep the product in use as long as possible (see [Life-01]).

Finally, the Digital Twin can contribute to the social dimension of sustainable development, notably by improving working conditions, safety and operator training through the simulation of high-risk environments.

[20] https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32022L2464
[21] https://finance.ec.europa.eu/news/commission-adopts-european-sustainability-reporting-standards-2023-07-31_en
[22] https://environment.ec.europa.eu/topics/chemicals/reach-regulation_en
[23] https://www.iea.org/policies/17701-industrial-emissions-directive-201075eu
[24] https://echa.europa.eu/fr/regulations/clp/understanding-seveso
[25] https://finance.ec.europa.eu/sustainable-finance/tools-and-standards/eu-taxonomy-sustainable-activities_en

INDEX

Circular economy stages covered by each opportunity

Life cycle in a Circular Economy

Impact reduction opportunities

Impact reduction opportunities		ECODESIGN	SUPPLY	MANUFACTURING	PACKAGING	DISTRIBUTION	USE	SHARING	REPAIRING	REUSE	REFURBISHING	REMANUFACTURING	DISASSEMBLY	RECYCLING	END OF LIFE
Reducing the environmental impact of the supply chain	[Supply-01]		X												
Reducing the environmental impact of component transport	[Supply-02]		X												
Extending product life and reducing the impact of use through ecodesign	[Ecodesign-01]	X													
Reducing the energy and resource consumption of a production line	[Production-01]			X	X										
Reducing the material and energy footprint of production by reducing the scrap rate	[Production-02]			X	X										
Increasing the lifespan of equipment and its components	[Indus Asset-01]			X	X										
Optimization and dynamic adaptation of the IT/OT environment	[Indus Asset-02]			X	X										
Reducing environmental impact when (re-)designing or reconfiguring a production line	[Indus Asset-03]	X													
Eco-responsible choices in plant design	[Indus Asset-04]	X													
Reduced energy consumption and environmental impact of maintenance operator travel	[Maintenance-01]			X	X		X								
Reduced consumption of spare parts thanks to predictive maintenance	[Maintenance-02]			X	X		X								
Reducing the environmental impact of the distribution network	[Delivery-01]					X									
Reducing the environmental impact of product distribution	[Delivery-02]					X									
Compliance with environmental regulations thanks to traceability	[Regulation-01]	X	X	X	X	X	X								X
Optimizing a region's resources	[Territorial-01]		X	X	X	X	X					X	X	X	
Facilitating the reuse of components through traceability	[Reuse-01]									X	X	X	X		
Reducing the impact of the product in use	[Use-01]						X								
Extending product useful life	[Life-01]						X	X	X	X	X				
Facilitating recycling through traceability	[Recycling-01]													X	

Impact reduction opportunities by indicator category

Categories of environmental indicators

Impact reduction opportunities		GHG EMISSIONS	MATERIAL	WATER	ENERGY	TRANSPORT	SERVICE LIFE	WASTE	POLLUTION	RECYCLING	LAND ARTIFICIALIZATION
Reducing the environmental impact of the supply chain	[Supply-01]	X				X			X	X	
Reducing the environmental impact of component transport	[Supply-02]	X				X					
Extending product life and reducing the impact of use through ecodesign	[Ecodesign-01]	X		X	X		X		X		
Reducing the energy and resource consumption of a production line	[Production-01]		X	X	X						
Reducing the material and energy footprint of production by reducing the scrap rate	[Production-02]		X	X	X			X			
Increasing the lifespan of equipment and its components	[Indus Asset-01]						X				
Optimization and dynamic adaptation of the IT/OT environment	[Indus Asset-02]		X		X						
Reducing environmental impact when (re-)designing or reconfiguring a production line	[Indus Asset-03]	X	X	X	X				X	X	
Eco-responsible choices in plant design	[Indus Asset-04]	X	X	X	X				X	X	X
Reduced energy consumption and environmental impact of maintenance operator travel	[Maintenance-01]	X				X			X		
Reduced consumption of spare parts thanks to predictive maintenance	[Maintenance-02]						X				
Reducing the environmental impact of the distribution network	[Delivery-01]	X				X					
Reducing the environmental impact of product distribution	[Delivery-02]	X				X					
Compliance with environmental regulations thanks to traceability	[Regulation-01]	X	X		X				X	X	
Optimizing a region's resources	[Territorial-01]	X	X	X	X	X			X	X	
Facilitating the reuse of components through traceability	[Reuse-01]						X			X	
Reducing the impact of the product in use	[Use-01]	X	X	X	X	X			X		
Extending product useful life	[Life-01]						X				
Facilitating recycling through traceability	[Recycling-01]		X							X	

Alliance INDUSTRIE DU FUTUR

Created in 2015, the Alliance Industrie du Futur (AIF) is a non-profit association which organizes and coordinates, on a national level, the initiatives, projects and work of SMEs for the modernization of industrial tools and the transformation of their economic model, in particular through the contribution of new technologies.

With Frédéric Sanchez as its president since March 2021, it is responsible for the **Solutions Industry of the Future Sector** certified by the National Industry Council: **www.solutionsindustriedufutur.org**.

To this end, it leads the project groups of the Strategic Sector Contract. Its commitment: to integrate the employee, with their expertise and interpersonal skills, as a key element in the success of this process. The goal is to reposition the French offer of solutions for the industry of the future at the heart of the country's industrial revival.

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