MATERIAL EFFICIENCY FOR CIRCULAR ECONOMY: FROM ASSESSMENTS TO OPTIMIZATIONS

Thierry CORMENIER	Matthieu BRIENS	Marcel CHEVALIER	Karim HELAL
Schneider Electric – France	Schneider Electric – France	Schneider Electric – France	Schneider Electric – France
thierry.cormenier@se.com	matthieu.briens@se.com	marcel.chevalier@se.com	karim.helal@se.com

ABSTRACT

The environmental performance of an ecosystem requires optimizations from the design stage to the end of life demonstrating the ability of its products and system to be reintroduced inside the lifecycles trying to regenerate natural systems and minimizing the environmental footprint. Paying special attention to use phase optimization will contribute to extending the lifespan of the products and system. To improve the material efficiency the linear model shall be transformed into a circular model, in which the regulatory initiatives could merge household appliances and industrial equipment. To understand the various capabilities, an overview of the standardization works about material efficiency for circular economy in Europe is necessary. The horizontal standards, all in progress, focus primarily on assessments of various criteria of energy-related products (ERPs). To complete efficient assessments, IEC standards dealing with dependability enable the optimization of products and systems designs and their use phase. To reach the final optimization, accurate aging models that are validated by tests and completed by digital tools embedding adaptive models of failure rate.

INTRODUCTION

To build this kind of ecosystem, which combines product and system life cycles, several trade-offs must be carried out at the design stage, between the functions at product or system levels. The customers' needs must remain a main function and safety must always be prioritized over all other functions. The final environmental performance is defined using a reference life time (RLT), defined in accordance with environmental and operating conditions. This requires an accurate functional analysis classifying the functions, defining the architecture and the verification plan of the ecosystem. This paper will give examples related an electrical distribution equipment, using dependability technics and assessing different criteria of material efficiency for circular economy such as the durability, reliability, and maintainability. Circularity and dependability assessments should confirm the hypothesis aiming optimized designs and supporting the asset management. The first clause will present this context, which is aimed at minimizing the environmental footprint.

In all cases, the mission profile used for the design reflects the best-known scenario of the use conditions to assess the expected lifespan. To get an accurate assessment, accelerated tests could be necessary to complete the physical model of the studied part, enabling the verification of the defined mission profile. This will be presented through an example on shielded solid insulation system (2SIS) in second chapter.

When these technics are completed by analyses to optimize the analytics, the valuation for the asset management is improved. The presented study focuses on designed wireless thermal sensors [1] that are expected to be used over shielded insulated parts while the original design of the first sensor was aimed only on active parts.

Even, when the physical aging laws are known, the wear or fatigue of the products might still be difficult to assess, even when using relevant analytics, especially due to the interdependencies of the influencing factors, such as the climate change. To solve this problem, a new approach assessing the health index and aging of the products through adaptive models of failure rate will be presented to open new horizons for electrical equipment.

FUNCTIONS OF THE CIRCULARITY

The main principles of the circular economy [4] are:

1) Design and manufacture out waste and pollution
   a. Energy savings
   b. Lowest environmental footprint associated with the reference lifetime linked to use conditions.
2) Keep materials, products and system in use
   a. Optimized use conditions to reach the expected durability
   b. Repair, reused, upgrade
3) Regenerate natural system
   a. Remanufacture
   b. Recycle, recover

These principles are assessed during the product and system lifecycles as shown in Figure 1, closing the loop.

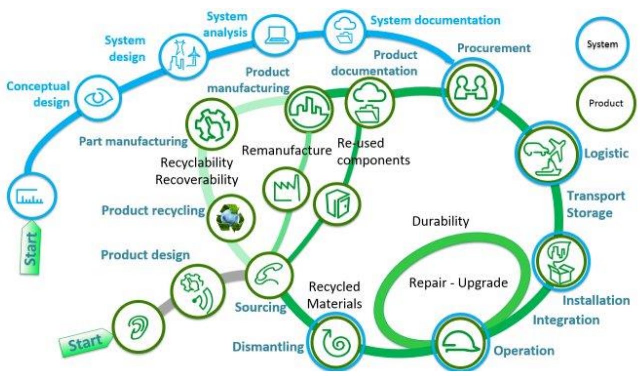

Figure 1: System and product lifecycles

In addition, within the Ecodesign European directive, horizontal CEN CENELEC and ETSI standards or reports are in progress further the European Commission's request through the mandate M/543[5]. A summary is shown Figure 2 knowing the knowledge that the list can evolve because the works are in progress. This is completed with the ETSI TR 103 476 report that addresses Information and Communication Technology (ICT) - Definition of approaches, concepts and metrics.

Doc	Title of deliverables	Ref	Leader
TR	Definitions related to material efficiency (NWI65684)	Pr TR 45550	CENELEC
EN	General method for the assessment of the durability of energy related products (JT010003)	Pr EN 45552	CEN
EN	General method for the assessment of the ability to repair, reuse and upgrade energy related products (NWI 65685).	Pr EN 45554	CENELEC
EN	General method for the assessment of the ability to re-manufacture energy related products (NWI 65686).	Pr EN 45553	CEN
EN	Methods for assessing the recyclability and recoverability of energy related products (JT010001).	Pr EN 45555	CEN
EN	General method for assessing the proportion of re-used components in an energy related product. (NWI 65709).	Pr EN 45556	CEN
EN	General method for assessing the proportion of recycled material content in an energy related product. (JT010002).	Pr EN 45557	CEN
EN	General method to declare the use of critical raw materials in energy related products. (NWI 65687).	Pr EN 45558	CENELEC
EN	Methods for providing information relating to material efficiency aspects of energy related products. (NWI 65688).	Pr EN 45559	CENELEC

Figure 2: CEN CENELEC JTC10 Drafted documents.

The main principles of circular economy focus on achieving the lowest environmental footprint, as described in the document Pr EN 50693 related to environmentally conscious design, as described within the Pr IEC/ISO 62959 document.
In addition, any deviation with the reference life time (RLT) can be assessed, using the document Pr EN 45552, which deals with durability assessment methodologies, mainly based on a robust functional analysis after environmental and operating conditions descriptions. Figures 3 and 4 show examples of parameters that should complete the current ratings of an electrical distribution products and system architecture. Answering to the questions "what for?" the user-related functions should be identified, while answering the questions "how?" the product or system-related functions should orientate the design of the product or system. For more details see EN 12973, the standard related to value management, and IEC 62347 for the guidance on system dependability specifications related to the IEC 60300 series of standards.

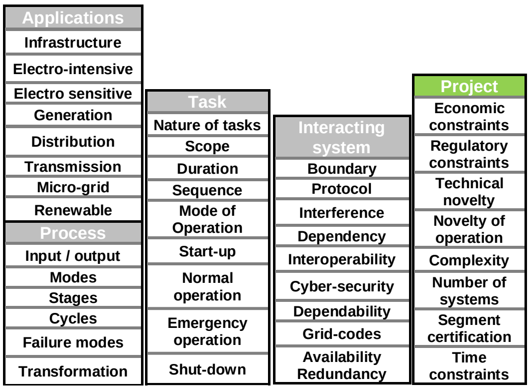

Figure 3: Electrical distribution functional parameters (Applications, interfaces, data models, innovations, etc.)

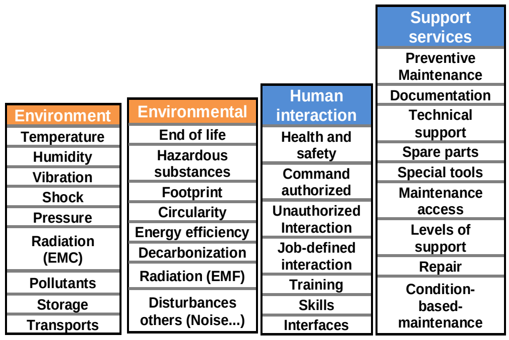

Figure 4: Electrical distribution functional parameters (Conditions, operations, environmental efficiencies, etc.)

The final performance of products and systems, environmentally conscious designed shall be in accordance with the standardization framework (Figure 5).

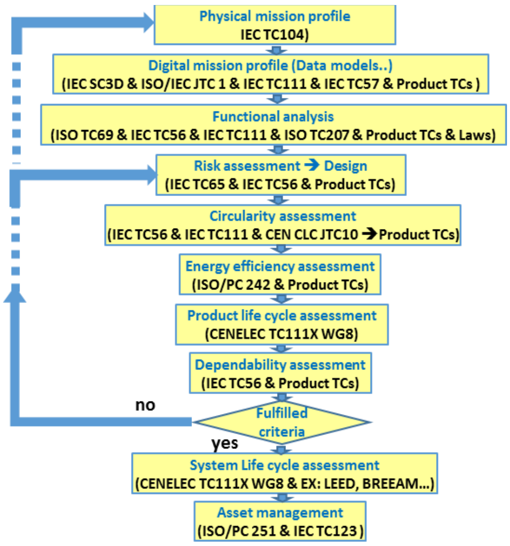

Figure 5: Environmentally conscious design

The final performance of a sustainable system should use the dynamic assessments during the use phase. This performance is optimized if the data models from upstream to downstream life phases are interoperable. The ontology might be a solution for solving this important issue and contribute to the environmental performance.

This highlights that all active parts such as transformers, motors, electrical equipment, or others should be monitored to assess their aging, health index and failure rate.

2SIS BUSBAR AGING ASSESSMENTS

A durability and reliability assessment related to material efficiency was presented during the previous CIRED session [2] 2017, dealing with how an innovative technology of medium voltage shielded solid insulated system (2SIS) busbar has passed through a complete validation method of accelerated aging tests to assess its lifetime.
The principle of the methodology was to split the study in

two sub-studies:
The first one performed accelerated aging tests (IEC 62506 methods for product accelerated testing) on a high quantity of material samples to build a complete knowledge and a data-base of the material behavior and degradation mechanisms in various operating conditions. Many aging methodologies related to mechanical degradation mechanisms (time-temperature-superposition principle, Boltzmann principle, etc.), chemical and physical degradation mechanisms have been investigated over many aging hours (> 12.000 hours) by performing an accelerated life test (ALT) and accelerated degradation test (ADT). Many stress factors (temperature, humidity, water immersion, pollutions, etc.) and material properties (surface resistivity, loss factor, dielectric strength, permittivity, compression set, stress relaxation, tensile strength, oxidation induction time, etc.) have been investigated to feed the degradations models such as:

- Arrhenius methodology - IEC 60216-1,
- Flynn, Wall and Derek Toop methodologies Williams Landel and Ferry

The choice of the relevant aging model has been validated through various characterization methods.

The second step of the methodology was intended to investigate the behavior of the busbar itself and to confirm that the material behavior after processing and over-molding of the conductor is the same then on samples. To do this, the same tests that were performed on material samples have been reproduced on busbars. Moreover, additional constraints (temperature and humidity cycling) and stress factors (permanent electrical field) have been added to the aging study. Finally, it allowed the assessment that the same failure mode can be observed on material samples and on the final component, and that the aging model can be used to predict the busbar lifetime.

These two sub-studies have highlighted that due to the viscoelastic nature of the material, the main stress factor that generates part failure is high temperatures leading to compression loss due to stress relaxation and thermo-oxidation degradation mechanisms. In addition, functional end-of-life criteria of the component has been linked to the material end-of-life criteria.

Reliability and lifetime extrapolations were performed by confronting the aging model to various mission profiles (See Figure 6), which can be very different depending on the environmental and operating conditions as well as the product life cycle stage. The mission profiles of electricity and utility distributors infrastructures, commercial and industrial buildings, large sites, and outdoor and indoor infrastructures have been analyzed and compared after the aging model application.

The survey has proven that operating and environmental conditions are very different from one application to another. Considering one global mission profile is not the most relevant way to assess the aging as the conditions change. However, the best-known scenario is required to define a reference life time for an environmental assessment.
When facing to several mission profiles, each individual use case should be studied and if any, iterative method will be used to optimize the reliability, using sensors and analytics to assess the dependability of the MV equipment.

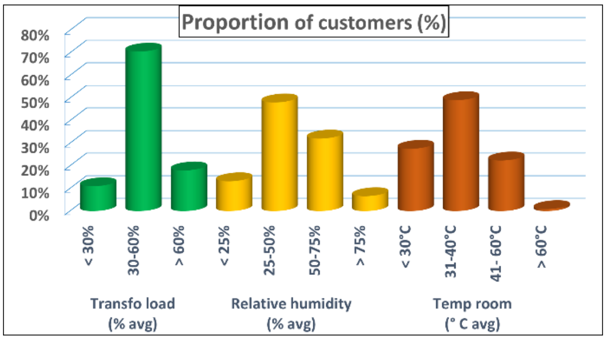

Figure 6: Mission profiles differences for HV/MV users

As shown in Figure 7, this study demonstrated the robustness of the 2SIS busbars, compared to other technologies, when MV equipment is exposed to special service conditions. When exposed to these conditions, MV equipment should be classified in accordance with the IEC TS 62271-304 which has been revised and published in 2019. Otherwise, precautions shall be taken for non-classified switchgear as advised in this IEC specification (see Annex C), especially when MV equipment is exposed to non-conductive solid deposits, or thermal and humidity cycles, met when installed near a coastal area.

Environmental Conditions Leading to MV Equipment Degradations	Proportion of users (%)	AIS Sensibility	GIS Sensibility	2SIS Sensibility
Temperature	73%	++	++	++
Humidity	66%	++	+	-
Dust	47%	++	-	-
Chemical Pollutions (Corrosive Agents, Sulphur, Ozone, etc.)	46%	++	++	-
Vibrations	39%	+	+	+
Shocks	39%	+	+	+
Fat Pollutions (Grease, Hydrocarbons, Vapors, etc.)	30%	++	-	-
Saline Atmosphere	27%	++	++	-
Others	5%	+	+	+

Figure 7: Degradation factors on MV equipment

Moreover, previous analysis allowed to the clear determination of the design limits and how to optimize the durability and reliability of the switchgear. That data can be collected, using the Easergy sensors as presented at the previous CIRED session [1]. The thermal sensor TH110 has been designed to monitor active parts. The substation monitoring device collects data and embeds analytics, enabling the monitoring solid shielded insulation parts' temperature and the surrounding humidity. The study examines the busbars and the bushings.

ANALYTICS FOR THERMAL MONITORING

The monitoring shall identify its scope, regarding its limitation and regarding the scope of the protection. For this, the alarm shall operate before the thermal limit of the surrounding components is reached and allow the MV equipment to operate under normal service conditions, combining the nominal current and maximum temperature.

Thermal sensors integration in switchgears is always performed as close as possible to connection points. Nevertheless, the probe of the Easergy TH110 sensor is never installed directly on the expected hot spot, nor on the weakest component (surrounding component that has the lower thermal withstand). This means that a thermal transfer occurs through an insulation part. A gap is identified between the current temperature of the connection (i.e. the weakest part or component) and the measured location where the sensor is installed. This is due to the thermal resistance and capacitance effects which should be assessed through a dedicated study as follows:

1) Identify the insulated parts (busbars, bushings, plug-in connectors, etc.)
2) Carry out a series of thermal tests to identify the discrepancy from the hot spot (core connection) and the measurement (see Figure 8) The stability is an information associated with the normative conditions, which is if the temperature change is less than 1K in 1hour. The same series of tests has been carried out on the bushings.

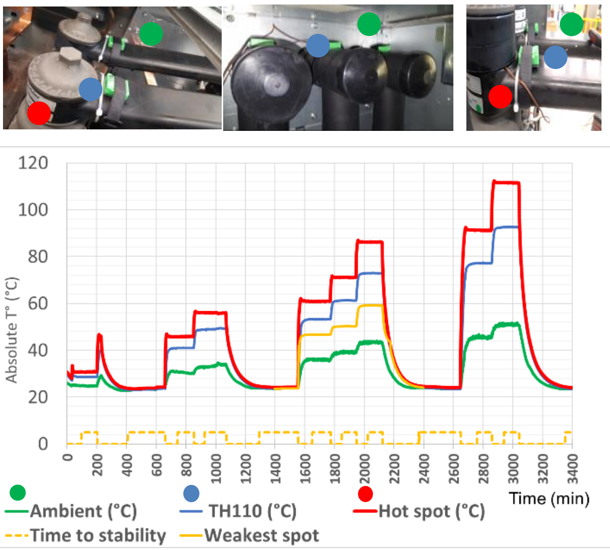

Figure 8: Thermal measurements of insulated parts

3) Identify the influencing factors such as the current, and the thermal transfers such as conduction and convection. The ambient temperature variations should be modelled under air flow control. As described in Figure 9, the focus is to measure the temperature rise, to avoid the disturbance coming from the ambient air, and to identify if a transfer rate would be constant under the usual temperature and to determine which conditions would affect a reverse model.

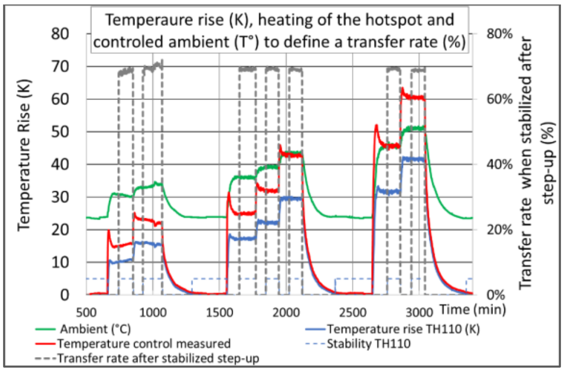

Figure 9: Transfer rate after stabilized step-up

4) Carry out a series of verification tests without the control of ambient temperature, to demonstrate that the study would be able to define the hot spot through a measurement beside the host spot. For that a comparison is needed between the controlled hotspot and the calculated hot spot through the reverse model fed by the temperature rise of the measurement as shown in Figure 10 with respective sequence numbers ❶❷❸.

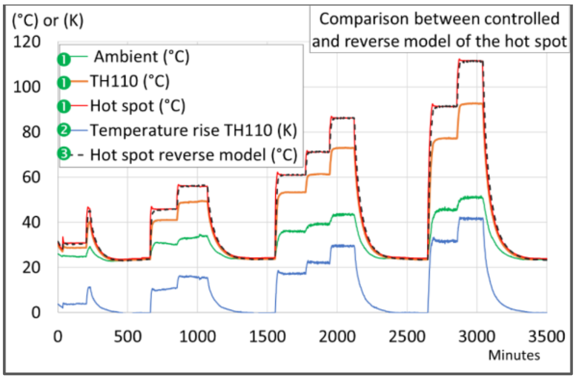

Figure 10: Calculated hot spot of a connection

5) When the weakest spot of a part is at third place along the insulated phase, meaning it is not near the hot spot or near the measurement, an additional series of tests is required to linked them. This is easier because this is usually an inner part not far from the defined hotspot.

The aging and analytics studies, embedded with the dependability studies, demonstrated their robustness in anticipating the degradations of the part that was exposed to aging. This led to a longer lifespan of MV equipment and contributed to material efficiency. In addition, these data feed a tool that uses these physical models and is completed by a statistical model to assess the aging, combining its influencing parameters when installed on electrical installations.

ADAPTIVE MODELS OF FAILURE RATE

As explained in the first chapter, there are numerous influencing factors of aging are they are very often interdependent. The digitization and artificial intelligence technics provide more knowledge about the asset's life: in this way, and with adequate sensors, it is possible to monitor the environmental conditions (temperature, hygrometry, corrosive gases level, salt concentration in atmosphere, etc.) and the usage conditions (number of operations or trips, variation of intensity, harmonics and voltage impacting the asset, etc.) with a sampling rate that is relevant for providing a precise view of the asset's mission profile.

In parallel, we can also monitor the different failures the asset will experience, and more precisely, for each part of the asset: mechanics, electronics, or electrotechnics.

The methodology we have developed has been patented in 2018 [3], and is briefly described in Figure 11. It mixes a physical approach based on first principles, providing information about the level of degradation for each asset part. Then we have transformed this information into failure rate values, relying on statistical models.

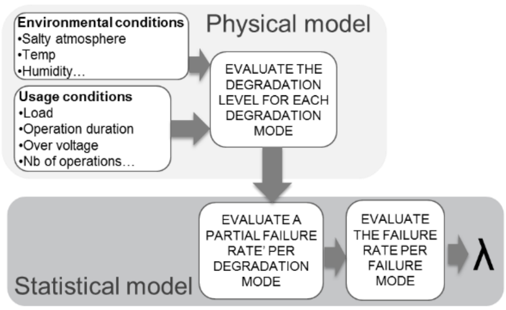

Figure 11: Methodology for aging models

As stated in the IEC 60050-192, which focuses on the definitions of dependability, we differentiated between:

- degradation modes, which we linked with the physical evolution of the asset with respect to time, environmental factors, and usage conditions (but that do not lead immediately to a failure),
- and failure modes, which characterizes an asset failure, and may result as the outcome of one or several degradation mode(s).

In practice, we defined six steps, which are as follows:

1. Identify sub-assemblies.
2. List degradation modes.
3. Match degradation modes and failure modes.
4. Set failure prioritization.
5. Reallocate failure rates on degradation modes.
6. Attach a kinetic law for each degradation mode.

The steps defined above are sufficient to build a robust aging model for assets [3]. Additionally, we can add a step to switch from aging indicators to failure rates. This last step is crucial to assess the durability of the product as required within the Pr EN 45552 document. The developed technics is very helpful for the system approach, as highlighted by the product and system life cycles. Especially when we need to forecast the probability evolution of minimal cut sets in a given system, with respect to environment and usage conditions, and therefore optimize globally the maintenance tasks for this system.

CONCLUSION

New technologies contribute to feed the ecosystems as identified during the last CIRED session [1]. The environmental footprint optimization shall be considered in its globality when environmentally conscious design and life cycle assessment become better and more covered by the standardization framework. Several countries and regions identified the necessity of identifying the indicators of the circularity where some of them asked the standardization committees to integrate these parameters inside their respective standards [5]. It will be necessary to associate the conditions for which any assessment of the circularity, and of a products and systems will be valid. For that, their dependability assessment, such as their durability and reliability, are required as related to the usage conditions. Due to the variations of the conditions dynamic and new adaptive approaches, using artificial intelligence technics will contribute to the material efficiency optimization for the circular economy.

The next step is how to harmonize the flow of the secured data in various models inside the product and system life cycles when several words have different definitions and the same definitions refer to several words, even inside standardization frameworks. To close the loop of the circular economy, ontology applied to applicable data models might solve this issue if it is itself also built under a standardization framework.

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