Reuse Allocation in LCA: Methodology & Modelling

Beste Eco-op Project:
quantifying environmental benefits of remanufacturing vs new

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koninklijke metaalunie

CS STAAL

Botau Engineering Construction
EEN UNIEKE COMBINATIE VAN MENSEN EN MACHINES

HTC

THE HAGUE UNIVERSITY OF APPLIED SCIENCES

Presentation Structure

1. Goal KKO meeting
2. Recap:
   - Project goal, questions
   - Principles for reuse allocation in LCA, methodology

3. Update, results
   - Modelling with reuse allocation method on case study
   - Expert review/feedback session
   - Try-out / demo

4. Wrap-up and follow up
   - Results, answers
   - Things to do, discussion, feedback

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1. Meeting goal

- Recap project aim
- Present results
- Gather feedback, discuss ideas

2. Project Goal

Develop an LCA-based ‘tool’ that supports modelling remanufactured vs. new equipment

Focus:

Environmental impact allocation over multiple life cycles considering reuse

Objective:

Transparent and consistent allocation methodology embedded in a decision tool

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2. Research Questions

- Which allocation method gives the most fair results when using components in several product life cycles?
  - How to visualize impacts for different lifecycles
  - How to choose lifecycle length
  - How to combine LCC insights with LCA insights
  - Which LCA tool to use and which database
    - In what way are specific databases and tools comparable in results?

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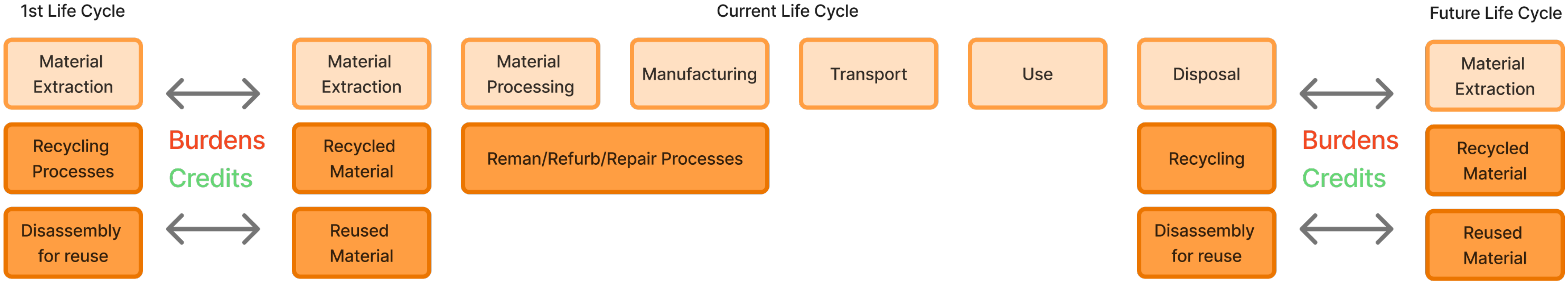
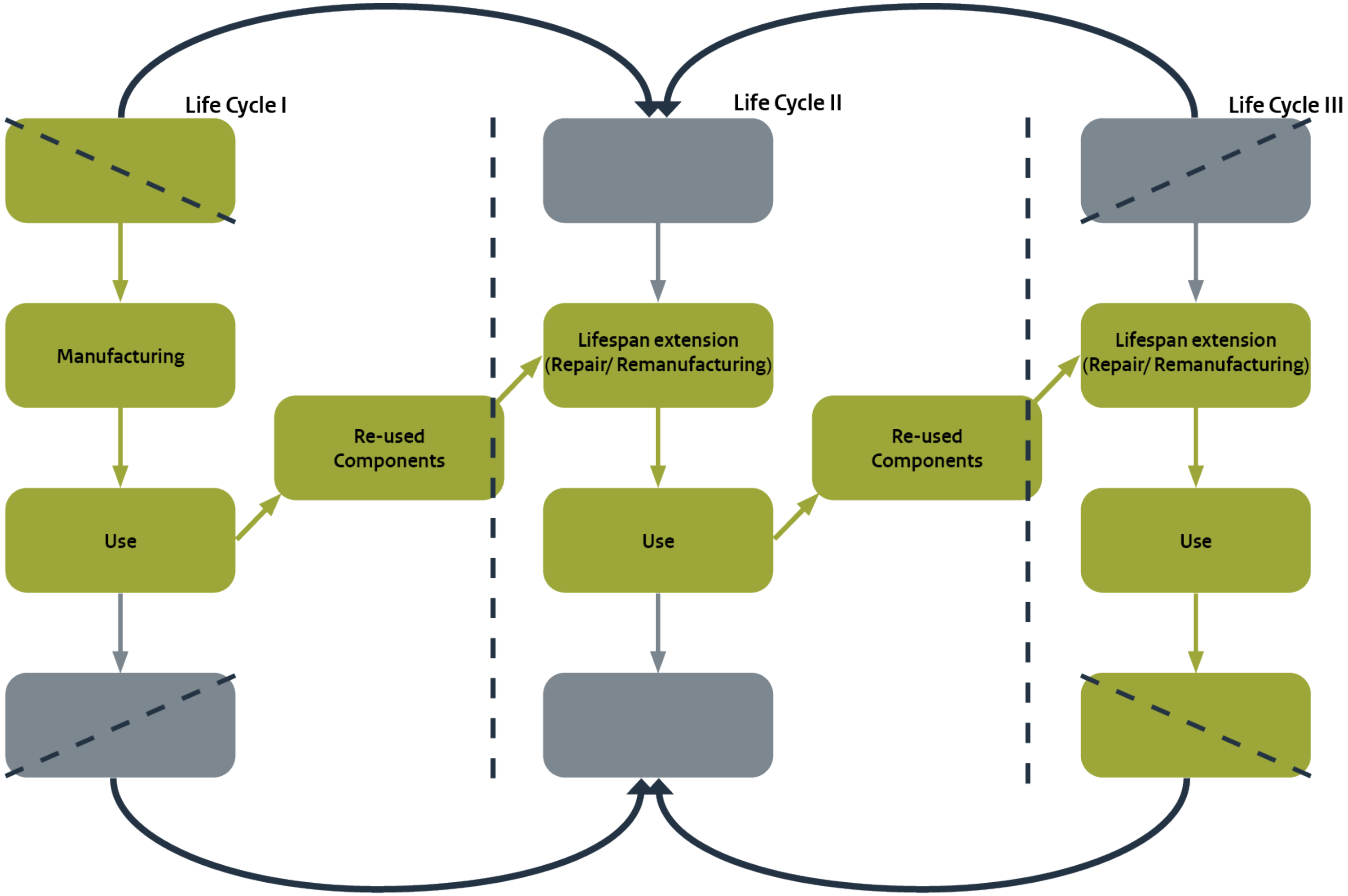
Challenges in Accounting for Reuse and Recycling

Credit and burden allocation over multiple life cycles



The Allocation Chaos



Based on: world steel association (eigen bewerking)

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Principles for Reuse Allocation

Q: How to apply an allocation approach which shares "initial" **material burdens** and **end-of-life burdens** between **all cycles** by considering on a **part level** what has been reused, **in which cycle**, and for **how many service years?**

→ There are defined principles for reuse allocation which have been considered

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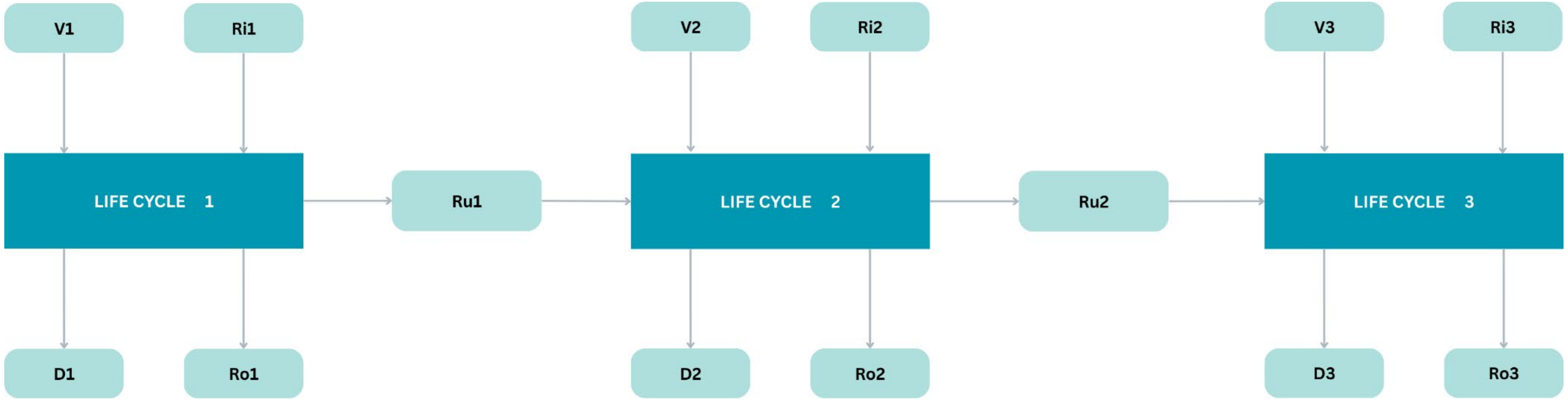
Principles for Reuse Allocation

1. Burdens from initial virgin material use and end-of-life processes should be shared across all reuse life cycles, all of which must be explicitly modelled.



*The overall system should be assessed

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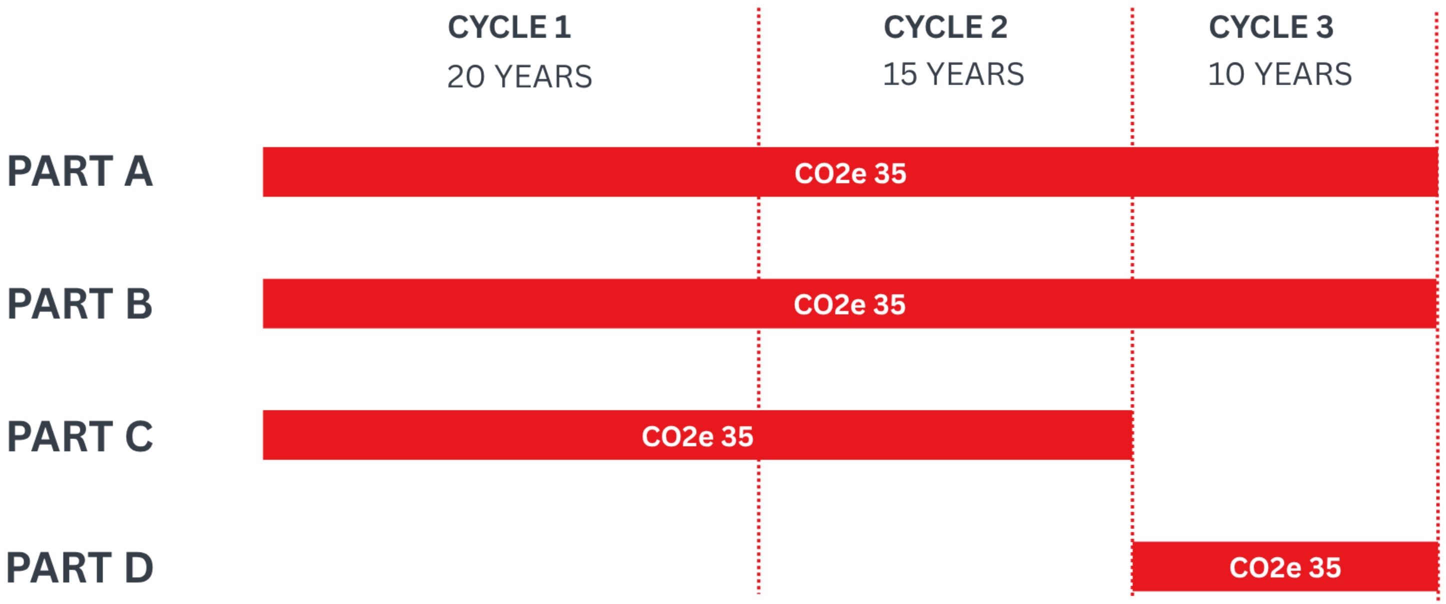
Principles for Reuse Allocation

6. Reuse burdens should be shared based on how long parts or components are used in each life cycle, reflecting their changing value and quality over time.



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Existing Allocation Approaches

1. Cut-off method
2. EN 15804+A2 (cut-off + module D)
3. Circular Footprint Formula (CFF) from (PEF)
4. 50:50 approach
5. Linear Degression (LD) Approach
6. Circular Economy LD Approach
7. Distribution by number of cycles (N lives)

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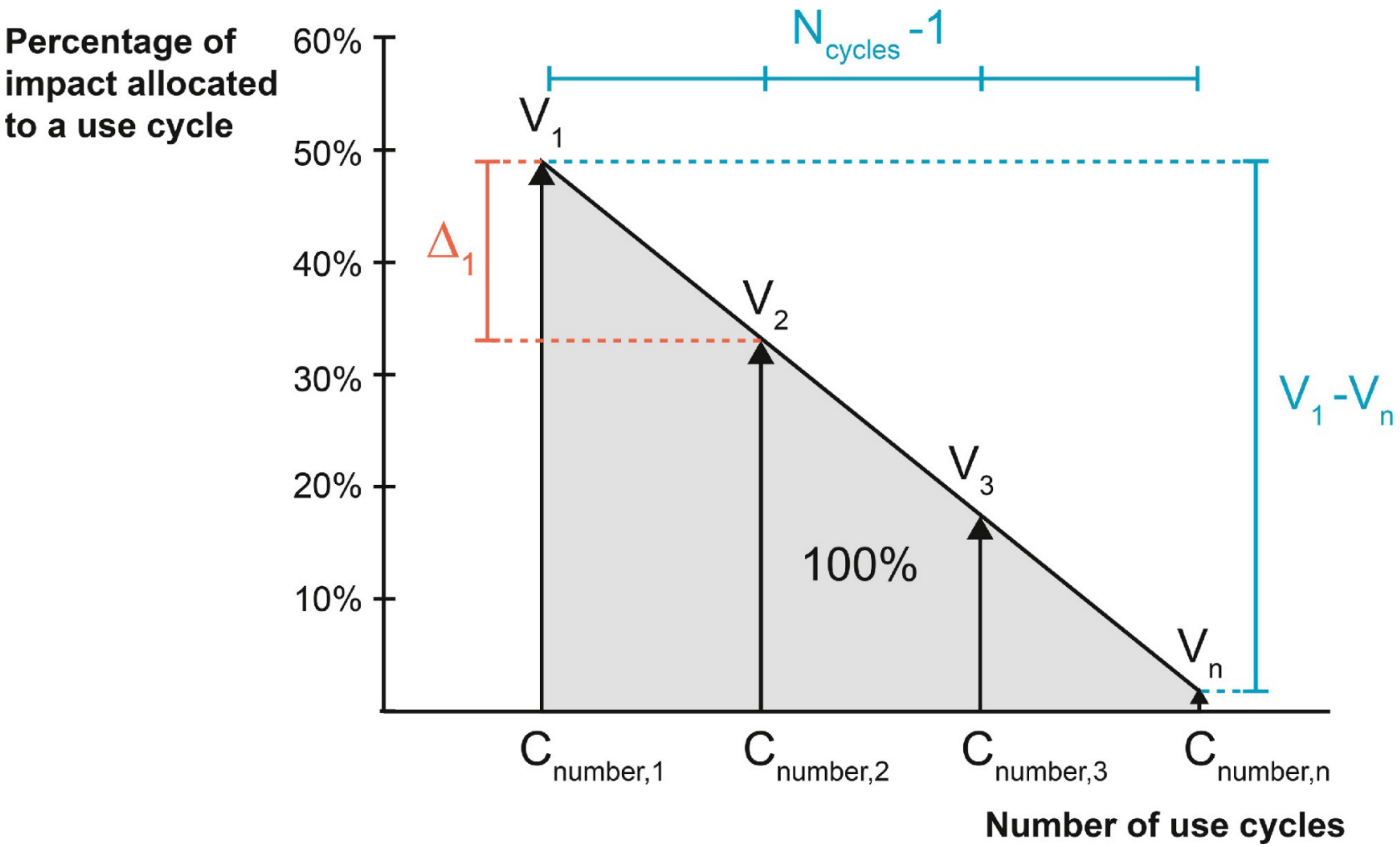
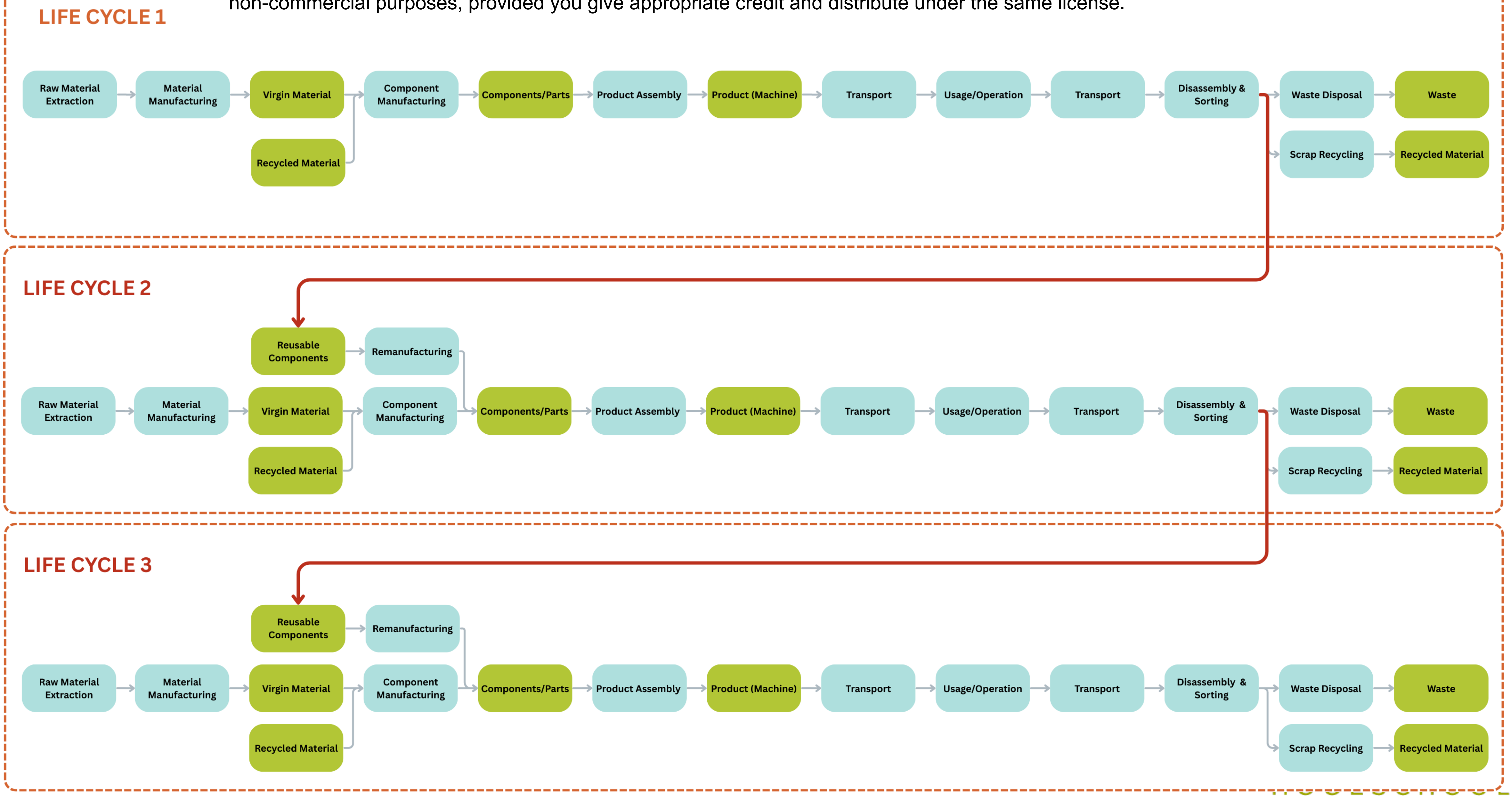
Allocation Method	Description	Pros	Cons	Regulatory Compliance	References
Simple Cut-off	Assigns environmental burdens to the first service life; subsequent reuse has zero burden	Simple, widely accepted, avoids double counting	Doesn't show connection to earlier or later cycles (full view), burden shifted to next user, no upstream circular incentive	Compliant with ISO 14044 and EN 15804	https://worldsteel.org/wp-content/uploads/Guidance-on-methodologies-for-modelling-reuse-and-remanufacture-in-LCA-Studies.pdf
EN 15804+A2 (Cut-off + Module D)	Past cycles are excluded (cut-off), the current cycle is assessed (A–C), and potential future benefits are reported in Module D.	Clarity of modules, separate module for future benefits, transparent	Doesn't capture full circularity; focuses on current and future use, ignoring past cycles and system loops	Fully compliant with EN 15804+A2 and ISO 14044	https://iopscience.iop.org/article/10.1088/1755-1315/1078/1/012015/pdf
Circular Footprint Formula (CFF)	Applied at EOL, multiple formulas assess allocation between current and future cycles based on amount reused and a quality factor	Enables the assessment of all EoL scenarios possible, suitable for all materials	Complex to implement; requires extensive data, quality factor difficult to determine	Aligned with Product Environmental Footprint (PEF)	https://environment.ec.europa.eu/system/files/2021-12/Annexes%201%20to%202.pdf https://link.springer.com/article/10.1007/s11367-016-1244-0
50:50 Approach	Splits burdens evenly between first and subsequent product lives	Simple, splits equally between cycles	Arbitrary split; may not reflect true environmental flows between multiple cycles (3+)	Not compliant with ISO 14044; simplified approach	https://www.sciencedirect.com/science/article/pii/S0921344921002925#sec0031
Linear Digression (LD)	Initial material burden decreases linearly over reuse cycles, while end-of-life burdens increase linearly as the final cycle bears the highest share.	Reflects diminishing impact, intuitive for multi-cycle use; considers all cycles, reflects uncertainty of future cycles in distibution	Requires extensive data to map all cycles as well as specific assumptions for EOL and reuse scenarios	Non-compliant (ISO/EN); emerging method in academic literature	https://www.mdpi.com/2071-1050/12/22/9579
Circular Economy Linear Digression (CE LD)	Same as LD model adjusted to more granular part level assesment and addition of degradation rate factor (F)	Fair ex-ante allocation, Includes all cycles without double counting, Upstream/downstream impacts remain visible throughout.	Requires assumed future cycles, sensitive to degradation factor accuracy, data-intensive, limited regulatory recognition	Non-compliant (ISO/EN); emerging method in academic literature	https://www.sciencedirect.com/science/article/pii/S0921344921002925#sec0031
Avoided Burden (Consequential LCA) eg. World Steel Association Method	Credits reuse of part/component with avoided burden of virgin production and manufacturing	Shows avoided consequence; net envrionmental impact, incentivises r-strategies	Needs strong data; complex, risk of overestimating benefits (double counting) over multiple cycles	Compliant with ISO 14044 in consequential LCA framework	https://worldsteel.org/wp-content/uploads/Guidance-on-methodologies-for-modelling-reuse-and-remanufacture-in-LCA-Studies.pdf

Method \ Criteria	A. Multi-Cycle System Scope	B. Reuse Incentive	C. Service-Life Proportional	D. Reflect Uncertainty	E. No Double Counting	F. Reproducibility	G. Comprehensibility
Cut-off Method	🙁	😐	🙁	😐	🙂	🙂	🙂
EN 15804+A2	😐	😐	🙁	😐	😐	🙂	😐
Circular Footprint Formula	🙂	🙂	😐	🙁	🙂	🙁	😐
50:50 Approach	🙁	😐	🙁	🙁	🙂	🙂	🙂
Linear Digression (LD)	🙂	🙂	😐	🙂	🙂	🙂	🙂
Circular Economy LD	🙂	🙂	🙂	🙂	🙂	😐	🙂
Avoided Burden	😐	🙂	😐	🙁	😐	🙁	😐

Circular Economy Linear Digression (CE LD)



(van Stijn et al., 2021)


LIFE CYCLE 1
Raw Material Extraction
Material Manufacturing
Virgin Material
Recycled Material
Component Manufacturing
Components/Parts
Product Assembly
Product (Machine)
Transport
Usage/Operation
Transport
Disassembly & Sorting
Waste Disposal
Waste
Scrap Recycling
Recycled Material
LIFE CYCLE 2
Reusable Components
Remanufacturing
Raw Material Extraction
Material Manufacturing
Virgin Material
Recycled Material
Component Manufacturing
Components/Parts
Product Assembly
Product (Machine)
Transport
Usage/Operation
Transport
Disassembly & Sorting
Waste Disposal
Waste
Scrap Recycling
Recycled Material
LIFE CYCLE 3
Reusable Components
Remanufacturing
Raw Material Extraction
Material Manufacturing
Virgin Material
Recycled Material
Component Manufacturing
Components/Parts
Product Assembly
Product (Machine)
Transport
Usage/Operation
Transport
Disassembly & Sorting
Waste Disposal
Waste
Scrap Recycling
Recycled Material

Which Stages (processes) are Relevant?

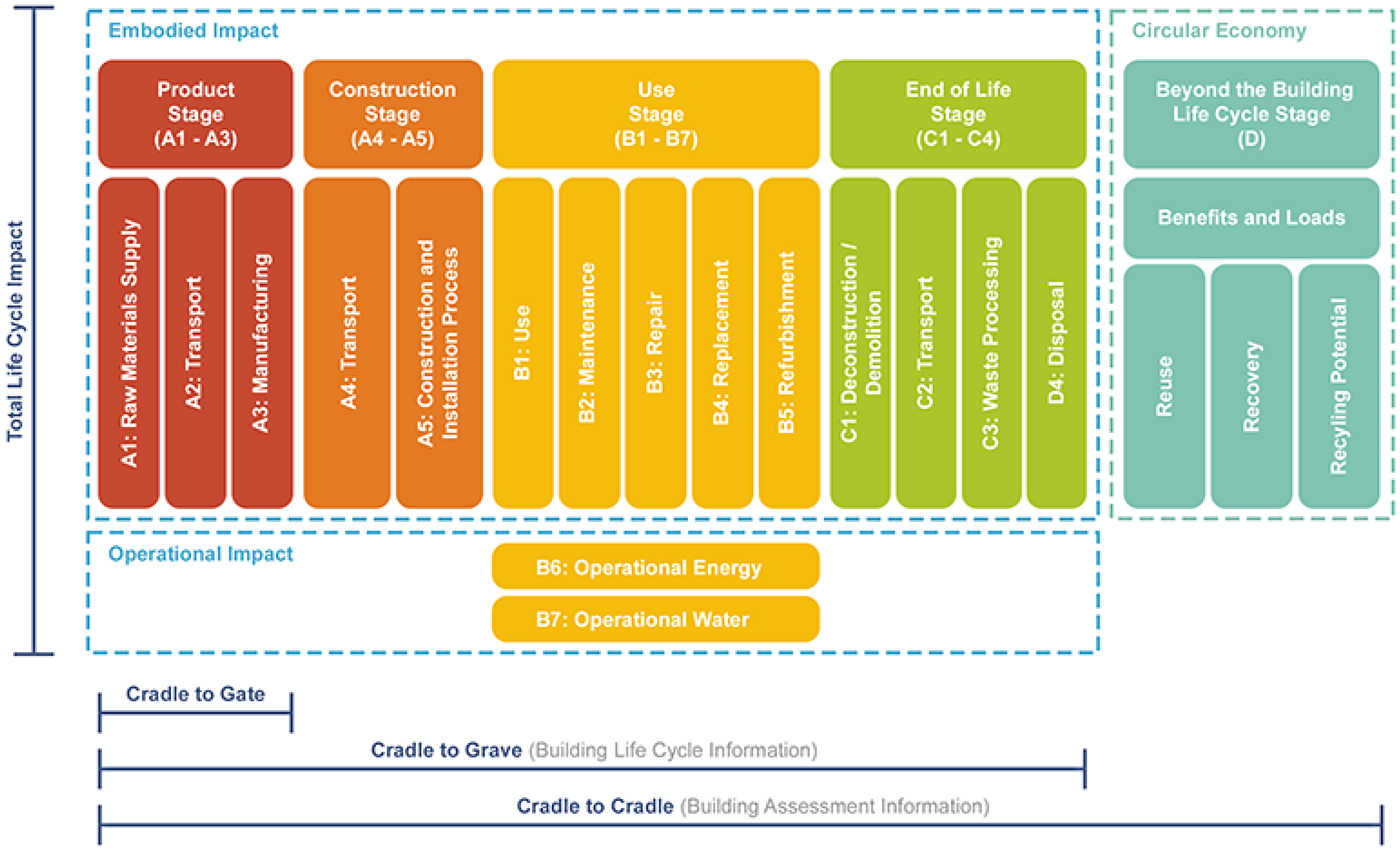


Figure 1. Building life-cycle stages (adapted from EN 15978:2011, via Building Enclosure Online)

Which stages does the CELD consider?

Component Level Focus:

Manufacturing – material extraction, processing, component manufacturing

EOL Disposal – not recycling, not energy recovery, impacts related to end-of-life disposal

Refurbishing – activities related to restoring the functionality and extending the service life

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How CELD divides burdens across life-cycle stages

(Manufacturing Impacts)
CELD assigns the "highest impact share" to this first (use) life cycle

(End-of-Life Impacts)
CELD assigns the "highest impact share" to the last (use) life cycle

(Refurbishing Impacts)
Distributed equally between all cycles where the component is reused.

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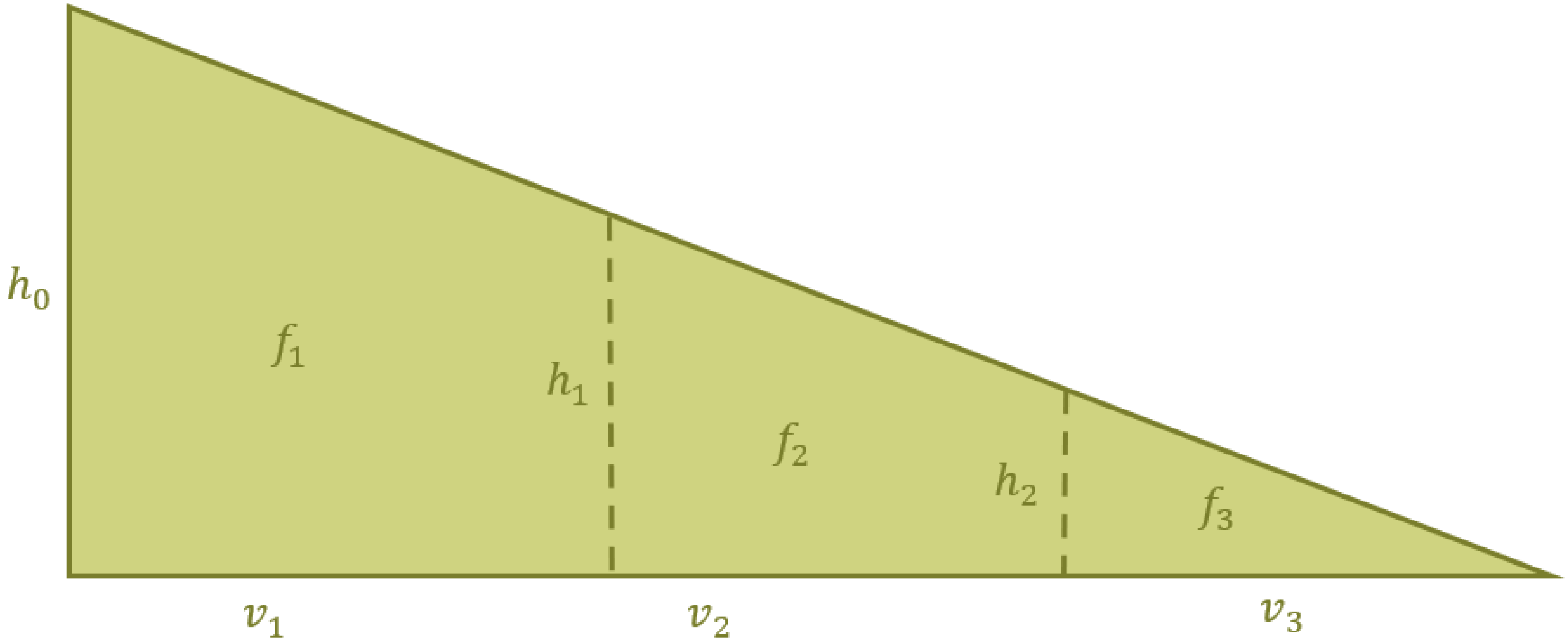
Adjusted CE LD Method

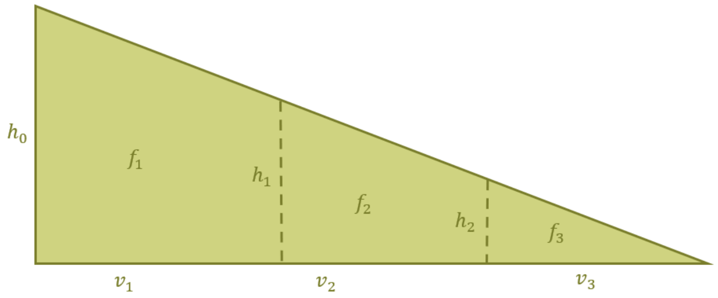


- Area of triangle = total environmental burden
- X-axis represents total service life (sum of all cycle lengths in which the component is used)
- Y-axis represents the relative impact intensity (highest at start or end, depending on stage)

How CELD divides burdens across life-cycle stages

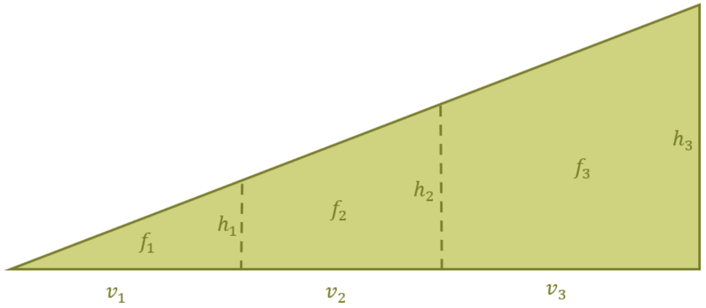
(Manufacturing Impacts)

- The peak of the triangle is at the beginning of the first cycle.
- Burden decreases linearly across the total lifetime of the reused component.



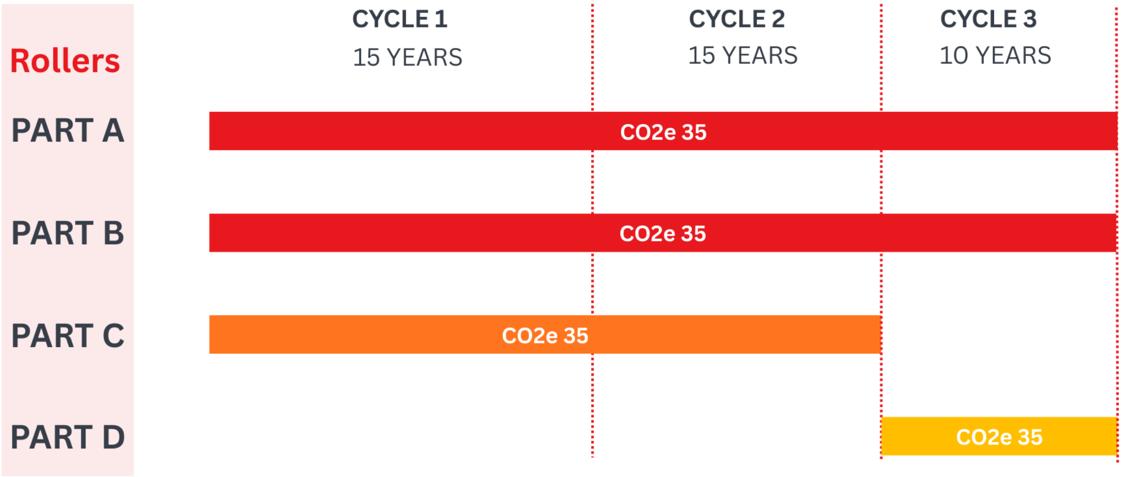
(End-of-Life Impacts)

- The triangle is reversed in time (burden increases toward the end).
- The peak of the triangle is the end of the component's final use.
- The fractions are applied in reverse order



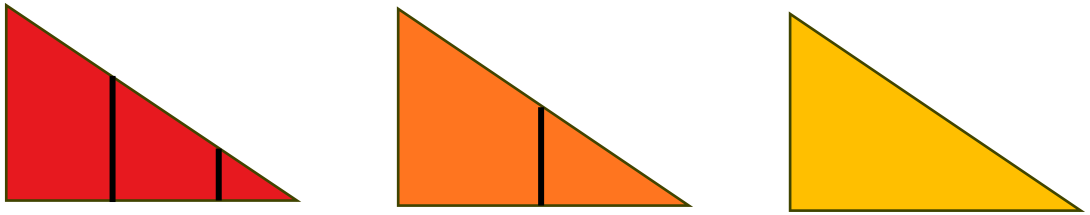
(Refurbishing Impacts): Distributed equally between all cycles where the component is reused.

Example CE LD Allocation



These block rows represent the environmental impacts per component

These triangles represent the total burden per component, the black lines are the split of burden per cycle



PART A PART C PART D

Why Choose this Approach?

1. Captures all life cycles

-> distributes impacts across every use cycle, not just the first,

2. Fairly rewards reuse

-> first/last cycle doesn't carry disproportional burden

3. Service-life–based allocation

-> burdens are allocated proportionally to the share of total service life delivered in each use cycle

4. Handles future uncertainty

-> future reuse uncertainty (e.g., likelihood of a 3rd or 4th life)

5. No double counting/mass flow consistent

6. Distributes material and EOL burdens across reuse cycles

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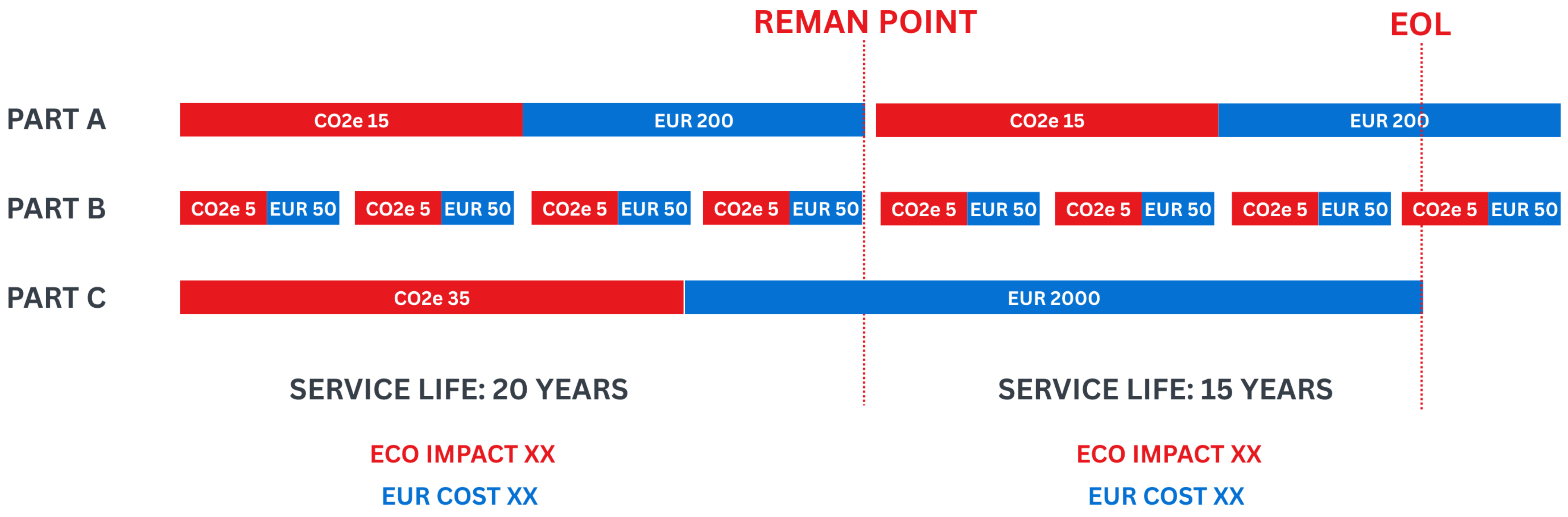
Key Idea Behind Decision Tool



Visual Dashboard - Decision Tool

Component	Material	Burden (kg CO2e) Cycle 1	Burden (kg CO2e) Cycle 2	Burden (kg CO2e) Cycle 3	Allocated Cycle 1	Allocated Cycle 2	Allocated Cycle 3	Multiplicity	MinLife	MaxLife	Reuse	Functional Service Life	1–40
System	94140	40607	26140	27393	34574	30664	28901						12 / 12 / 12
		43%	28%	29%	37%	33%	31%						
Frame	Cast Steel	12843	0	0	7135	4281	1427	1	40	60	1	50	Frame
Rollers	Tool Steel	8304	0	0	8304	0	0	3	12	48	1	12	Rollers 1A
Rollers	Tool Steel	8304	0	0	8304	0	0	3	12	48	1	12	Rollers 2A
Rollers	Tool Steel	8304	0	0	8304	0	0	3	12	48	1	12	Rollers 3A
Rollers	Tool Steel	0	8304	0	0	8304	0	3	12	48	1	12	Rollers 1B
Rollers	Tool Steel	0	8304	0	0	8304	0	3	12	48	1	12	Rollers 2B
Rollers	Tool Steel	0	8304	0	0	8304	0	3	12	48	1	12	Rollers 3B
Rollers	Tool Steel	0	0	8304	0	0	8304	3	12	48	1	12	Rollers 1C
Rollers	Tool Steel	0	0	8304	0	0	8304	3	12	48	1	12	Rollers 2C
Rollers	Tool Steel	0	0	8304	0	0	8304	3	12	48	1	12	Rollers 3C
Guides	Tool Steel	105			105	0	0	1	10	20	0	15	Guides A
Guides	Tool Steel		105		0	105	0	1	10	20	0	15	Guides B
Guides	Tool Steel												Guides C
Hydraulic Cylinders	Steel	110	0										
Hydraulic Cylinders	Steel	110	0										
Hydraulic Cylinders	Steel	110	0										
Hydraulic Cylinders	Steel	110	0										
Hydraulic Cylinders	Steel	110	0										
Hydraulic Cylinders	Steel	110	0										
Hydraulic Cylinders	Steel	110	0										
Hydraulic Cylinders	Steel	110	0										
Hydraulic Cylinders	Steel	110											
Hydraulic Cylinders	Steel	110											
Hydraulic Cylinders	Steel		110										Hydraulic Cylinders 9B
Hydraulic Cylinders	Steel		110										Hydraulic Cylinders 10B
Hydraulic Cylinders	Steel			110	0	0	110	10	20	30	0,8	25	Hydraulic Cylinders 1B
Hydraulic Cylinders	Steel			110	0	0	110	10	20	30	0,8	25	Hydraulic Cylinders 2B
Hydraulic Cylinders	Steel			110	0	0	110	10	20	30	0,8	25	Hydraulic Cylinders 3B
Hydraulic Cylinders	Steel			110	0	0	110	10	20	30	0,8	25	Hydraulic Cylinders 4B
Hydraulic Cylinders	Steel			110	0	0	110	10	20	30	0,8	25	Hydraulic Cylinders 5B
Hydraulic Cylinders	Steel			110	0	0	110	10	20	30	0,8	25	Hydraulic Cylinders 6B
Hydraulic Cylinders	Steel			110	0	0	110	10	20	30	0,8	25	Hydraulic Cylinders 7B
Hydraulic Cylinders	Steel			110	0	0	110	10	20	30	0,8	25	Hydraulic Cylinders 8B
Motor Windings	Copper	74			74	0	0	1	10	20	0	15	Motor Windings A
Motor Windings	Copper		74		0	74	0	1	10	20	0	15	Motor Windings B
Motor Windings	Copper			74	0	0	74	1	10	20	0	15	Motor Windings C
Motor Housing	Steel	308	0	0	207	75	25	1	30	40	1	36	Motor Housing
Pump	Cast Steel	77			77	0	0	1	10	15	0	12	Pump A
Pump	Cast Steel	77			77	0	0	1	10	15	0	12	Pump B

Scenario 2:
Rollers last for only 12 years

Lifecycle 1 through 3 span 12 years

So more rollers and other components are needed

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Decision Tool – What & Why?

1. **Utilize LCA outcomes**
2. **Predictive & Scenario Modelling**
3. **Determining Optimal Life Cycle Lengths**

   Shows how different use cycle durations influence total system impacts and long-term sustainability outcomes.
4. **Optimising Remanufacturing Decisions**

   When remanufacturing or refurbishing a component makes sense based on environmental impact reduction
5. **Creating Circular Design Strategies**

   Translates LCA results into design insights, highlighting which components to redesign for longevity or repeated refurbishment.
6. **Quantifying Long-Term Environmental Benefits**
7. **Prioritising High-Impact Components**

HTC Case – Model Overview

Purpose

- Calculate how environmental burdens are distributed across **three consecutive life cycles** of a product.
- Account for cases where components are **reused**, **refurbished**, or **fully replaced**.

Component Pathways

- **Replace**: Component is newly manufactured for each cycle.
- **Refurbish**: Component is restored and reused depending on remaining service life.

Impact Allocation Method

Dynamically distributes environmental impacts based on:

- Component's **service duration** within each cycle
- Whether the component is **reused or replaced**
- A **linear digression method** that spreads manufacturing and disposal burdens over time

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HTC Case Study for Tool Development

Assumptions/Limits:

1. Refurbishment activities are limited to metallization and powder coating
2. Module B (use stage) is excluded
3. Exclusion of assembly & disassembly on a system level
4. System lifespan 30 years divided evenly over 3 cycles
5. Excludes A4-5 (transport to customer and installation)

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Scenario Descriptions

Scenario 1: 3x new manufacturing

- Total 30 years, no remanufacturing, newly manufactured every cycle

Scenario 2: partial remanufacturing

- Total 30 years, some parts are reused/refurbished (majority is not)

Scenario 3: moderate remanufacturing

- Total 30 years, a moderate amount parts are reused/refurbished

Scenario 4: max efficiency in remanufacturing

- Total 30 years, max efficiency: all remanufactured parts last 30 years

Scenario 5: changing life cycle lengths (10/5/5):

- Total 20 years, C1 = 10years, C2 = 5 years, C3 = 5 years

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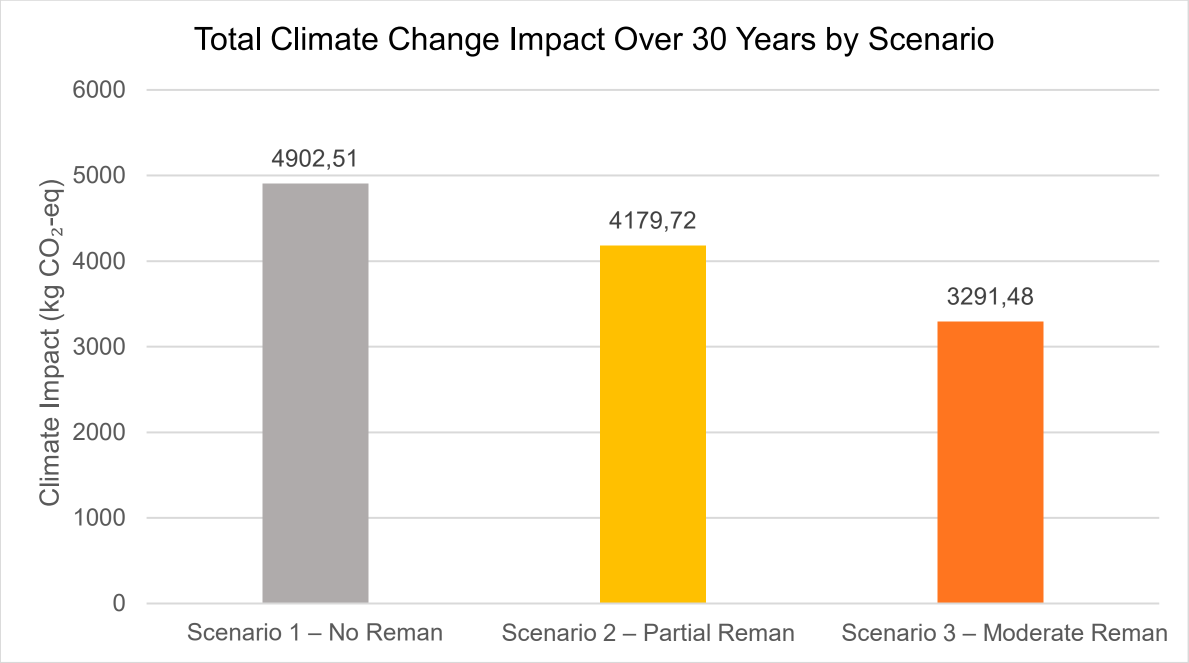
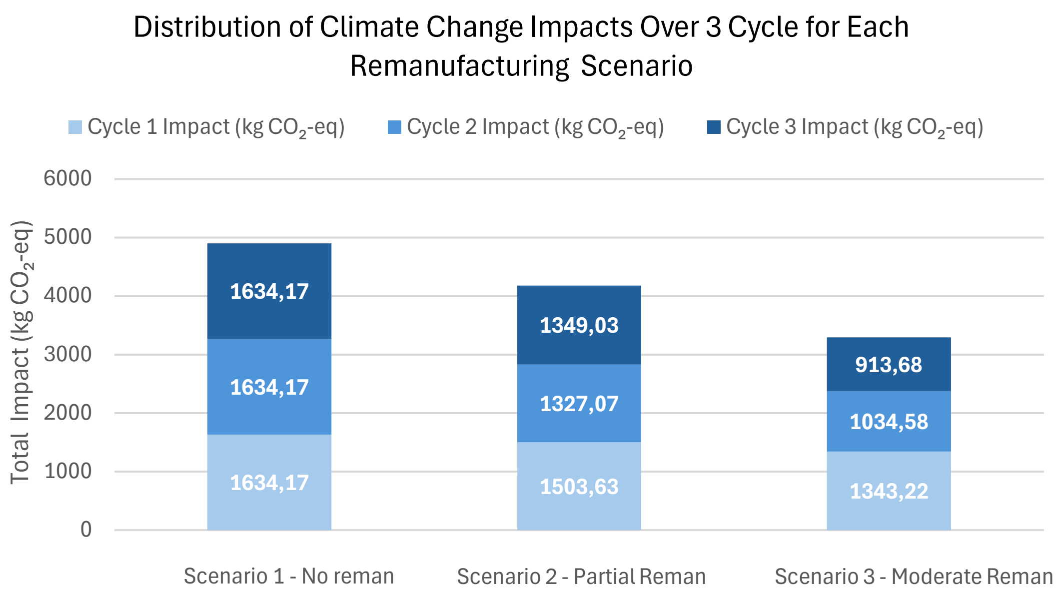
Overall Results Scenario 1,2,3

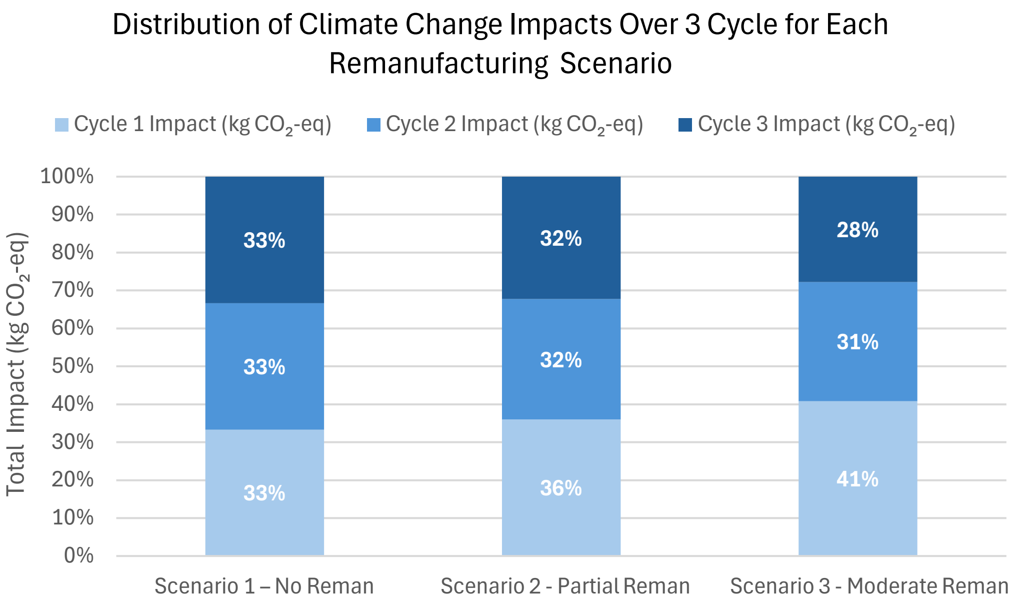


-> The more you reuse/refurb parts the lower your environmental impact

Results Scenario 1,2,3 by CELD Allocation Approach



Absolute Values (kgCO2eq) Across Cycles



Relative Distribution (%) Across Cycles

-> The highest portion of the impact goes to the first impact and the lowest to the final use cycle
-> Account for lower probability of final life cycle

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The Cut-off Allocation Approach

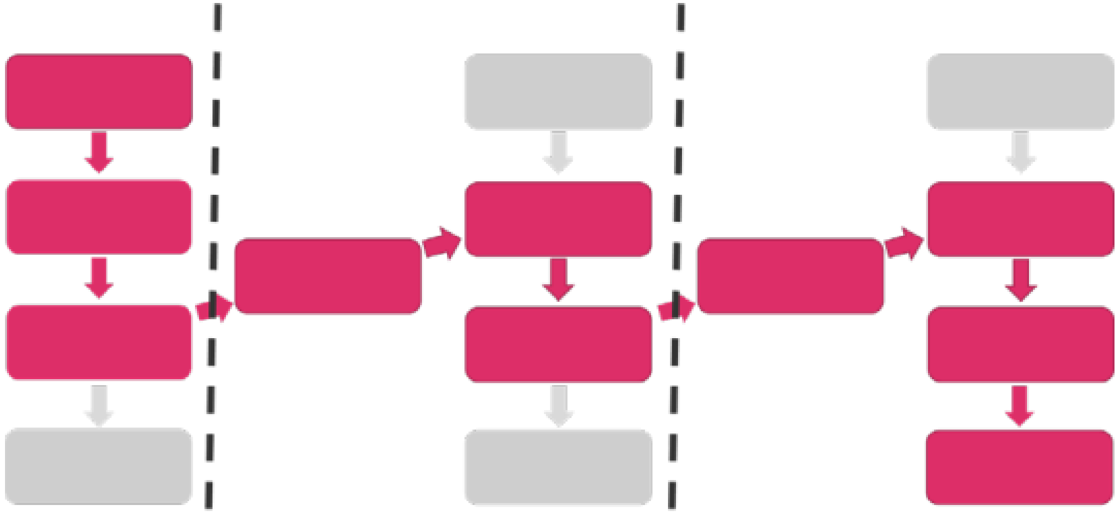
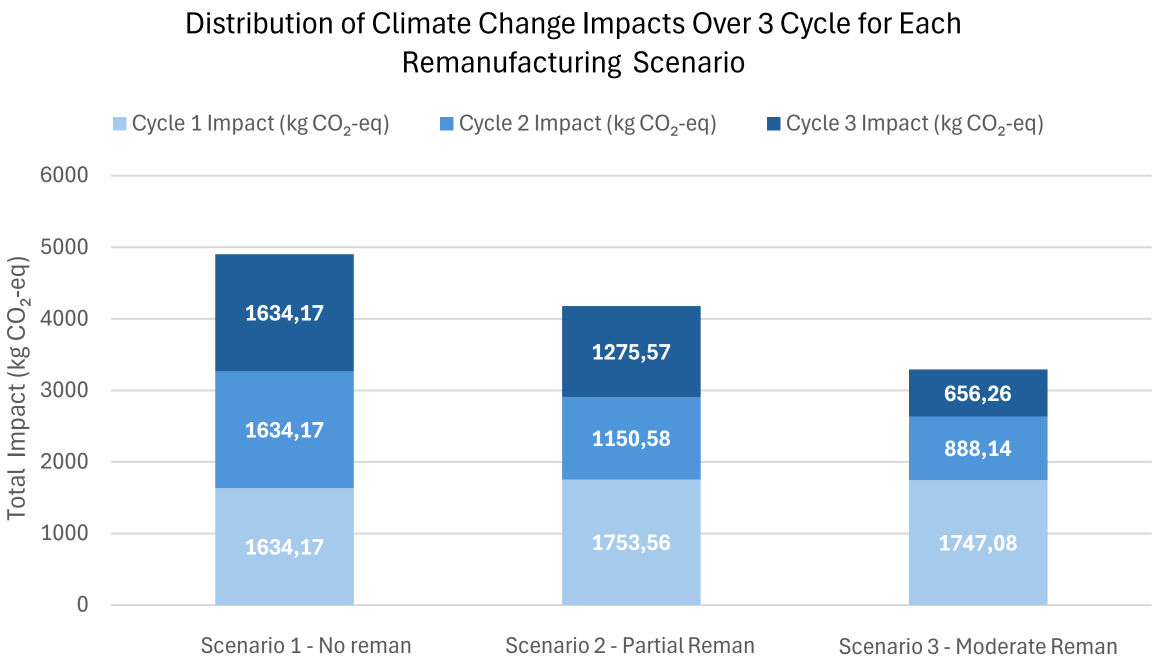
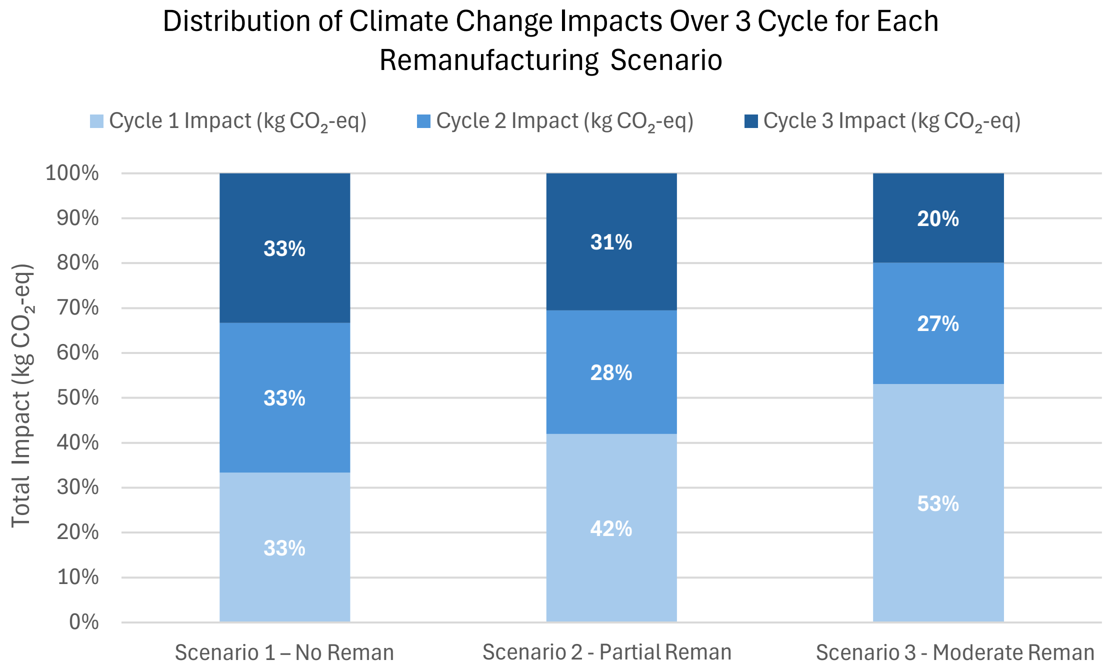


Figure 2: The simple cut-off approach as specified in the International EPD System.

 https://www.lifecyclecenter.se/wp-content/uploads/2020_05_Modeling-recyling-in-life-cycle-assessment-1.pdf

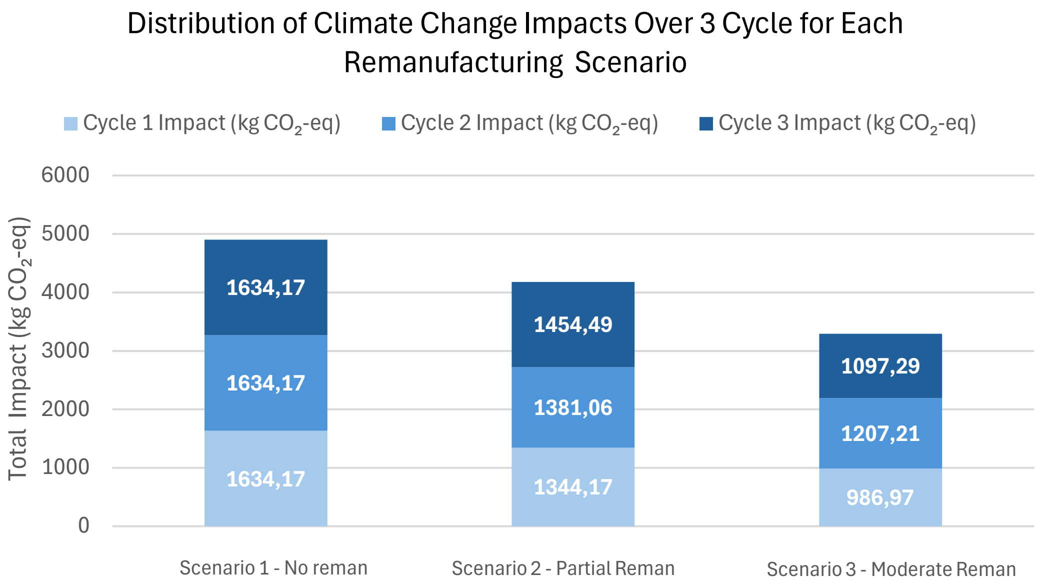
Results Scenario 1,2,3 by Cut-off Allocation Approach

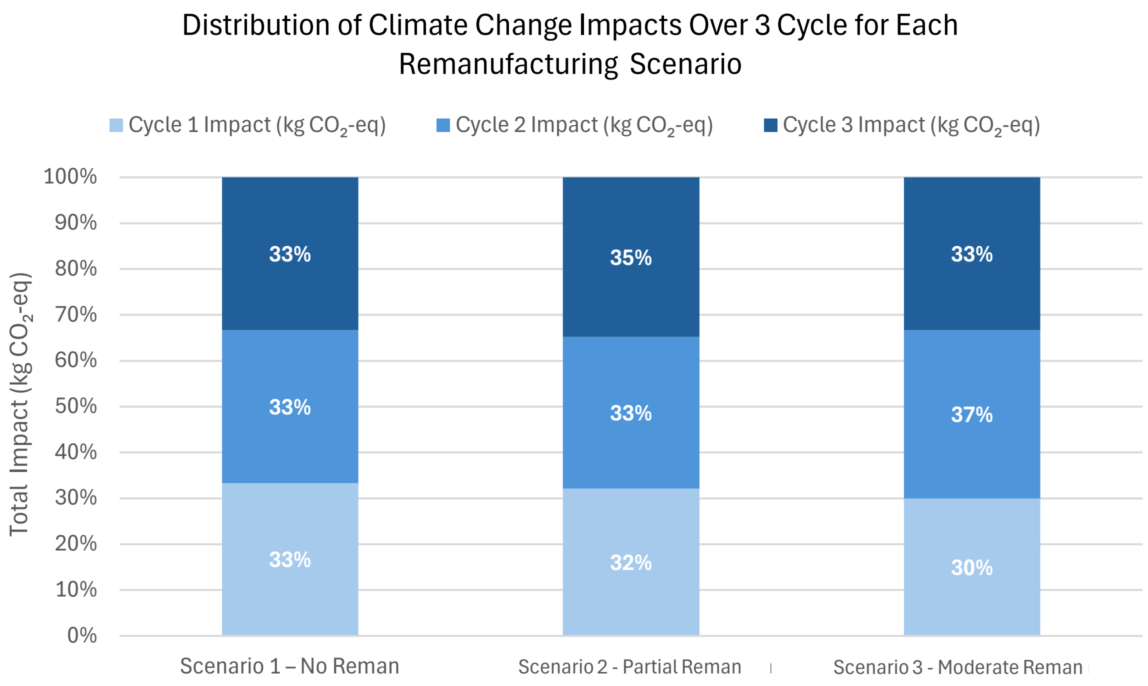




-> The first cycle bears the majority of the impact which increases the more parts are reused/refurbished (higher remanufacturability not rewarded

Results Scenario 1,2,3 by Equal Share (n-cycles)





-> The cycle that requires the most part replacements carries the highest burden, thus if parts are reused into cycle 2 but also need to be replaced in cycle 2 then distribution is not fairly allocated

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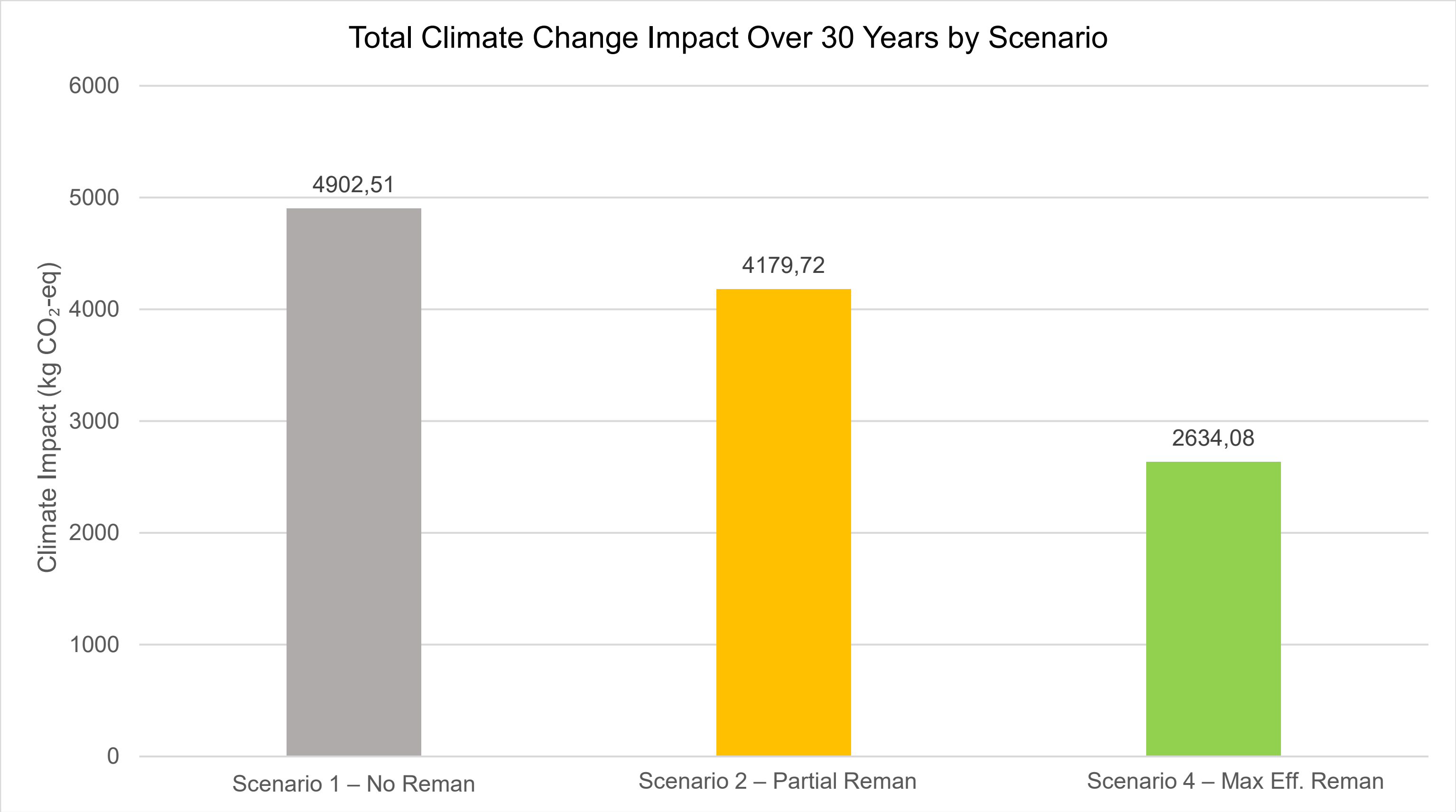
Results Scenario 4 – max efficiency of reman



➔ Higher reuse, lower replacements = much lower environmental impact

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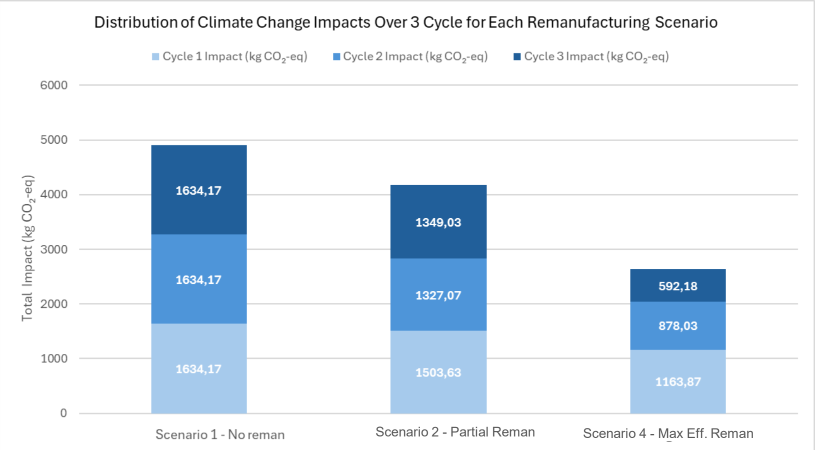
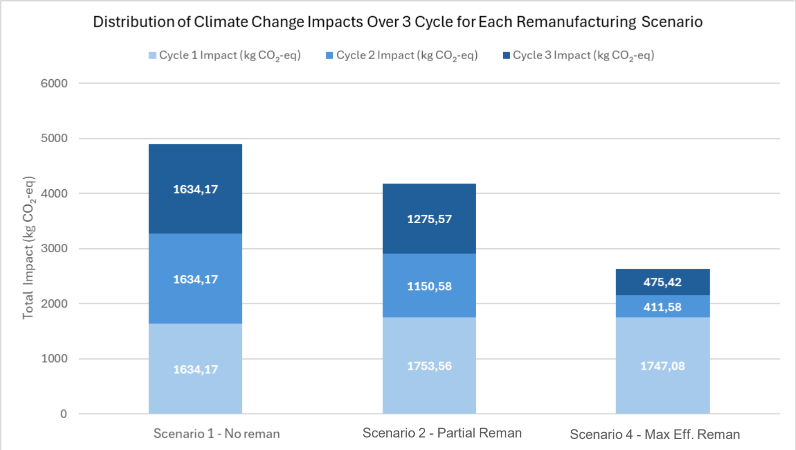
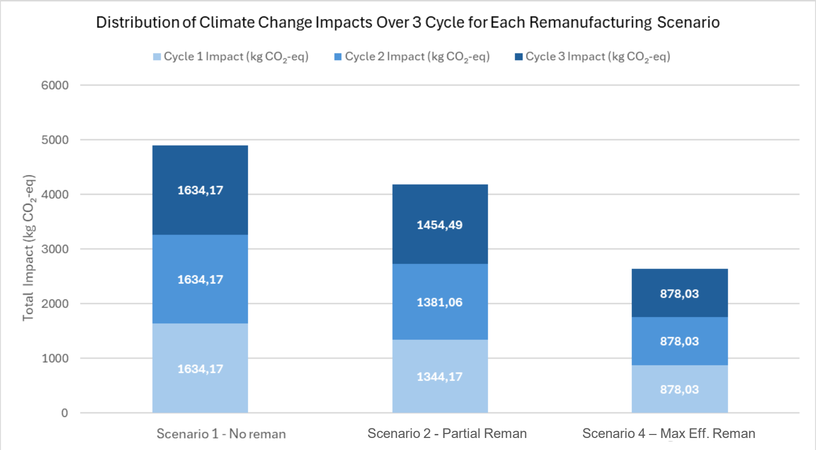
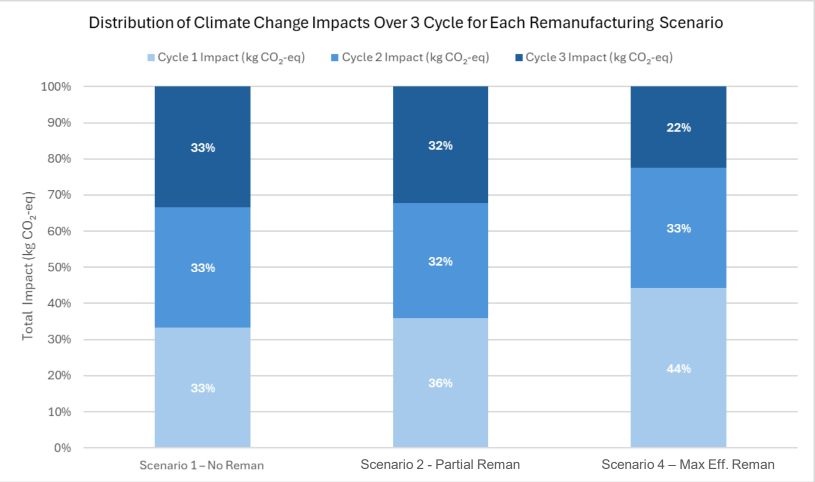
Results Scenario 4 – max efficiency remanufacturing

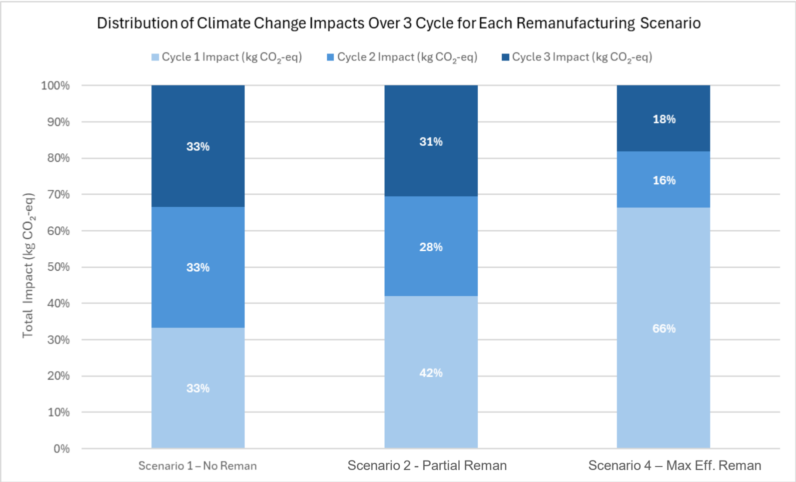
CE LD | Cut-off | Equal Split

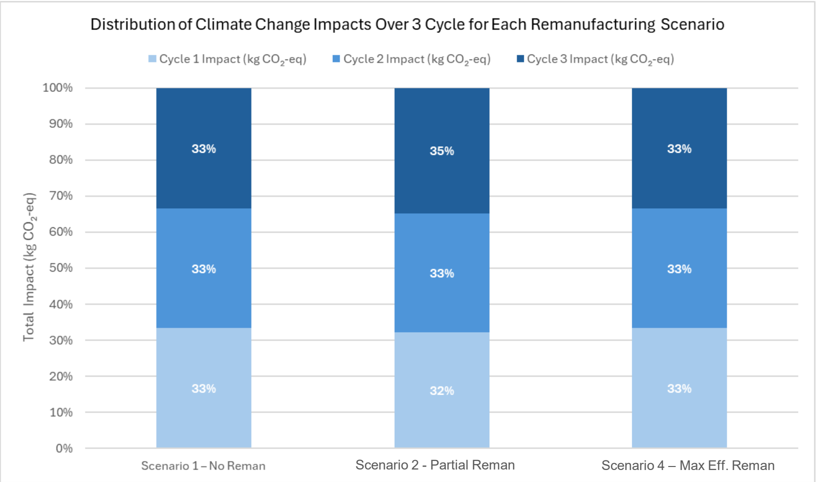






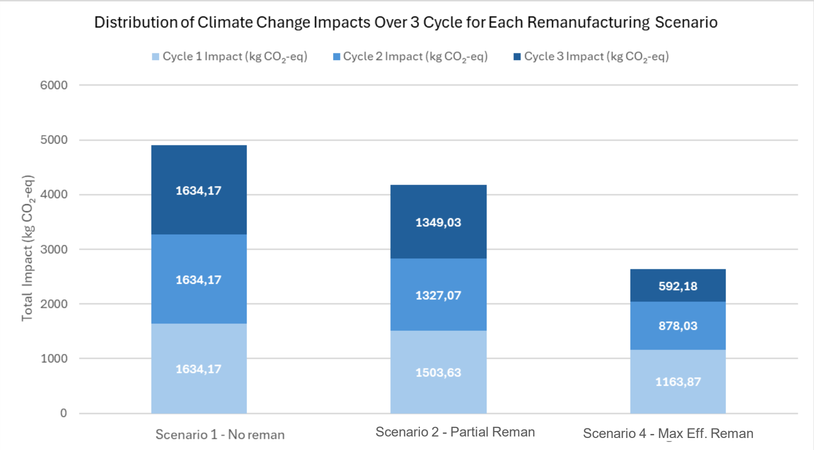


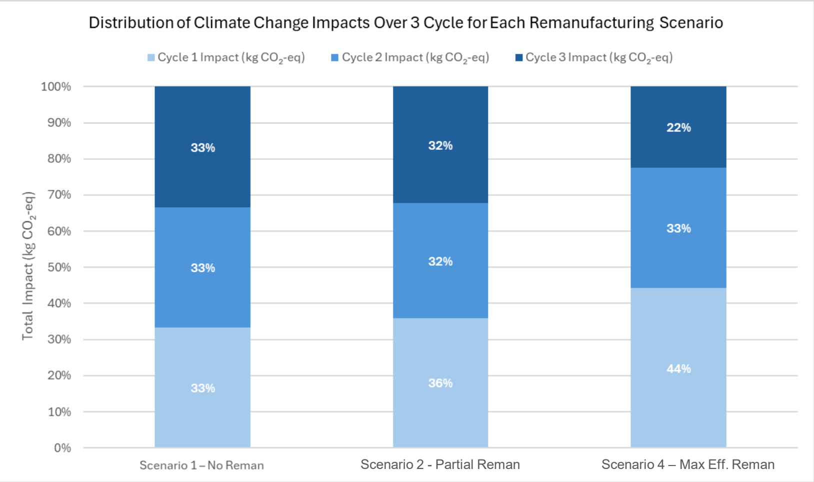




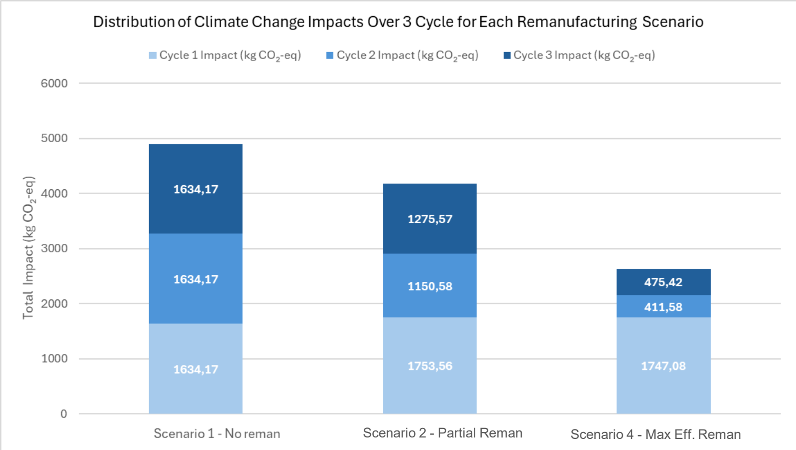
Results Scenario 4 – Max efficiency remanufacturing

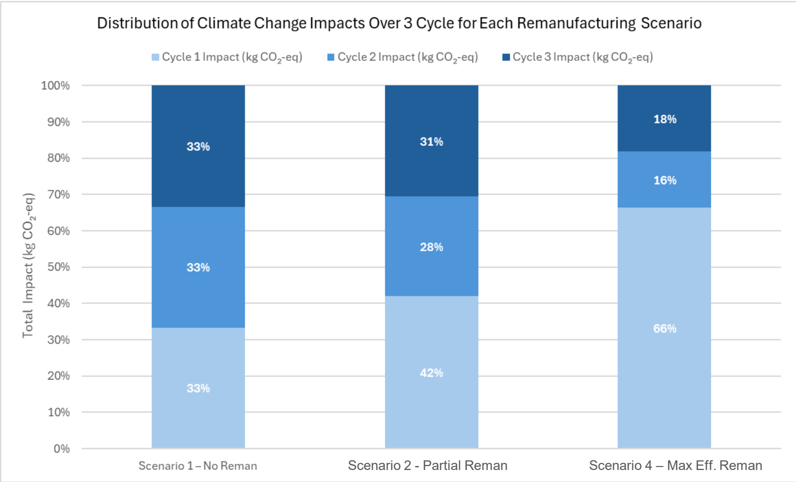
CE LD



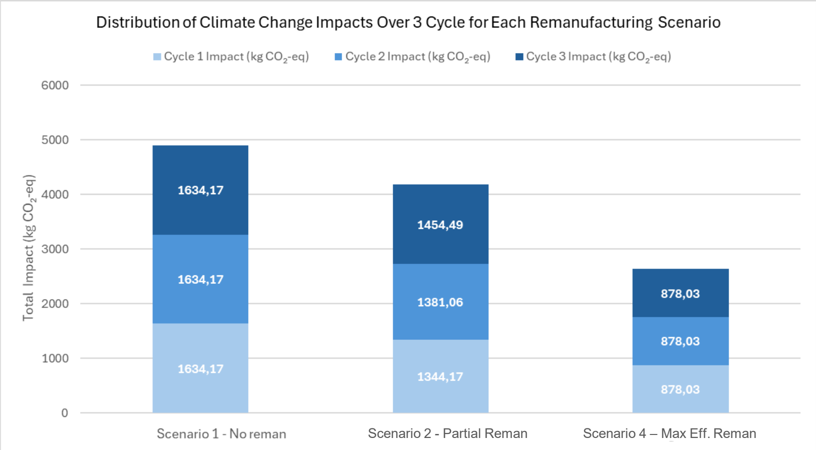


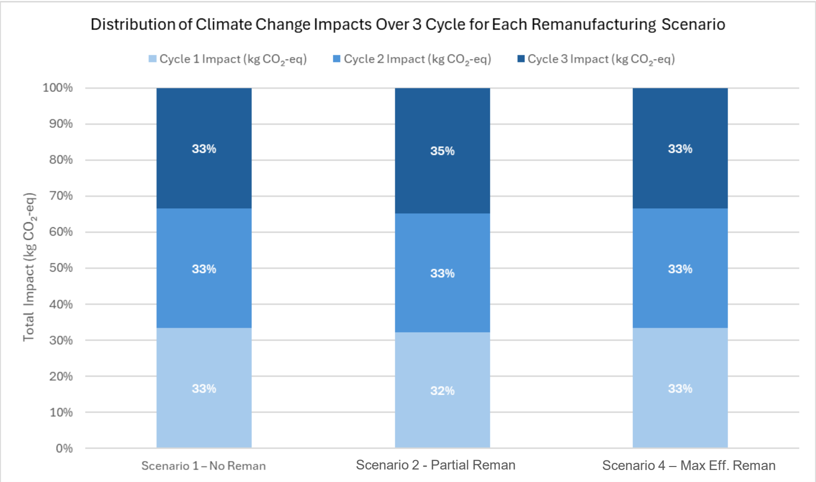
Cut-off





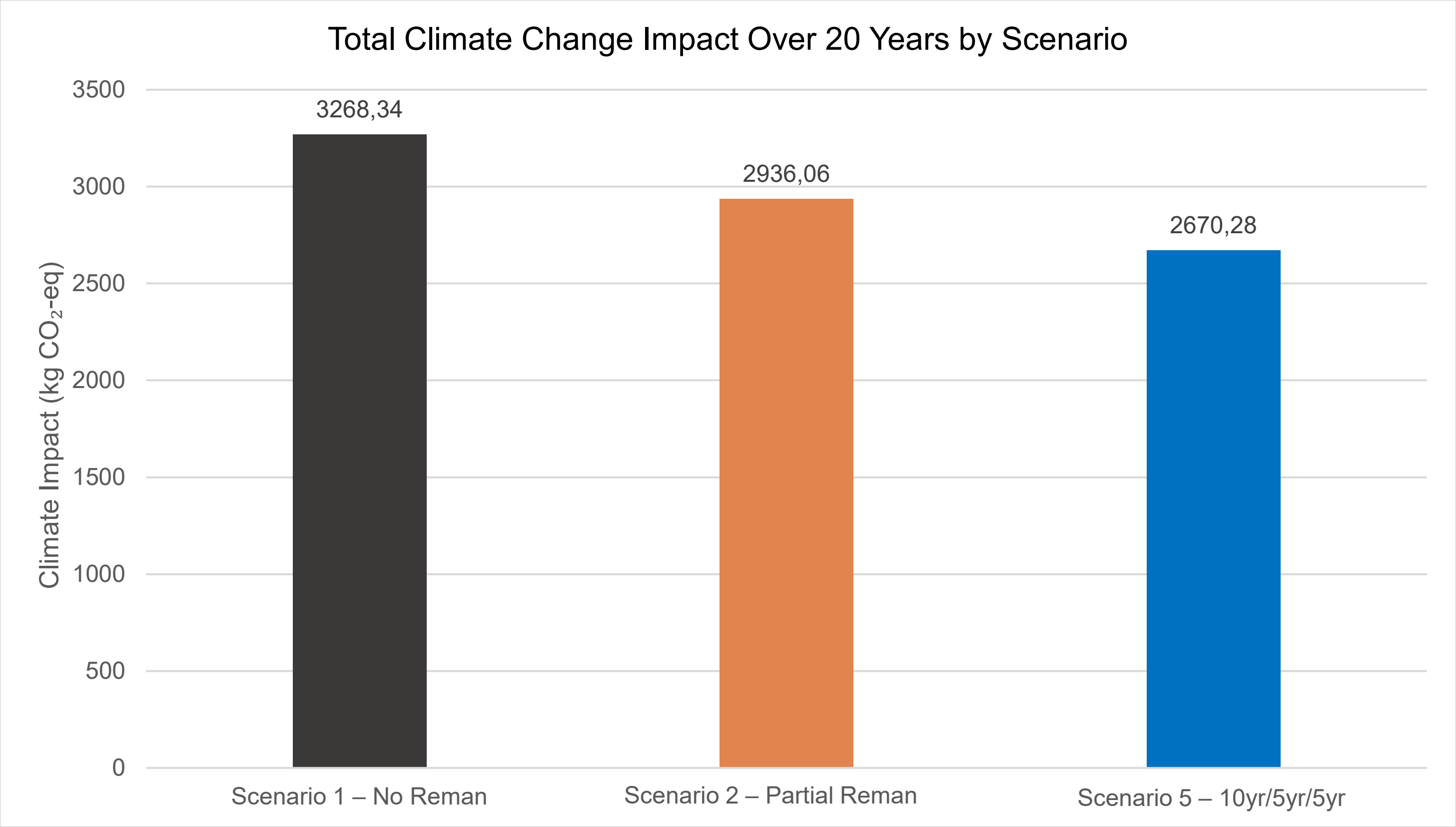
Equal Split





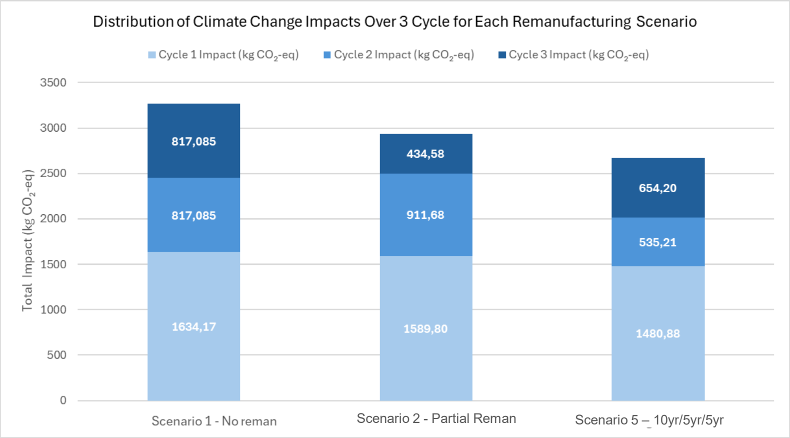
-> CELD most fair distribution considering likelihood of 3rd cycle in ambitious scenario

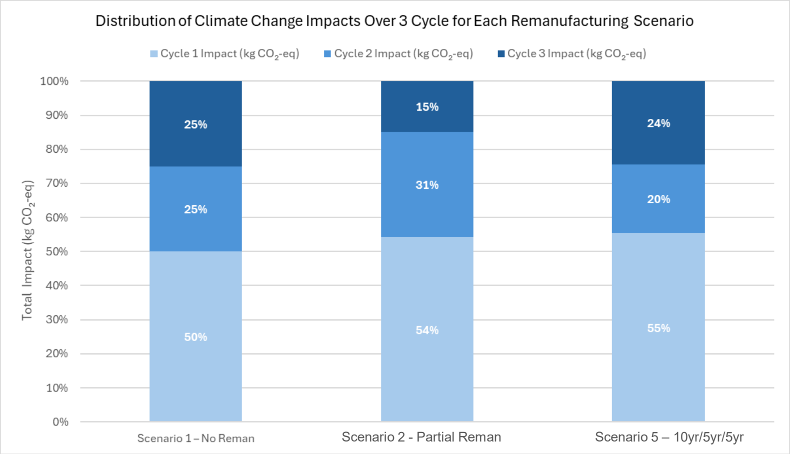
Results Scenario 5 - (10yr/5yr/5yr)



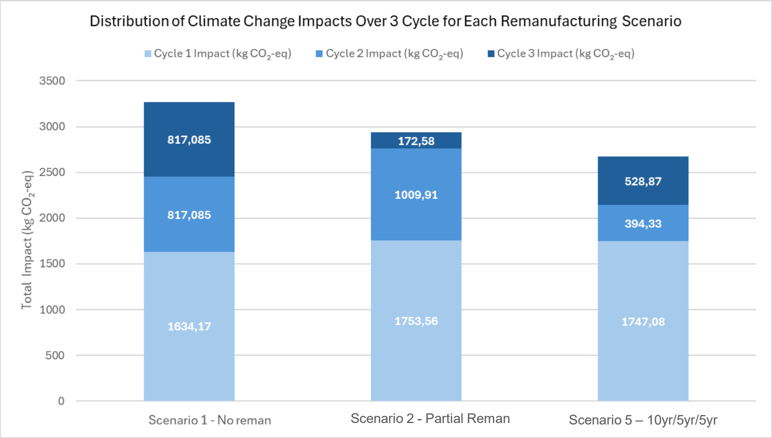
Results Scenario 5 – (10yr/5yr/5yr)

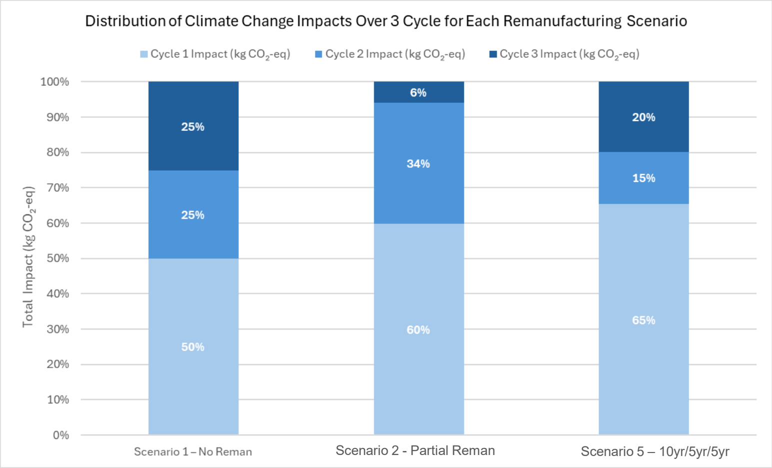
CE LD



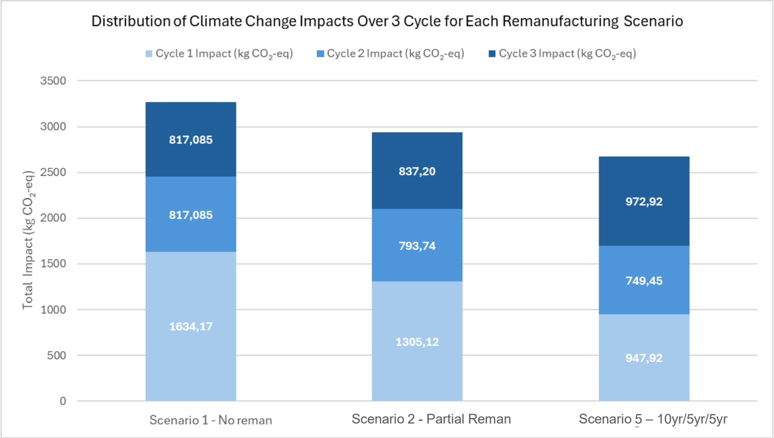


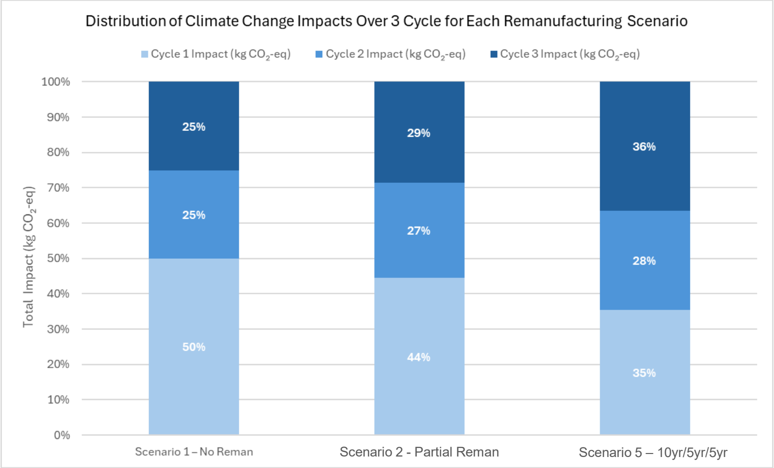
Cut-off





Equal Split





-> If cycle lengths are different (unequal) is distribution still fair
-> Cut-off: potential for green washing by creating short 1st life
-> Equal split: doesn't take into account cycle length – disproportional allocation

Wrap-up

- Allocation method that was the ‘winner’ from initial research: Linear degression method
- This method has been applied in (simplified) case studies on both Botau and HTC products

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Wrap-up

In progress / to-do

- We use(d) Footprintcalc and Idemat as LCA tools. These use different databases

- An Expert LCA was conducted.
  - The desire is to compare results on our cases for different scenario's and compare for both tools / databases.

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Follow up

Potential ideas:

- Incorporate LCC for full TCO (LCA+LCC)
- Visualization Dashboard
- Automatic Calculations for Optimization Routes
- Improve UI/ debug

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Discussion & Feedback

- Thank you for feedback!

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Thank you!