Reliability of electronics: From safety-critical systems to environmental sustainability

Chiara Sandionigi, CEA

chiara.sandionigi@cea.fr

Summer school SUSTAIN-E, Grenoble

17 June 2025

Agenda

Reliability of electronics: Background

Reliability for environmental performance

- A new R strategy for circular economy
- Related concepts in standards and legislation
- Introduction to eco-reliability
- Amortization of environmental impacts

Reliability for absolute sustainability

- Introduction to absolute sustainability
- Joint assessment of reliability, environmental impacts and environmental limits
- Compensation lifetime

Agenda

Reliability of electronics: Background

OBJECTIVE

❖ Provide the basic concepts related to reliability

Reliability for environmental performance

- A new R strategy for circular economy
- Related concepts in standards and legislation
- Introduction to eco-reliability
- Amortization of environmental impacts

Reliability for absolute sustainability

- Introduction to absolute sustainability
- Joint assessment of reliability, environmental impacts and environmental limits
- Compensation lifetime

Reliability definition

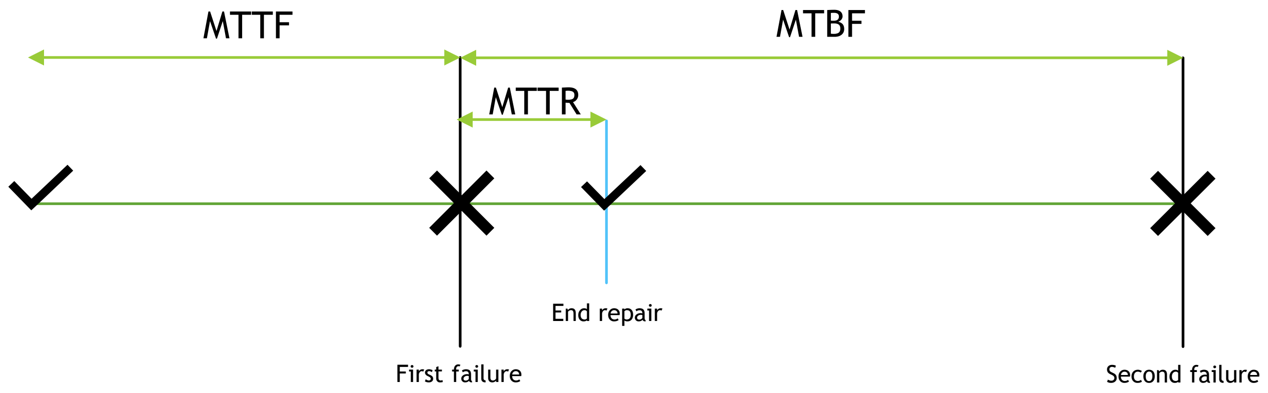
- Reliability is defined as the probability that an item (component, system, product) will perform its intended function for a stated period of time under a specified mission profile

Important elements of the definition:

- Probability
  - A value between 0 and 1
- Time
  - Item working until time t
  - $0 \leq R(t) \leq 1$
    - $R(t) = 0$ means the item is certain to fail
    - $R(t) = 1$ means the item is guaranteed to function (ideal, but unrealistic)
- Mission profile
  - A time sequence of environmental and operational stresses that the item is expected to encounter
  - It includes mechanical, electrical, thermal, and usage-related stresses

Some reliability metrics

- MTTF: Mean Time To Failure
  - Average time that an electronic component or system operates before it fails
- FIT: Failures In Time
  - Rate of failures (reciprocal of MTTF) generally reported as failures per billion hours of operation
- MTTR: Mean Time To Repair
  - Measure of service interruption
- MTBF: Mean Time Between Failures
  - MTTF + MTTR



Dependability: The umbrella concept

- **Reliability** is a core attribute of dependability
- **Dependability** is a comprehensive concept that defines the trustworthiness of an item

Other core attributes of dependability:

- **Availability**
  - Measure of the service accomplishment with respect to the alternation between the two states of accomplishment and interruption

$$Availability = \frac{MTTF}{MTTF + MTTR}$$

- **Maintainability**
  - Ease and speed with which a system can be repaired or modified after failure
- **Safety**
  - Absence of catastrophic consequences on users and environment
- **Integrity**
  - No improper system alterations
- **Confidentiality**
  - Protection of sensitive information from unauthorized access

Attribute	Focus
Reliability	Over time
Availability	At a moment
Maintainability	After a failure
Safety	Upon failure
Integrity	Data/function correctness
Confidentiality	Security

Fault – Error – Failure chain

Fault

- A defect or flaw in a component or system that has the potential to cause an error
- May be physical (e.g., broken solder joint), design-related (e.g., underrated capacitor) or external (e.g., radiation strike)
- Type of faults:
  - Transient (soft): Temporary fault that occurs for a short duration and disappears without physical damage
  - Intermittent: Fault that occurs sporadically under certain conditions, often due to marginal hardware (operation near the edge of limits) or unstable connections
  - Permanent (hard): Persistent fault resulting from physical damage or irreversible degradation

Error

- Deviation in the internal state of a system caused by a fault
- Multiple errors may result from a single fault

Failure

- Visible deviation of the system's output or behavior from its expected operation

Stage	Description
Fault	Cause
Error	Internal incorrect state
Failure	Observed deviation in behavior

Fault detection and tolerance

- The causal chain Fault – Error – Failure is foundational in reliability engineering
  - Design detection mechanisms (detect faults and errors before failures)
  - Implement fault tolerance (mask or recover from faults)
  - Analyze failure modes and effects (e.g., Failure Modes and Effects Analysis, Fault Tree Analysis)

Fault detection

- Detection of faults early to prevent or mitigate failures
- Mechanisms: Built-In Self-Test, watchdog timers, parity/error checking, signal monitoring, sensor feedback, diagnostics software

Fault tolerance

- Ability of a system to continue functioning correctly
- Achieved using redundancy, error correction, recovery
- Hardware-based, software-based or hybrid

- Improving reliability involves additional cost, complexity, resource usage or performance impact

Reliability applications

Safety-critical systems

- Reliability is essential in safety-critical systems
  - Systems whose failure could result in loss of life, severe injury, environmental harm, or major property damage
  - Examples: Aircraft control systems, Medical devices, Nuclear power control systems, Automotive
- Regulations and certifications demand predictable and provable reliability (e.g., ISO 26262)
- Use of fault tolerance is mandatory

Non-safety-critical systems

- Reliability is about user trust, competitiveness, and cost management
  - Systems whose failure does not pose a risk to human life, health, or the environment, and typically results only in loss of functionality, convenience, or performance
  - Examples: TVs, smartphones, consumer IoT, gaming devices
- Emphasis is on user satisfaction, cost-efficiency, and warranty periods
- Tolerable to have occasional failures if low cost and high availability are maintained

Agenda

Reliability of electronics: Background

- ❖ Reliability: Probability of the correct functioning of electronics for a period of time under specified conditions
- ❖ Reliability comes with a cost
- ❖ Not optional in safety-critical systems

TAKEAWAYS

Reliability for environmental performance

- A new R strategy for circular economy
- Related concepts in standards and legislation
- Introduction to eco-reliability
- Amortization of environmental impacts

Reliability for absolute sustainability

- Introduction to absolute sustainability
- Joint assessment of reliability, environmental impacts and environmental limits
- Compensation lifetime

Agenda

Reliability of electronics: Background

Reliability for environmental performance

- A new R strategy for circular economy
- Related concepts in standards and legislation
- Introduction to eco-reliability
- Amortization of environmental impacts

❖ What changes when considering reliability for environmental performance?

Environmental performance: Measurable outcomes related to an electronic product's or component's impact on the environment throughout its life cycle, including resource use, emissions and waste generation

OBJECTIVE

Reliability for absolute sustainability

- Introduction to absolute sustainability
- Joint assessment of reliability, environmental impacts and environmental limits
- Compensation lifetime

Agenda

Reliability of electronics: Background

Reliability for environmental performance

- A new R strategy for circular economy
- Related concepts in standards and legislation
- Introduction to eco-reliability
- Amortization of environmental impacts

Claim: Reliability can be considered as a strategy for circularity
- It is essential to guarantee a period of correct functioning

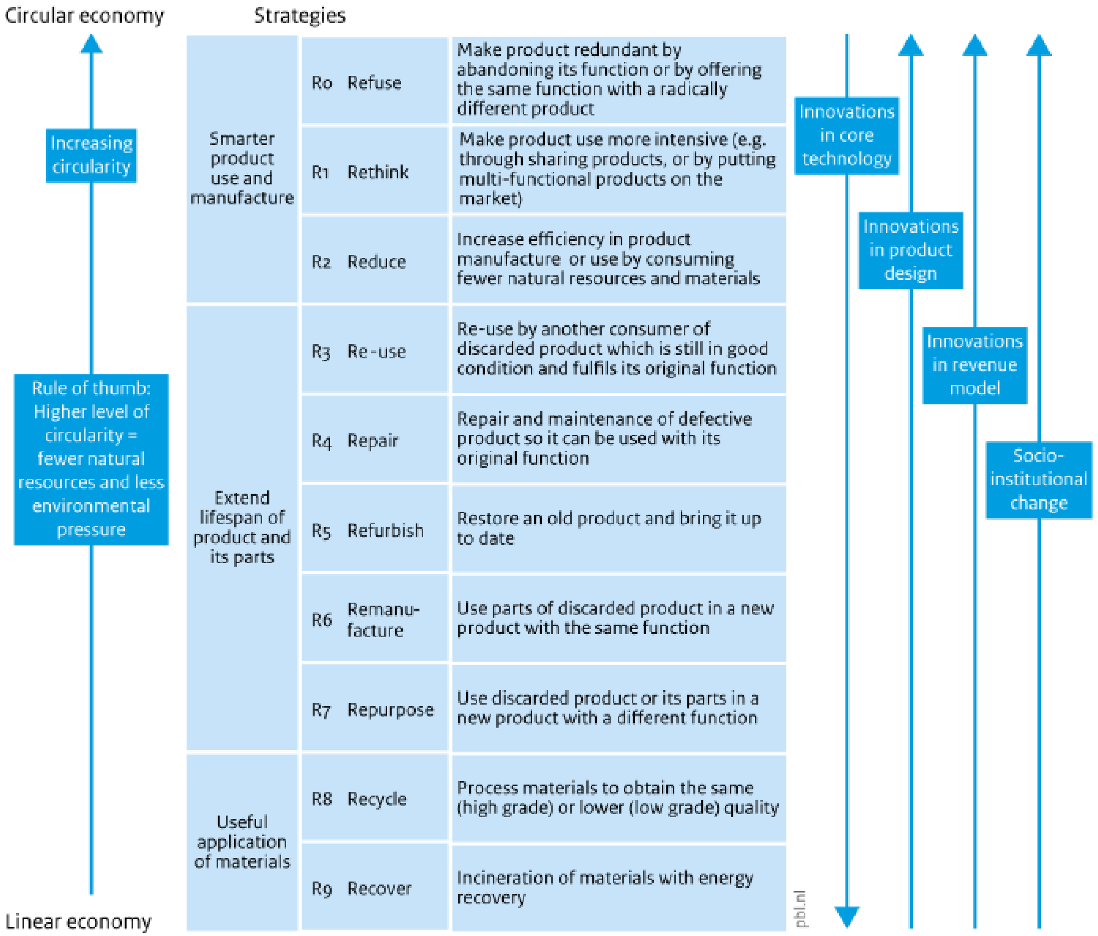
Reliability should enter into R frameworks

Reliability for absolute sustainability

- Introduction to absolute sustainability
- Joint assessment of reliability, environmental impacts and environmental limits
- Compensation lifetime

R frameworks

- R frameworks are seen as the ‘how-to’ of circular economy and thus a core principle of it
- All varieties of frameworks share a hierarchy
  - The first R viewed to be a priority on the second R and so on
- One of the most known frameworks is the 9R framework reported in a policy report of 2017
- Conceptual framework about the role of innovation in circular economy transitions in product chains
- Circularity strategies are grouped into three objectives
- A higher level of circularity means that the materials remain in the chain for a longer period
  - They can be applied after a product is discarded



Source: RLI 2015; edited by PBL

References
- *J. Kirchherr et al., ‘Conceptualizing the circular economy: An analysis of 114 definitions’, Resources, Conservation and Recycling, 2017*
- *J. Potting et al., ‘Circular economy: Measuring innovation in the product chain’, Policy Report, 2017*

Reliability as a new R strategy

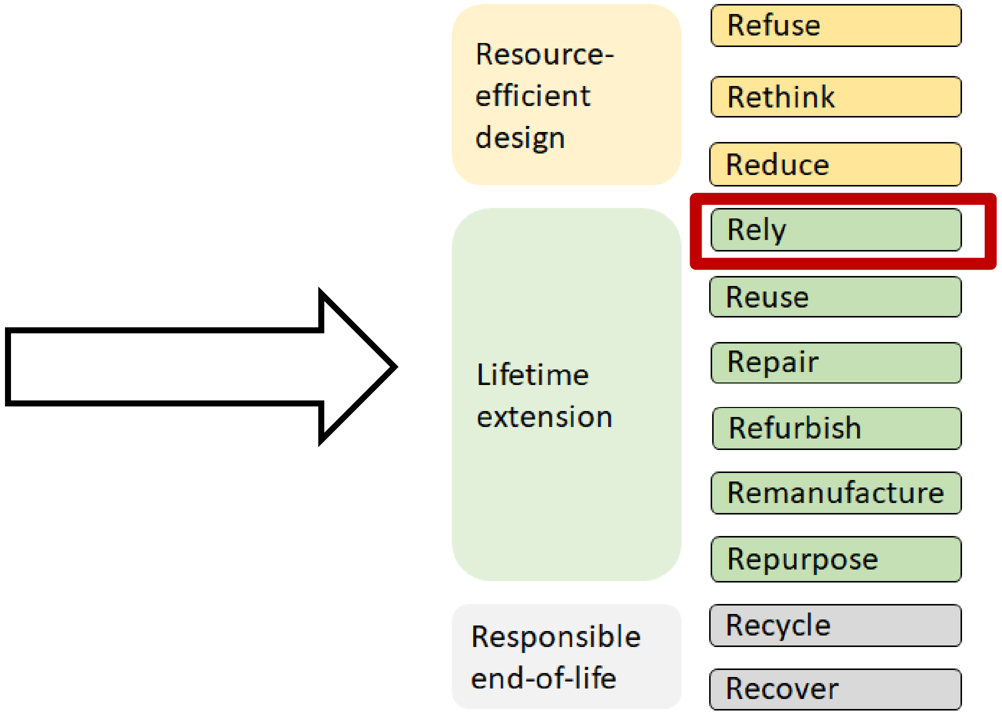
- R frameworks are general, not specific to a sector
- When designing electronics with the target of material efficiency, the reduction of the consumption of materials is not enough
  - It doesn't cover the durability aspects
- Rely is the priority strategy for lifetime extension

Smarter product use and manufacture	R0 Refuse	Abandon function or offer the same function with a different product
	R1 Rethink	Make product use more intensive (e.g. product sharing or multi-functional)
	R2 Reduce	Consume fewer natural resources and materials
Extend lifespan of product and its parts	R3 Reuse	Reuse by another consumer of discarded product in good conditions
	R4 Repair	Repair and maintenance of defective product with original function
	R5 Refurbish	Restore an old product and bring it up to date
	R6 Remanufacture	Use parts of discarded product in a new product with the same function
	R7 Repurpose	Use discarded product or parts in a new product with a different function
Useful application of materials	R8 Recycle	Process materials to obtain the same or lower quality
	R9 Recover	Incineration of material with energy recovery

WE ARE HERE

Adapted from
Potting et al., 'Circular economy: Measuring innovation in the product chain', 2017

- Guarantee and maximize the first life



References to R frameworks introducing Reliability
- *EPoSS working group, 'ECS sustainability and environmental footprint', 2023*
- *P. Blouet, 'Why sustainability is crucial for Europe's future', HiPEAC vision 2023*

Agenda

Reliability of electronics: Background

Reliability for environmental performance

- A new R strategy for circular economy
- Related concepts in standards and legislation
- Introduction to eco-reliability
- Amortization of environmental impacts

Reliability is starting to be considered a circularity strategy in conceptual frameworks, but not only

Reliability is recognized as a requirement for material efficiency in standards and legislation

Reliability for absolute sustainability

- Introduction to absolute sustainability
- Joint assessment of reliability, environmental impacts and environmental limits
- Compensation lifetime

A bird's-eye view on EU's ecodesign legislation

- The **Ecodesign for Sustainable Products Regulation (ESPR)** has officially replaced the **Ecodesign Directive 2009/125/EC**, marking a significant shift in the European Union's approach

Transition from Directive to Regulation

- **Directive 2009/125/EC** established a framework for setting ecodesign requirements specifically for energy-related products
- On 13 June 2024, the European Parliament and the Council adopted **Regulation (EU) 2024/1781**, which repeals Directive 2009/125/EC and establishes a new framework for setting ecodesign requirements for sustainable products
- The **ESPR** entered into force on 18 July 2024, initiating a transition period until 2030 during which the existing directive and its implementing measures will continue to apply alongside the new regulation

Feature	Directive 2009/125/EC	ESPR
Type of act	Indirect law	Direct law
Binding nature	Binds member states to results, but let them choose how to implement	Binds everyone directly in all member states
Requires transposition?	Yes	No
Scope	Energy-related products	Almost all physical products

Introducing resource efficiency

Key enhancements under ESPR

- **Broader scope**: While the previous directive applied only to energy-related products, the ESPR extend its scope to almost all physical products with limited exceptions (such as food, medicinal products,…)
- Digital Product Passports (**DPPs**): The ESPR mandates the implementation of DPPs for goods sold in the EU
- Comprehensive ecodesign requirements introducing **resource efficiency**: The ESPR introduces a wide range of ecodesign requirements, including the overall reduction of the environmental footprint and aspects like durability

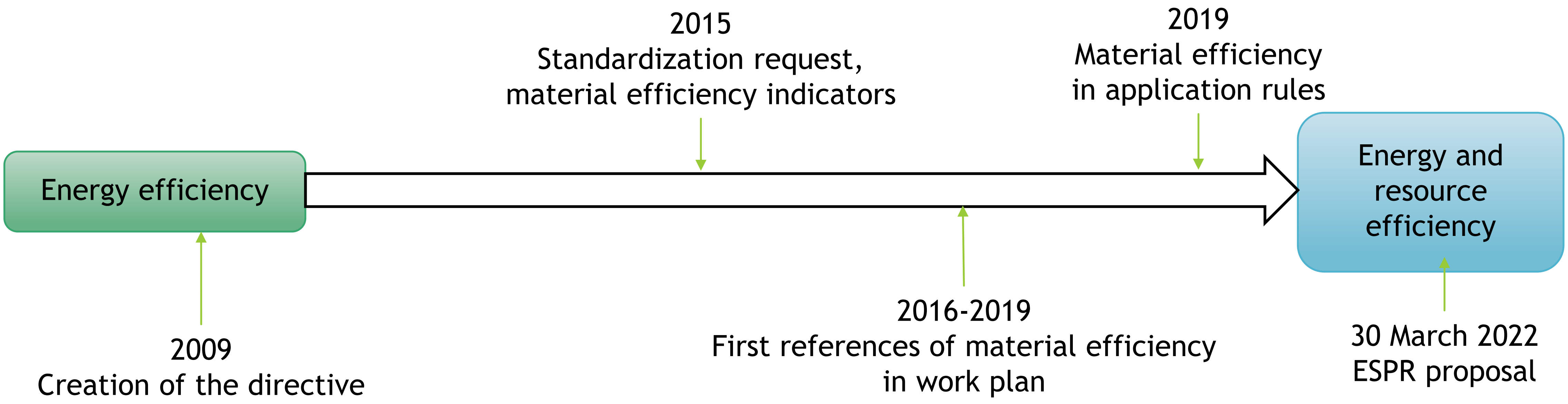
involves reliability

Resource efficiency

- Recovery of strategic and critical raw materials
- Reduce the expected generation of waste
- Increase the recycled content in products

From energy efficiency to resource efficiency

- In response to the European Commission's Circular Economy Action Plan, CEN and CENELEC established the Joint Technical Committee 10 (JTC 10) in 2015
  - The mandate of the committee was to develop standards addressing material efficiency aspects, such as durability
- The objective was to deliver two Technical Reports and eight European Norms, including
  - CLC/TR 45550:2020 – Definitions related to material efficiency
  - EN 45552:2020 – General methods for the assessment of the durability of energy-related products



Definitions of reliability and durability

EN 45552:2020

- Reliability: Probability that a product will perform as required under given conditions, including maintenance, for a given time without a limit event

ESPR (proposal 2022)

- Reliability: Probability that a product functions as required under given conditions for a given duration without a limiting event

ESPR (final version 2024)

- Reliability: Probability that a product functions as required under given conditions for a given duration without an occurrence which results in a primary or secondary function of the product no longer being performed

EN 45552:2020

- Durability: Ability to perform as required, under defined conditions of use, maintenance and repair, until a limit state leading to end of life is reached

ESPR (proposal 2022)

- Durability: Ability of a product to function as required, under specified conditions of use, maintenance and repair, until a limiting event prevents its functioning

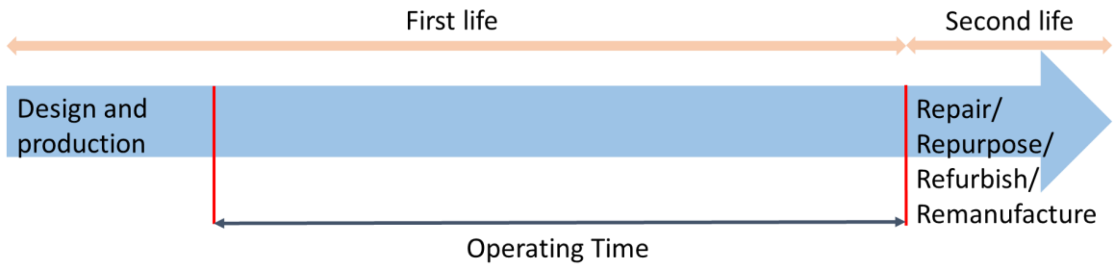
ESPR (final version 2024)

- Durability: Ability of a product to maintain over time its function and performance under specified conditions of use, maintenance and repair

Hypotheses on reliability for environmental performance

Hypotheses based on the definitions of the ESPR final version

- Durability involves reliability, performance, maintenance, repair
- Reliability is a probability of correct functioning for the **operating time** of the first life
  - Given conditions and given duration are specified for a life phase
  - For each new life phase (after the application of an R strategy for lifetime extension), reliability must be re-evaluated



Agenda

Reliability of electronics: Background

Reliability for environmental performance

- A new R strategy for circular economy
- Related concepts in standards and legislation
- Introduction to eco-reliability
- Amortization of environmental impacts

How to integrate both reliability and environmental aspects in the design of electronics?

Some examples on how to join reliability and environmental impacts from literature

Reliability for absolute sustainability

- Introduction to absolute sustainability
- Joint assessment of reliability, environmental impacts and environmental limits
- Compensation lifetime

Joining reliability and environmental impacts

2009
[1] Design of a robot with considerations of environmental impact (Toxic Potential Indicator) and reliability (thermal stress)

2012
[2] Eco-reliability : Theoretical analysis

2015
[3] Comparison of design choices for power electronics and sensors

2018
[4] Reliability of memories taking into account embodied and operational energy

References

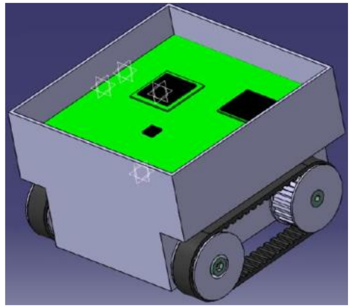
[1] Middendorf et al., 'Integration of reliability and environmental aspects in early design stages of electronics', International Symposium on Sustainable Systems and Technology, 2009

[2] Middendorf et al., 'Eco-reliability as a new approach of multi-criteria optimization', Electronics Goes Green, 2012

[3] Middendorf et al., 'Establishing eco-reliability of electronic devices in manufcturing environments', Global Conference on Sustainable Manufacturing, 2015

[4] Kline et al., 'Achieving secure, reliable and sustainable next generation computing memories', International Green and Sustainable Computing Conference, 2018

Integration of reliability and environmental aspects in early design stages of electronics



- First focus on both environmental performance and reliability for mechatronics
  - Example of a miniature robot
- Environmental assessment focused on material properties
  - E.g., Toxic Potential Indicator, Recycling Potential Indicator
- Recognition of the environmental dimension of reliability for long lived products
  - Reliability influences the time and cost of scheduled and unscheduled maintenance
  - Reliability influences the lifecycle concept and end-of-life options
  - Resource efficiency is improved if known good components can be reused, e.g. in conjunction with a dedicated spare part strategy
  - Focus on thermal and thermo-mechanical stress

Reference

- *Middendorf et al., 'Integration of reliability and environmental aspects in early design stages of electronics', International Symposium on Sustainable Systems and Technology, 2009*

Eco-reliability as a new approach for multi-criteria optimization

Context

- Reliability and environmental aspects generally do not have the highest optimization priority and respective issues are typically addressed towards the end of the design process
- In order to be on the safe side, a conventional product is slightly over-designed

Research Q&A

- What causes the integration of reliability and environmental aspects right from the beginning into the design process?
  - There are considerable overlaps and trade-offs between reliability and environmental impacts
  - A clearly defined lifetime and environmental strategy can be beneficial and accelerate design decisions
- What are the objectives that need to be balanced?
  - Overhead due to reliability, environmental impact, performance, cost

Contribution

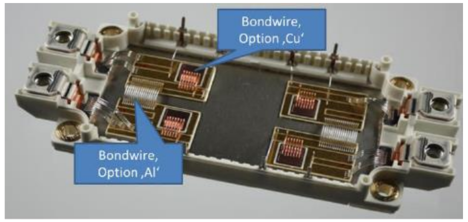
- Introduction of the neologism **eco-reliability**
  - Eco-reliability describes the inclusion of reliability aspects into the environmentally conscious design of electronic systems to address the originally separated domains from one mutual perspective
- Reliability as a factor of multi-criteria optimization with environmental impacts, performance and cost

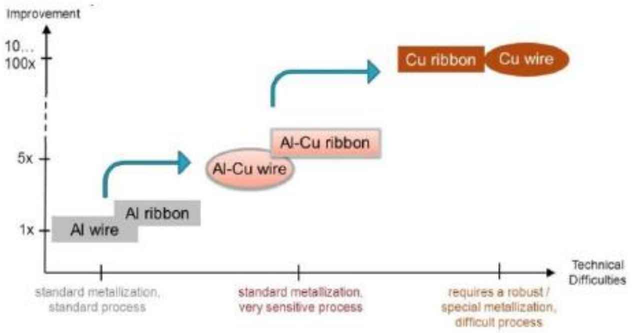
Reference

- *Middendorf et al., 'Eco-reliability as a new approach of multi-criteria optimization', Electronics Goes Green, 2012*

Establishing eco-reliability of electronic devices in manufacturing environments

- Application of eco-reliability to embedded electronics





Case study: Power electronics

- Active components electrically contacted by bondwires
- Two technological options: copper or aluminium wires
- Comparison of measures to increase the allowable number of thermal cycles during operation towards shift in environmental attributes
  - 14304 mg of copper vs 6748 mg of aluminium necessary in the case study to provide comparable electrical properties
  - The use of copper increases reliability by means of allowable thermo-cycles by factor 10 and upwards
  - Copper wires involve higher cost for the modification of the chip-metallization and more complex bonding processes
  - A material mix approach (copper wire coated with aluminium) is possible
  - Environmental indicators compared: Toxic Potential Indicator, Resource Availability and Risk Indicator, Cumulated Energy Demand, CO_2 emissions during production of primary and second metal, Weight
- Copper allows gain in lifetime but increases in environmental impacts, with the exception of direct costs associated only with the bulk material

	Weight	TPI	CED (prim.)	CO_2 (prim.)	CO_2 (sec.)	RARI	Costs	Lifetime
Cu/Al (ratio)	2.12	2.40	0.76	0.54	2.74	1.60	7.80	≈ 5-10

Reference

- *Middendorf et al., 'Establishing eco-reliability of electronic devices in manufcturing environments', Global Conference on Sustainable Manufacturing, 2015*

Achieving secure, reliable and sustainable next generation computing memories

- Design of memory systems taking into account
  - Reliability
  - Embodied and operational emissions
  - Performance
  - Security

- Traditional reliability solutions often suggest large storage overheads with a negative impact on embodied energy to minimize operational energy
- Reliability solutions should consider both embodied and operational energy

Example of contribution joining reliability and environmental impacts

- SFaultMap: Area-efficient fault map to improve reliability while minimizing embodied and operational energy
  - Bit-level fault map for use in memories with potential faults caused by process variations

References

- *Kline et al., 'Sustainable Fault Management and Error Correction for Next-Generation Main Memories', IGSC, 2017*
- *Kline et al., 'Achieving secure, reliable and sustainable next generation computing memories', International Green and Sustainable Computing Conference, 2018*

Agenda

Reliability of electronics: Background

Reliability for environmental performance

- A new R strategy for circular economy
- Related concepts in standards and legislation
- Introduction to eco-reliability
- Amortization of environmental impacts

Reliability guarantee a duration for the use phase

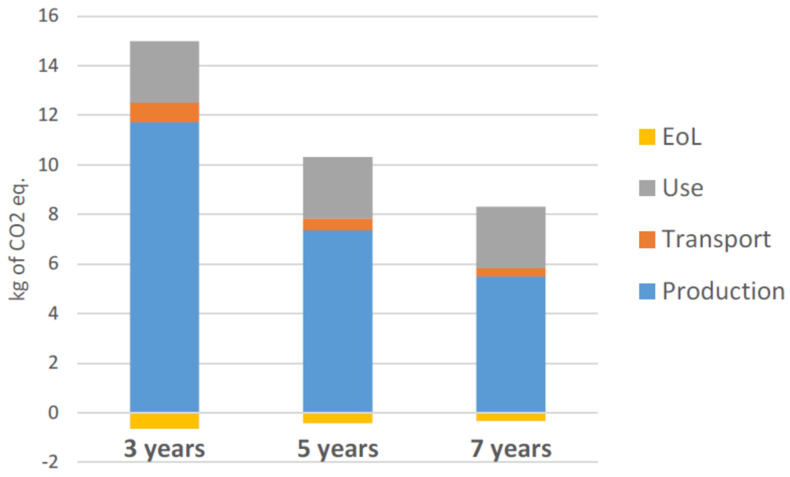
The duration of the use phase has effects on the environmental contributions per year

What are such effects and how are they evaluated?

Reliability for absolute sustainability

- Introduction to absolute sustainability
- Joint assessment of reliability, environmental impacts and environmental limits
- Compensation lifetime

Use phase duration's effects on environmental impacts



The duration of the use phase has effects on:

- the environmental contribution per year
- the compensation of the environmental impacts in case of replacement

Example of reduction of environmental contribution per year

- The LCA of a Fairphone 4 showed that extended use time (from 3 to 7 years) reduces the environmental contribution per year for the indicator Global Warming
  - Extending the lifetime to 5 years helps reduce the yearly emissions by 31%
  - A further extension to 7 years of use helps reduce the yearly impact by 44%

Example of compensation of environmental impacts for replacement

- In 2011, the Federal Agency of Environment in Germany commissioned a study to identify when the environmental impacts of a new notebook are compensated by its energy efficiency gains
- Impacts due to the production phase are so high that they cannot be compensated by gains in the use phase
  - For a gain of 10% in energy efficiency, the replacement of an older notebook can be justified after 33 to 89 years

References

- *D. Sanchez et al., 'Life Cycle Assessment of the Fairphone 4', 2022*
- *S. Prakash et al., 'Timely replacement of a notebook under consideration of environmental aspects', 2012*

Indifference point and break even analyses

- Some analyses evaluate architectural decisions by considering the expected lifetime

Indifference point

$$t_I = \frac{M_1 - M_0}{P_0 - P_1}$$

- Economic metric used to determine the point at which two alternatives have the same overall cost
- For electronics, time when the energy to manufacture and operate two competing system architectures is equivalent
  - If the expected lifetime is shorter than the indifference point, the architecture with the lower manufacturing cost minimizes the environmental impact
  - Otherwise, the architecture with the lower operational emissions is preferable

Break even point

$$t_B = \frac{M_1}{P_0 - P_1}$$

- Time when a new system will reach the same energy consumption of the system it will replace
  - Determines the lifetime required for the new system to compensate for its manufacturing cost through savings in operational emissions

Reference

- *D. Kline et al., 'GreenChip: A tool for evaluating holistic sustainability of modern computing systems', Sustainable Computing: Informatics and Systems, 2017*

Limits of reliability for environmental performance

- Lifetime extension helps to compensate the impacts on the environment and avoid e-waste
- Reliability allows to guarantee a duration of lifetime

- Very often the reliability of an electronic component or system is higher than the average use life
- Obsolescence is a major limit to technical lifetime
  - Technical obsolescence (e.g., standards or interfaces outdated)
  - Efficiency obsolescence (e.g., lack of efficiency when compared to new technologies)
  - Marketing obsolescence (e.g., new design)
- Issues of technical obsolescence can be avoided already in the concept phase

Reference

- *Middendorf et al., 'Establishing eco-reliability of electronic devices in manufcturing environments', Global Conference on Sustainable Manufacturing, 2015*

Agenda

Reliability of electronics: Background

Reliability for environmental performance

- A new R strategy for circular economy
- Related concepts in standards and legislation
- Introduction to eco-reliability
- Amortization of environmental impacts

TAKEAWAYS

- Reliability is recognized as a requirement for material efficiency
- Reliability and environmental impacts must be evaluated at early design phases and combined into a single strategy
- A trade-off must be analyzed with other design parameters

Reliability for absolute sustainability

- Introduction to absolute sustainability
- Joint assessment of reliability, environmental impacts and environmental limits
- Compensation lifetime

Agenda

Reliability of electronics: Background

Reliability for environmental performance

- A new R strategy for circular economy
- Related concepts in standards and legislation
- Introduction to eco-reliability
- Amortization of environmental impacts

Reliability for absolute sustainability

- Introduction to absolute sustainability
- Joint assessment of reliability, environmental impacts and environmental limits
- Compensation lifetime

OBJECTIVE

- ❖ What changes when considering reliability for absolute sustainability?

Absolute sustainability: Evaluation of whether human activities remain within the Earth's ecological limits, as defined by frameworks like the Planetary Boundaries

Environmental performance focuses on incremental improvements compared to a baseline

Agenda

Reliability of electronics: Background

Reliability for environmental performance

- A new R strategy for circular economy
- Related concepts in standards and legislation
- Introduction to eco-reliability
- Amortization of environmental impacts

Reliability for absolute sustainability

- Introduction to absolute sustainability
- Joint assessment of reliability, environmental impacts and environmental limits
- Compensation lifetime

Basic concepts related to absolute sustainability

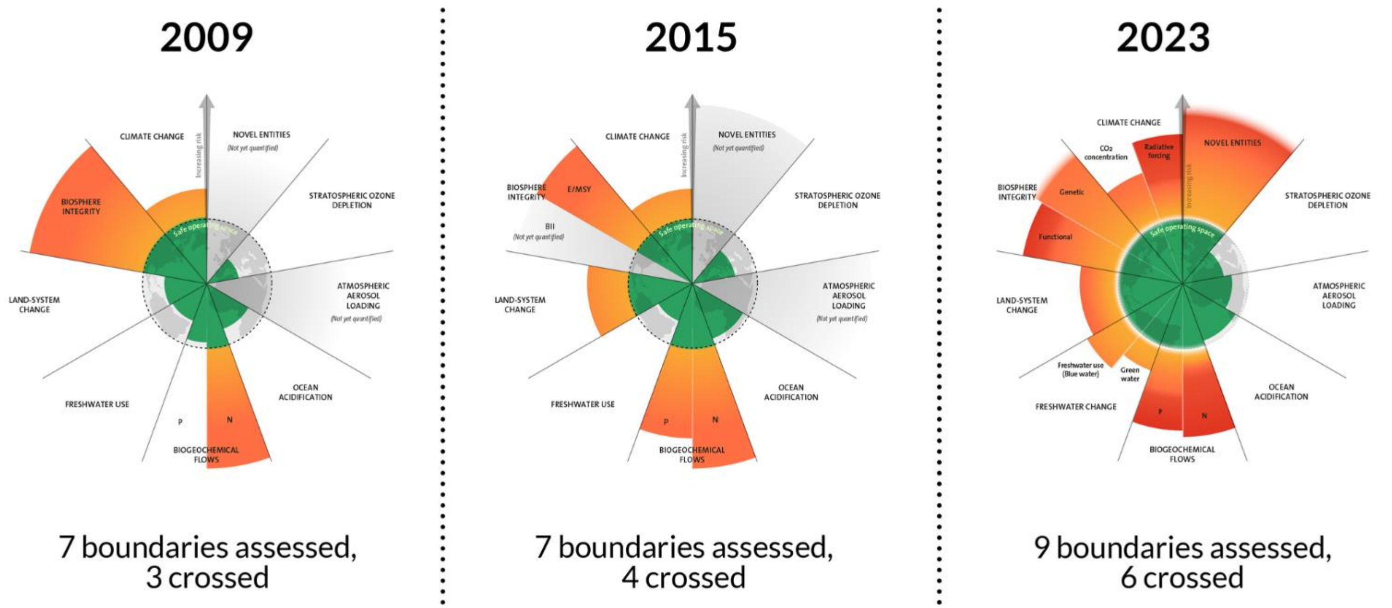
Introduction to sustainable development

- When talking about sustainability, we often refer to the Brundtland report
  - Officially titled *Our Common Future*, published in 1987 by the World Commission on Environment and Development
- It introduced the widely accepted definition of **sustainable development**
  - **Humanity has the ability to make development sustainable to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs**
- The concept of sustainable development does imply limits
  - **Not absolute limits but limitations imposed by the present state of technology and social organization on environmental resources and by the ability of the biosphere to absorb the effects of human activities**
- The concepts of sustainable development and absolute sustainability are different but complementary
  - Ideally, our development choices should fall within the boundaries defined by absolute sustainability while meeting the goals of the Brundtland approach

Brundtland report	Absolute sustainability
Limitations, not absolute limits	Non-negotiable ecological limits
Limitations not easily quantified	Based on biophysical data
Focus on human needs and fairness	Focus on ecological limits
Tries to balance environment, economy and society	Prioritizes environment

Absolute sustainability assessment: Planetary boundaries

Some tools help identifying whether human activity remains within the ecological capacity of the planet, i.e., absolute sustainability, rather than relative or efficiency-based metrics



- The planetary boundaries framework highlights the risks from human pressure on critical global processes that regulate the stability and resilience of the Earth
- The planetary boundaries were first proposed in 2009 by a group of 28 scientists
- The update of 2023 quantified 9 processes and concluded that 6 boundaries are transgressed

- Each boundary has a quantitative threshold (a safe operating space)
- The quantification gives a scientific basis for evaluating absolute sustainability

Reference

- *Azote for Stockholm Resilience Centre, Stockholm University. Based on Richardson et al. 2023, Steffen et al. 2015, and Rockström et al. 2009*

Absolute sustainability assessment: Global Footprint Network

Purpose

- Measure human demand on nature relative to Earth's ecological capacity to regenerate

Key features

- Calculates the Ecological Footprint: the area of biologically productive land and water needed to produce consumed resources and absorb waste (especially CO_2)
- Compares this with biocapacity: Earth's capacity to regenerate those resources
- Defines the Earth Overshoot Day (EOD): the date when humanity's demand exceeds Earth's regenerative capacity for the year

$$EOD = \frac{Earth's\ biocapacity}{Humanity's\ ecological\ footprint} \cdot 365$$

- The biocapacity of a surface represents its ability to renew what people demand, by producing biological materials used by humans and absorbing the generated waste materials given current technology and management practices
  - Expressed in global hectares
  - Land use types: carbon uptake land, forest land built-up land, cropland, grazing land, fishing ground
  - The forest land serves two footprint categories: carbon footprint and forest products footprint
  - The carbon uptake land is the only land use type exclusively dedicated to tracking a waste product (carbon dioxide)

Reference
- *footprintnetwork.org*

Carrying capacities and sharing principles

Absolute sustainability methods compare the environmental impacts to assigned carrying capacities

Carrying capacity

- The maximum persistent impact that the environment can sustain without suffering perceived unacceptable impairment of the functional integrity of its natural systems or, in the case of non-renewable resource use, that corresponds to the rate at which renewable substitutes can be developed

Sharing principle

- A principle used to assign carrying capacity

Sharing principle	Description
Equal per capita	Assigned share is the same for all individuals
Grandfathering	Assigned share is proportional with environmental impact in a reference year
Economic value added	Assigned share is proportional to economic value added

Reference

- *A. Bjorn et al., 'Review of life-cycle based methods for absolute environmental sustainability assessment and their applications', Environmental Research Letters, 2020*

Agenda

Reliability of electronics: Background

Reliability for environmental performance

- A new R strategy for circular economy
- Related concepts in standards and legislation
- Introduction to eco-reliability
- Amortization of environmental impacts

Reliability for absolute sustainability

- Introduction to absolute sustainability
- Joint assessment of reliability, environmental impacts and environmental limits
- Compensation lifetime

How to join absolute sustainability and reliability for the design of electronics

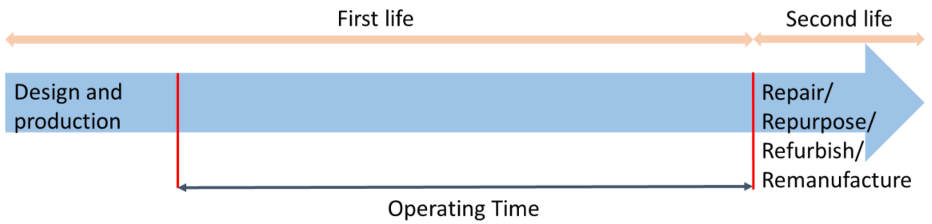
Proposal of eco-reliability metric

- Proposal of a metric to maximize reliability while minimizing environmental impacts, taking into account limits

$$Ecoreliability = \frac{Operating\ time}{System\ Earth\ equivalent\ Time}$$

Operating time

- Duration of functioning as required under given conditions without a limiting event



System Earth equivalent Time

- Time necessary to regenerate or recover the resources consumed
- Focus on carbon emissions

$$SET = \frac{\text{System ecological footprint}}{\text{Earth forest land biocapacity}} * 365$$

Land use type	Carbon uptake land	Forest land	Built-up land	Cropland	Grazing land	Fishing ground
Land type	Forest land		Built-up land	Cropland	Grazing land	Fishing ground

$$\text{Biocapacity [CO2]} = \text{Biocapacity [gha]} * \frac{YF}{\text{EQF}}$$

Reference

- *C. Sandionigi, 'Eco-reliability: A new metric for the eco-design of electronic systems', SusTech, 2024*

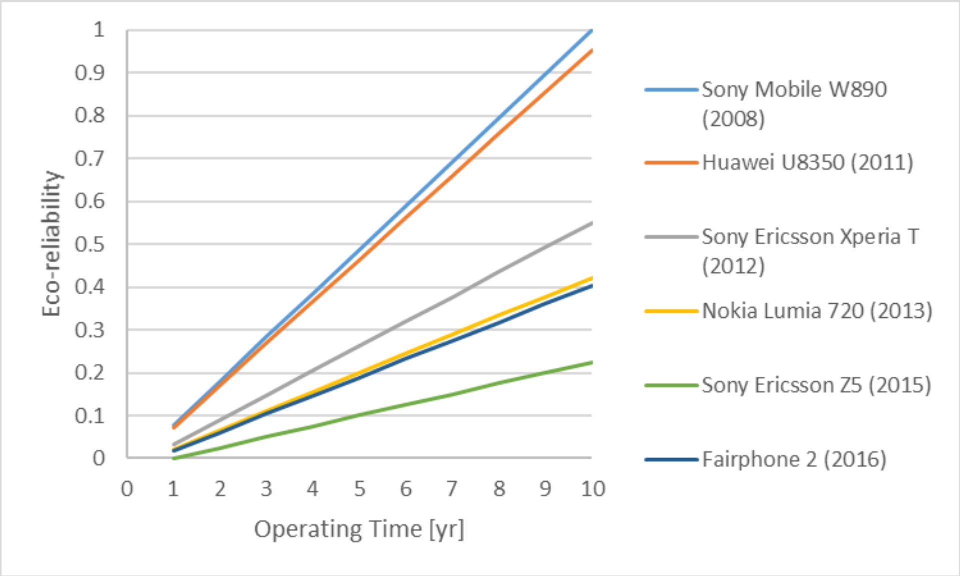
Example of eco-reliability computation

Objectives of the eco-reliability metric:

- Quick comparison of different designs of a same electronic system or component
- Comparison of different electronic products for a quick positioning of their environmental sustainability

Case study: Integrated circuits of smartphones

- Data of carbon footprint for the integrated circuits of different smartphones produced between 2008 and 2016
- For each circuit, Earth forest land biocapacity of the production year of the corresponding smartphone



Reference

- *C. Sandionigi, 'Eco-reliability: A new metric for the eco-design of electronic systems', SusTech, 2024*

Agenda

Reliability of electronics: Background

Reliability for environmental performance

- A new R strategy for circular economy
- Related concepts in standards and legislation
- Introduction to eco-reliability
- Amortization of environmental impacts

Reliability for absolute sustainability

- Introduction to absolute sustainability
- Joint assessment of reliability, environmental impacts and environmental limits
- Compensation lifetime ← How environmental sustainability plays a role in the guarantee of a lifetime

Proposal of compensation lifetime metric

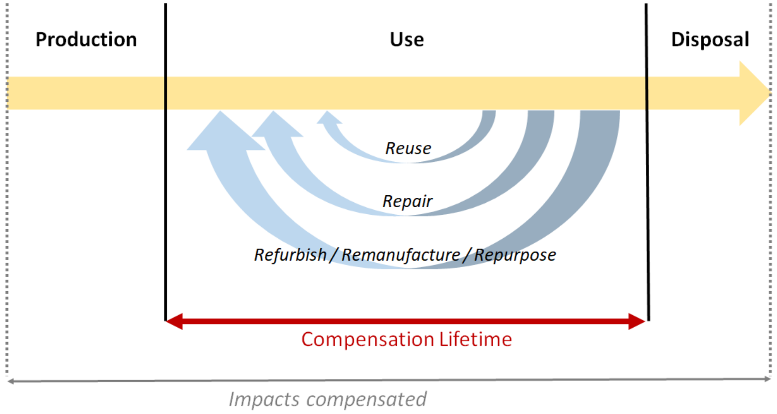
- The disposal of electronics should be driven by the consideration of environmental limits, and not by obsolescence aspects

Compensation lifetime

- Duration of lifetime that allows compensating the end-to-end carbon footprint of an electronic component or system

$$CL = \frac{Embodied_{CO2}}{Budget_{CO2\_year} - OperationalCO_{2\_year}}$$

$$Operational_{CO2\_year} < BudgetCO_{2\_year}$$



Carbon budget

- $Budget_{CO2}$: Area under a CO_2 emission trajectory that satifies assumptions about limits on cumulative emissions estimated to avoid a certain level of global mean surface temperature rise
- Based on identification of a carrying capacity and definition of one or more sharing principles

Reference

- *C. Sandionigi, 'Towards absolute sustainability of electronics: A lifetime to compensate carbon footprint', SusTech, 2025*

Examples of compensation lifetime

- Compensation lifetime calculated considering two smartphones with different Global Warming impacts and taking into account various carbon budget

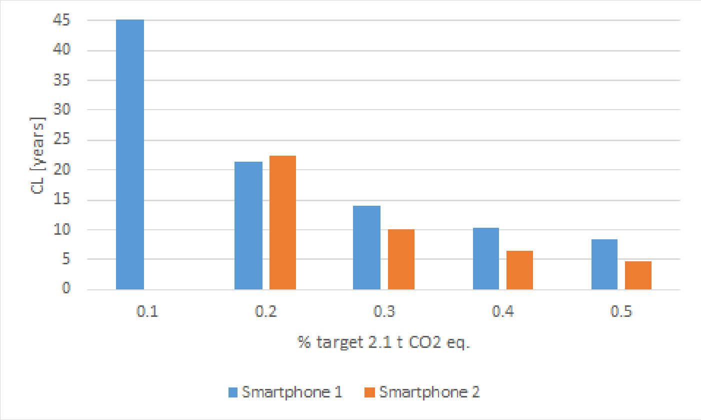
	$Embodied_{CO2}$	$Operational_{CO2\_year}$
Smartphone 1	85.3	0.22
Smartphone 2	38.45	2.48

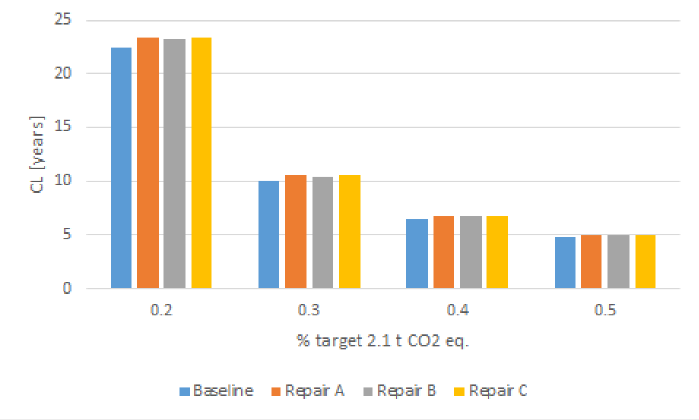
Carbon budget

- Carrying capacity: 2.1 tCO_2eq. per capita
- Sharing principle: grandfathering

Scenarios

- Baseline: Operation without maintenance
- Repair A: Device sent, module substituted
- Repair B: Device sent, component substituted
- Repair C: New module received





Reference

- *C. Sandionigi, 'Towards absolute sustainability of electronics: A lifetime to compensate carbon footprint', SusTech, 2025*

Agenda

Reliability of electronics: Background

Reliability for environmental performance

- A new R strategy for circular economy
- Related concepts in standards and legislation
- Introduction to eco-reliability
- Amortization of environmental impacts

Reliability for absolute sustainability

- Introduction to absolute sustainability
- Joint assessment of reliability, environmental impacts and environmental limits
- Compensation lifetime

TAKEAWAYS

- ❖ Sustainable development implies limits
- ❖ Absolute sustainability introduces ecological limits based on biophysical data
- ❖ It is possible to join absolute sustainability and reliability in the design of electronics through new metrics

Conclusions

- Reliability of electronics, up to now seen as a constraint mainly for safety-critical applications, becomes a lever in our hands to guarantee the lifetime of components and systems
- There is a close relationship between reliability and environmental impacts in electronics
  - Lifetime is recognized as a major influence factor of environmental impacts
- Although traditionally viewed separately, reliability and environmental impacts should be examined in conjunction
  - Combination of existing competencies
  - Novel methods for trade-off balancing, together with traditional design parameters

The trade-off between reliability and environmental impacts need to be understood and quantified

Throw-away products
- Low amortization
- No overhead

High-lifetime products
- High amortization
- Overhead

- Environmental limits should be taken into account for a sustainable development of electronics
- Integration of limits in the design process is an open challenge