Analysis and Decision Support of Circular Economy Strategies in Power Electronics

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Co-encadrante de la thèse: *Thècle Alix*

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VIVAE Project

VIVAE is a forward-looking initiative dedicated to advancing circularity within the field of power electronics.

Objectives

- Support circularity
- Facilitate multiple life cycles
- Save residual value
- Prevent being totally recycled after first use
- Value extension

Projet-ANR-21-CE10-0010
anr

Agenda

Motivation

- *Power electronics*
- *E-waste*
- *Circular economy*
- *Scope of the study*
- *Research activity*

Decision Tree

- *Basics of the decision tree*
- *Conceptual level*
- *Case study at conceptual level*
- *Implementation level*

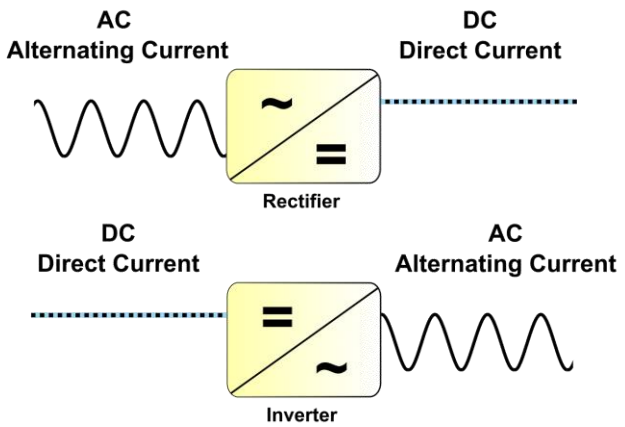
Index

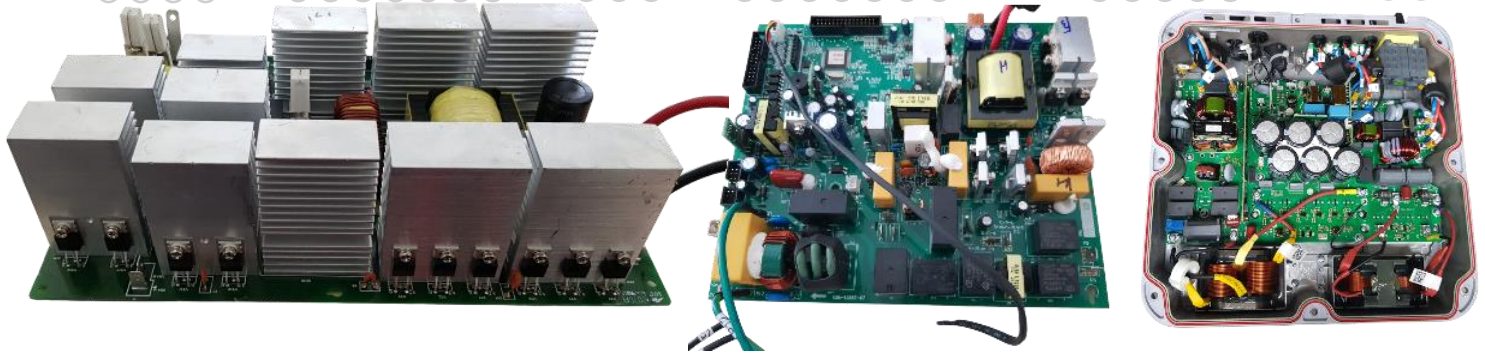
- *Equation*
- *Benchmark*
- *Results*

Conclusion & Perspectives

Power Electronics

Control and convert electrical power





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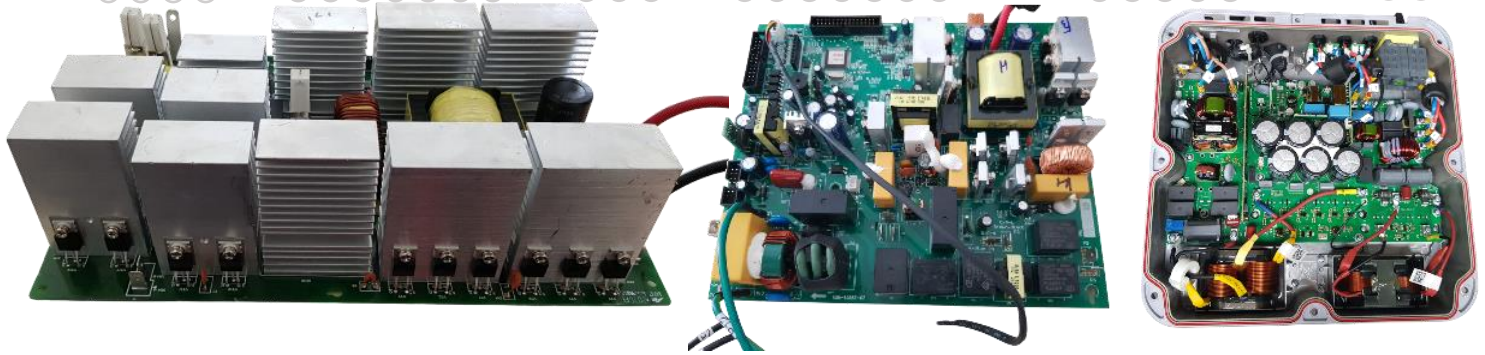
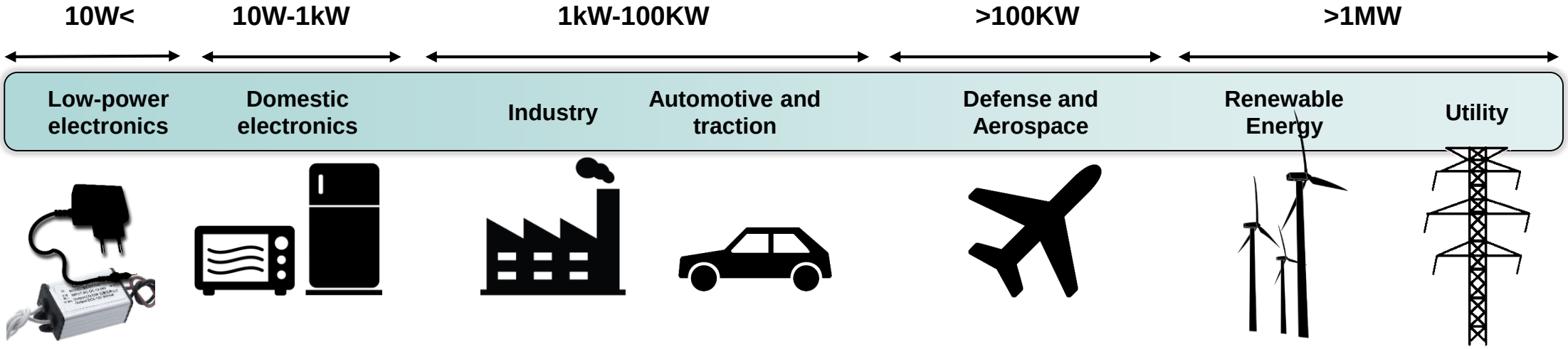


70% of electricity flows through at least one power electronics converter

(ABB. Power Electronics: Revolutionizing the world's future energy systems)



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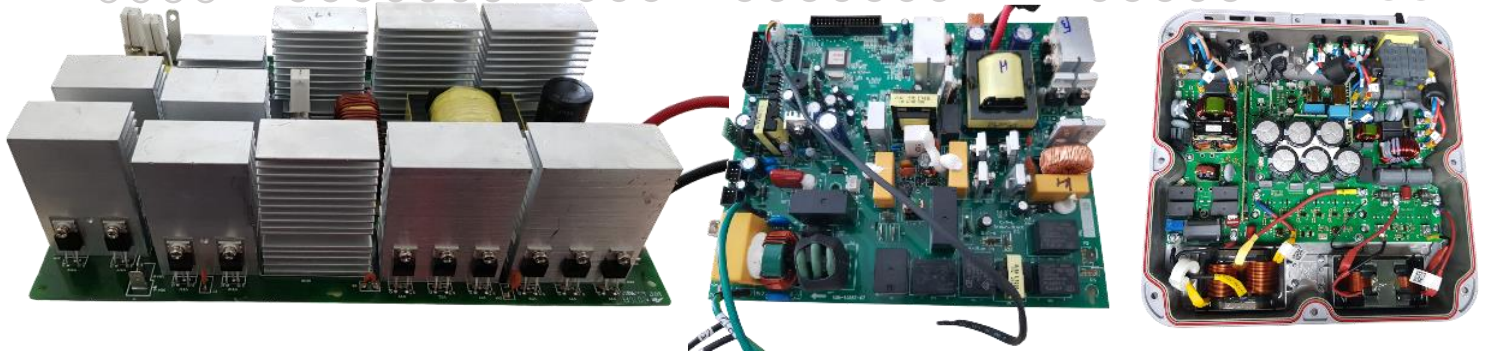

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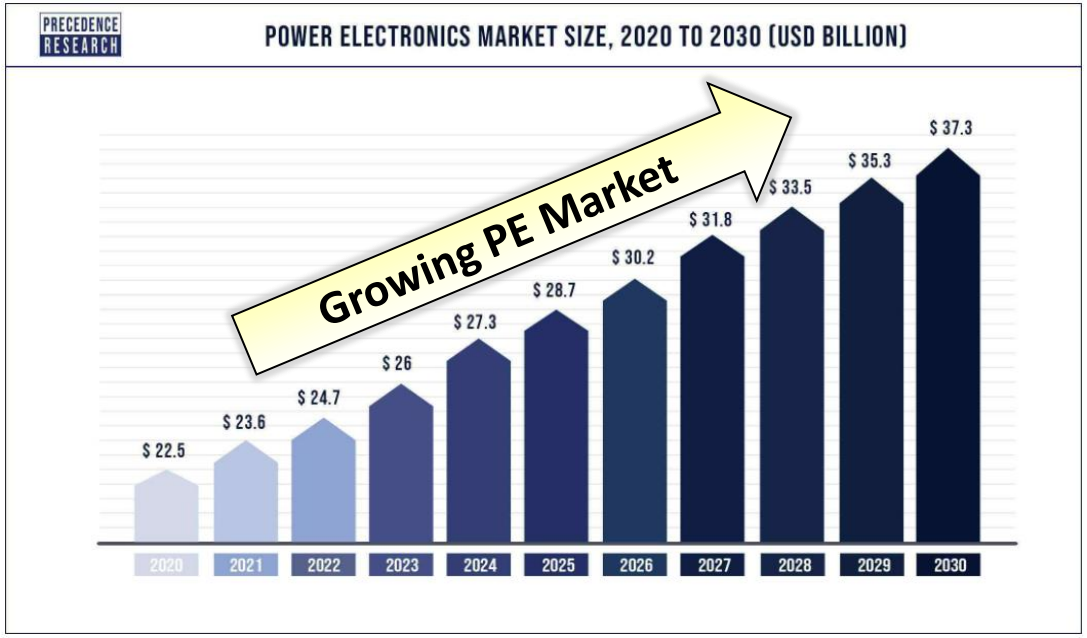

(Power Electronics Market Size, precedenceresearch.com)

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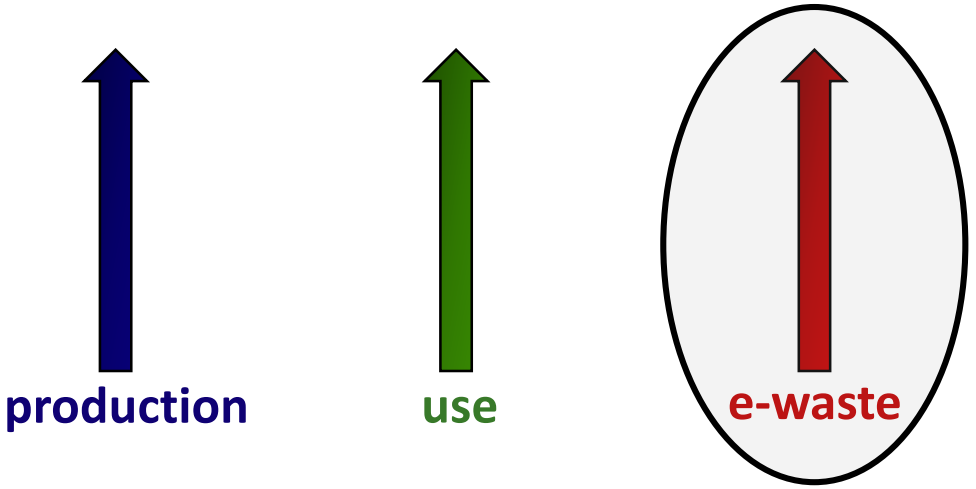
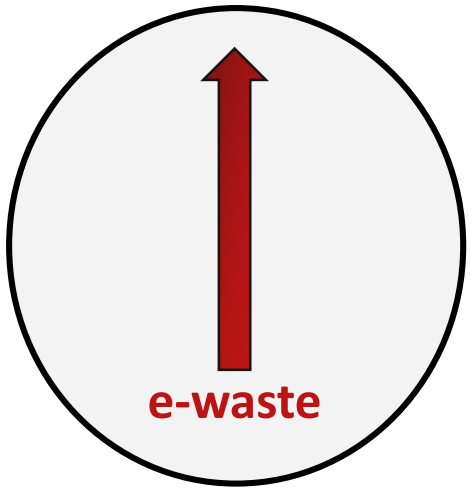


E-waste



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Global E-waste Monitor 2020

Generated	*Projection for 2030*
53 Mt in 2019	74.7 Mt

Global E-waste Monitor 2024

Generated	*Projection for 2030*
62 Mt in 2022	82 Mt

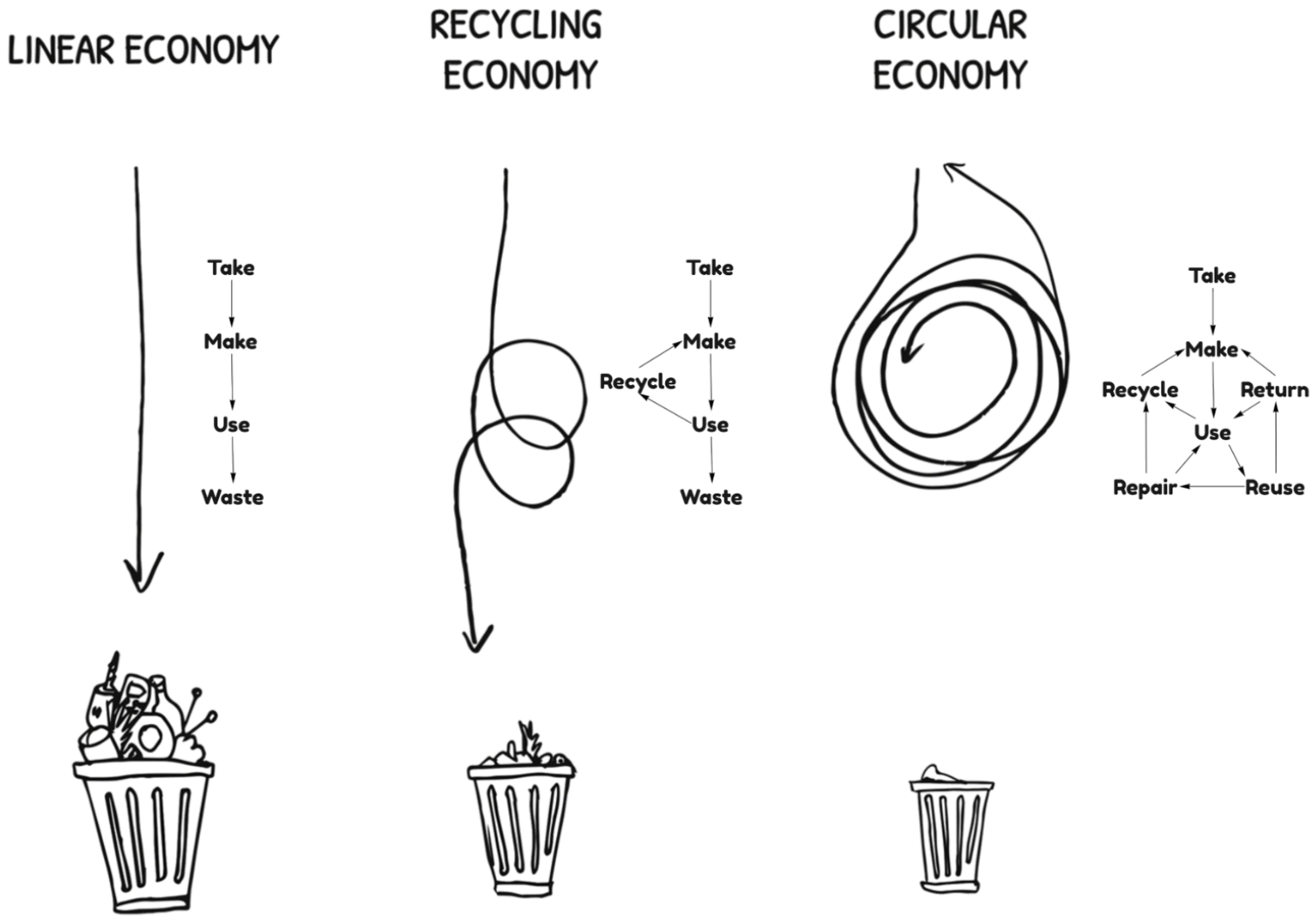
In just four years, the projected e-waste for 2030 surged by

7.3 million metric tons

?

Circular Economy

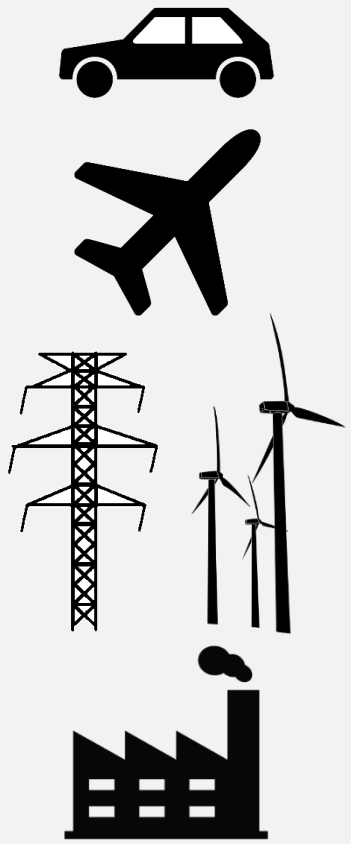
Circular Economy



How to consider circular economy for power electronics

Necessary steps to initiate circular economy

Use Stage



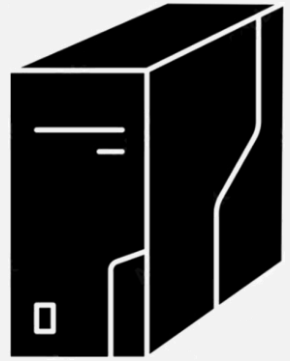
End of Use

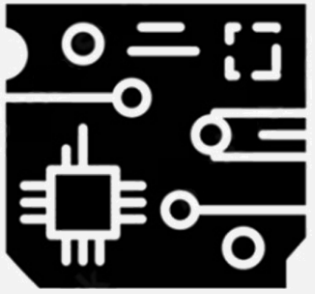
- Obsolete
- Failed
- Broken
- Reached to EoL
- Performance limitations
- Badly designed (reliability)

Collection

- By manufacturer
- By retailer
- By third party
- By municipal

Received

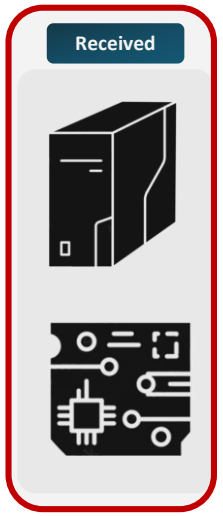




Linear economy

Necessary efforts for circular economy

Scope of the study



What to do

with these PE products

?

R-Strategies

- Direct reuse
- Repair
- Refurbish
- Remanufacture
- Repurpose
- Reuse comp.
- Recycling

Functional recovery

Material recovery

More preferable

Less preferable

Research activity

Research Question

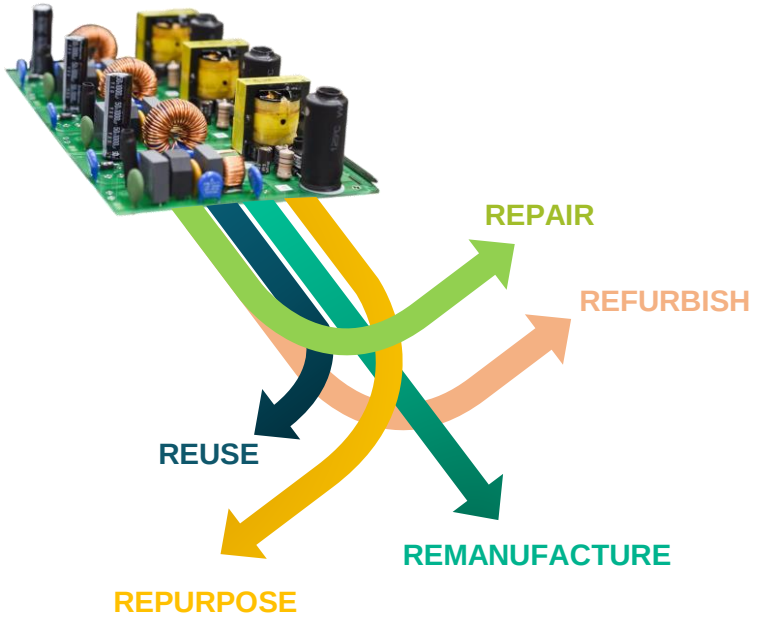
How can the optimal **circular economy strategy** be selected to reintroduce **end-of-use PE products** into the economy, while preserving their **functional value** ?

Research Objective

Find an optimal way to determine the **circular economy strategy** for **end-of-use PE products**

Research Methodology

Identify the **different paths and actions** that should be done in order to determine the best **circular economy strategy** for **end-of-use PE products**



Why decision tree

- Breaking down process into sequential steps
- Effective way to map all steps, interrelations
- Providing a layered analysis

DECISION TREE

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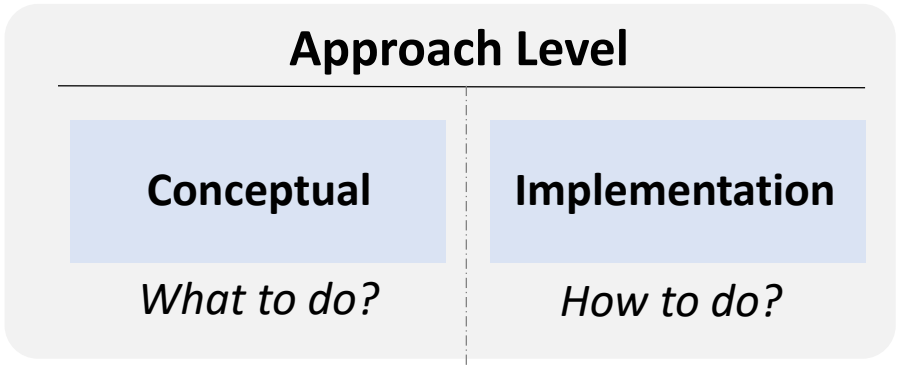
Basics of the decision tree



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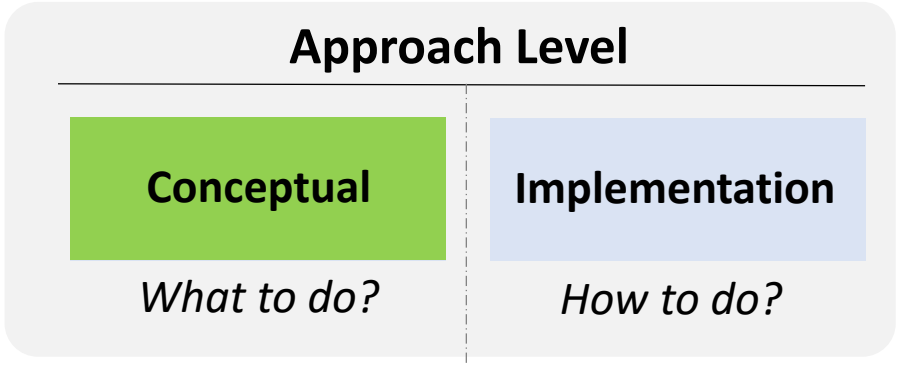


“What to do to determine the R-strategy for PE?”

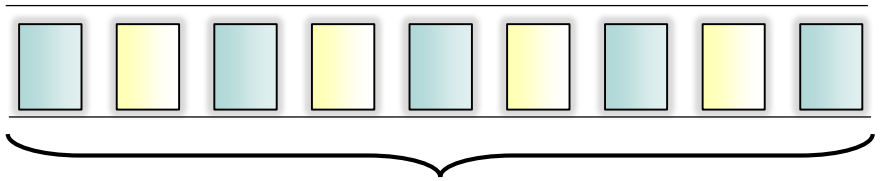
Main objective

Basics of the decision tree

Approach Level

Conceptual	**Implementation**
What to do?	*How to do?*

“What to do to determine the R-strategy for PE?”



smaller and manageable activities

Basics of the decision tree

Approach Level

Conceptual	Implementation
What to do?	*How to do?*

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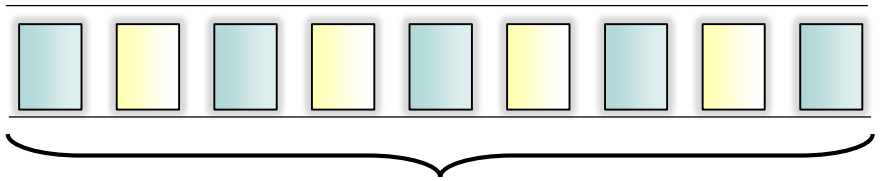

smaller and manageable activities

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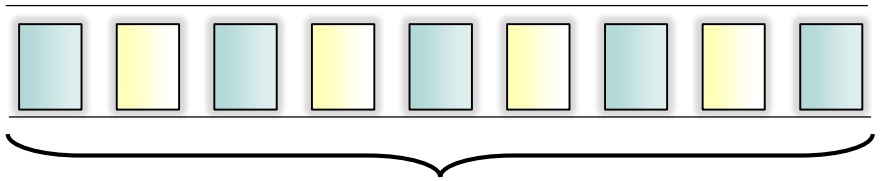
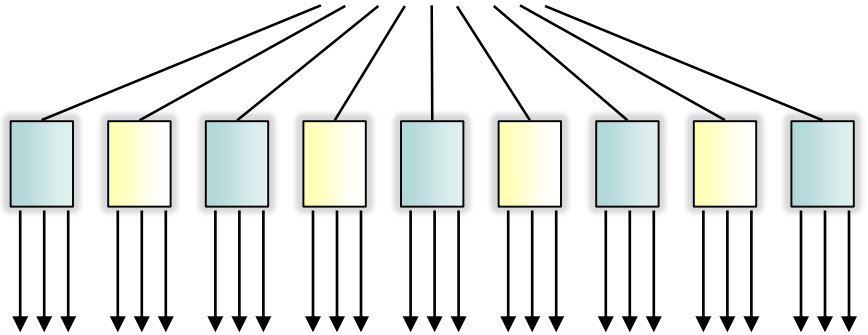


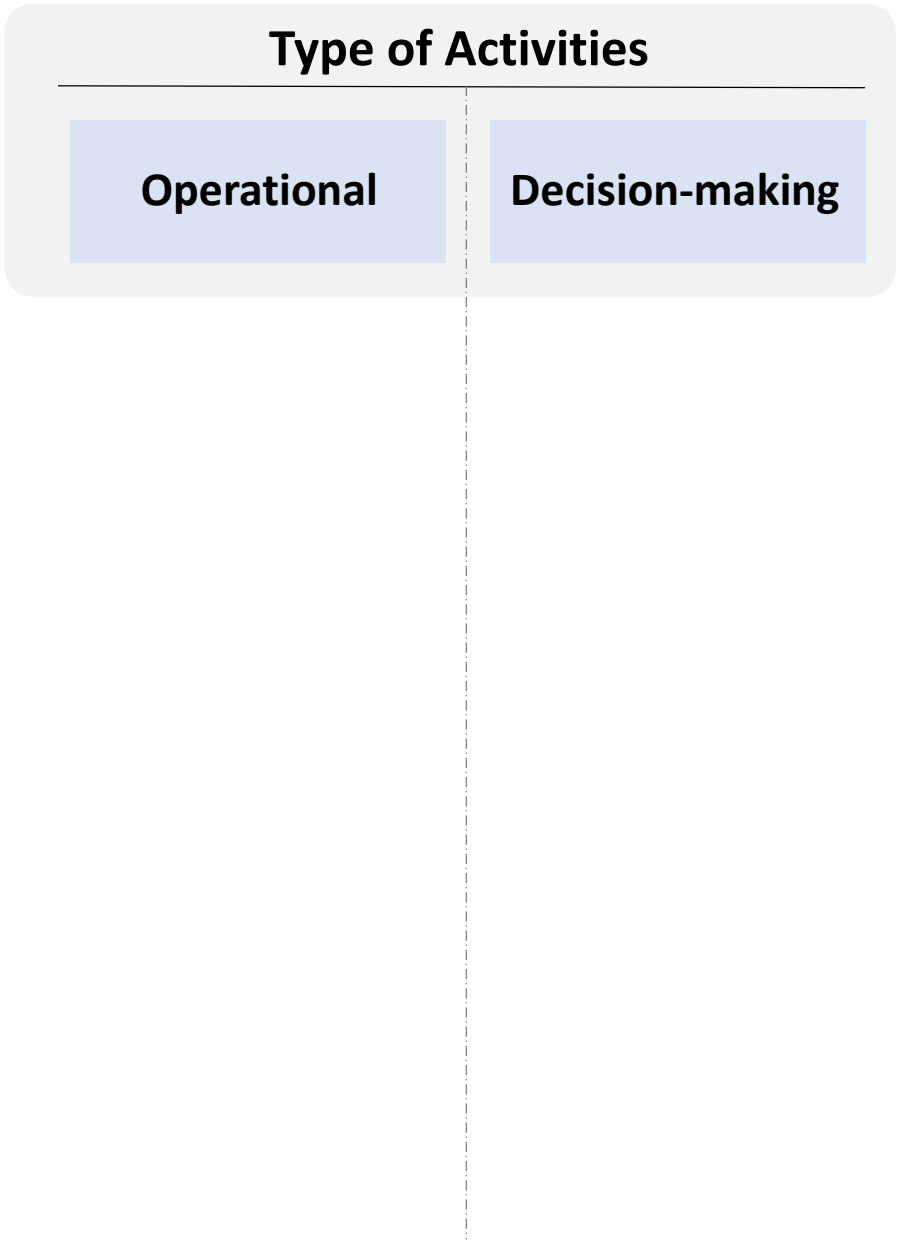
smaller and manageable activities

“How to perform each activity?”



detail each activity

Basics of the decision tree



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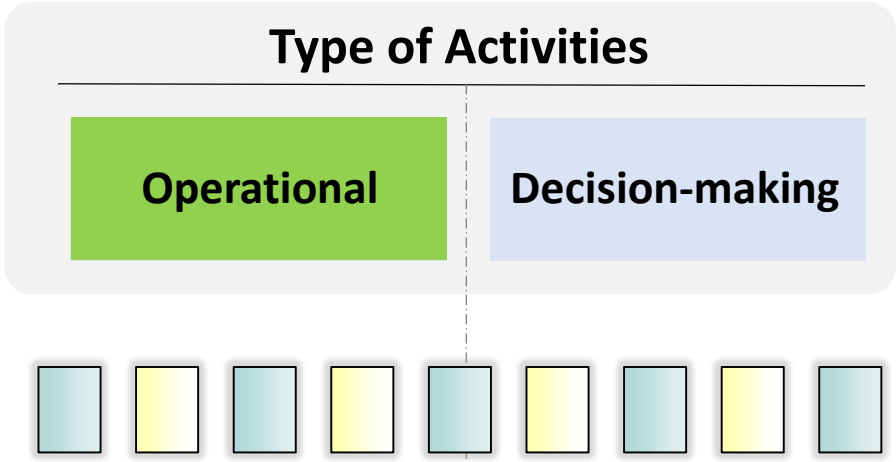

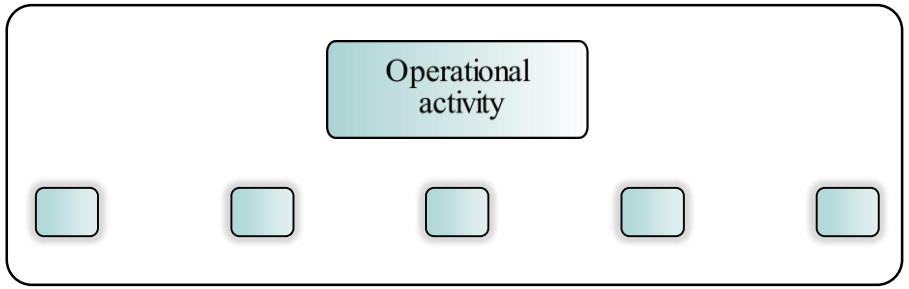

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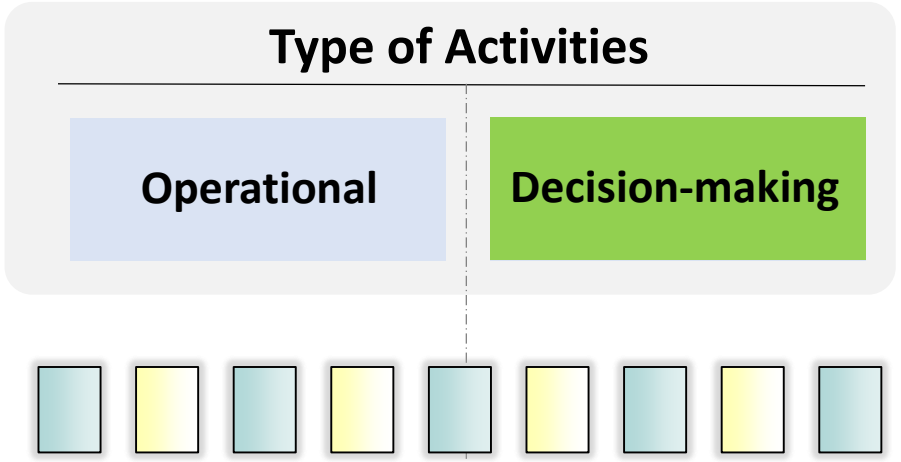

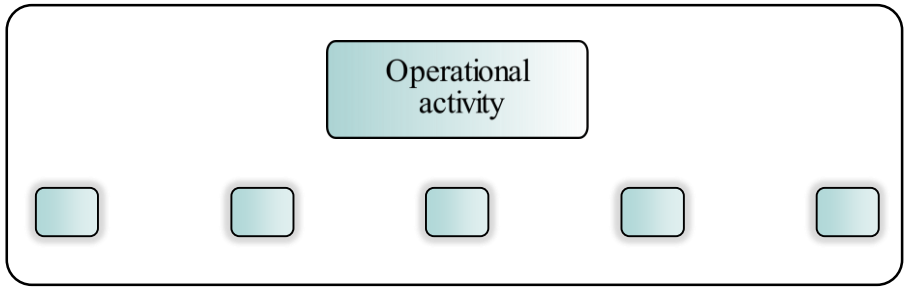

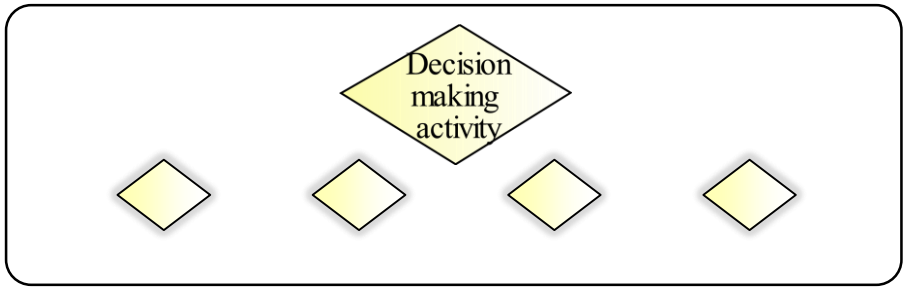

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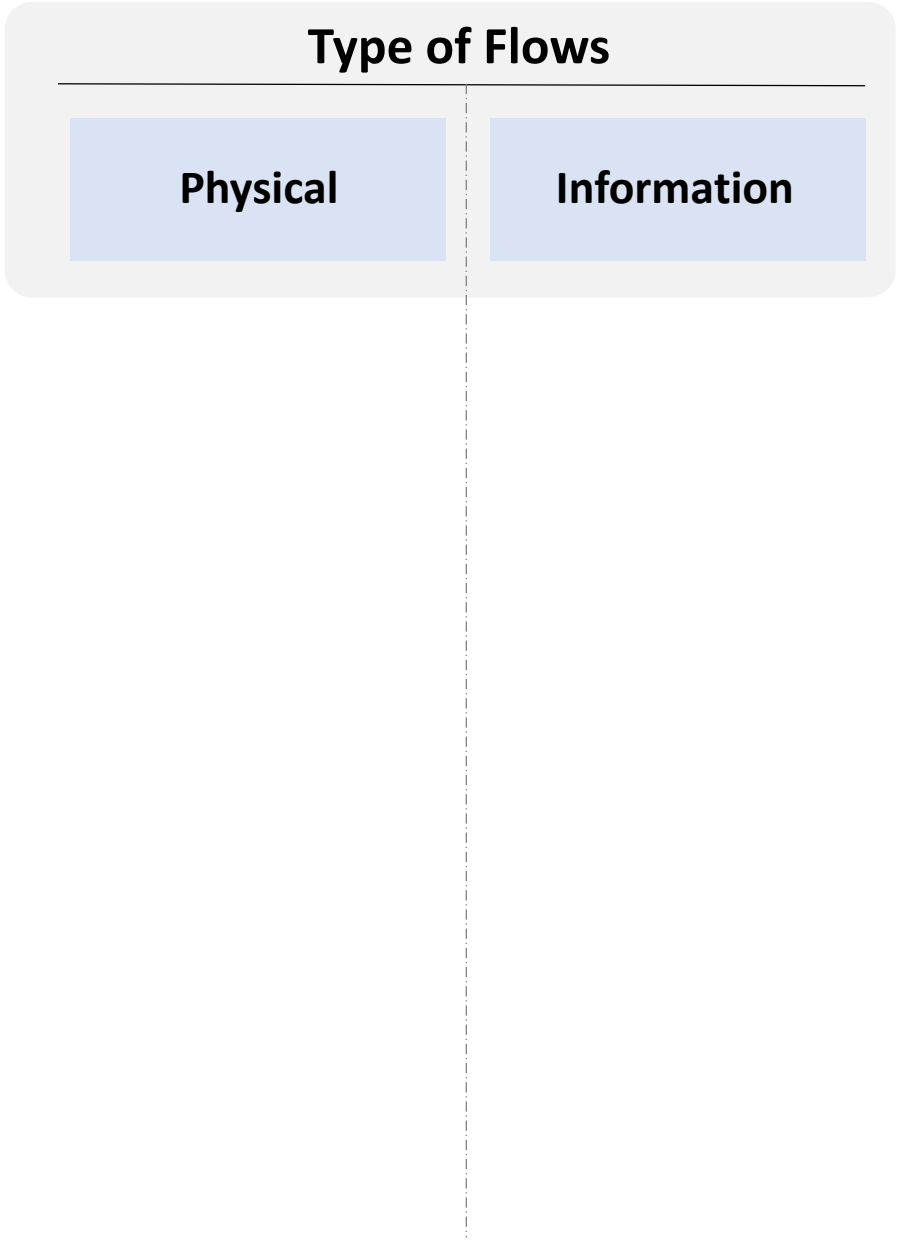
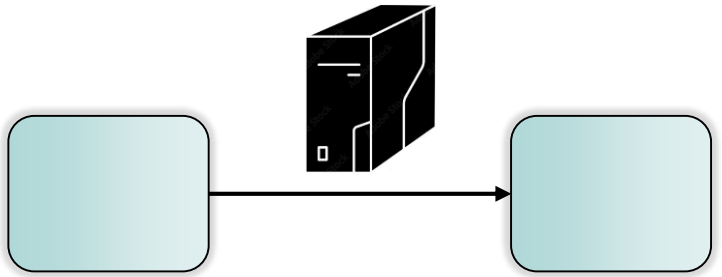


Basics of the decision tree

Type of Flows

Physical	Information



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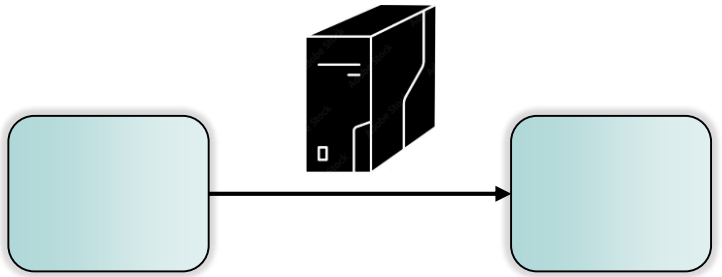
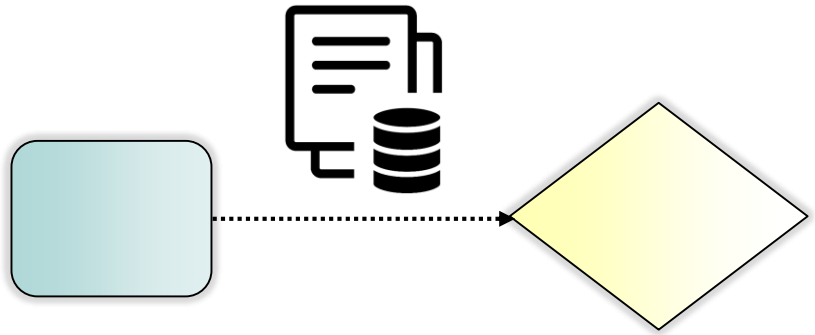
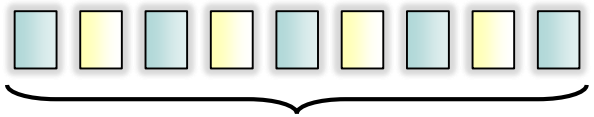




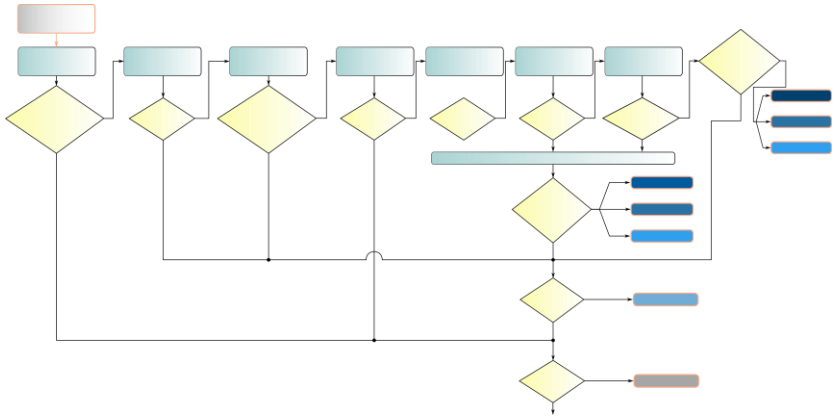
Basics of the decision tree

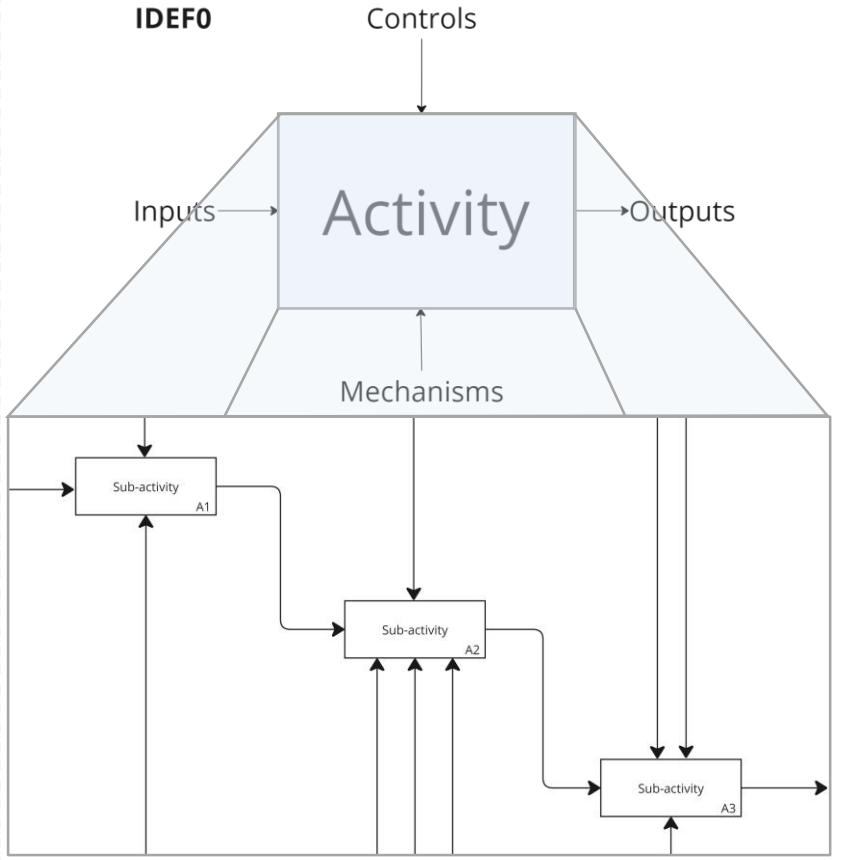
Modeling Languages

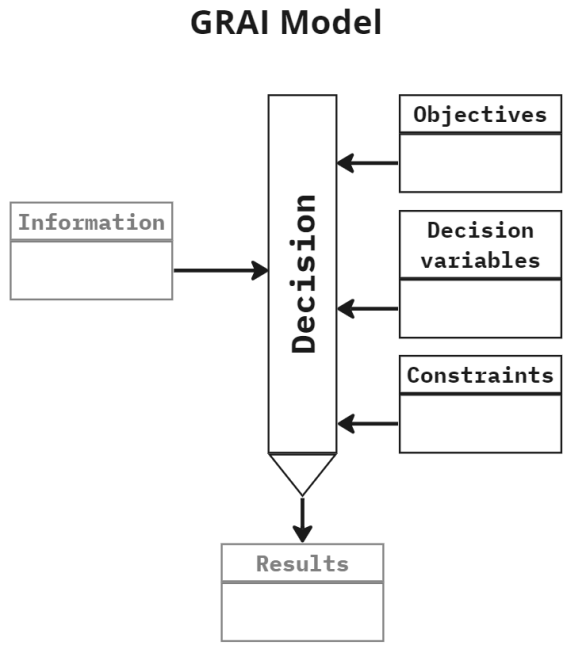
Flowchart | **IDEF0** | **GRAI Net**



smaller and manageable activities







Conceptual level

Operational activity

Implementation level

Implementation level

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Received

What to do

with these
PE products

?

R-Strategies

- Direct reuse
- Repair
- Refurbish
- Remanufacture
- Repurpose
- Reuse comp.
- Recycling

Decision Tree

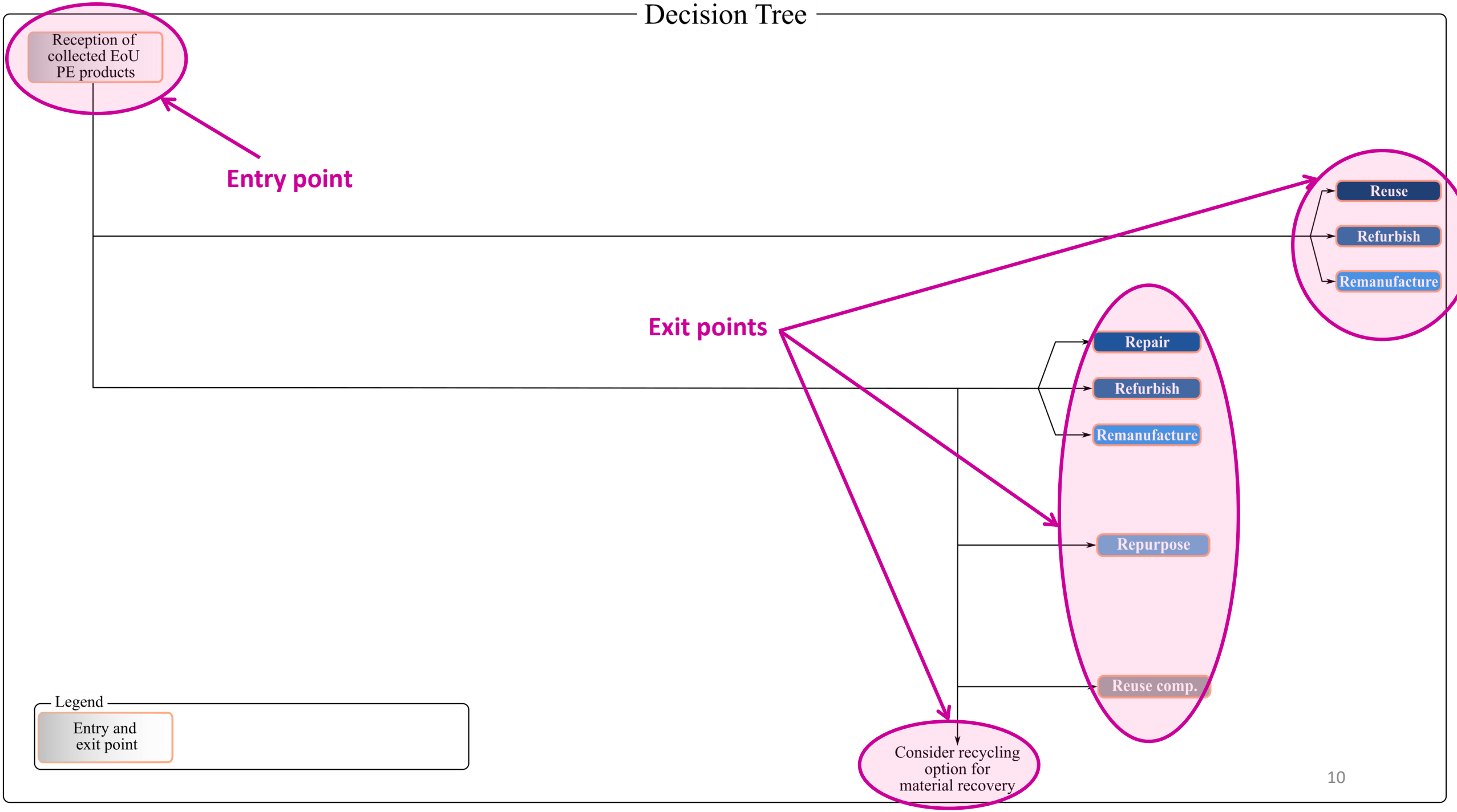
Reception of collected EoU PE products

- Reuse
- Refurbish
- Remanufacture
- Repair
- Refurbish
- Remanufacture
- Repurpose
- Reuse comp.
- Consider recycling option for material recovery

Legend

Entry and exit point

Decision Tree



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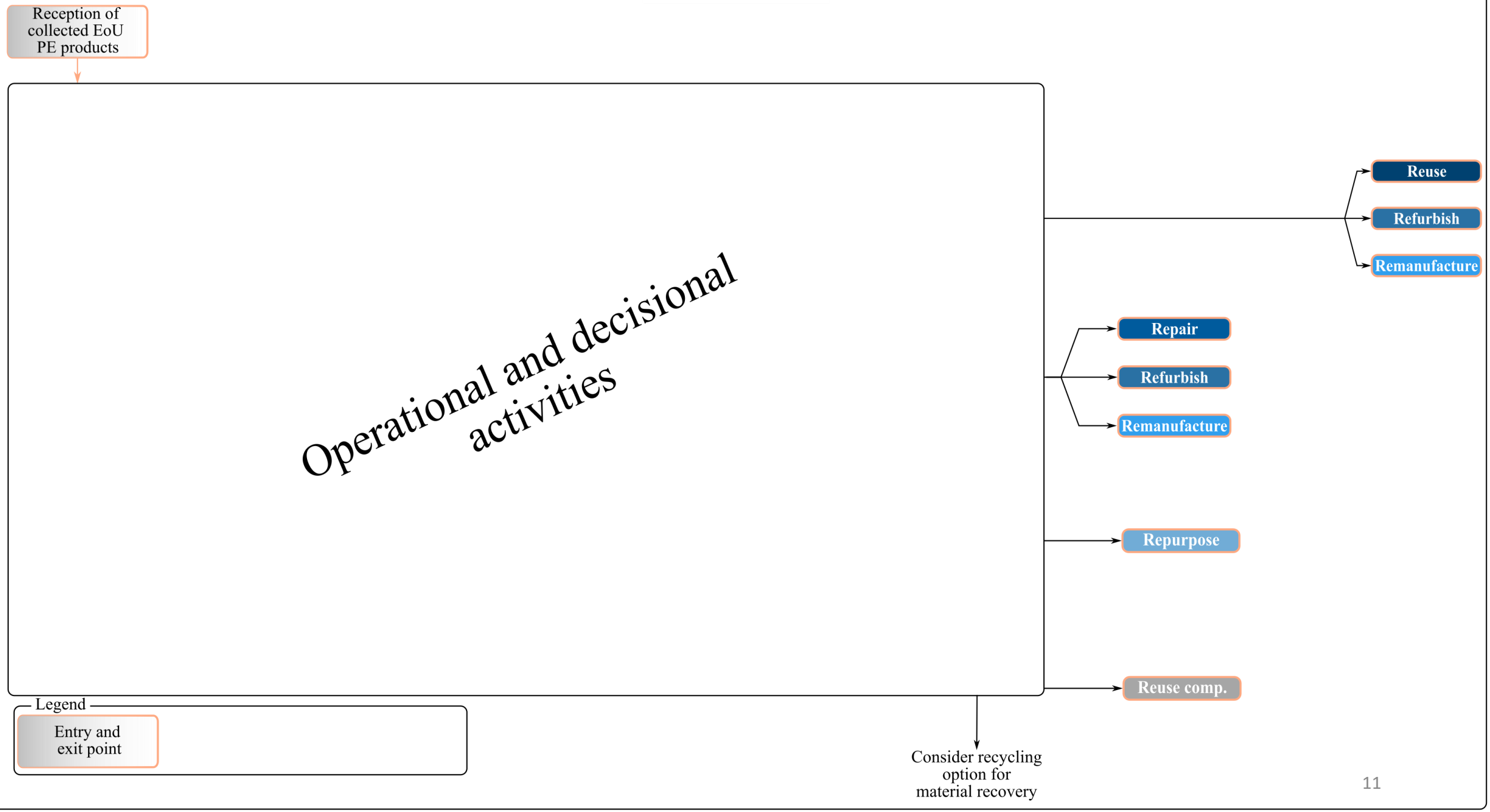

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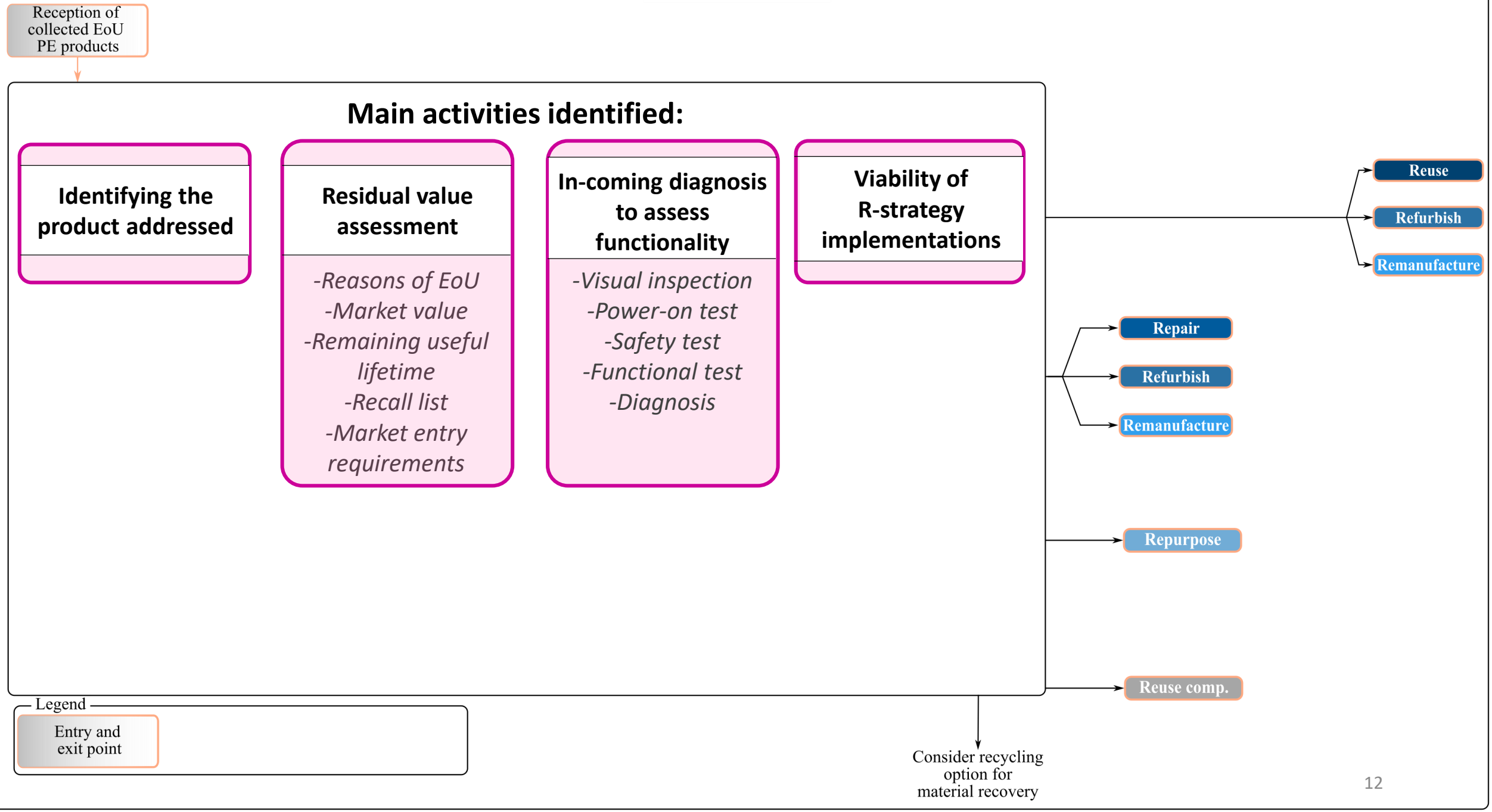

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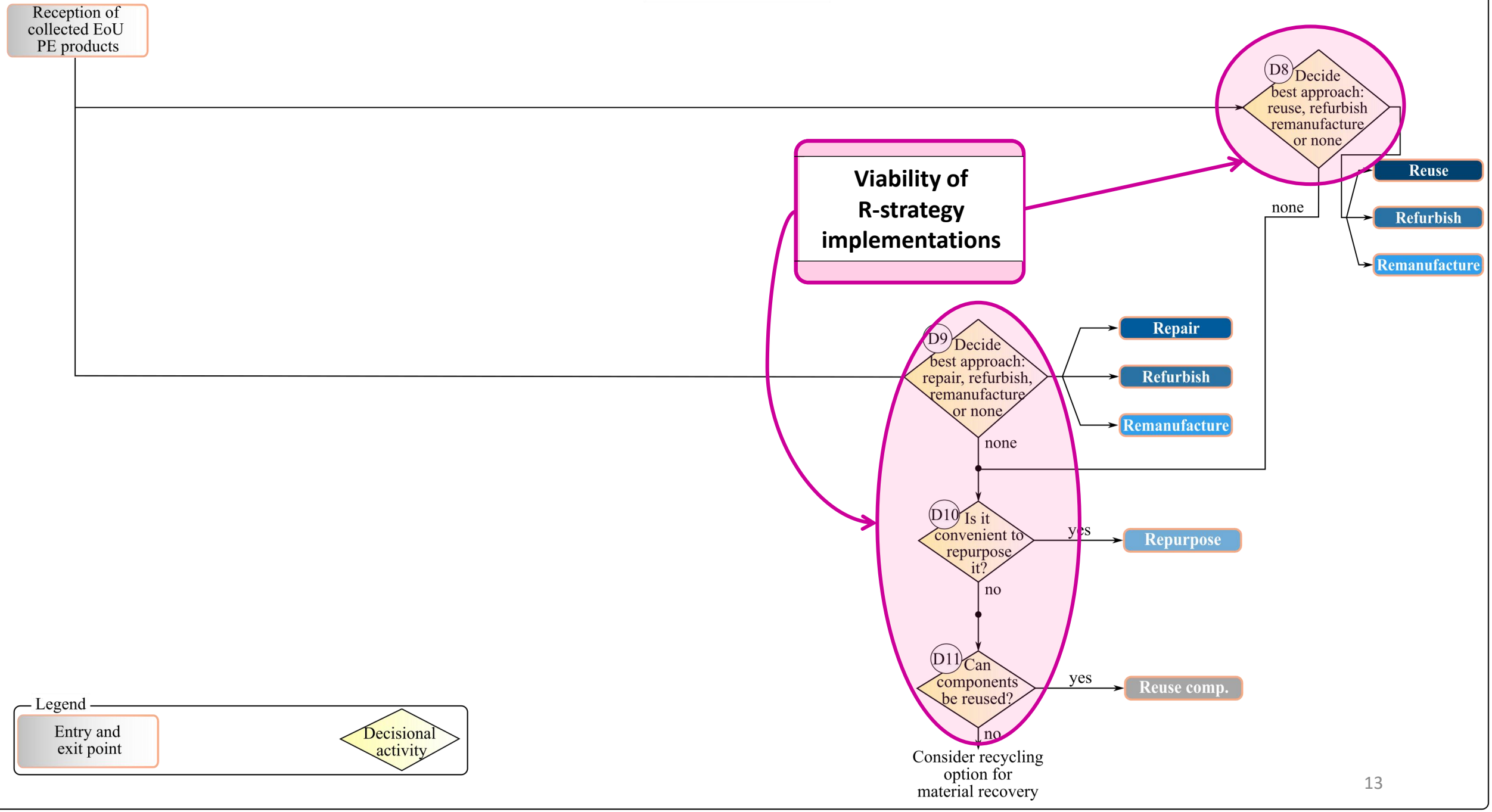

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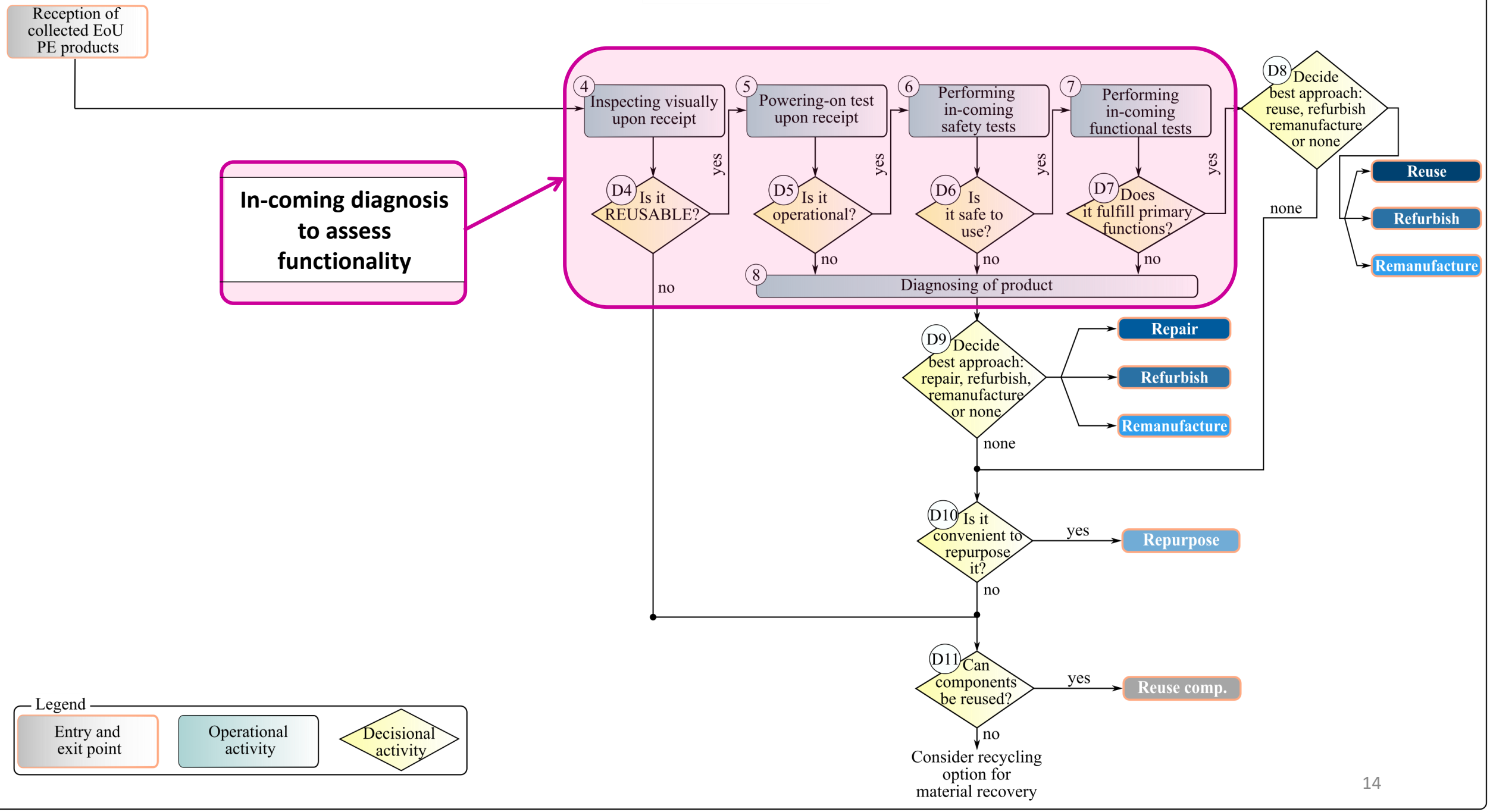

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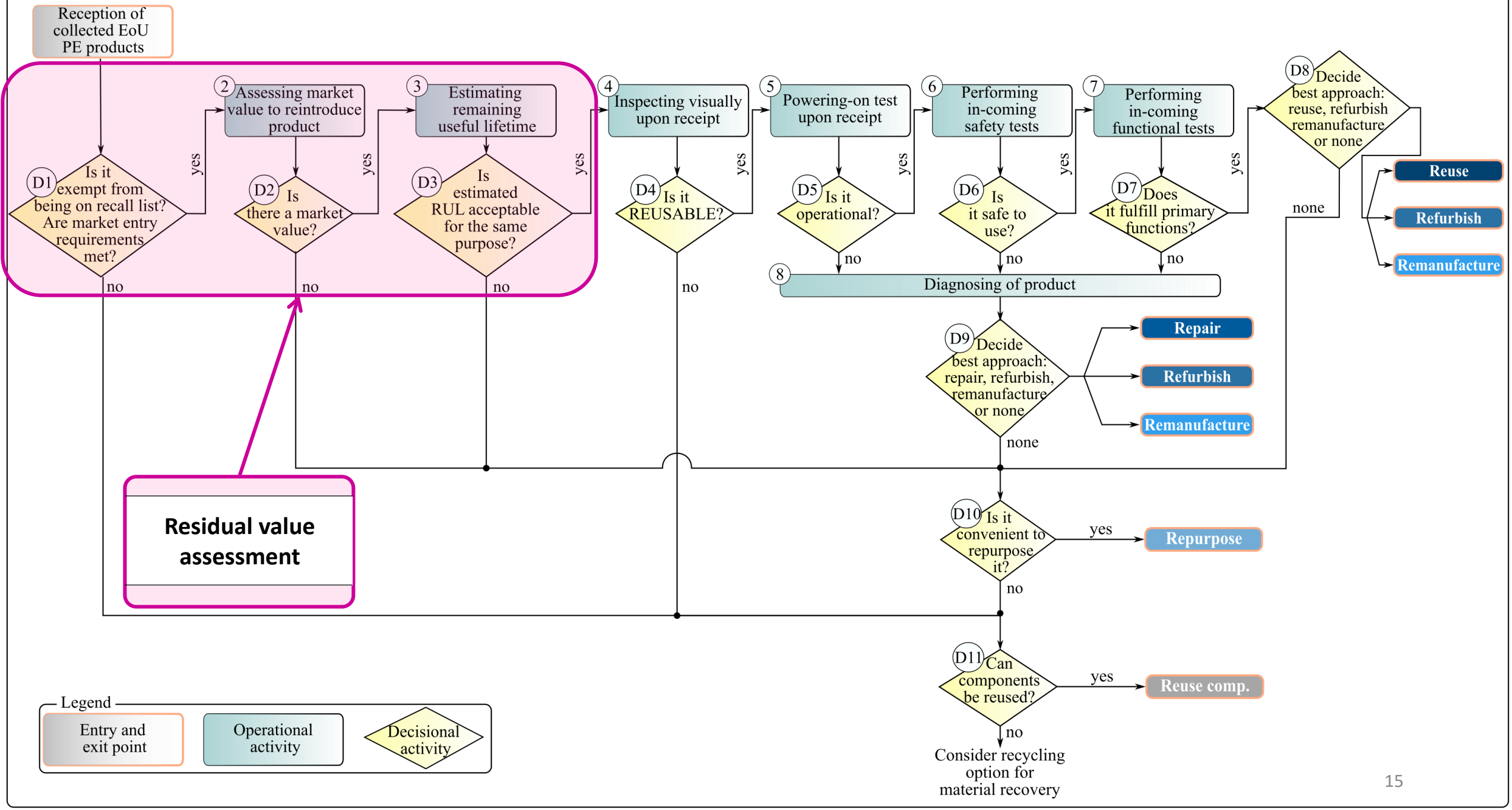

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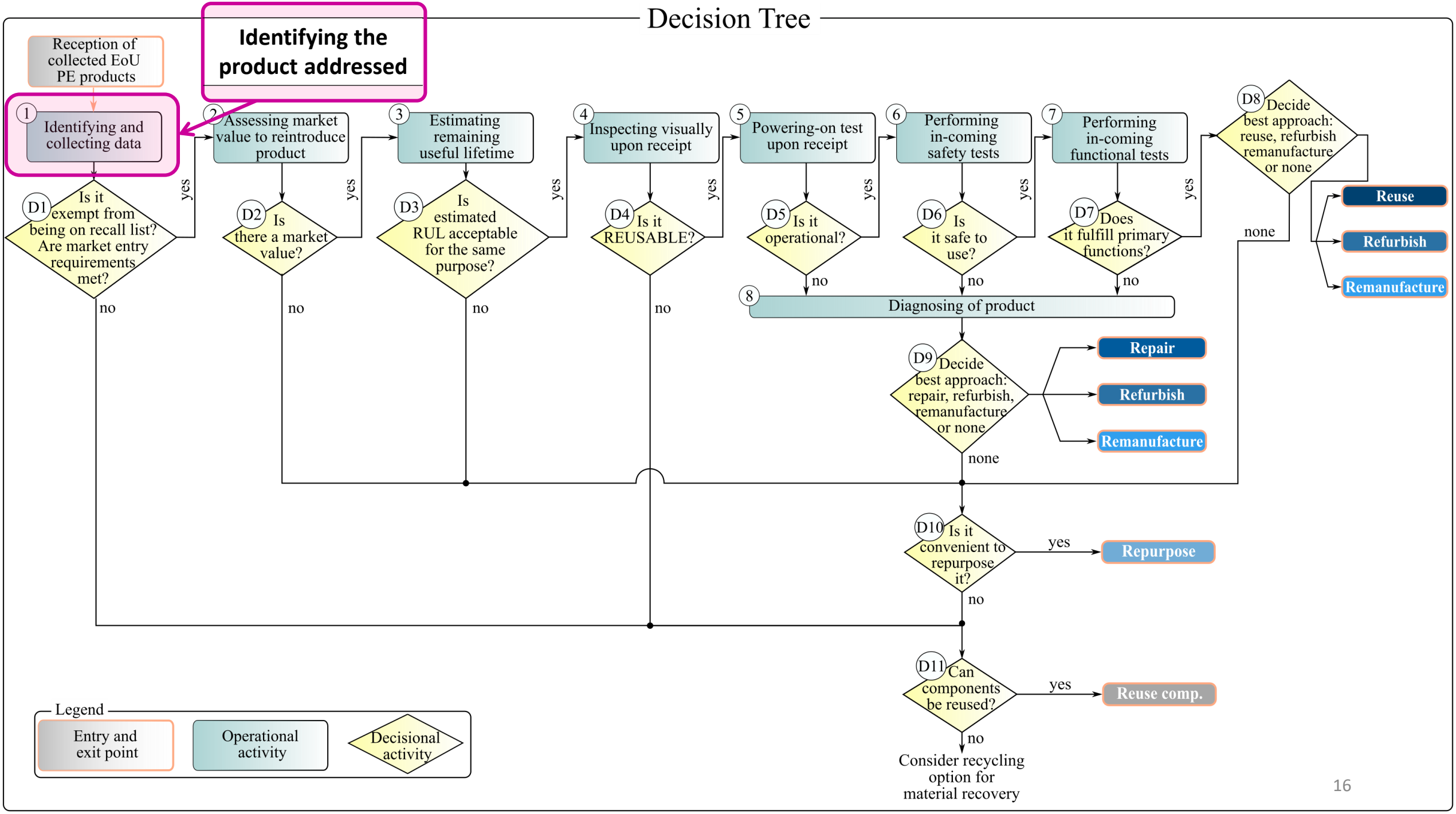

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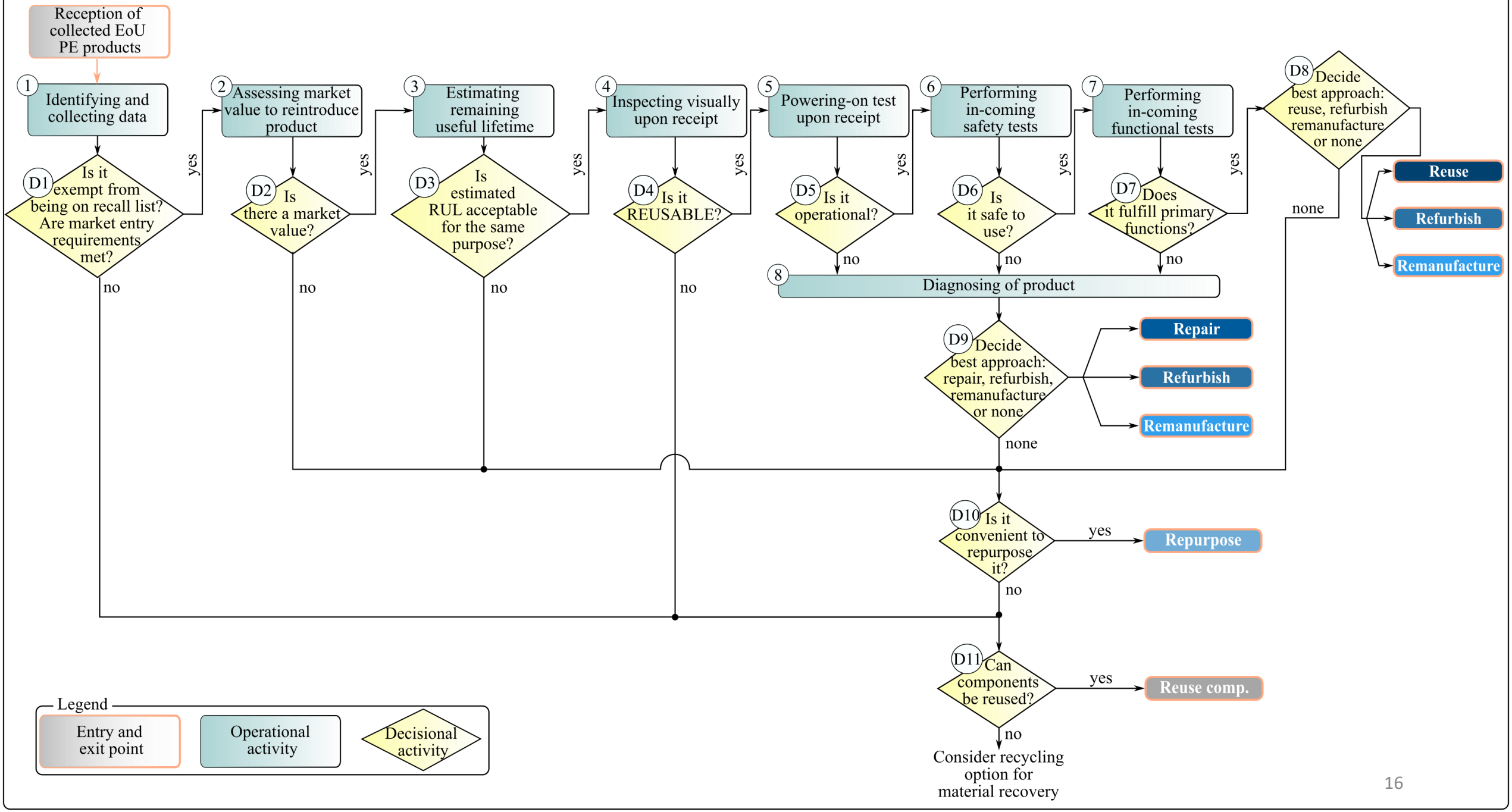

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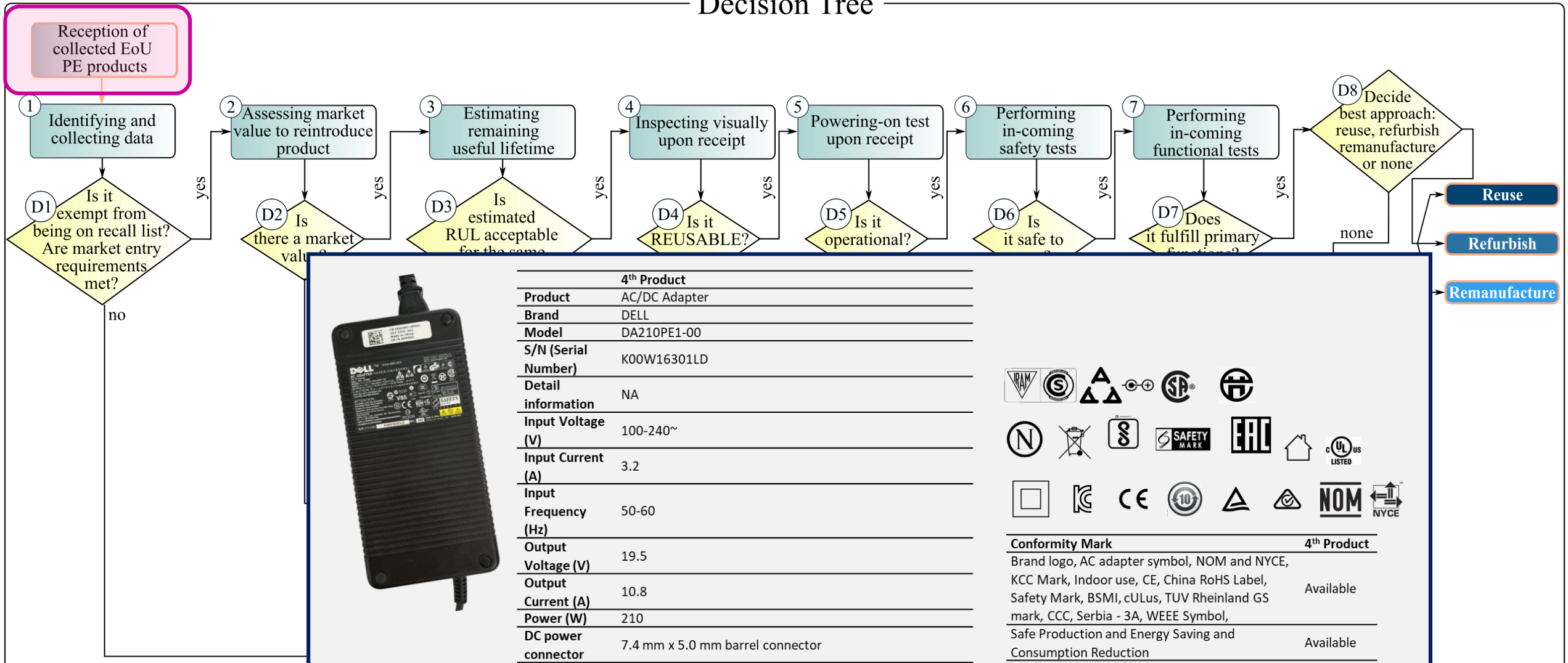
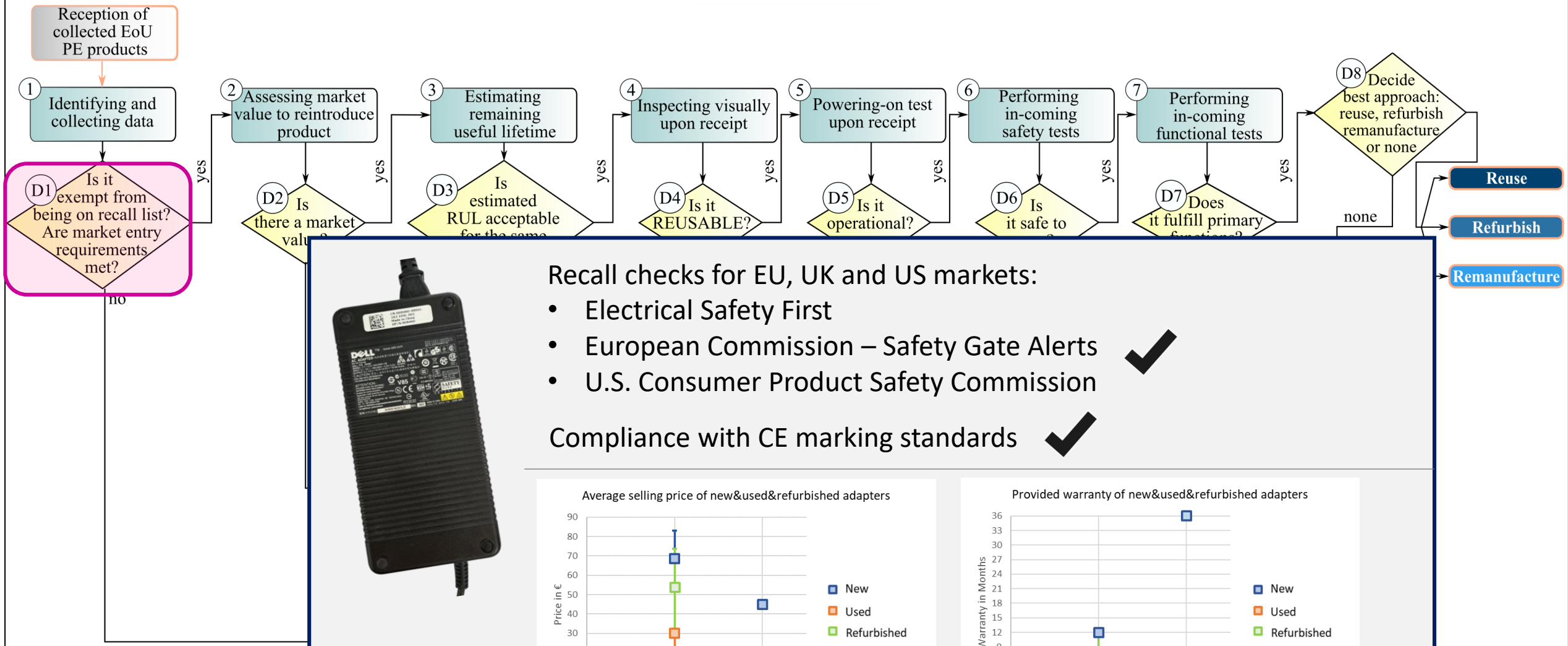


	4th Product
Product	AC/DC Adapter
Brand	DELL
Model	DA210PE1-00
S/N (Serial Number)	K00W16301LD
Detail information	NA
Input Voltage (V)	100-240~
Input Current (A)	3.2
Input Frequency (Hz)	50-60
Output Voltage (V)	19.5
Output Current (A)	10.8
Power (W)	210
DC power connector	7.4 mm x 5.0 mm barrel connector
AC connector	IEC 60320 C14
AC cable power cord	IEC 60320 C13
LED indicator	On the power supply
List of compatible products (not limited to)	Dell Latitude E(2100, 4200, 4300, 4310, 5400, 5410, 5500, 5510, 6400, 6410, 6420 XFR, 6500, 6510, 6530). Precision series: M(2400, 4400, 4500, 4600, 4700, 6400, 6500, 6600, 6700)
Energy Efficiency	V class

Conformity Mark	4th Product
Brand logo, AC adapter symbol, NOM and NYCE, KCC Mark, Indoor use, CE, China RoHS Label, Safety Mark, BSMI, cULus, TUV Rheinland GS mark, CCC, Serbia - 3A, WEEE Symbol,	Available
Safe Production and Energy Saving and Consumption Reduction	Available
C tick	-
Product certification for export to Ukraine	-
CU TR/GOST	Available
Class II equipment with functional earthing, Type Approval for Market Access in Morocco, Market of Moldova, EAC, Argentine conformity, Indian conformity, RoHS,	-
Norway compliance	Available
North American energy efficiency requirements, Japan conformity	Available

Decision Tree

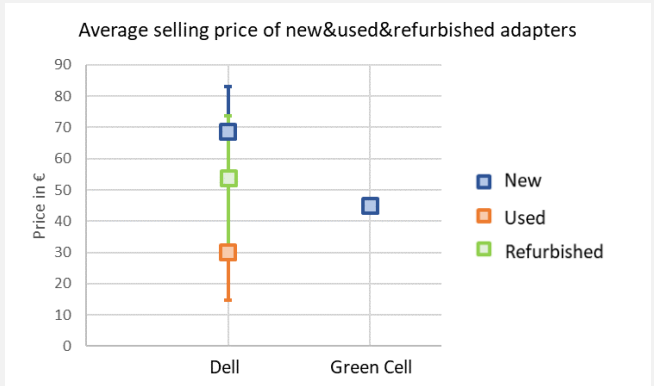


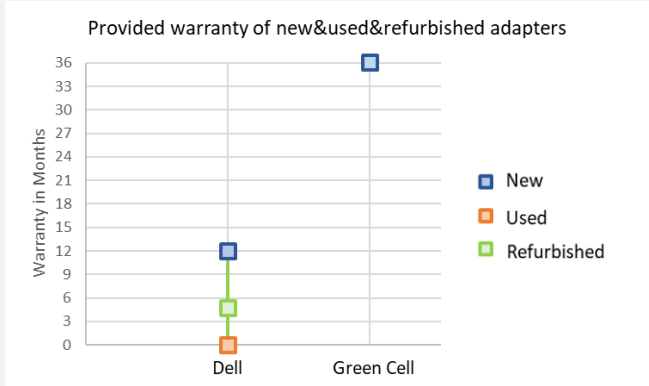
Recall checks for EU, UK and US markets:

- Electrical Safety First
- European Commission – Safety Gate Alerts
- U.S. Consumer Product Safety Commission

✓

Compliance with CE marking standards ✓





No information about

- Operation hours
- Date of purchase
- Aging factors
- Expected **service life** of the adapters

Decision Tree

Visual inspection

-Housing, cables, labels..

Power-on test

Quick check if product is operational

Safety test

-Visual inspection
-Electrical tests
-Temperature test

Functional test

-Technical specification
-Functionalities

Reception of collected EoU PE products
1 Identifying and collecting data
D1 Is it exempt from
2 Assessing market value to reintroduce product
D2 Is
3 Estimating remaining useful lifetime
D3 Is estimated
4 Inspecting visually upon receipt
D4 Is it
5 Powering-on test upon receipt
D5 Is it nal?
6 Performing in-coming safety tests
D6 Is it safe to use?
7 Performing in-coming functional tests
D7 Does it fulfill primary functions?
D8 Decide best approach: reuse, refurbish remanufacture or none
Reuse
Refurbish
Remanufacture
yes
no
none
Diagnosing of product
D9 Decide best approach: repair, refurbish, remanufacture or none
Repair
Refurbish
Remanufacture
D10 Is it convenient to repurpose it?
Repurpose
D11 Can components be reused?
Reuse comp.
Consider recycling option for material recovery

Visual inspection

-Housing, cables, labels..

Power-on test

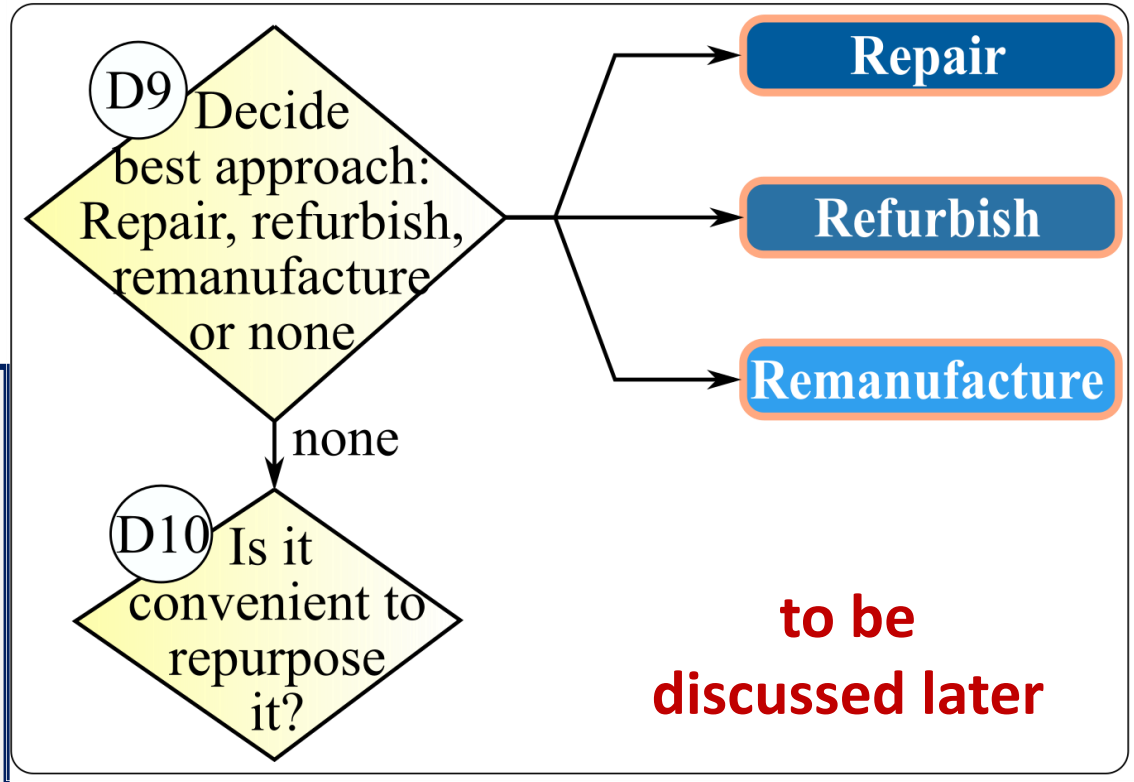
Quick check if product is operational

Safety test

-Visual inspection
-Electrical tests
-Temperature test

Functional test

-Technical specification
-Functionalities



to be discussed later

Agenda

Motivation

- *Power electronics*
- *E-waste*
- *Circular economy*
- *Scope of the study*
- *Research activity*

Decision Tree

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- *Conceptual level*
- *Case study at conceptual level*
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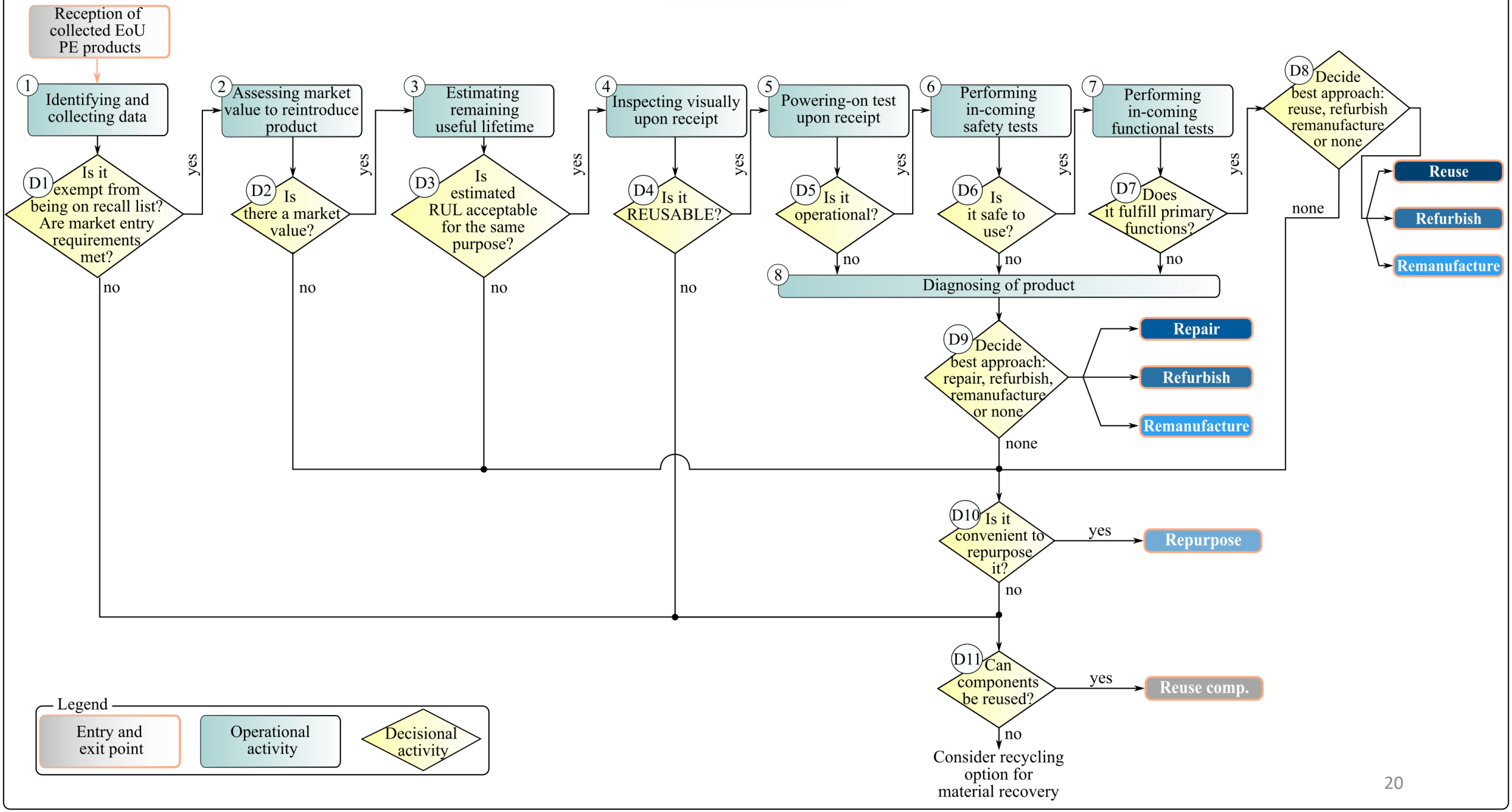
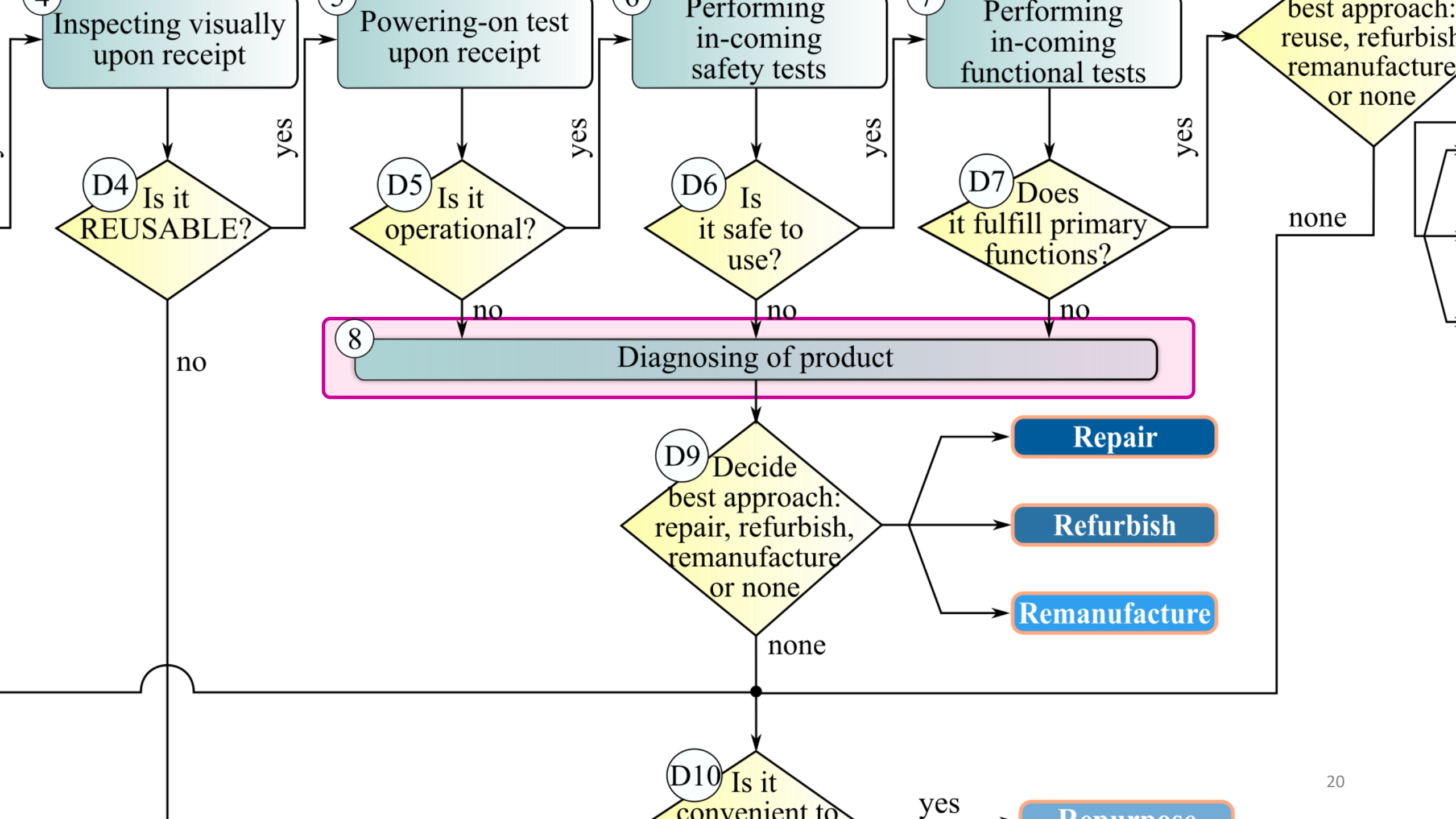
Index

- *Equation*
- *Benchmark*
- *Results*

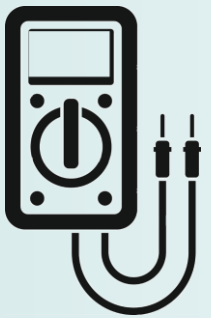
Conclusion & Perspectives

Decision Tree




Inspecting visually upon receipt
Powering-on test upon receipt
Performing in-coming safety tests
Performing in-coming functional tests
best approach: reuse, refurbish remanufacture or none
D4 Is it REUSABLE?
D5 Is it operational?
D6 Is it safe to use?
D7 Does it fulfill primary functions?
yes
no
none
8 Diagnosing of product
D9 Decide best approach: repair, refurbish, remanufacture or none
Repair
Refurbish
Remanufacture
D10 Is it convenient to

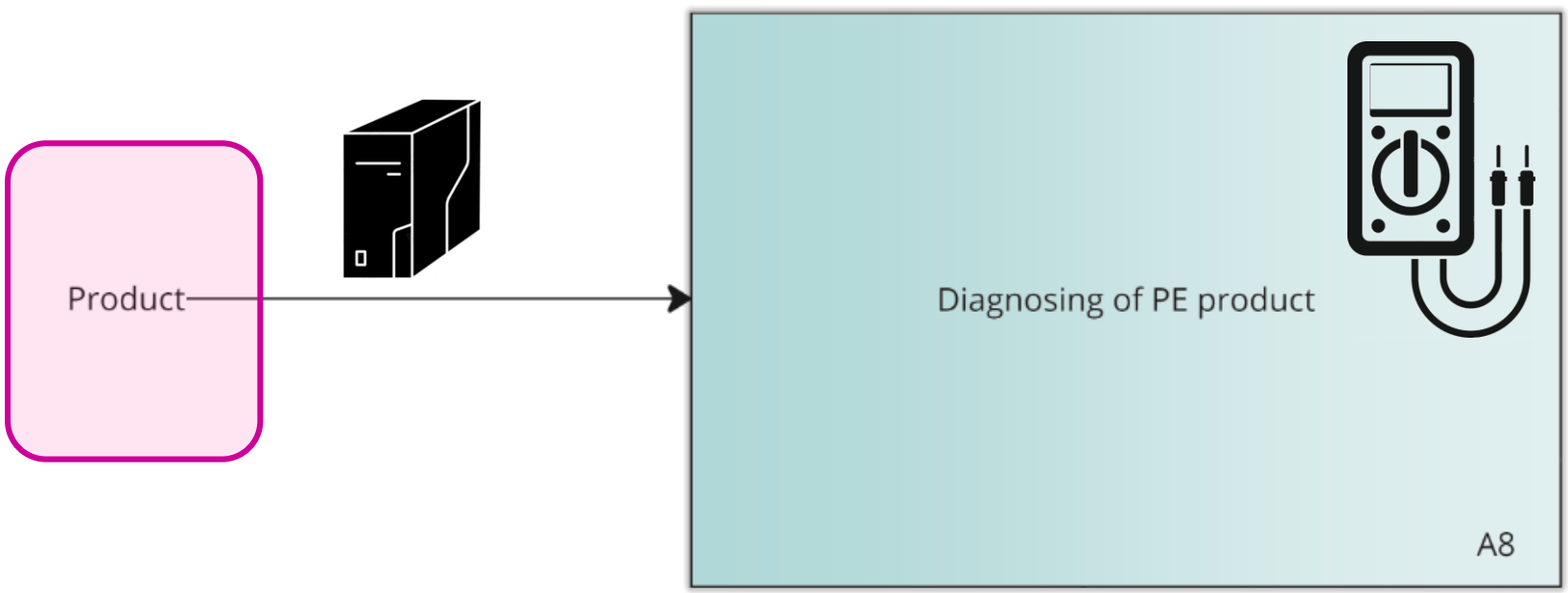
Diagnosing of PE product



A8

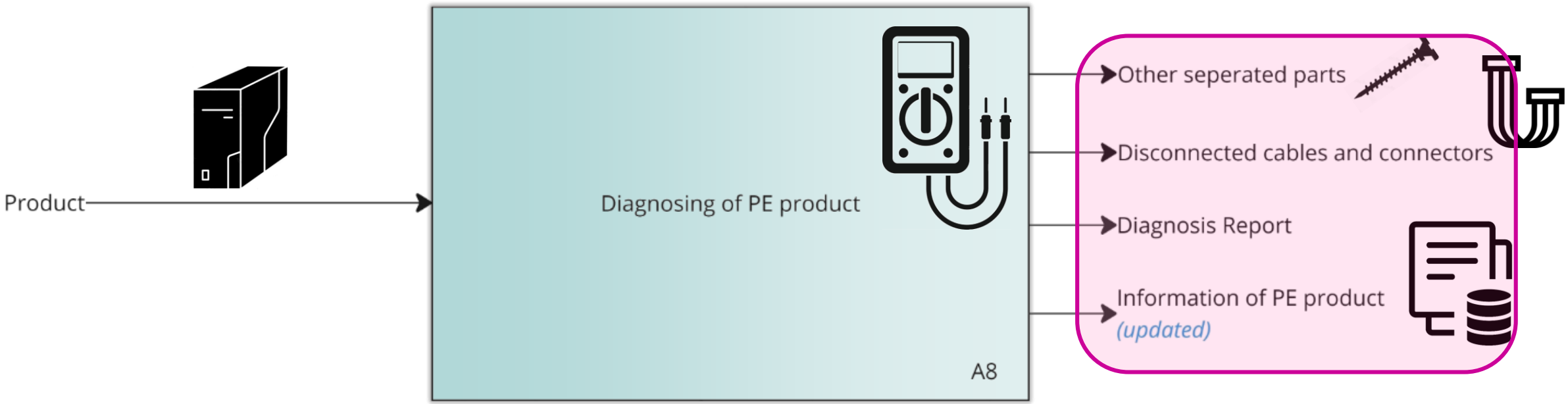
Node: A-0	Title: Determining Effective Value Recovery Options	No: 8

Inputs to activity



Node: A-0	Title: Determining Effective Value Recovery Options	No: 8

Output from activity



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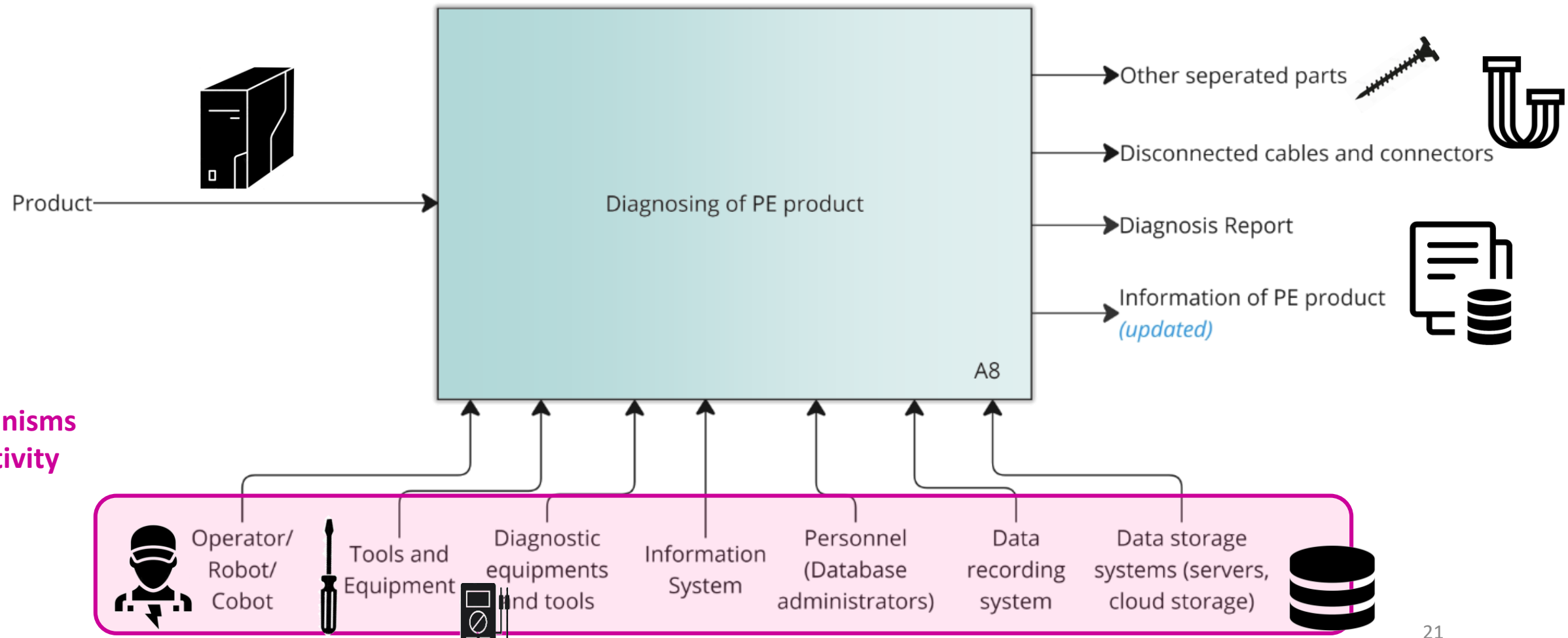

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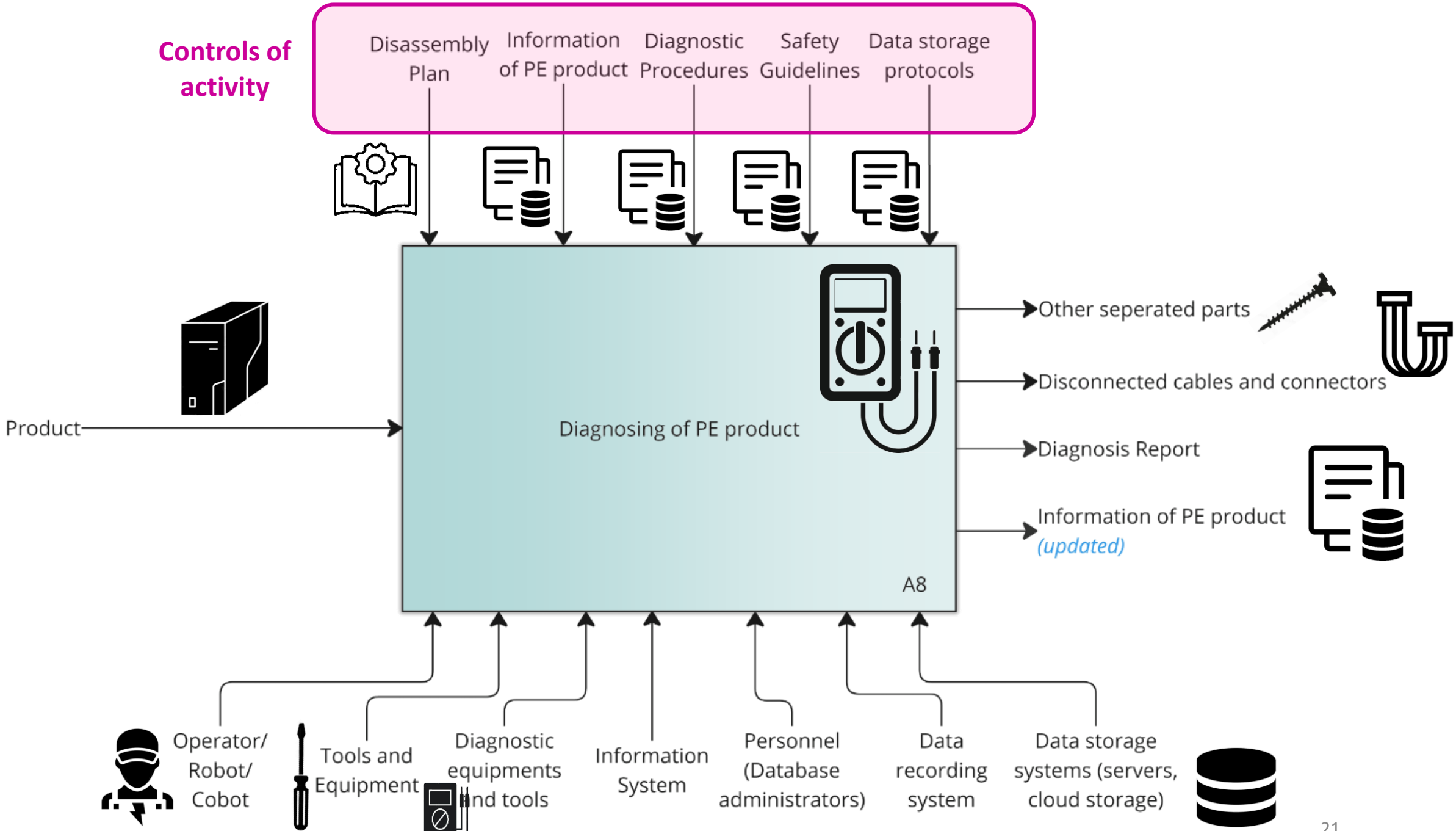

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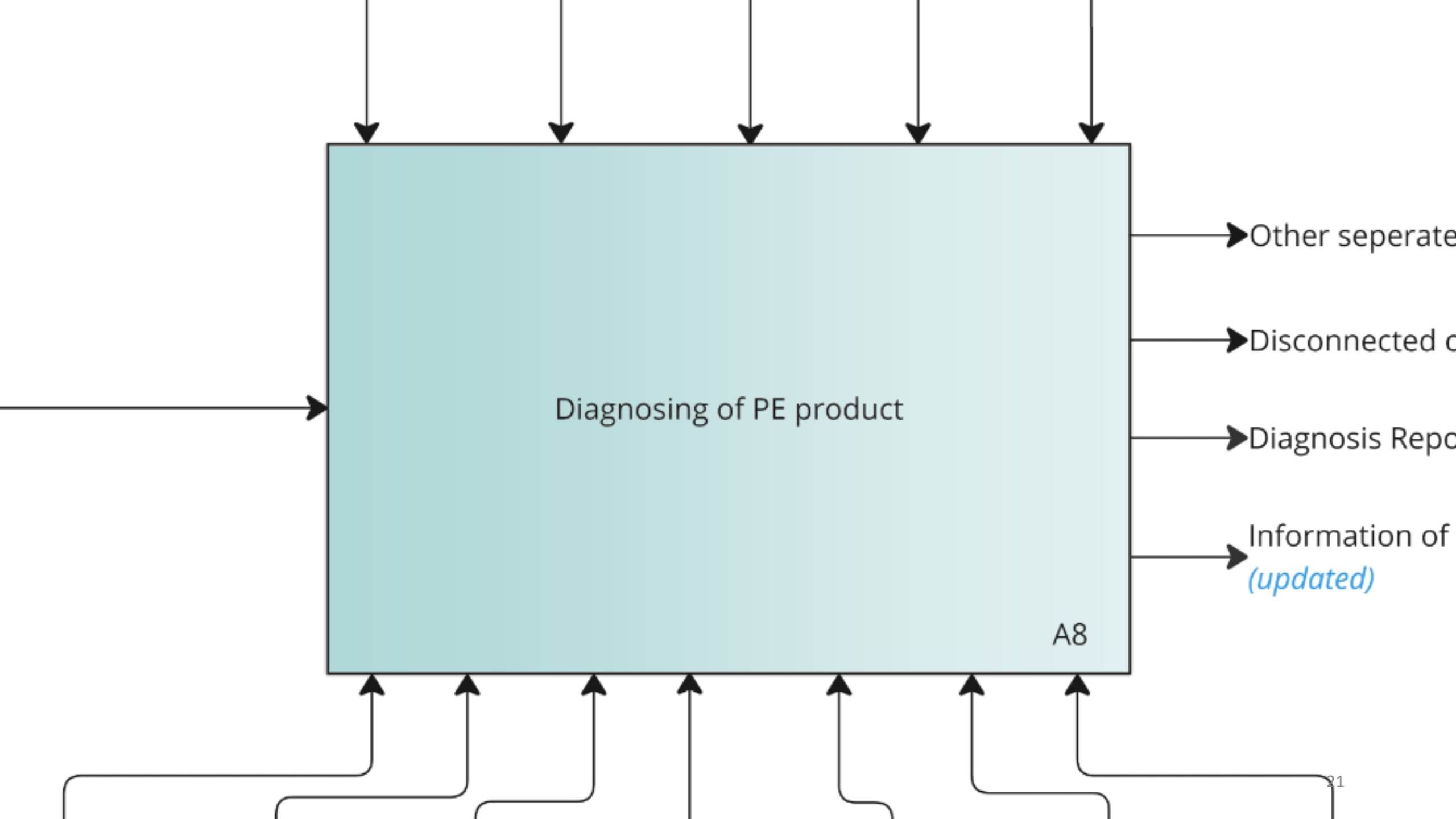
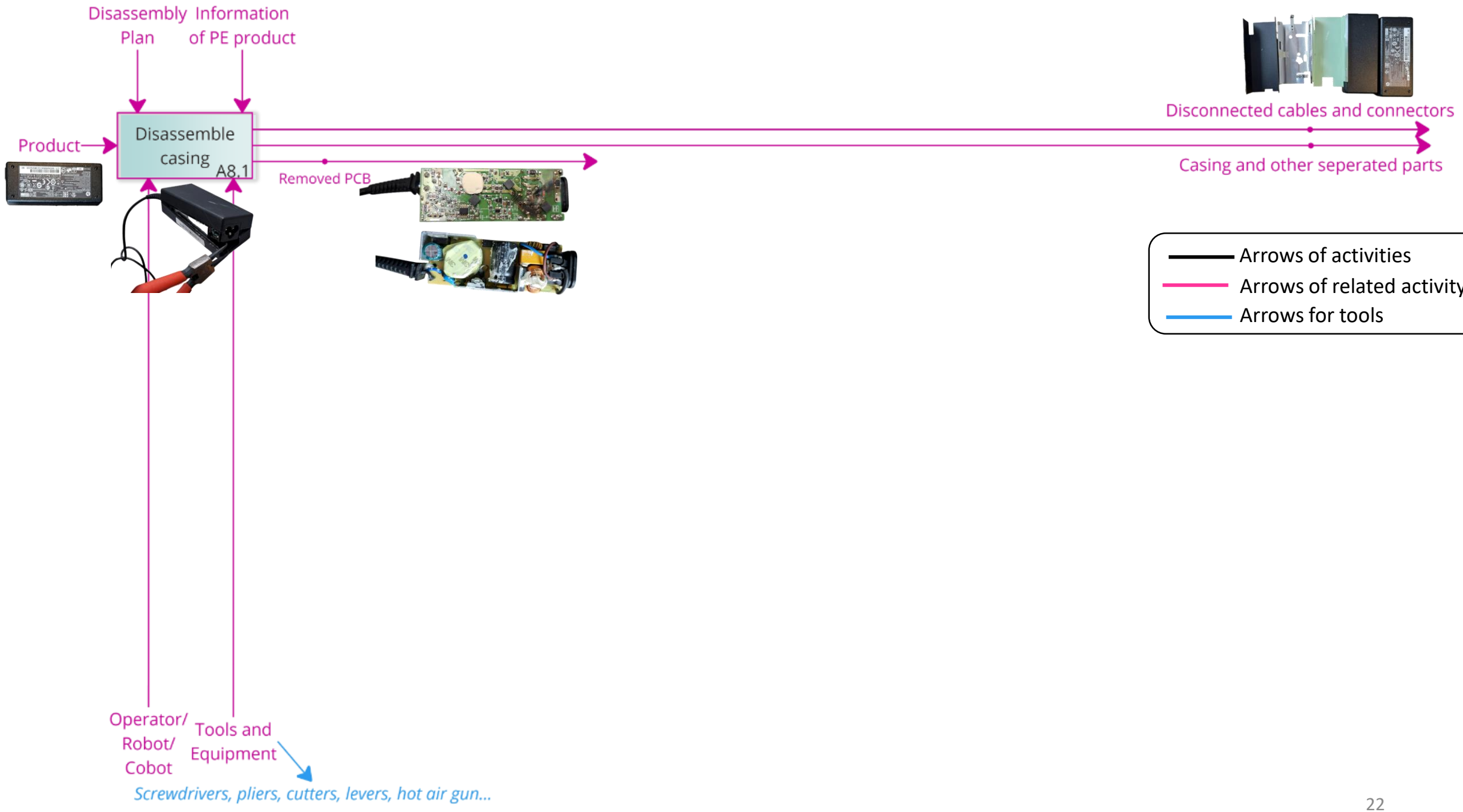
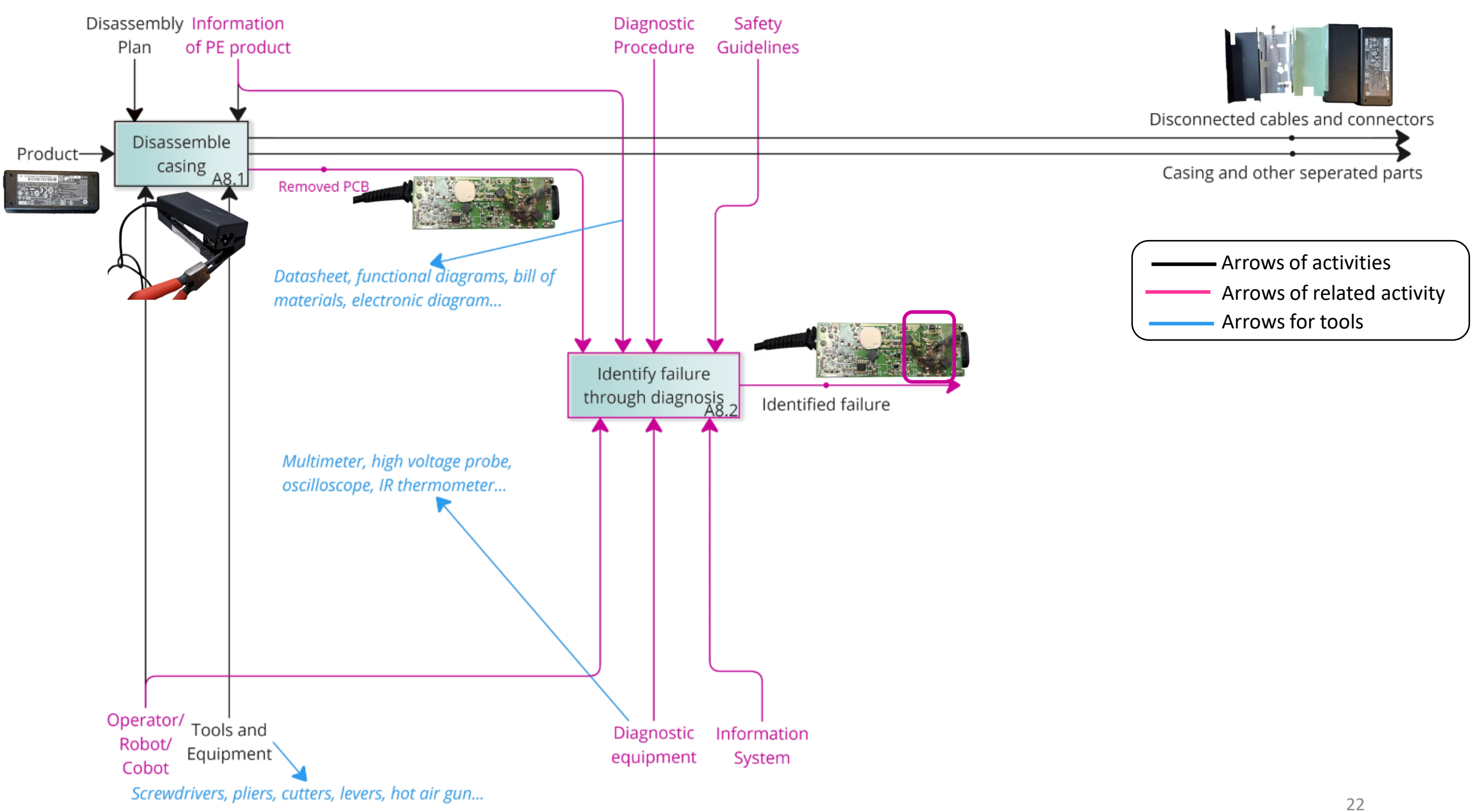

Diagnosing of PE product
A8
Other seperate
Disconnected c
Diagnosis Repo
Information of
(updated)



Node: A8	Title: Diagnosing of PE product	No:



Node: A8	Title: Diagnosing of PE product	No:

Disassembly Plan

Information of PE product

Diagnostic Procedure

Safety Guidelines

Data storage protocols

Disconnected cables and connectors

Product

Disassemble casing A8.1

Removed PCB

Casing and other seperated parts

Arrows of activities

Arrows of related activity

Arrows for tools

Datasheet, functional diagrams, bill of materials, electronic diagram...

Identify failure through diagnosis A8.2

Identified failure

Multimeter, high voltage probe, oscilloscope, IR thermometer...

Saving data A8.3

Diagnosis Report

Information of PE product *(updated)*

Operator/ Robot/ Cobot

Tools and Equipment

Screwdrivers, pliers, cutters, levers, hot air gun...

Diagnostic equipment

Information System

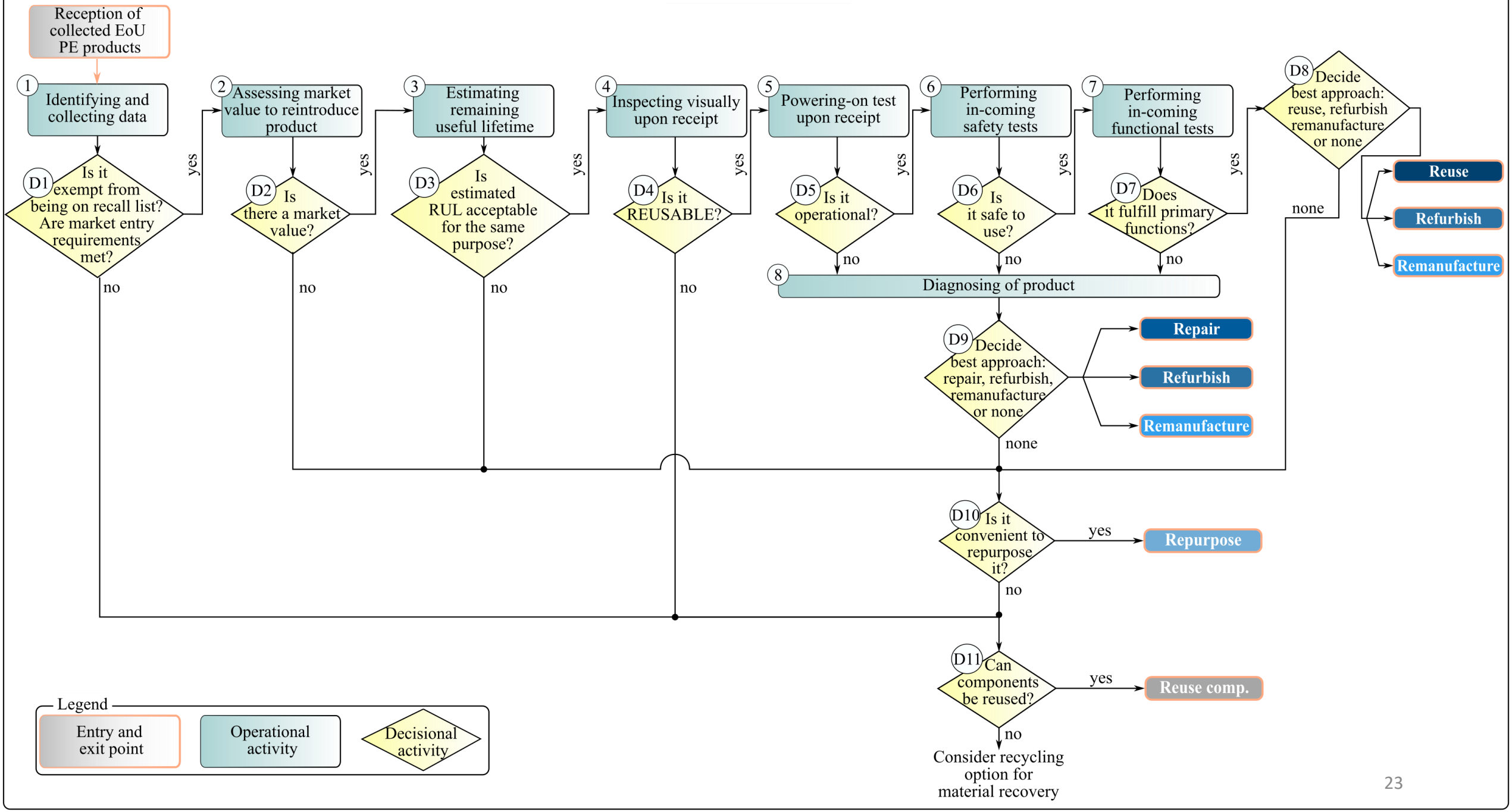
Personnel (Database administrators)

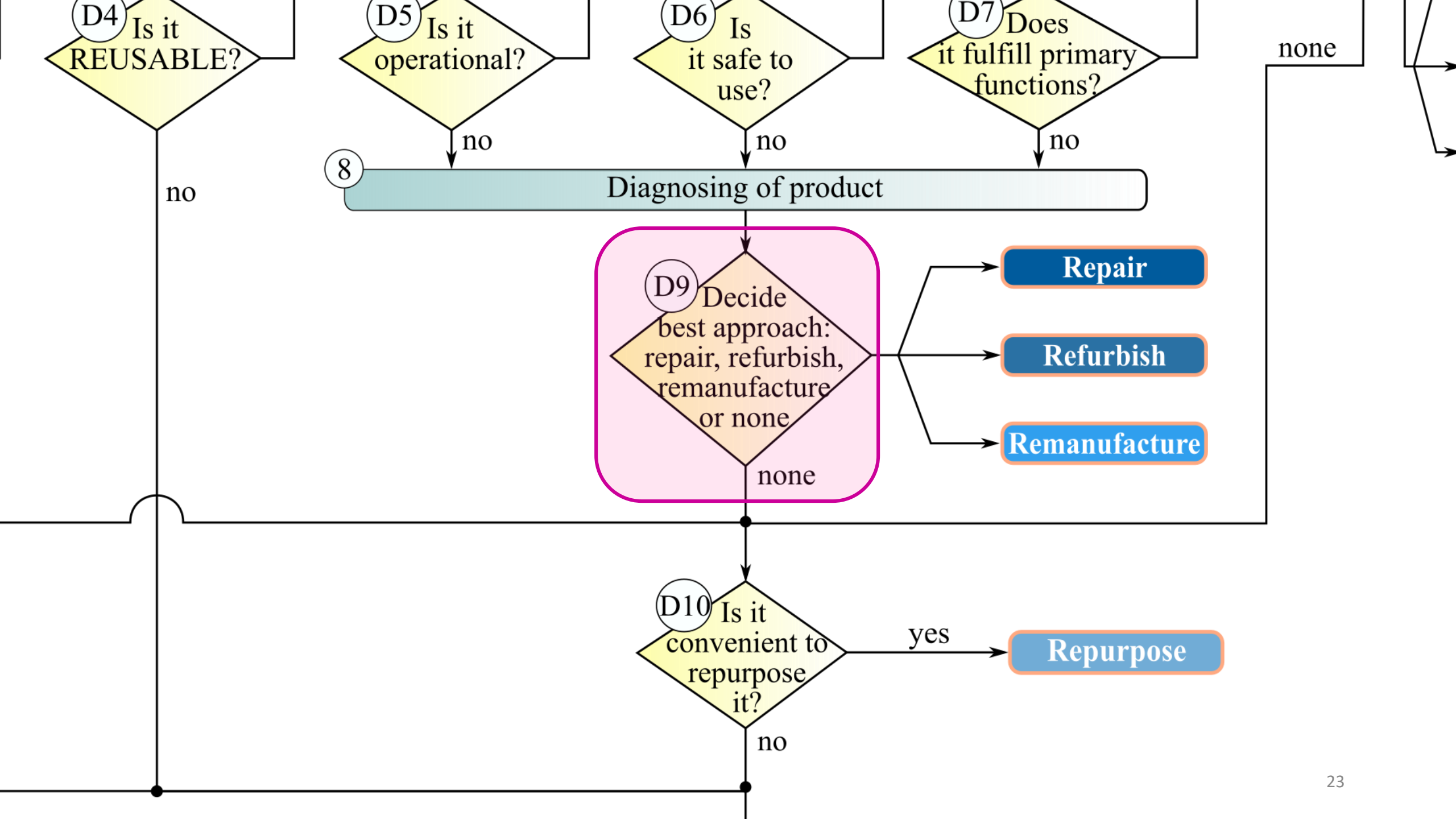
Data recording system

Data storage systems (servers, cloud storage)

Node: A8	Title: Diagnosing of PE product	No:

Decision Tree




D4
Is it REUSABLE?
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Diagnosing of product
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none
Repair
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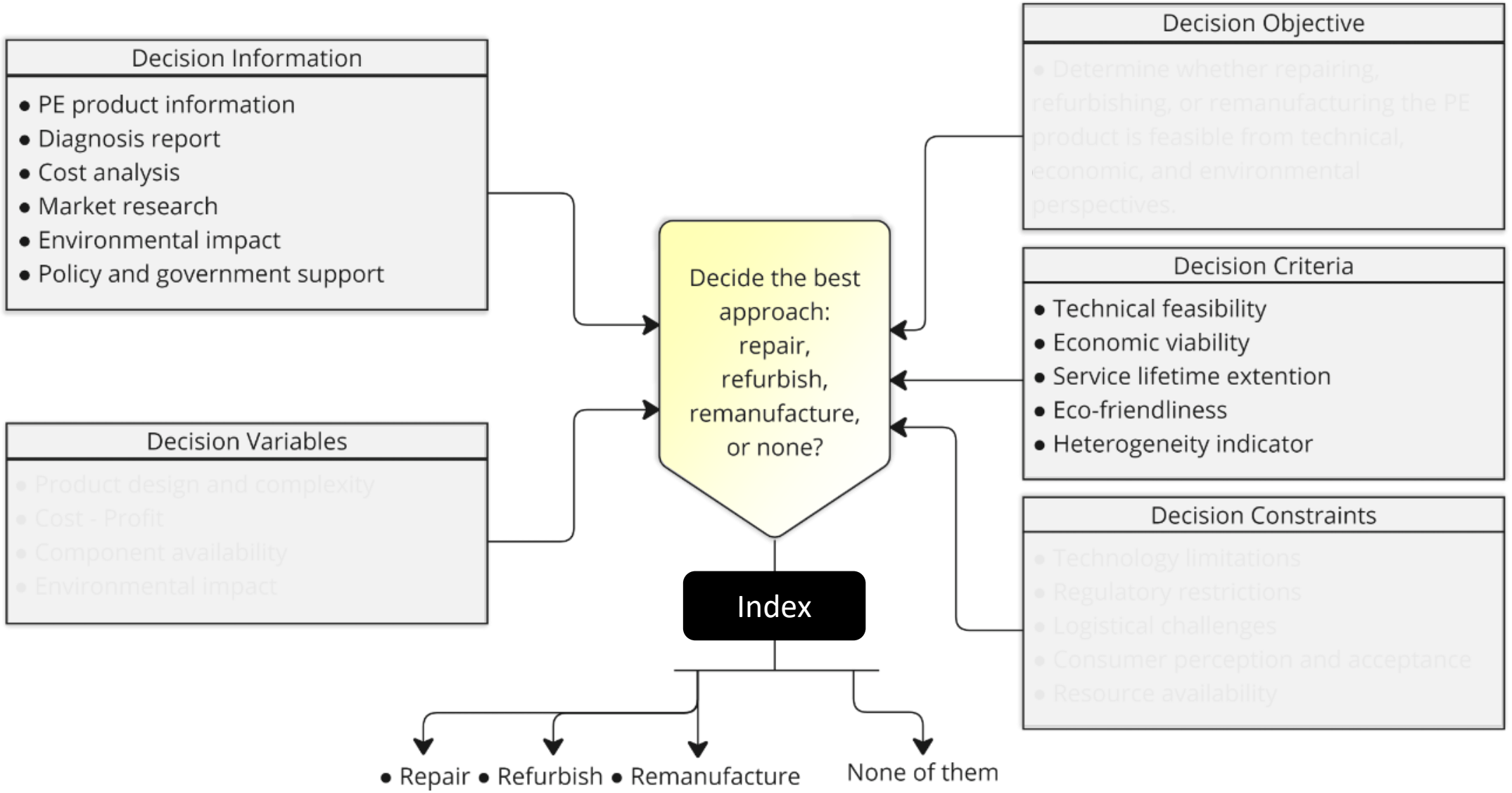
Remanufacture
D10
Is it convenient to repurpose it?
yes
Repurpose
no



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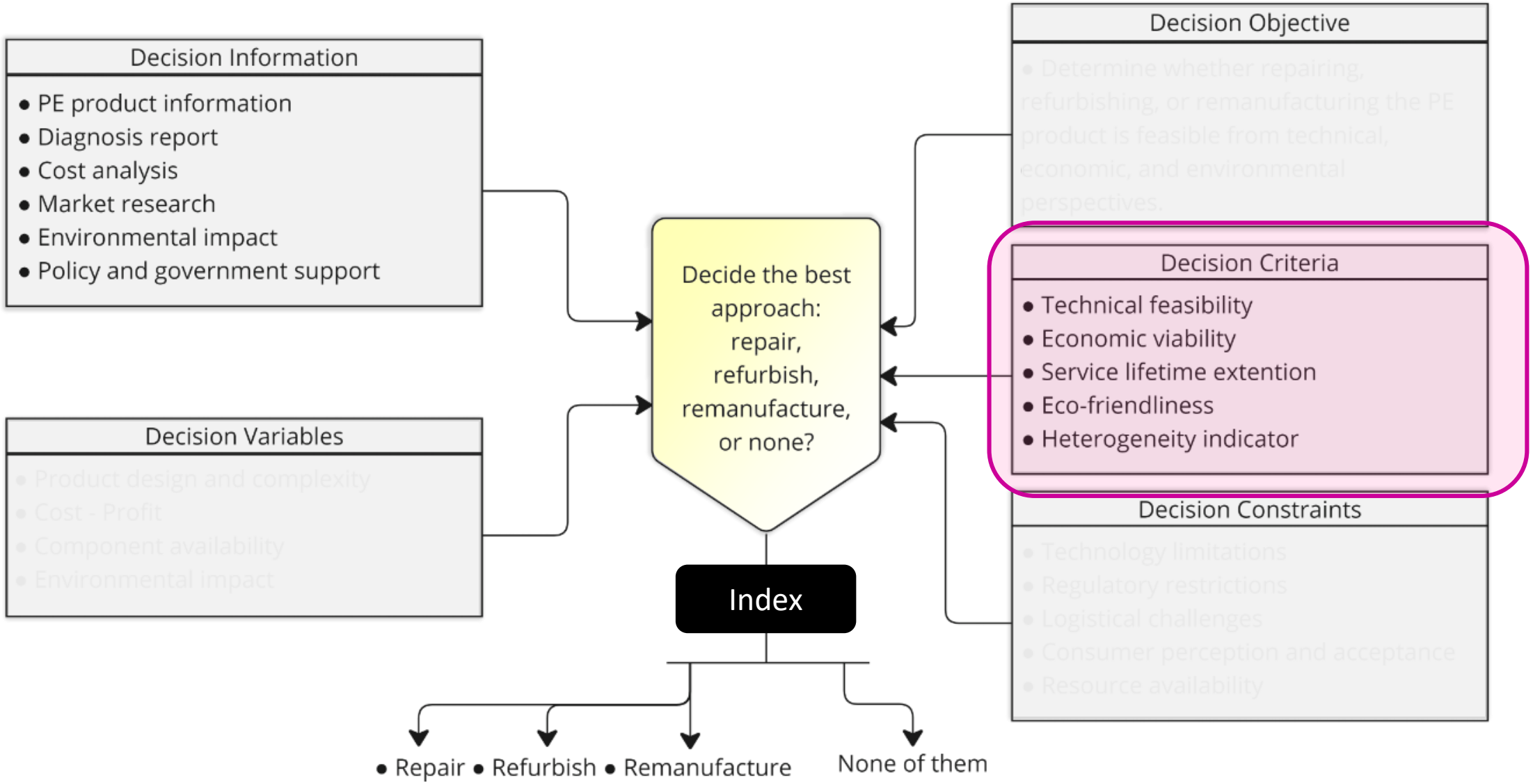
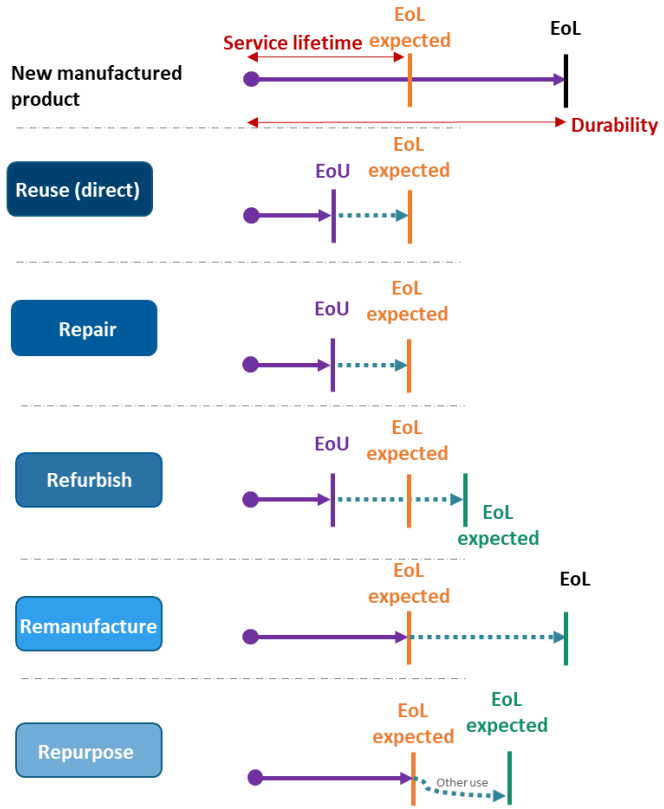


Node: A-0	Title: Determining Effective Value Recovery Options	No:

Multifaced decision

Decision Criteria
• Technical feasibility • Economic viability • Service lifetime extention • Eco-friendliness • Heterogeneity indicator



Technical Feasibility

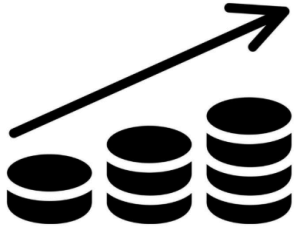
- Can be measured the active **effort** we put on the product

Technical Feasibility = Min ($Effort_{repair}$, $Effort_{refurbish}$, $Effort_{remanufacture}$, $Effort_{New}$)

Economic Viability

- Comparison based on the **revenue** expected

Economic Viability = Max (R_{Repair}, $R_{Refurbish}$, $R_{Remanufacture}$, R_{New})



Service Lifetime Extension

- Comparison among the **service lifetime** obtained after R-strategy

Service Lifetime Extension = f (RUL_{repair}, $RUL_{refurbish}$, $RUL_{remanufture}$, RUL_{new})

Russell, J. D., & Nasr, N. Z. (2023). Value-retained vs. impacts avoided: the differentiated contributions of remanufacturing, refurbishment, repair, and reuse within a circular economy.

Multifaced decision

Decision Criteria
• Technical feasibility • Economic viability • Service lifetime extention • Eco-friendliness • Heterogeneity indicator

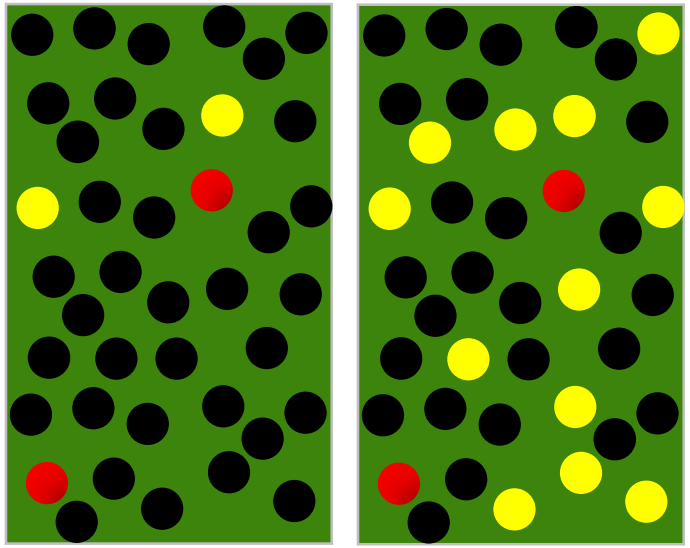
Eco-friendliness

- Seeking the solution which is more eco-friendly.

$$\text{Eco-friendliness} = \text{Max}\,(E_{repair}, E_{refurbish}, E_{remanufacture}, E_{New})$$

Heterogeneity Indicator

- Heterogeneity refers to **lifespan** of the components in this criteria



Components with high-lifetime

Components with moderate high-lifetime

Components with moderate low-lifetime

$$\text{Technical Feasibility} = \text{Min}\,(\text{Effort}_{repair}, \text{Effort}_{refurbish}, \text{Effort}_{remanufacture}, \text{Effort}_{New})$$

$$\text{Economic Viability} = \text{Max}\,(R_{Repair}, R_{Refurbish}, R_{Remanufacture}, R_{New})$$

$$\text{Service Lifetime Extension} = f\,(RUL_{repair}, RUL_{refurbish}, RUL_{remanufture}, RUL_{new})$$

$$\text{Eco-friendliness} = \text{Max}\,(E_{repair}, E_{refurbish}, E_{remanufacture}, E_{New})$$

Impact of Heterogeneity Indicator

Need for an index

Decision depends on different parameters

Agenda

Motivation

- *Power electronics*
- *E-waste*
- *Circular economy*
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Decision Tree

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- *Case study at conceptual level*
- *Implementation level*

Index

- *Equation*
- *Benchmark*
- *Results*

Conclusion & Perspectives

Equation

$$CVI = K_{effort} \times \left(\frac{MV_{threshold}}{MV_{estimated}}\right) \times \left(1 - \frac{\beta}{100}\right) + K_{RUL} \times \frac{\gamma}{100} + K_{ecofriendly} \times \left(1 - \frac{\varphi}{100}\right) + K_{heterogenity} \times \frac{\xi}{100}$$

4 main components

Indexes simplify complex data into a single variable for decision-making. **While various aggregation methods exist, additive aggregation is the most common, used in 86.5% of cases as reported by Martinez Leat et al. (2020)**. This method involves summing normalized indicator values, often using the weighted arithmetic mean.

(J. Martínez Leal et al., Sustainability, 2020)

Equation

$$CVI = K_{effort} \times \left(\frac{MV_{threshold}}{MV_{estimated}}\right) \times \left(1 - \frac{\beta}{100}\right) + K_{RUL} \times \frac{\gamma}{100} + K_{ecofriendly} \times \left(1 - \frac{\varphi}{100}\right) + K_{heterogenity} \times \frac{\xi}{100}$$

Where:

- K_{effort} : Coefficient for effort
- $MV_{threshold}$: Minimum acceptable market value that justifies the R-strategy economically
- $MV_{estimated}$: Estimated market value of the product based on current market data
- β : Effort required to implement the R-strategy in % with respect to new product

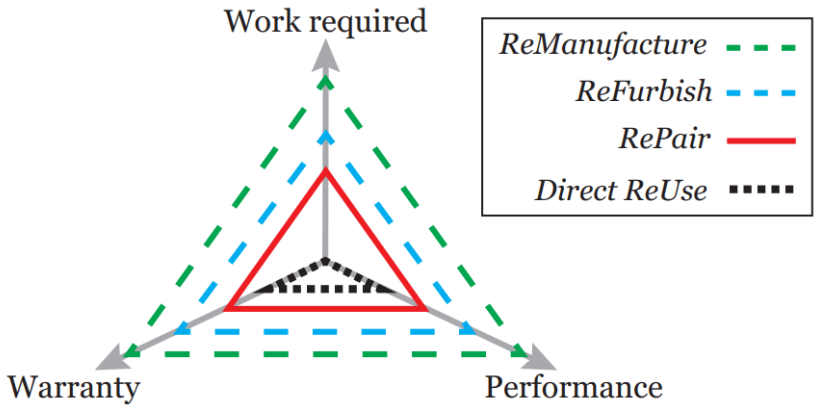
- K_{RUL} : Coefficient for remaining useful life
- γ : Obtained service lifetime after R-strategy in % with respect to new product

- $K_{ecofriendly}$: Coefficient for eco-friendliness
- ϕ : Environmental impact in % with respect to new product

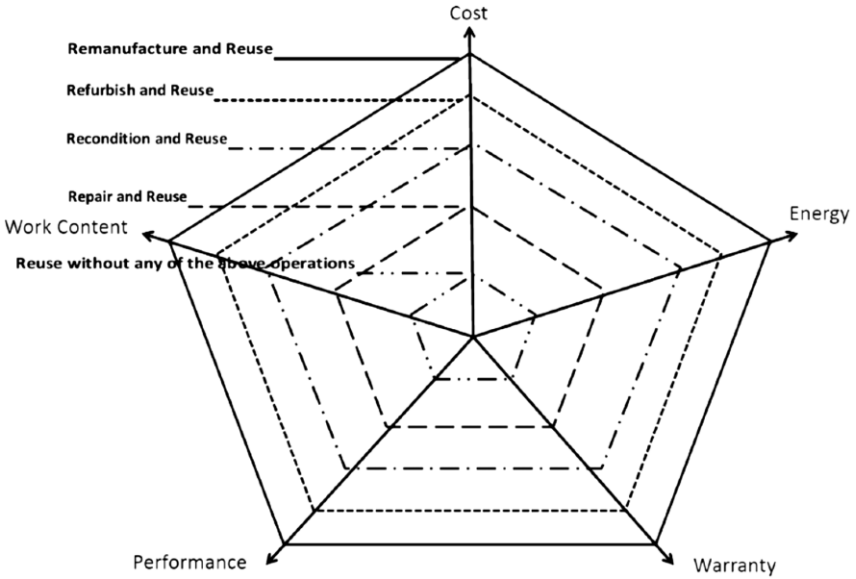
- $K_{heterogeneity}$: Coefficient for heterogeneity
- ξ : Impact of heterogeneity indicator in % with respect to new product

Benchmark

Product Cycle	$MV_{estimated}$	Required effort β	Service Lifetime γ	Environ. Impact ϕ	Low Het. (1st assumption)	Moderate Het. (2nd assumption)
New	100%	Very high	New	Very high	Highly suitable	Less suitable
Remanuf.	80%	High	As-new	High	Not suitable	Suitable
Refur.	70%	Moderate	High	Moderate	Not suitable	Highly suitable
Repaired	50%	Low	RUL	Low	Suitable	Suitable
Reused	50%	Very low	RUL	Very low	Suitable	Suitable



(A. M. King et al., Sustainable development, 2006)



(Gharfalkar, M. et al. Waste Management & Research, 2016)

K_{effort} : 0.5	K_{RUL} : 0.5	$K_{eco\text{-}friendly}$: varies between 0 and 1	$K_{heterogeneity}$: 0.5

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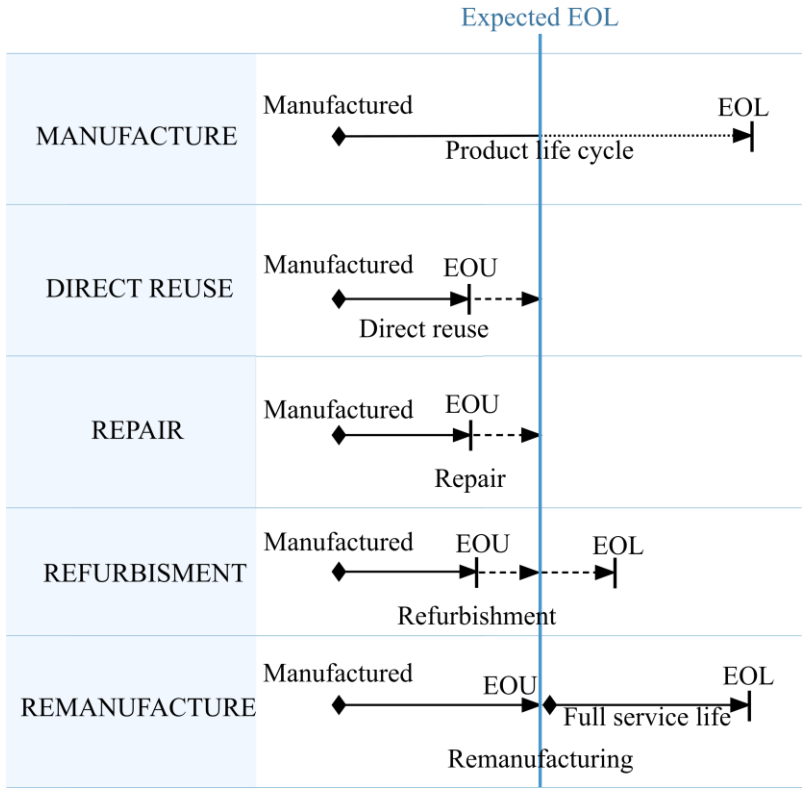

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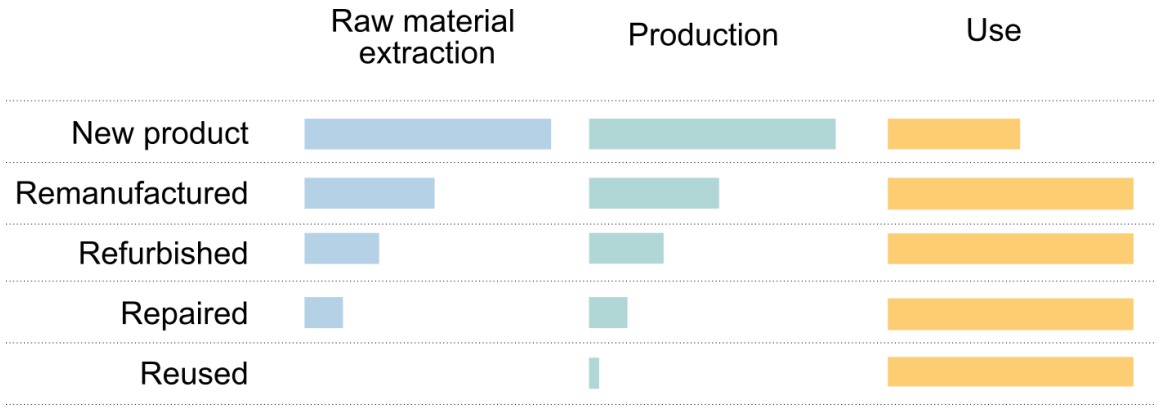

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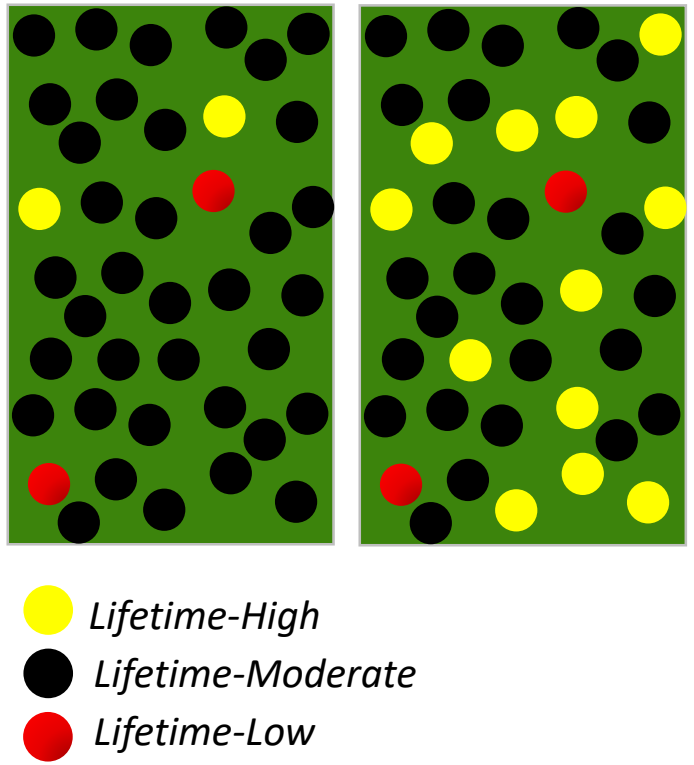

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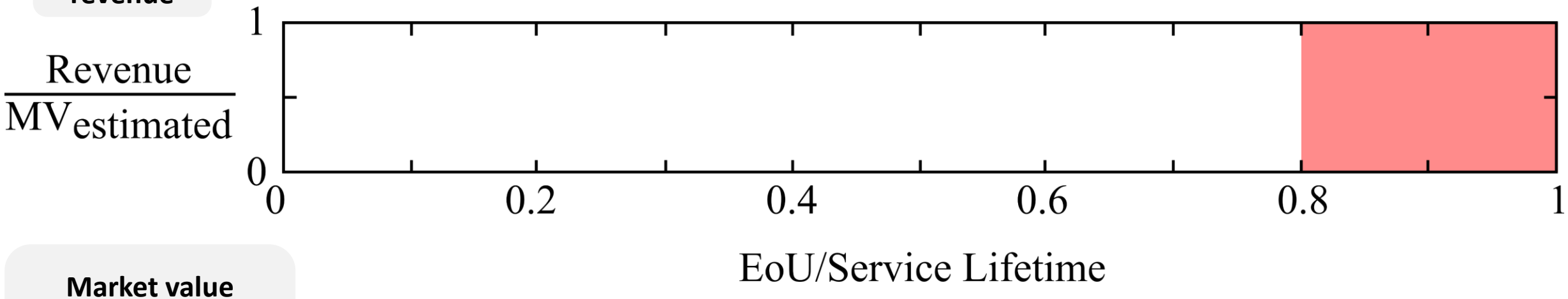
Plotting the index

Expected revenue

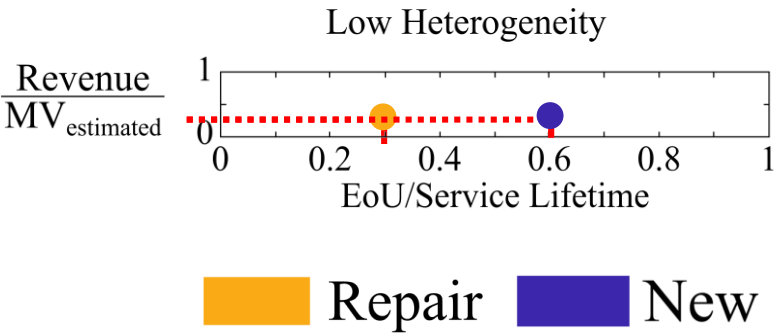


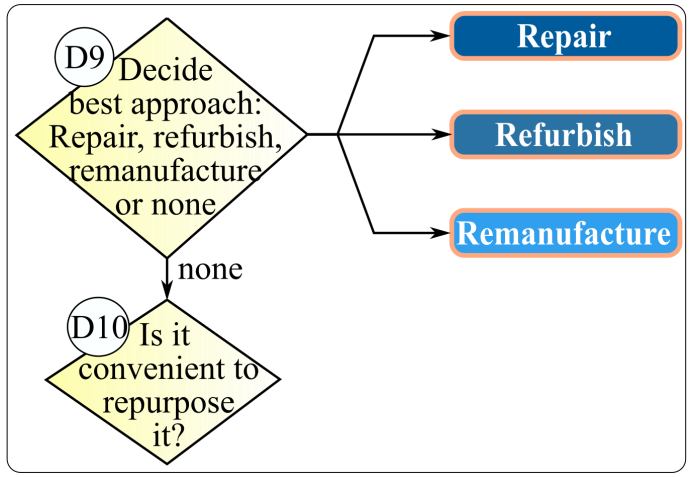
Market value (depends on R-strategy)

How long the product has been used

Expected service life of the product

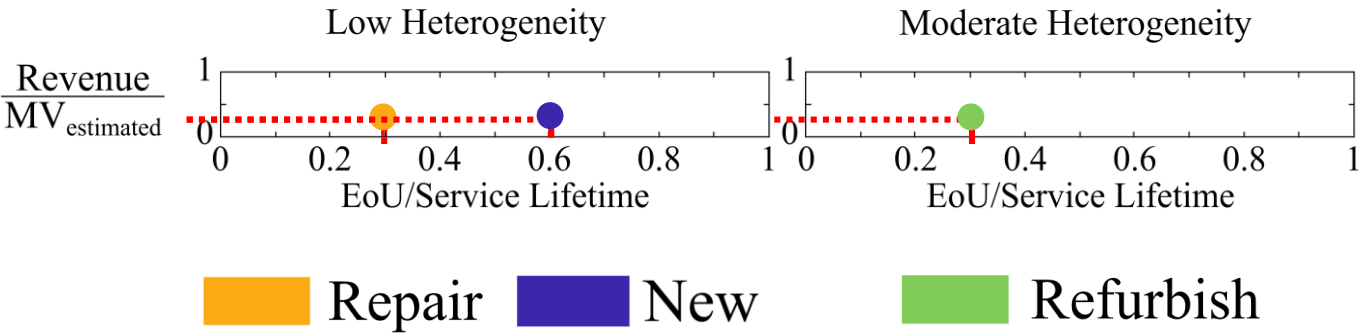
Interpreting the index results

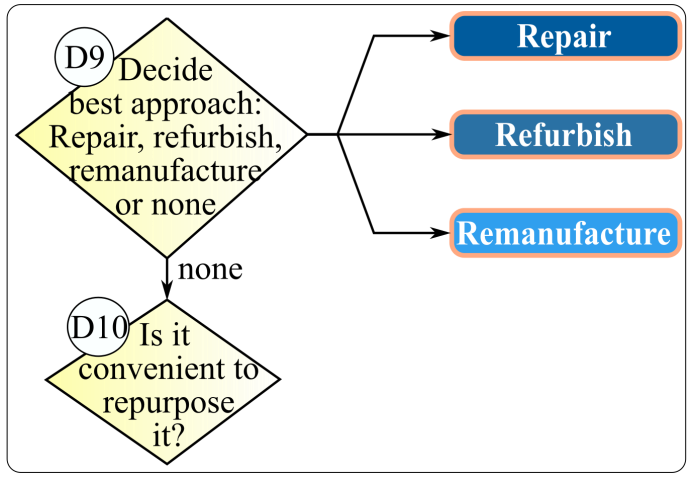




K_{effort} : 0.5	K_{RUL} : 0.5	$K_{eco\text{-}friendly}$: 0.3	$K_{heterogeneity}$: 0.5

Interpreting the index results





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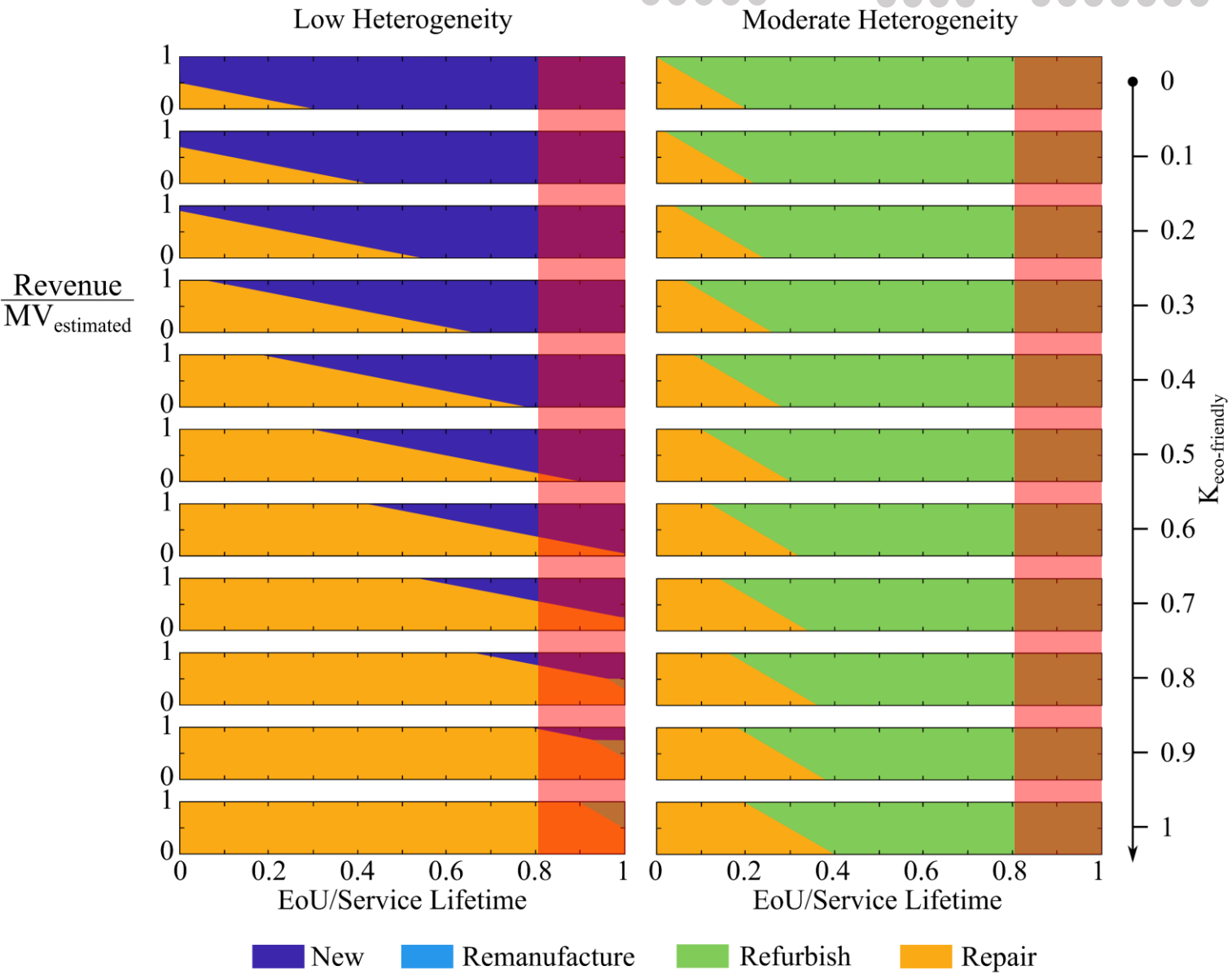
Results



Remarks

- **Uncertainties** and their potential impact on decision-making
- Probable of **overlap** within similar areas
- Checking the **individual results**
- Having potential for practical applications

K_{effort} : 0.5	K_{RUL} : 0.5	$K_{eco\text{-}friendly}$: varies between 0 and 1	$K_{heterogeneity}$: 0.5

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Index

- *Equation*
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Conclusion

1. Addressed gaps in CE and PE by elaborating on technical, economic, and environmental factors

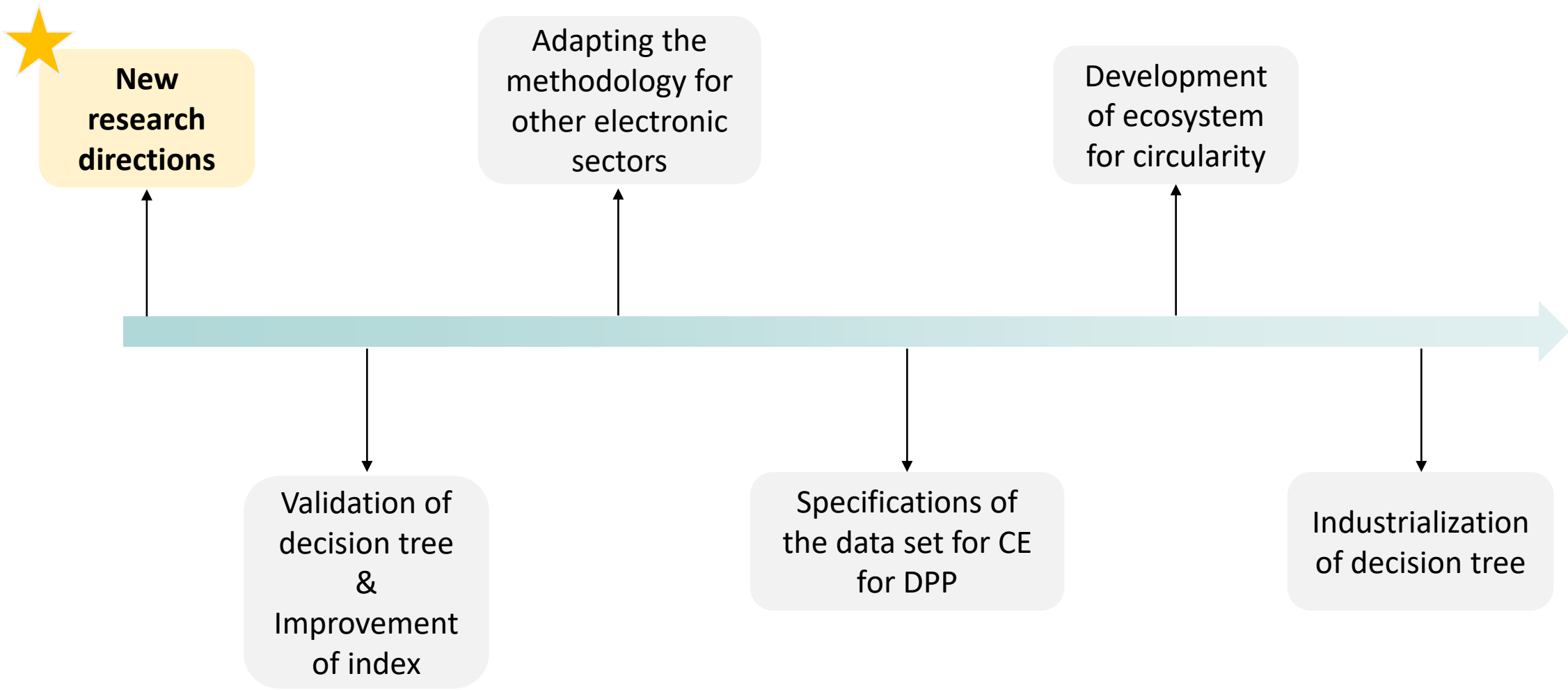
2. Provided a foundation for implementing the transition to CE in EoU PE

3. 1. Short term: Decision tree rationalizes experience for CE applied to **EoU PEs**
   2. Medium term: Thanks to it, we can tailor the design of **New PEs** for CE-strategies

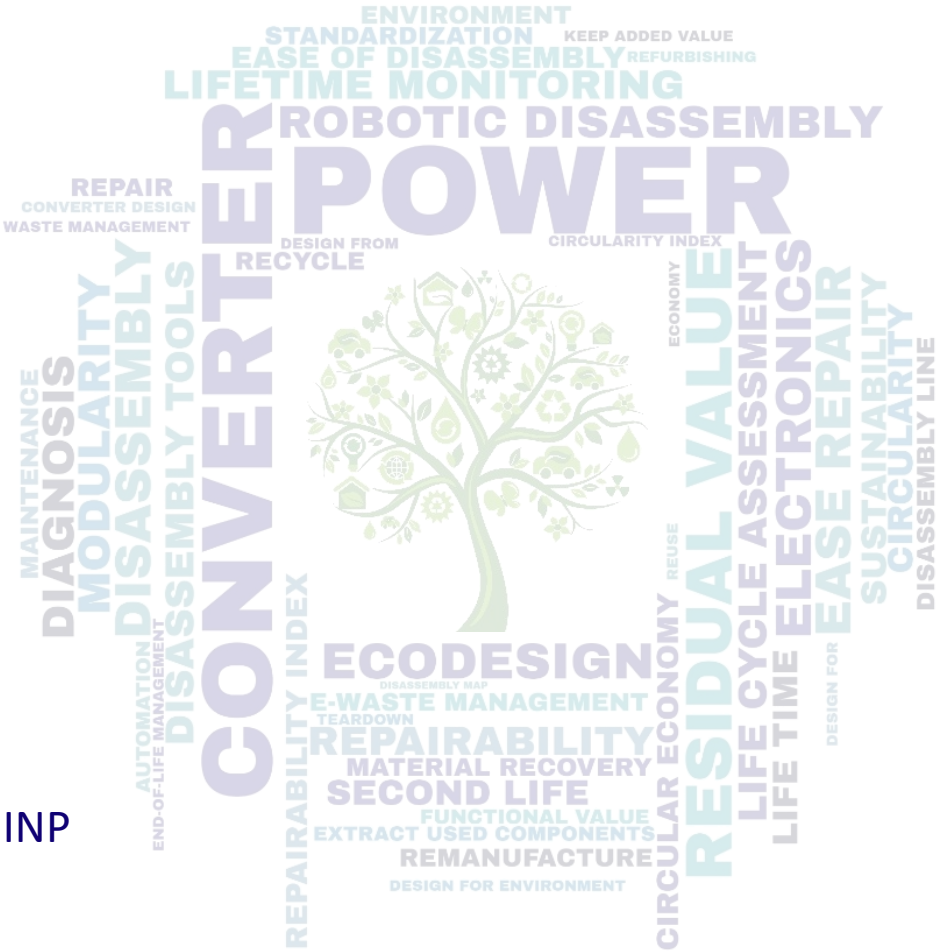
4. CVI encodes such experience and can evolve upon it to drive the design of **New and Circular PEs**

★ Need data access for decision-making and strategies for future ecosystem developments

Perspectives



Thank You
For Your Attention



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