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Eco-reliability: A new metric for the eco-design of electronic systems

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Abstract— To limit the increasing environmental impact of electronics, current research and development efforts focus on material efficiency, in addition to the achievements towards energy efficiency. For the objective of material efficiency, the reliability of electronics becomes mandatory not only for the usual safety-critical applications but for every system as a guarantee of lifetime. This paper defines the first quantitative metric to evaluate the joint contributions of reliability and environmental impact when designing an electronic system. With a focus on Integrated Circuits, whose manufacturing contributes to a great share of electronics emissions, it shows how the metric can be integrated in a design flow, changing the current design paradigm mostly driven by performance, power and area. Results at both system and circuit levels demonstrate the interest of the metric for a quick comparison of designs or products.

Keywords— *Eco-reliability, Reliability, Environmental impact, Eco-design, Integrated Circuits, Electronic Computing Systems, Circular Economy*

I. INTRODUCTION

Climate change is one of the greatest challenges the world is currently facing since, if no action will be taken, it will significantly impact and endanger human wellbeing. In 2015, the Paris Agreement (PA) set the ambitious but mandatory objective of limiting climate change to a global warming between 1.5 and 2 °C at the end of the century. The European Green Deal goes in the same direction of limiting climate change through the commitment to remake Europe's economy towards climate neutrality by 2050. Climate change is so driving political and public environmental awareness, together with other environment-related challenges as growing water pollution, waste disposal and rapid consumption of natural resources. To contrast these ever-growing problems, every economic sector needs to reduce its carbon footprint through an approach of sustainable development.

As defined in the Brundtland Report in 1987 [1], sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs. The Triple Bottom Line, coined by John Elkington in 1994, defines a framework for sustainability taking into account three lines: environmental, economic and social [2]. This paper focuses on the environmental line.

When coming to the electronic sector, digital technologies play a double role in the race towards environmental sustainability. On one side, they can help reduce or avoid Greenhouse Gas (GHG) emissions significantly by optimizing processes or providing alternatives in many domains (transportation, energy, manufacturing, etc.). On the other side, they also have a significant environmental impact in terms of resources consumption, GHG emissions and e-waste, which are all on a massive increasing trend. A great share of electronics emissions is due to the production, and more specifically to Integrated Circuit (IC) manufacturing [3] [4], which is becoming more complex, energy and resource intensive with new technology nodes. Focusing on IC manufacturing, it is necessary to sustain a reduction of the carbon footprint at a rate of 8% each year to be aligned with the 1.5-2 °C PA pathway. It is very unlikely that carbon footprint reduction could be fast enough without limiting the global production volume. This can be achieved by avoiding the planned obsolescence marketing strategy and promoting longer lifetime and circular economy of electronics.

In this context, the reliability of electronics, up to now seen as a constraint for safety-critical applications, becomes a lever in our hands to guarantee the lifetime of the systems. Thus, reliability starts gaining priority in the optimization process jointly with environmental aspects. In contrast, in the previous practices, these constraints were mostly treated at the end of the design process or not addressed at all, and reliable systems were usually slightly overdesigned in order to be on the safe side.

The aim of this work is to understand how reliability can contribute towards an environmental sustainability transition. The paper explores the environmental dimension of reliability and claims that the environmental impacts must be taken into account jointly to reliability and not as a separate dimension. With a focus on IC, it will show how it is possible to change the current electronic design paradigm mostly driven by the usual parameters Performance, Power and Area (PPA). The main innovative contribution is the definition of a new metric, eco-reliability, which for the first time quantifies the joint contributions of reliability and environmental impacts on electronics.

II. RELATED WORKS

One of the first works considering the integration of reliability and environmental aspects for the design of electronics appeared in 2009 [5], when most lifetime and environmental assessments were done in the post-design phase. The work focuses on mechatronics, which use the synergies from the interaction of electronics, mechanics and information technology. It presents an example of conceptual design of a miniature robot with some considerations on environmental issues and reliability properties. A Life Cycle Assessment (LCA) is out of the scope of the work because of the limitation in time and unavailability of data, as stated by the authors. The environmental impact and the reliability are evaluated independently and by considering only one indicator for each aspect: the Toxic Potential Indicator for the environmental impact, the thermal and thermo-mechanical stress for reliability. Such indicators are not generic enough to cover the environmental and reliability aspects.

In 2012, the same main authors proposed the neologism Eco-reliability taking into account three perspectives: Ecology, Economy and Reliability [6]. They identify three main objectives for eco-reliability: reduction of the consumption of resources, reduction of the impact on nature and increase of the product value. The work aims at highlighting the interdependencies among the three perspectives as a process of multi-criteria decisions, but no metrics or formulas are provided to quantify the multi-criteria optimization. Thus, the analysis of the interdependencies remains at theoretical or qualitative level.

The same research team further investigated the eco-reliability concept in 2015 [7]. In this vision, eco-reliability is seen as the inclusion of reliability aspects into the environmentally conscious design of electronic systems. The work tries to address the domains of environment and reliability from one mutual perspective on specific technical examples: power electronics and distributed sensor nodes. For power electronics, the authors compare the choice of aluminium and copper wires for reliability and environmental aspects. For sensor nodes, they present individual trade-offs as examples of eco-reliability. The work doesn't provide metrics or frameworks to generalize the analysis of eco-reliability to different application scenarios.

Other works introduced the environmental dimension of reliability. In [8], the authors summarize their previous works on the design of reliable and sustainable memories. They tune their designs for improving reliability while minimizing both operational and embodied energy.

In a recent literature review about Design for X approaches addressing circular economy [9], reliability has been presented as an ability oriented at slowing and extending the lifecycle to prolong the use phase of the products. Latest, eco-reliability has been indicated as a specific recommendation for the ECS-SRIA Roadmap 2023 [10]. Following these research directives and with respect to the previous works, this paper proposes the first quantitative metric to evaluate the joint contributions of environmental impacts and reliability during the early stages of design of an electronic system.

III. RELIABILITY FOR ENVIRONMENTAL SUSTAINABILITY IN CURRENT AND UPCOMING LEGISLATION

Reliability becomes a mandatory constraint for material efficiency in current and upcoming legislation.

Up to 2022, the reference directive on eco-design at European scale was the directive 2009/125/EC for energy-related products (i.e., any product having an impact on energy consumption during its use). It has been at the origin of the creation of energy labels for energy-consuming products. The upcoming regulation on eco-design introduces new requirements that highlight notions of material efficiency and transparency instead of energy efficiency. It is intended to replace the directive 2009/125/EC and to extend eco-design requirements to all electronic products placed on the European market, with some minor exceptions that are still not identified for the moment. The proposal, appeared in March 2022, is the Ecodesign for Sustainable Product Regulation (ESPR) [11]. It is important to note that a regulation is distinct from a directive from a legal point of view and stronger. The passage from the directive 2009/125/EC to the ESPR shows how, while in the past the environmental analysis of electronics was often narrowed down to energy use, the total resource consumption and the lifetime are now seen as equally important.

The standards CEN-CENELEC 45552 – 45559 are a solid reference for the ESPR. They are applicable to all energy-related product already concerned by the directive 2009/125/EC and they introduce some indicators of material efficiency with the related computation methods. Among the indicators, there are durability and reliability.

The requirements for material efficiency defined up to now are durability, reuse, repair and possibility of refurbishment. For the durability requirement, the environmental dimension of reliability receives recognition particularly in terms of its contribution to long lived products. In the ESPR, the durability is defined as the ability of a product to function as required, under specified conditions of use, maintenance and repair, until a limiting event prevents its functioning. The reliability is defined as the probability that a product functions as required under given conditions for a given duration without a limiting event. It is worth noting that, in the standard EN 45552, the definition of reliability includes maintenance, but it has been discarded in the ESPR. For the eco-reliability metric, this paper adopts the reliability definition given in the ESPR since it will be the reference at European level.

IV. THE ECO-RELIABILITY METRIC

In order to design electronic systems sustainable from the environmental point of view, two aspects must be evaluated jointly:

- The impacts on the environment for the production and use of the system;
- The expected Operating Time.

While the first aspect must be minimized, the second one must be extended as much as possible to compensate the impacts on the environment and avoid e-waste. The evaluation must also consider that the two aspects are linked: the reliability determines the Operating Time of the system, and the environmental impact for the use phase is estimated for a given Operating Time. It is worth noting that, as defined in the ESPR, the reliability allows estimating the Operating Time before appealing to circular economy strategies like repair, repurpose, refurbish or remanufacture. It is a recognized concept and various quantitative metrics have been proposed to estimate it. Also for the environmental impacts it is possible to find equations and indicators in literature [12]. Nevertheless, no metrics or equations have been proposed to evaluate the joint contributions of the two aspects.

Here the eco-reliability metric is introduced to quantify the joint contributions of the two aspects. The eco-reliability is the ratio between the Operating Time of the system and a new metric called System Earth equivalent Time (SET).

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

The Operating Time and the SET are measured in the same unit of time. In the following, these two concepts are detailed.

A. Operating Time

The Operating Time is defined as the duration of functioning of the system as required under given conditions without a limiting event. It doesn't include a possible second lifetime of the system after applying the circular economy strategies of Repair, Refurbish, Remanufacture or Repurpose. The strategy of Reuse by other users, however, is included since the focus is on the integrity of the system; this strategy implies that the system is just discarded by a previous user, without modifications that would demand a new reliability analysis.

The Operating Time is defined as the sum of a first Mean Time To Failure (MTTF) and subsequent Mean Times Between Failures (MTBF, for systems employing fault tolerance or mitigation techniques with internal recovery capabilities), as shown in the following equation and in Figure 1. The MTBF includes the mean time to detect and recovery from a failure.

$$\text{Operating Time} = \text{MTTF} + \sum_{i=0}^n \text{MTBF}_i$$

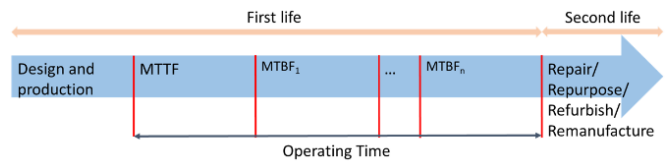


Fig. 1: Operating Time for a system considering n internal recoveries

B. System Earth equivalent Time

The Europe's long-term vision to 2050 is to live within planetary boundaries [13]. The metric of SET, proposed here for the first time, integrates the concept of boundaries, since this work estimates that a metric related to environmental sustainability must take into account an environmental budget besides the environmental impact.

For the evaluation of the impact, the environmental indicator considered in the SET is the carbon footprint. It is the most studied indicator and it is provided as a quantity of GHG emissions in kilograms carbon dioxide equivalent (ISO 14067).

To define the SET, firstly it is necessary to introduce the concept of Earth Overshoot Day (EOD) [14], originally conceived by Andrew Simms and the starting point for our method. The EOD marks the date when humanity's demand for ecological resources and services in a given year exceeds what Earth can regenerate in that year. The international research organization Global Footprint Network (GFN) [15] calculates the EOD by dividing the amount of ecological resources Earth is able to generate in one year by the humanity's demand for that year, and multiplying by 365, the number of days in a year.

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

The biocapacity of a surface (here the whole Earth, but more limited regions can be considered) 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. In the National Footprint and Biocapacity Accounts (NFBA), it is expressed in global hectares (gha) and calculated by multiplying the physical area by the Yield Factor (YF) and the appropriate Equivalence Factor (EQF). The YF, defined in $\text{tCO}_2 \cdot \text{wha}^{-1} \cdot \text{yr}^{-1}$ (where wha is World average hectares for a given land use type and yr is year), accounts for differences between countries in productivity of a given land type. The EQF, defined in gha wha^{-1} , converts a specific land type into gha [16]. These two factors introduce the concepts of land use type and land type, necessary in the following to understand our considerations for the focus on electronics. The land use types considered by the NFBA are the following: carbon uptake land, forest land, built-up land, cropland, grazing land and fishing ground. The carbon uptake land is the only land use type exclusively dedicated to tracking a waste product: carbon dioxide. In addition, it is the only land use type for which biocapacity is not currently explicitly defined. For biocapacity,

the forest land serves two footprint categories: carbon footprint and forest products footprint [17].

The methodology relies on the latest edition of the NFBA, which unavoidably presents a time gap with the evaluation time due to United Nations' reporting procedures. To address the gap, Global Footprint Network establishes trendlines from the National Footprint and Biocapacity Accounts data and extends those trendlines to the evaluation year. Where possible, more recent data from reputable sources (e.g., Global Carbon Project or International Energy Agency (IEA)) are incorporated to strengthen the assessment for the gap years.

In 2022, the EOD fell on July 28th [18]. The most recently reported data for this evaluation has a time lag of about 4 years, hence the 2022 edition reports results up to 2018. Since the EOD is based on the current year's consumption, nowcasting is needed to provide an estimation of where humanity's demands stand compared to the planet's biocapacity.

Overshoot Days can be computed also at other levels than Earth. A Country Overshoot Day is the date on which Earth Overshoot Day would fall if all of humanity consumed like the people in that country. In 2023 (year of this paper), it has been estimated that two of the EU's largest economies reached their Country Overshoot Days in May: May 4th for Germany and May 5th for France. Also a Personal Overshoot Day can be computed at individual level [19].

An alternative view of the EOD is the computation of how many planets would be necessary to satisfy a certain ecological footprint. At Earth level, the following formula applies:

$$\#Earths = \frac{\text{Humanity's ecological footprint}}{\text{Earth's biocapacity}}$$

This formula can be applied also at country or individual level by considering the Country ecological footprint or the Personal ecological footprint.

As for other human activities, the manufacturing and use of an electronic product has an impact on the environment in terms of resources consumption and GHG emissions. The SET is the time necessary to regenerate or recover the resources consumed for the production and use of the electronic system. This new metric is defined as follows:

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

The computation of the SET limits the Earth biocapacity to the forest land use type, which is the only land related to the production and use of electronic systems (as indicated in the framework of the NFBA [16]). The Earth forest land biocapacity and the System ecological footprint are defined in CO₂. The System ecological footprint can be obtained by performing an LCA of the system. Since the environmental budget (the Earth forest land biocapacity) is evaluated at

global level, also the environmental impact (the System ecological footprint) must be evaluated at global level by taking into account the worldwide production volume of systems. The Earth forest land biocapacity is based on the data provided by the GFN. Since the data related to biocapacity are available in gha, the biocapacity is converted in CO₂ by considering the YF and EQF of forest land as follows:

$$\text{Biocapacity [CO}_2\text{]} = \text{Biocapacity [gha]} \cdot \frac{YF}{EQF}$$

While it is necessary to maximize the EOD, the SET must be minimized.

V. ECO-RELIABILITY RESULTS

The main objective of the eco-reliability metric is the quick comparison of different designs of a same electronic system or component. The metric also allows comparing different electronic products for a quick positioning of their environmental sustainability.

In the following, the work considers a selection of various electronic systems and components for which ecological footprint data are available in literature. The operating time is varied in an interval between 1 and 10 years and a min-max normalization is applied for the comparison of the case studies. In our future work, the System ecological footprint will be computed by LCA and the operating time will be obtained through reliability analysis for different designs of a same system or component.

A. Electronic systems case studies

Case study 1: IoT devices. The first case study takes into account the worldwide production of Internet-of-Things (IoT) devices. In upcoming years, the number of IoT devices is expected to surge up to tens of billions of physical objects. The induced absolute carbon footprint is estimated to reach more than 1000 MtCO₂/yr in 2027 [20].

For the computation of the SET, the Earth forest land biocapacity of 2027 cannot be taken into account since of course the data are not available. The last available data are of 2018 [15]. Such values can be considered optimistic since it is possible to note a decreasing Earth forest land biocapacity throughout the years.

The computed SET for this scenario is about 35 days. This means that the IoT sector alone requires more than one equivalent month of Earth forest land biocapacity for the production of the devices.

Case study 2: ICT. The second case study considers the worldwide Information and Communication Technologies (ICT). Their carbon footprint was evaluated at about 2200 MtCO₂ equivalent in 2020 [21]. As in the previous example, the last available data of 2018 are considered for the Earth forest land biocapacity. The estimated SET is about 76 days.

Case study 3: Smartphones. The third case study takes into account the lifetime of a smartphone. This example considers the data of the System ecological footprint for a single

smartphone, not for a worldwide production of smartphones. In [4], the typical carbon footprint generated over a smartphone lifetime (for its production, transport, use and end of life) is estimated to be about 70 kgCO₂. According to the data reported in [22], this value could refer to a smartphone with an environmental impact similar to the one of the Sony Ericsson Z5 produced in 2015. Taking into account 2015 as reference year, it is possible to estimate a production volume of 1314 million of units [23]. Considering the Earth forest land biocapacity in 2015, the computed SET is about 7 days.

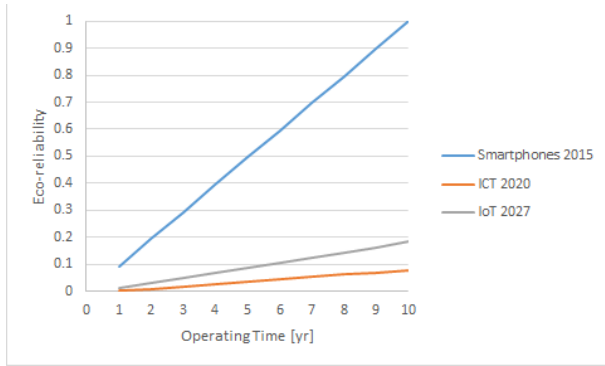


Fig. 2: Eco-reliability metric for different electronic systems

Figure 2 shows the evolution of the eco-reliability metric for the previous case studies by considering increasing Operating Times. It is possible to assume that the smartphones and IoT scenarios are included in the ICT one. Nevertheless, the selected case studies are related to different years and are probably based on different LCA data.

B. Integrated Circuits case study

Here some examples of eco-reliability computation for different ICs are provided. The work considered the data of carbon footprint for the ICs of different smartphones produced between 2008 and 2016 [22]. For each IC, it considered the Earth forest land biocapacity and the Earth population of the production year of the corresponding smartphone.

The resulting eco-reliability values are shown in Figure 3 for Operating Times included between 1 and 10 years. An outlier is present: the Fairphone 1 IC. This is caused by the different modeling approach and data sets used for Fairphone 1, especially theecoinvent data leading to significantly lower results of environmental impact [24].

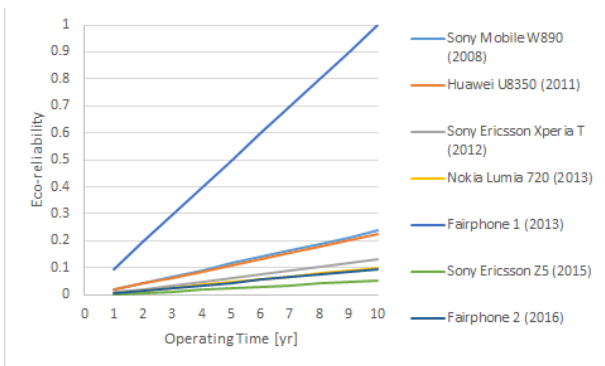


Fig. 3: Eco-reliability metric for smartphones ICs

VI. THE ENVIRONMENTAL DIMENSION OF RELIABILITY AS A DESIGN STRATEGY

This section explains how to exploit the environmental dimension of reliability in a circular economy perspective and, with a focus on IC to show the effectiveness of the approach, how to integrate eco-reliability in a design flow for a comparison of different design choices.

A. Reliability for circular economy

The circular economy allows implementing environmentally sustainable production and extending the products' lifetime. Many authors view R frameworks as the 'how-to' of circularity and thus a core principle of it [25]. Circular economy is most frequently depicted as combination of Reduce, Reuse and Recycle activities (3R framework). The 4R framework introduces Recover as the fourth R, while the 5R principle of waste management consider Refuse, Reduce, Reuse, Repair and Recycle. Other frameworks consider up to 10 Rs [26]. All varieties of R frameworks share a hierarchy where the first R is viewed to be a priority to the second R and so on.

The 9R framework [26], shown in Figure 4, is a conceptual framework developed at the request of the Dutch Ministry of Infrastructure and the Environment. It is a well-known and generic mean for circular economy, not specific to electronic products. The strategies are identified according to three objectives: Smarter product use and manufacture; Extend lifespan of product and its parts; Useful application of materials.

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

Fig. 4: The 9R framework (adapted from [27])

This paper claims that, when designing electronic systems with the target of material efficiency, the reduction of natural resources and materials is not enough since it doesn't cover the durability aspects. Starting from the 9R framework, this work completes the list of strategies by adding the ones specific to electronic systems. The additional strategies are Rely and Reconfigure. They allow taking into account the properties of dependability and the possibility of reconfiguration, both necessary in a perspective of material efficiency. The Reconfigure strategy, discussed in [27], is introduced here just to provide a global vision of the strategies necessary for a circular economy of electronics. Moreover, it is worth noting that the dependability property, related to the Rely strategy, includes various attributes besides reliability, such as security. The focus of this work is set to reliability.

The new R framework specific to electronic systems is shown in Figure 5. With the introduction of the two strategies, it has been considered useful to distinguish the specification phase, related to the global product concept (Refuse, Rethink), from the design phase, aiming to minimize the environmental impacts, maximize the expected lifetime and ease circular economy (Reduce, Rely, Reconfigure). The eco-reliability metric allows evaluating jointly the impact of the Reduce and Rely strategies.

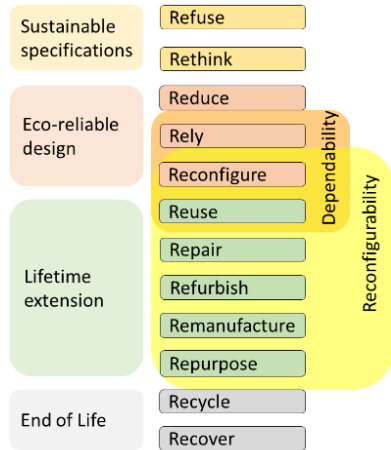


Fig. 5: R framework for electronic systems

B. Eco-reliable design flow

ICs are key building blocks of the electronic systems and their production has the major contribution in GHG emissions. Their design is usually driven by the standard parameters PPA. The constraint of reliability is taken into account only when the circuit is designed for safety-critical applications.

Here it is shown how the eco-reliable design of the new R framework and the eco-reliability metric can be applied when designing IC. Figure 6 presents the framework summarizing these aspects. The phases of specifications and design are strictly connected in a loop of inputs and feedbacks. In the first phase, driven by the Refuse and Rethink strategies and refined with the feedbacks, the designer specifies the needs for the architecture, the possible implementing technologies and the envisioned mission profiles. In the second phase, the IC is designed by following the three main strategies:

- **Reconfigure.** The architecture is defined by taking into account the possibilities of multiple life cycles. The possibilities of reconfiguration are evaluated according to the selected technologies. The PPA parameters are estimated.
- **Rely.** The dependability parameters are evaluated. For the scope of this paper, the parameters of interest are the MTTF and MTBF of the circuit.
- **Reduce.** An LCA is performed to estimate the circuit ecological footprint in CO₂.

The outputs of the Reduce and Rely strategies are used by an Eco-reliability calculator which computes the SET and the

Operating Time. The eco-reliability metric is then taken into account together with the PPA parameters to identify the best configuration of the circuit.

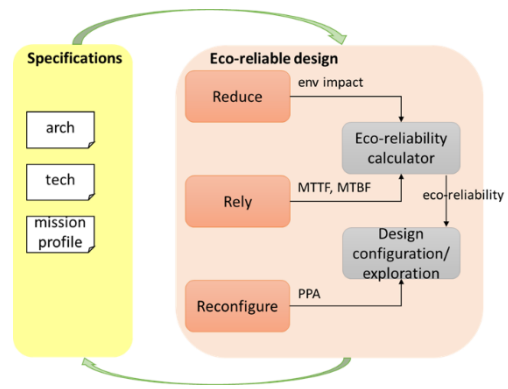


Fig. 6: Eco-reliable design framework for Integrated Circuits

VII. CONCLUSIONS AND PERSPECTIVES

This work proposed for the first time a metric to quantify the joint contribution of reliability and environmental impact of electronics. It showed how the metric can be used to quickly compare different design choices or systems.

The next step is the application of the framework for the eco-reliable design of an IC. In the future, the eco-reliability could be exploited also to identify a minimum Operating Time that must be guaranteed to compensate the environmental impact.

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