Eco-design Assessment of Elevator Electrical Equipment

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Περιεχόμενα

1. Foreword

Environmental protection is the practice of protecting the natural environment for the benefit of both the environment and humanity. With awareness of environmental protection increasing worldwide, the demand for more efficient products that reduce energy and resource consumption is more urgent than ever. The potential environmental impacts associated with products have sparked interest in developing methods to better understand and minimize these impacts.

Life-cycle assessment (LCA) is a technique used to assess environmental impacts associated with all stages of a product life cycle, from raw material extraction through materials processing, manufacturing, distribution, use, repair and maintenance, to disposal or recycling. LCAs may help avoid a narrow perspective on environmental concerns by compiling an inventory of relevant energy and material inputs and environmental releases, evaluating the potential impacts associated with these inputs and releases, and interpreting the results to support more informed decision-making.

An important aspect of environmental awareness in modern companies is the ISO 14000 family of standards, which provides practical tools for companies and organizations of all kinds seeking to manage their environmental responsibilities. ISO 14006 provides guidelines to assist organizations in establishing, documenting, implementing, maintaining and continually improving the management of eco-design as part of an environmental management system (EMS).

Vertical transportation products are indispensable to urban mobility and accessibility. Modern elevator systems integrate multiple electrical, electronic and communication subsystems within a complex installation environment. Combining these systems with an eco-design approach is both a technical and environmental challenge.

Elevator electrical and electronic equipment represents a critical part of modern vertical transportation systems and includes a wide range of control, communication and power distribution subsystems. The optimization of these systems through eco-design approaches can contribute to reduced material consumption, improved installation efficiency and lower environmental impact throughout the product life cycle.

In the present study, emphasis is given to eco-design improvements applied to the electronic equipment and wiring architecture of the elevator system, with particular focus on cable length optimization and reduction of material consumption.

2. Introductory information

KLEEMANN Hellas S.A. is active in the design, manufacturing and marketing of integrated lift systems. It is one of the largest companies in this sector in the European and international markets and produces more than 10,500 lift systems annually. Since 2012, KLEEMANN has implemented an environmental management system (EMS) for its facilities. The system is certified according to ISO 14001 and covers the production facilities (offices and factories) located in the industrial area of Kilkis, Greece. The company also applies a quality management system certified according to ISO 9001 and implements eco-design principles in accordance with ISO 14006.

The strategic objective of the company is sustainable development in full alignment with environmental protection, leading to environmentally optimized products. This objective is achieved through the adoption of principles, criteria and mechanisms related to environmental protection, pollution prevention and protection of human health, while supporting the preservation of natural resources and continuous environmental improvement.

The integration of LCA methodologies into product development is becoming an increasingly important part of the company's research and development activities. Eco-design approaches contribute to the development of products and systems with improved environmental performance throughout their life cycle.

In this context, the present study focuses on eco-design improvements applied to elevator electrical and electronic equipment, with emphasis on wiring architecture optimization and reduction of material consumption.

3. Description of steps and procedures of eco-design

Scope: Eco-design is an approach to product design with special consideration for the environmental impacts associated with a product throughout its life cycle. In LCA, the product life cycle is typically divided into raw material extraction, manufacturing, transportation, use, maintenance and end-of-life treatment. Eco-design aims to reduce the environmental footprint of products by integrating environmental considerations into the design and development process.

System boundaries: The flow of energy and materials, as well as the environmental impacts associated with each stage of the system, are evaluated throughout the product life cycle. The system boundaries defined in the present study include the receipt of raw materials at the company's facilities up to the final recycling and disposal stages of the product.

Data requirements: The data required for the completion of the study include the quantities of materials and energy associated with the entire life cycle of the product, as well as the quantification of their environmental impacts. However, in every life cycle assessment study, part of the required information is obtained from relevant background datasets and literature sources. As the system boundaries expand, the analysis of inputs and outputs becomes increasingly complex. In cases where no suitable primary data are available, the best available data and estimations are used.

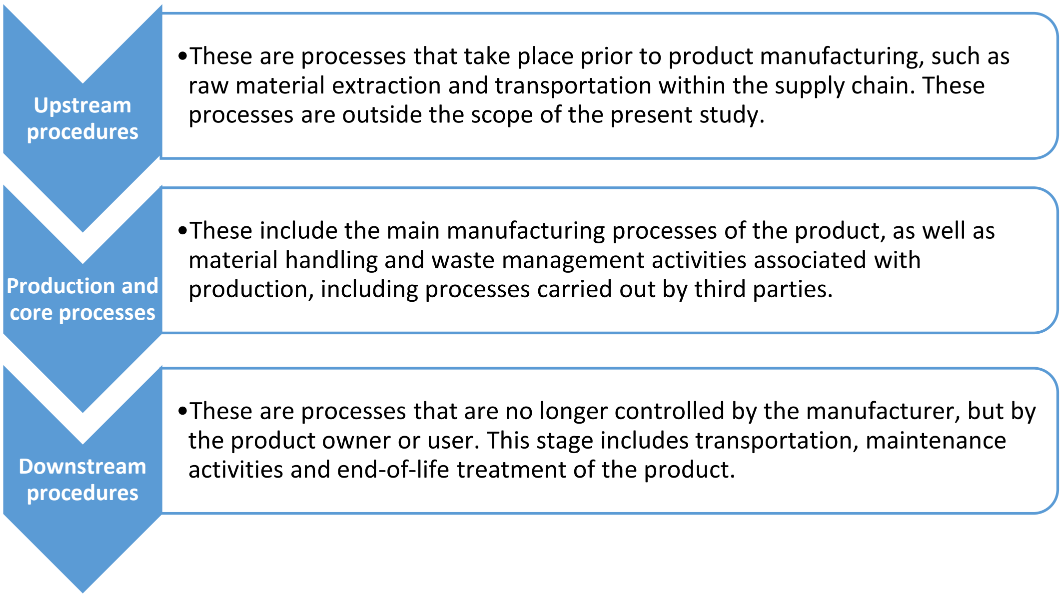
The data related to the production processes are based on company-specific information, while the impacts associated with raw material extraction and upstream production processes are based on background datasets available in the LCA software database.

In the present study, special emphasis is given to eco-design improvements related to the electrical and electronic equipment of the elevator system, including wiring architecture optimization and reduction of material consumption through improved cable routing methodologies.

Figure 1: Key eco-design principles applied throughout the product life cycle, focusing on material reduction, optimized production and improved environmental performance.

3.1. Procedure description

In order to evaluate the environmental aspects associated with the product life cycle, the system boundaries are divided into upstream, core production and downstream processes. The following diagram illustrates the general procedure description and system scope considered in the present study.



Upstream procedures

- These are processes that take place prior to product manufacturing, such as raw material extraction and transportation within the supply chain. These processes are outside the scope of the present study.

Production and core processes

- These include the main manufacturing processes of the product, as well as material handling and waste management activities associated with production, including processes carried out by third parties.

Downstream procedures

- These are processes that are no longer controlled by the manufacturer, but by the product owner or user. This stage includes transportation, maintenance activities and end-of-life treatment of the product.

3.2. Calculations and environmental impact assessment

Environmental impact assessment is used as a criterion for identifying improvement actions aimed at reducing the environmental footprint of the product. For the purposes of the present study, the LCA software SimaPro® 8 was used, applying the ReCiPe Endpoint (Hierarchist) method for the evaluation of the environmental impacts.

In the present document, the system boundaries of the study extend from the receipt of raw materials at the company’s facilities up to the final disposal and recycling stages of the product.

The eco-design methodology is applied to the electrical and electronic equipment of the elevator system, focusing on improvements related to wiring architecture optimization and reduction of material consumption. The implementation of optimized cable routing methodologies and revised cable calculation rules contributes to reduced material use, improved installation efficiency and lower environmental impact.

4. Product structure and reference model

The present eco-design assessment focuses on the electrical and electronic equipment of a traction electric passenger lift system. Particular emphasis is given to the optimization of the wiring architecture and the reduction of material consumption associated with cable installation.

Previous life cycle assessment studies performed on complete elevator systems have indicated that electrical and electronic equipment represents one of the most environmentally significant subsystems of the installation. As illustrated in the following figure, the electrical and electronic equipment category presents one of the highest overall environmental contributions compared to the remaining elevator sub-assemblies.

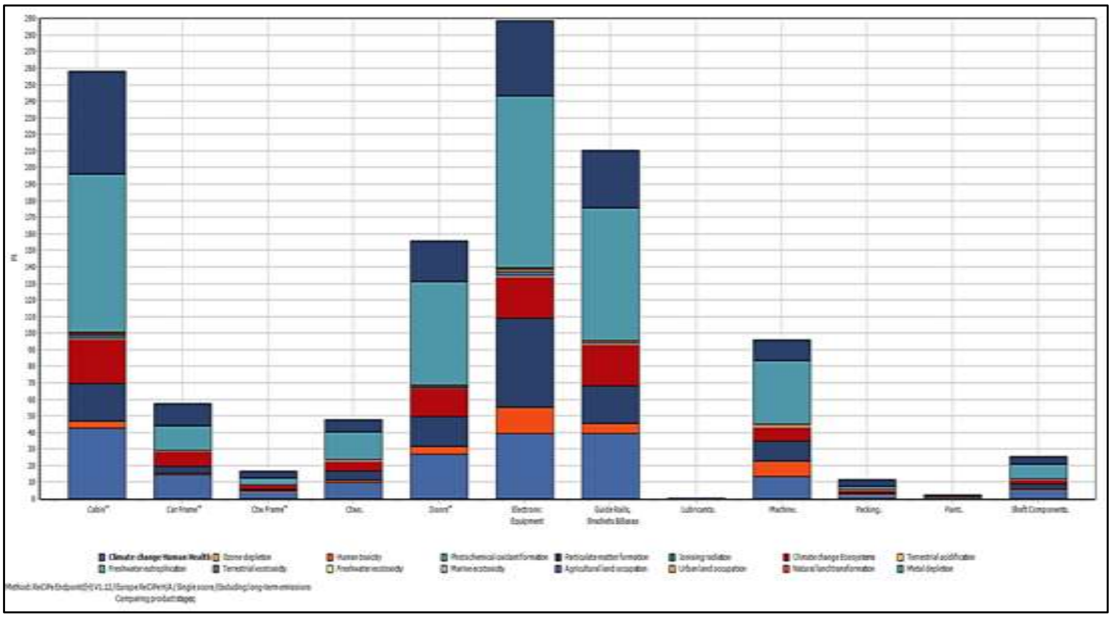


Figure 2: Indicative environmental contribution analysis of elevator sub-assemblies based on previous complete elevator system life cycle assessments.

This increased environmental contribution is mainly associated with the high quantities of copper-containing cable infrastructure, electronic components and energy-intensive upstream material production processes. Based on these findings, the present study focuses specifically on the cable infrastructure and wiring architecture of the elevator system, aiming to investigate targeted eco-design improvements in one of the most environmentally significant subsystems identified in previous assessments.

The study is based on a reference elevator configuration representative of a typical medium-rise passenger lift installation. The assessed system includes the main electrical and electronic subsystems of the elevator, such as control panels, travelling cables, shaft wiring, communication lines and associated electrical equipment.

The eco-design activities performed within the scope of the study included the development of optimized cable routing methodologies, revised cable calculation rules and additional digitalization initiatives related to destination control systems (DCS).

The quantitative environmental assessment presented in this report focuses exclusively on wiring architecture optimization and cable material reduction.

The reference installation characteristics are following presented:

Table 1: Reference installation characteristics

Parameter	Value
Type	Traction electric passenger lift
Machine room	MRL
Nominal load	1050 kg
Nominal speed	1.0 m/s
Travel	18.29 m
Pit depth	1380 mm
Usable headroom	3000 mm
Suspension	2:1

4.1. Significant Aspects

One of the most significant eco-design improvements implemented in the present study concerns the optimization of the electrical wiring architecture of the elevator system. In conventional installation practices, cable quantities were often estimated using simplified rules based on approximate cable lengths per floor or installation zone. Although this approach ensured installation flexibility, it frequently resulted in cable overdimensioning, unnecessary material consumption and increased installation variability.

In the framework of the present project, the R&D department carried out an extensive evaluation of the electrical installation architecture in order to identify all locations where cable length optimization could be achieved. Particular emphasis was given to travelling cables, shaft wiring and communication lines associated with the electrical and electronic equipment of the elevator system.

As part of this process, a revised cable calculation methodology was developed based on the actual routing paths of the cables within the installation. The new methodology replaces simplified estimation practices with routing-based calculation rules derived from the real installation configuration and cable routing requirements.

Representative examples of the routing-based cable calculation methodology and standardized cable routing paths developed during the project are presented below.

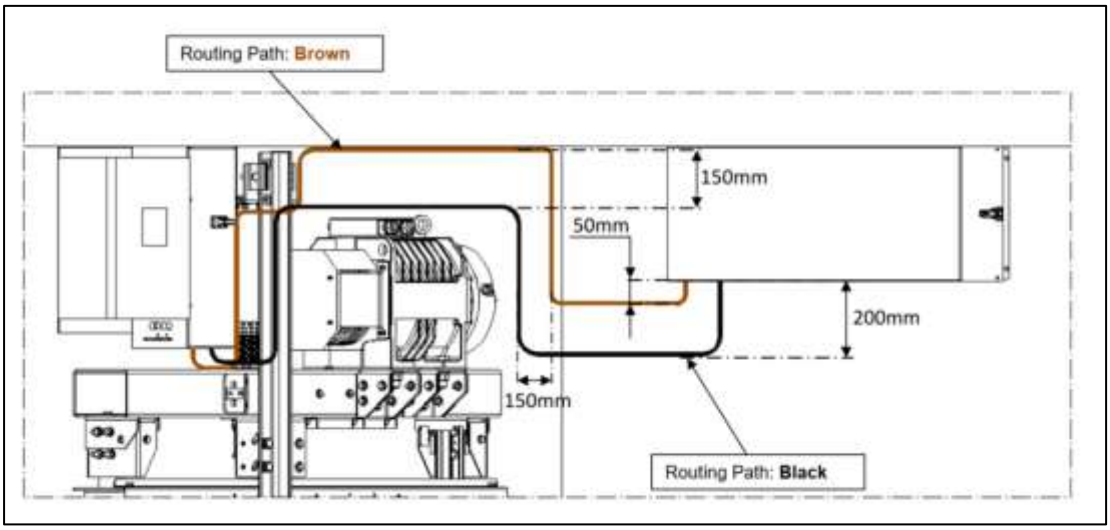


Figure 3: Example of optimized cable routing paths and routing distance standardization within the machine area.

In parallel, a new installation manual was developed in order to standardize cable routing practices and provide detailed installation guidance to installers. The manual defines optimized routing paths and installation methods, ensuring that only the required cable lengths are used during installation.

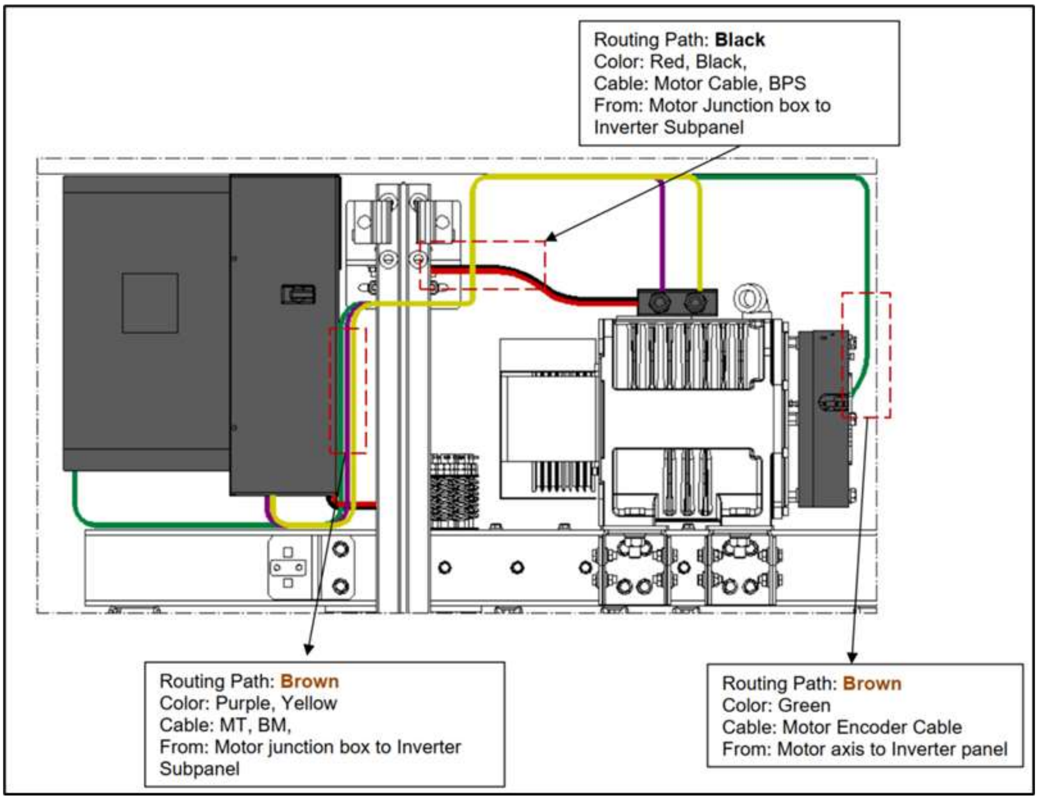


Figure 4: Detailed routing definition for motor and inverter cable installation paths used in the revised cable calculation methodology.

This approach contributes to:

- Reduction of cable material consumption
- Reduction of unnecessary material overdimensioning
- Improved installation consistency and standardization
- Reduced installation waste and unused cable leftovers
- Improved environmental performance associated with cable production and transportation

In addition to the wiring optimization activities, further eco-design improvements were investigated in the field of DCS. More specifically, part of the conventional wired terminal infrastructure and panel-based interfaces was replaced by Android-based tablet interfaces communicating through network-based architectures. The new approach introduced a hybrid digital control environment combining tablet-based user interaction with conventional elevator communication systems, reducing the need for dedicated physical wiring and hardware infrastructure in selected applications. The development activities also included the evaluation of alternative communication architectures, interface optimization, software debugging and logging frameworks, as well as the development of standardized communication and integration approaches between the user interfaces and the elevator control systems.

In addition to the reduction of physical infrastructure requirements, the new digital architecture contributes to improved installation flexibility, simplified configuration management and supports the gradual digitalization of elevator electrical and electronic systems.

Due to the optional nature of DCS installations and the variability between projects, a detailed material inventory and quantitative LCA assessment through SimaPro were not performed for this subsystem within the scope of the present study. Therefore, the quantitative environmental assessment presented in this report focuses exclusively on wiring architecture optimization and cable material reduction.

5. Analysis of life cycle parameters of the electrical and electronic equipment

The life cycle analysis performed within the framework of the present eco-design assessment focuses on the electrical and electronic equipment of the elevator system, with particular emphasis on cable infrastructure and associated material consumption. The study evaluates the environmental impact associated with the optimized wiring architecture by comparing the reference installation configuration with the revised cable routing and calculation methodology developed during the project.

The following sections present the material inventory, system parameters and environmental impact assessment associated with the evaluated electrical and electronic subsystems.

The life cycle analysis, which represents an important and integral tool within the eco-design process, is generally divided into the following main life cycle stages:

Although the general life cycle approach includes all stages from raw material acquisition to end-of-life treatment, the present study focuses specifically on the stages and parameters directly affected by the electrical wiring optimization process. Therefore, particular emphasis is given to raw materials, cable-related manufacturing impacts, transportation aspects associated with material quantities, installation-related material consumption and end-of-life considerations associated with the evaluated electrical and electronic equipment.

Energy consumption during the operational use phase of the elevator system was not quantitatively evaluated within the scope of the present study, since the assessment focuses specifically on material optimization and wiring architecture improvements rather than operational energy performance.

Particular attention is given to the optimization and reduction of:

- Copper used in electrical wiring and cable infrastructure
- Polymer insulation and sheath materials associated with cable installations
- Auxiliary electrical and communication components related to the wiring architecture
- Unnecessary cable overdimensioning and installation material waste

5.1. Raw materials

The company is gradually seeking cooperation with suppliers that comply with environmental criteria and relevant environmental standards. Up to the present time, a significant percentage of suppliers operate, at minimum, with an environmental management system certified according to ISO 14001.

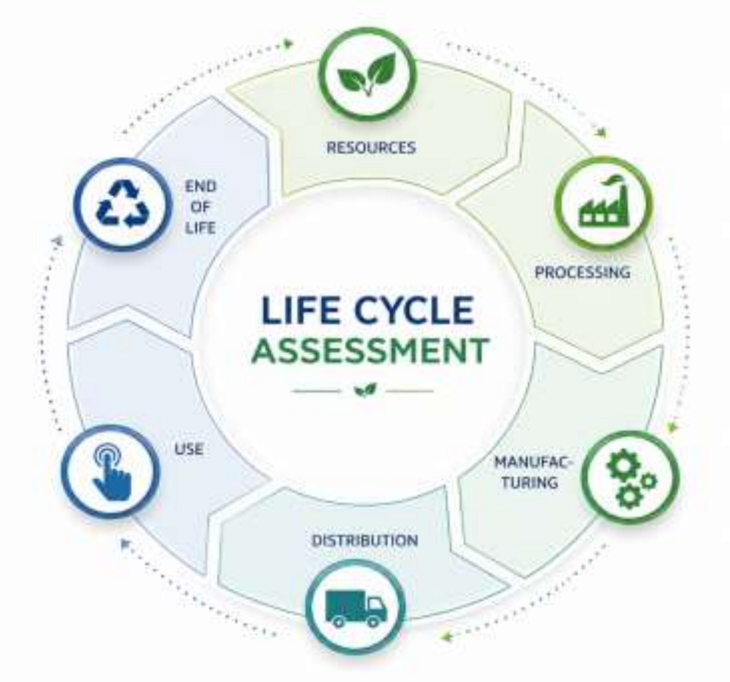


Figure 5: Life cycle stages associated with the eco-design assessment methodology.

The life cycle inventory assessed in the present study is mainly associated with the cable infrastructure and related installation materials used in different areas of the elevator system. The most significant material quantities are related to copper and polymer-based cable materials, including PVC, polypropylene (PP) and LSHF cable compounds. Based on the evaluated sub-assemblies, the total quantity of the assessed installation materials was reduced from 84.75 kg to 65.02 kg following the implementation of the optimized cable routing and calculation methodology.

In addition, a significant part of the conventional PVC-based cable infrastructure can now be optionally replaced by low smoke halogen free (LSHF) cable solutions. The introduction of this option is primarily driven by environmental and safety considerations, as LSHF materials are associated with reduced emission of corrosive and toxic gases during combustion, lower smoke generation and improved environmental performance compared to conventional halogen-containing cable materials. The availability of LSHF cable alternatives supports the broader eco-design strategy applied to the elevator installation and provides customers with environmentally preferable cable configuration options.

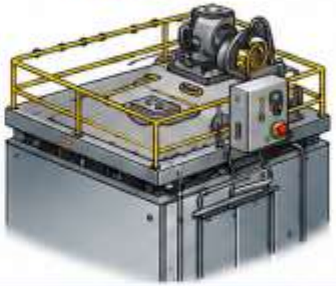
It should be noted that the present assessment and life cycle analysis do not include the entirety of the elevator electrical and electronic equipment, but focus specifically on the cable infrastructure and installation areas where optimization actions and eco-design improvements could be implemented. The remaining electrical and electronic equipment of the elevator system was considered unchanged between the reference and optimized configurations.

The evaluated areas are associated with the installation locations and routing starting points of the corresponding cable infrastructure. The subdivision into different sub-assemblies was performed for supervision, analysis and presentation purposes within the framework of the life cycle inventory assessment.

Among the evaluated sub-assemblies, the control panel represents the largest share of material consumption due to the concentration of cable infrastructure and associated installation materials.

Following is presented the evaluated sub-assemblies and their corresponding material composition used for the life cycle inventory assessment:

Car roof



Material	Amount (kg)
Polyvinylchloride, suspension polymerised (PVC)	0.94
Copper, cathode	3.10
Polypropylene (PP)	0.20
Tin	0.02
LSHF cable compound	4.00

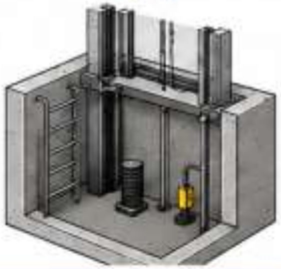
Headroom (YTO)

Material	Amount (kg)
Polyvinylchloride, suspension polymerised (PVC)	0.13
Copper, cathode	3.68
Polypropylene (PP)	0.29
Tin	0.05
LSHF cable compound	6.00

Control panel

Material	Amount (kg)
Polyvinylchloride, suspension polymerised (PVC)	2.75
Copper, cathode	19.27
Polyamide 6.6, glass filled (Nylon)	3.19
Polypropylene (PP)	1.50
Tin	0.07
LSHF cable compound	23.00

Pit



Material	Amount (kg)
Polyvinylchloride, suspension polymerised (PVC)	0.85
Copper, cathode	0.32
Polypropylene (PP)	0.02

Shaft

Material	Amount (kg)
Polyvinylchloride, suspension polymerised (PVC)	0.01
Copper, cathode	0.01
Switch, toggle type	0.01
Transistor, auxiliaries and energy use	1.00

5.2. Manufacturing processes

The manufacturing-related impacts associated with the evaluated installation materials are primarily linked to the production of electrical cables and auxiliary cable infrastructure components. Since the cables used in the evaluated installation are externally supplied products and are not manufactured internally by the company, no separate production-level manufacturing analysis was performed. The assessment of manufacturing impacts was therefore based on literature data and background datasets available within the SimaPro database and the corresponding life cycle inventory libraries.

The most significant manufacturing processes considered in the assessment are related to copper production and refining, polymer compounding and extrusion processes associated with cable insulation and sheath materials, as well as cable preparation and assembly activities related to the installation infrastructure. The upstream process network generated through SimaPro also indicates the strong dependence of cable manufacturing activities on energy-intensive processes, particularly electricity generation associated with copper and polymer production.

Within the framework of the present project, the company revised the cable calculation and routing methodology in order to reduce unnecessary cable lengths, material overdimensioning and installation waste. The optimized routing approach contributes indirectly to the reduction of the manufacturing impacts associated with raw material processing, cable production and transportation activities through the lower quantities of installation materials required for the reference installation.

5.3. Transportation & Packaging

Transportation: The average transportation distance from our premises to the installation site is estimated at approximately 800 km, based on representative installation data and typical transportation routes. The transportation of materials is assumed to be performed using freight vehicles with an average cargo capacity of up to 16 tonnes.

Packaging: Packaging associated with the evaluated cable infrastructure mainly consists of wooden pallets or cable drums, nylon and plastic wrapping materials, carton packaging and small metallic fastening elements used for transportation and storage purposes.

Since no project-specific packaging inventory was available for the evaluated cable infrastructure, the packaging quantities presented below were estimated indicatively based on typical transportation and storage practices used for cable distribution and delivery to the installation site.

Table 2: Indicative packaging materials associated with the evaluated cable infrastructure.

Material	Quantity [kg]
Wood pallet / cable drums	2.5 – 4
Nylon / plastic wrapping materials	0.5 – 1
Steel (nails, staples, fastening elements)	0.1 – 0.3
Carton boxes / labels	0.3 – 1.5

5.4. Installation

KLEEMANN provides the installer with detailed routing instructions and standardized installation practices through the newly developed cable routing manual. The installation methodology is based on predefined cable routing locations and calculated routing paths, ensuring that the installer knows the exact starting points, routing paths and final connection locations of the cable infrastructure within the installation.

Compared to conventional installation practices based on approximate routing estimations, the revised methodology results in a significant improvement in installation consistency and material utilization. An overall reduction of approximately 30% in cable-related installation material requirements was achieved through the optimized routing and calculation approach.

5.5. Operation – Use

The present assessment focuses on the cable infrastructure and wiring-related installation materials of the elevator system. In accordance with the defined system boundaries and the scope of the evaluated eco-design improvement actions, operational energy consumption was intentionally excluded from the quantitative assessment.

This decision is methodologically justified by the fact that the evaluated wiring optimization measures do not alter the operational characteristics or energy performance of the elevator drive system and therefore do not introduce any measurable variation in energy consumption during the use phase. The dominant operational energy-related environmental impacts of elevator systems are primarily associated with traction motor efficiency, drive system performance and elevator usage patterns, which fall outside the scope of the current cable infrastructure optimization study.

Consequently, the inclusion of operational energy consumption would not provide additional insight regarding the environmental benefits achieved through the evaluated eco-design measures and could obscure the material-related environmental improvements that constitute the primary focus of this assessment.

5.6. Maintenance - Repairs

The maintenance requirements associated with the evaluated cable infrastructure are limited to the standard inspection and maintenance procedures of the elevator system. Typical maintenance activities include visual inspection of cable routing and fastening points, verification of cable integrity and inspection for possible mechanical wear or damage.

KLEEMANN provides the necessary installation documentation and routing instructions in order to ensure standardized cable installation and improved accessibility during inspection and maintenance activities. Because maintenance requirements may vary depending on the installation conditions and the operational characteristics of each project, these activities are not calculated in detail within the scope of the present study.

The maintenance procedure, in addition to the transportation of technicians to the installation site, includes limited use of tools and auxiliary materials. Since the present study focuses specifically on cable infrastructure optimization and no substantial changes were introduced to the operational functionality of the elevator system, no detailed maintenance impact calculation was performed within the scope of the assessment.

Nevertheless, the implementation of predefined routing paths and standardized installation practices may contribute to improved accessibility during inspection and maintenance activities, as well as reduced variability during future repair or replacement procedures.

5.7. Disposal - Recycling

An important element of the final stage of the life cycle is the possibility for easy separation, dismantling and recycling of the installation materials after the end of their operational lifetime. In the case of the evaluated cable infrastructure, the most significant recyclable materials are copper conductors and metallic auxiliary components associated with the installation. The optimized wiring architecture developed within the framework of the present study contributes indirectly to reduced waste generation through the reduction of unnecessary cable quantities and installation leftovers during both installation and replacement activities.

The evaluated cable infrastructure mainly consists of copper and polymer-based materials, including PVC, polypropylene (PP) and low smoke halogen free (LSHF) compounds. Depending on the material type and the applicable waste management practices, parts of the evaluated materials may:

- Be material recycled
- Be thermally treated or incinerated
- End up at landfill disposal facilities

General disposal and recycling activities should be performed according to the applicable environmental regulations and waste management practices. During dismantling and separation activities, the main material categories associated with the evaluated installation materials are:

- Residues containing copper (cables and electrical wiring)
- Waste electrical and electronic equipment
- Metallic fastening and support elements
- Polymer-based cable insulation and sheath materials
- Waste intended for thermal treatment or landfill disposal

In addition, dedicated cable recycling processes and infrastructure are already widely established in most European countries and internationally, particularly due to the high recovery value of copper contained in electrical cables. Modern cable recycling practices allow the separation and recovery of metallic fractions and, depending on the recycling technology, partial recovery of polymer-based materials associated with cable insulation and sheath compounds.

Consequently, the evaluated cable infrastructure is considered compatible with existing recycling and material recovery practices commonly applied within the electrical and electronic waste management sector.

6. Environmental Impact Assessment

6.1. Terminology

Materials: For the calculation of the indicators related to material production, all relevant procedures are considered, from raw material extraction to the final production stage of the evaluated materials. The calculation also includes transportation processes associated with the production and distribution of the materials.

Manufacturing processes: Indicators related to manufacturing processes represent the emissions associated both with the production processes themselves and with the electricity consumption required for the production of the evaluated materials and cable infrastructure.

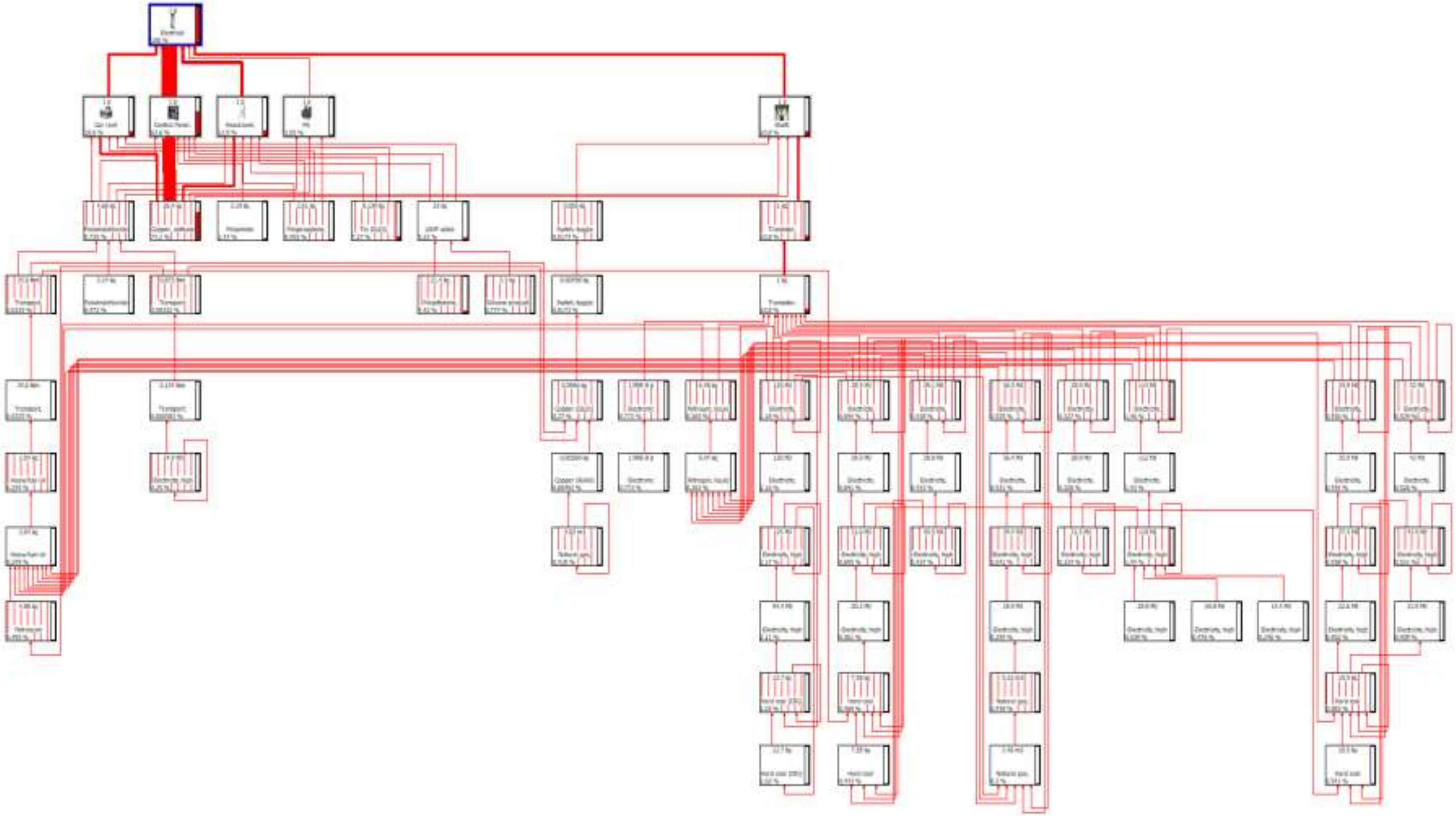
Transport: Transport indicators include the environmental impacts associated both with fuel production and fuel consumption during the transportation of the evaluated installation materials.

Power Consumption: Indicators related to energy consumption refer mainly to the upstream energy-intensive processes associated with the production of the evaluated cable materials, such as copper refining, polymer production and electricity generation. These indicators may vary depending on the electricity production technologies and energy mix applied in each country.

Disposal Procedures and collection: This category includes indicators associated with recycling activities, thermal treatment/incineration processes and landfill disposal scenarios related to the evaluated installation materials.

The results of the present study illustrate the environmental impact associated with the life cycle of the evaluated cable infrastructure and installation materials of the elevator system. It is also possible to perform the assessment using alternative environmental impact assessment methods available within the SimaPro® software environment.

First of all, the Product Structure Tree is presented, where the evaluated cable infrastructure is illustrated as a function of its life cycle stages, including material production, manufacturing-related processes, transportation and disposal scenarios. The evaluated sub-assemblies contributing the highest percentage of material consumption are described through the corresponding materials and associated processes. The tree displays materials whose content exceeds 0.24%.



6.2. Damage Assessment

In order to quantify the environmental impact of the evaluated installation materials across different environmental categories, characterization factors (CFs) are applied. Characterization factors express the contribution of a specific emitted substance to a particular environmental impact category. For example, they indicate the extent to which the emission of 1 kg of a substance contributes to impacts such as freshwater ecotoxicity, climate change or human toxicity.

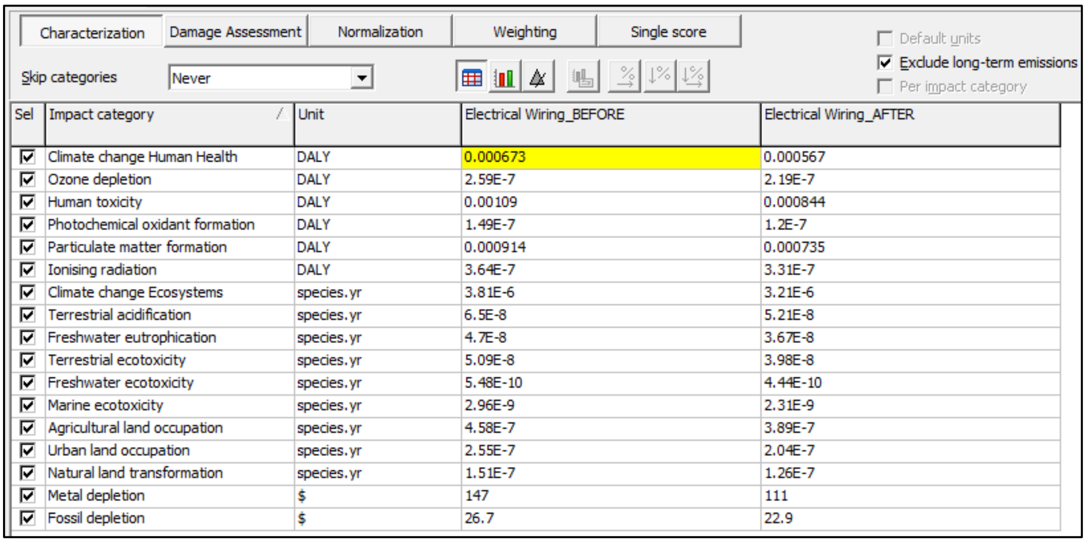
The following charts present a comparative evaluation between the reference and optimized cable infrastructure configurations across multiple environmental impact categories. Thereby they are illustrating the environmental benefits achieved through the optimized cable routing and material reduction approach.

The midpoint impact assessment results demonstrate a consistent reduction in environmental impacts across all evaluated categories following the implementation of the optimized wiring architecture. More specifically, reductions ranging approximately from 8% up to 25% are observed across the evaluated categories.

Indicatively:

- Climate change and human health related impacts are reduced by approximately 15–20%
- Human toxicity, freshwater ecotoxicity and terrestrial ecotoxicity indicators present reductions of approximately 20–22%
- Metal depletion presents one of the most significant improvements, with a reduction approaching 25%, mainly due to the reduced copper consumption
- Fossil depletion indicators are reduced by approximately 14–16%, reflecting the lower upstream energy demand associated with cable material production

Representative numerical results extracted from the SimaPro ReCiPe Endpoint assessment are presented below.



Skip categories: Never

☐ Default units
☑ Exclude long-term emissions
☐ Per impact category

Sel	Impact category	Unit	Electrical Wiring_BEFORE	Electrical Wiring_AFTER
☑	Climate change Human Health	DALY	0.000673	0.000567
☑	Ozone depletion	DALY	2.59E-7	2.19E-7
☑	Human toxicity	DALY	0.00109	0.000844
☑	Photochemical oxidant formation	DALY	1.49E-7	1.2E-7
☑	Particulate matter formation	DALY	0.000914	0.000735
☑	Ionising radiation	DALY	3.64E-7	3.31E-7
☑	Climate change Ecosystems	species.yr	3.81E-6	3.21E-6
☑	Terrestrial acidification	species.yr	6.5E-8	5.21E-8
☑	Freshwater eutrophication	species.yr	4.7E-8	3.67E-8
☑	Terrestrial ecotoxicity	species.yr	5.09E-8	3.98E-8
☑	Freshwater ecotoxicity	species.yr	5.48E-10	4.44E-10
☑	Marine ecotoxicity	species.yr	2.96E-9	2.31E-9
☑	Agricultural land occupation	species.yr	4.58E-7	3.89E-7
☑	Urban land occupation	species.yr	2.55E-7	2.04E-7
☑	Natural land transformation	species.yr	1.51E-7	1.26E-7
☑	Metal depletion	$	147	111
☑	Fossil depletion	$	26.7	22.9

Figure 6: Representative numerical environmental impact results generated in SimaPro for the reference and optimized cable infrastructure configurations.

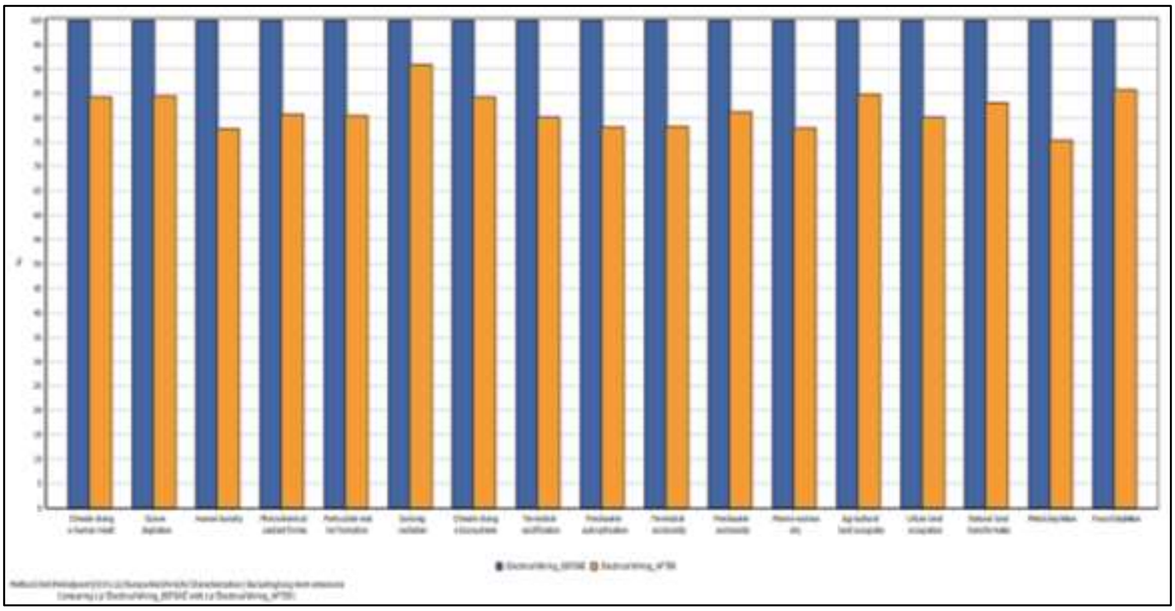


Figure 7: Midpoint environmental impact indicators before and after implementation of the optimized wiring architecture.

The observed improvements are primarily associated with the reduction of copper quantities, polymer-based cable materials and auxiliary installation materials required for the evaluated cable infrastructure. Since copper production and polymer manufacturing are strongly linked to energy-intensive upstream processes, the reduction of material quantities contributes directly to lower environmental impacts across multiple categories.

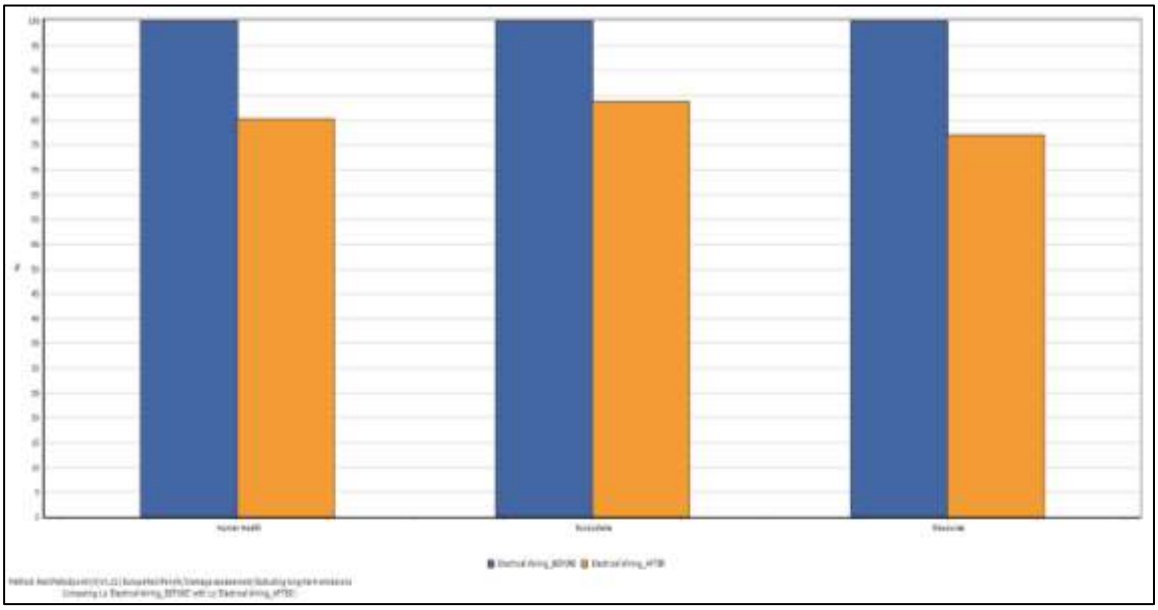


Figure 8: Endpoint damage categories associated with the evaluated cable infrastructure before and after optimization.

The endpoint damage assessment additionally demonstrates reductions in the categories of Human Health, Ecosystems and Resources. More specifically:

- Human Health damage indicators are reduced by approximately 20%
- Ecosystem-related damage indicators are reduced by approximately 15–16%

- Resource-related impacts present the highest improvement, with reductions approaching 23–24%

Overall, the results confirm that the implementation of routing-based cable calculation methods and standardized installation practices can contribute substantially to the environmental optimization of the evaluated cable infrastructure.

Damage assessment allows the grouping of individual impact indicators into broader categories using common units. For example, human health impacts are expressed in DALYs (Disability Adjusted Life Years), enabling the aggregation of impacts from different environmental mechanisms, such as climate change or carcinogenic emissions. This approach facilitates the interpretation and comparison of the overall environmental profile of the evaluated configurations.

6.3. Normalization

Normalization is a method that allows impact category indicator results to be compared against a common reference value. Typically, this reference corresponds to the average annual environmental load per person in a given region (e.g., Europe), enabling the different impact categories to be expressed in the same unit. This transformation facilitates the identification of the most significant environmental impacts relative to a common baseline and allows direct comparison between different impact categories.

The normalization results presented in the chart above confirm the environmental improvements achieved through the optimized cable routing and material reduction approach. The highest normalized impacts are associated mainly with the categories of metal depletion and fossil depletion, reflecting the significant contribution of copper production and energy-intensive upstream processes related to cable manufacturing.

Following the implementation of the optimized wiring architecture, substantial reductions are observed in these dominant categories. More specifically:

- Metal depletion indicators are reduced by approximately 24–25%
- Fossil depletion indicators are reduced by approximately 14–16%
- Climate change and human health-related impacts are reduced by approximately 15–20%
- Human toxicity and particulate matter formation indicators also present noticeable reductions compared to the reference configuration

In several additional categories, including photochemical oxidant formation, freshwater eutrophication and marine ecotoxicity, the optimized configuration demonstrates consistent, although smaller, reductions in normalized environmental impact.

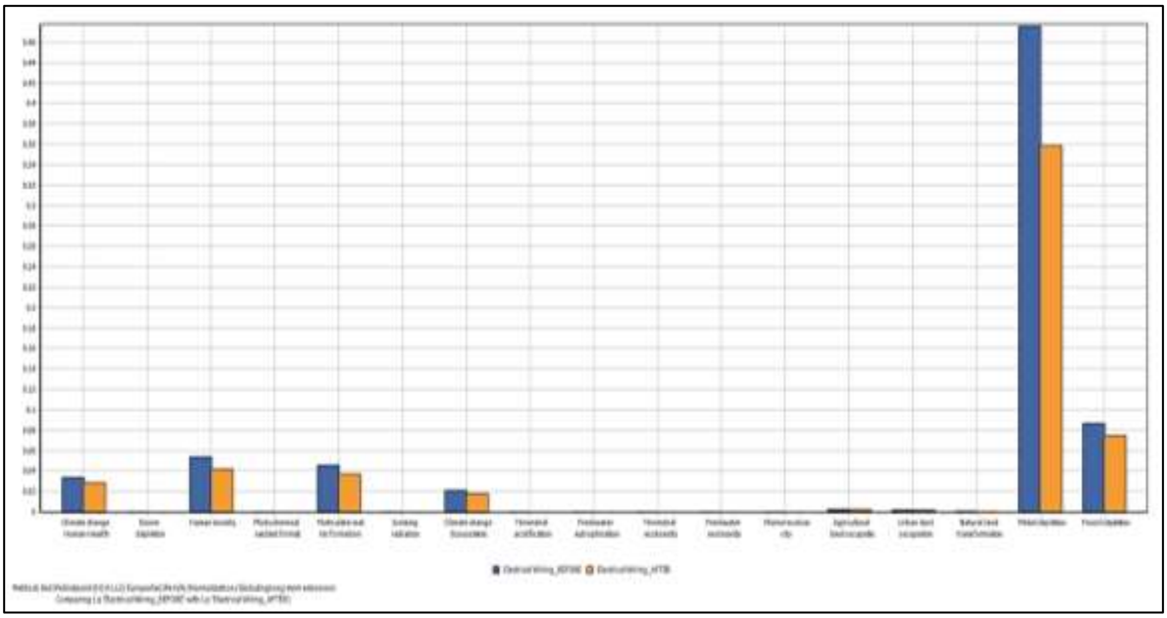


Figure 9: Normalized environmental impact indicators after implementation of the optimized cable routing methodology.

Overall, the normalization results reinforce the findings of the characterization and damage assessment stages, confirming that the optimized cable infrastructure presents a lower environmental burden across the majority of the evaluated impact categories. The results additionally highlight the importance of material reduction strategies, particularly regarding copper-containing cable infrastructure, in minimizing the overall environmental footprint of the installation.

6.4. Weighting

The weighting method allows the aggregation of all environmental impact categories into a single overall environmental performance indicator. This is achieved by assigning weighting factors to the different impact categories according to established environmental valuation principles. Weighting therefore reflects the relative importance of different environmental effects in relation to societal and environmental priorities. The unit used in the weighting stage of the Life Cycle Assessment is the Pt (Point). One Pt represents the average annual environmental load generated by one European inhabitant. Consequently, weighting results provide an overall indication of the environmental relevance of the evaluated impacts in relation to a common societal reference framework.

The weighting results presented in the following graphs confirm the environmental improvements achieved through the optimized cable routing and material reduction approach. The endpoint weighting assessment highlights three principal environmental damage categories: Human Health, Ecosystems and Resources.

Among these categories, the highest contribution is associated with the Resources category, mainly due to the consumption of copper and polymer-based cable materials together with the upstream energy demand associated with their production processes. Following the implementation of the optimized wiring architecture, a substantial reduction is observed in the Resources category, approaching approximately 22–24% compared to the reference configuration.

Human Health indicators also present a significant reduction of approximately 15–18%, reflecting the lower environmental burden associated with upstream electricity generation, material processing and manufacturing activities related to cable production. Ecosystem-related impacts demonstrate smaller but still noticeable improvements, with reductions approaching approximately 10–15%.

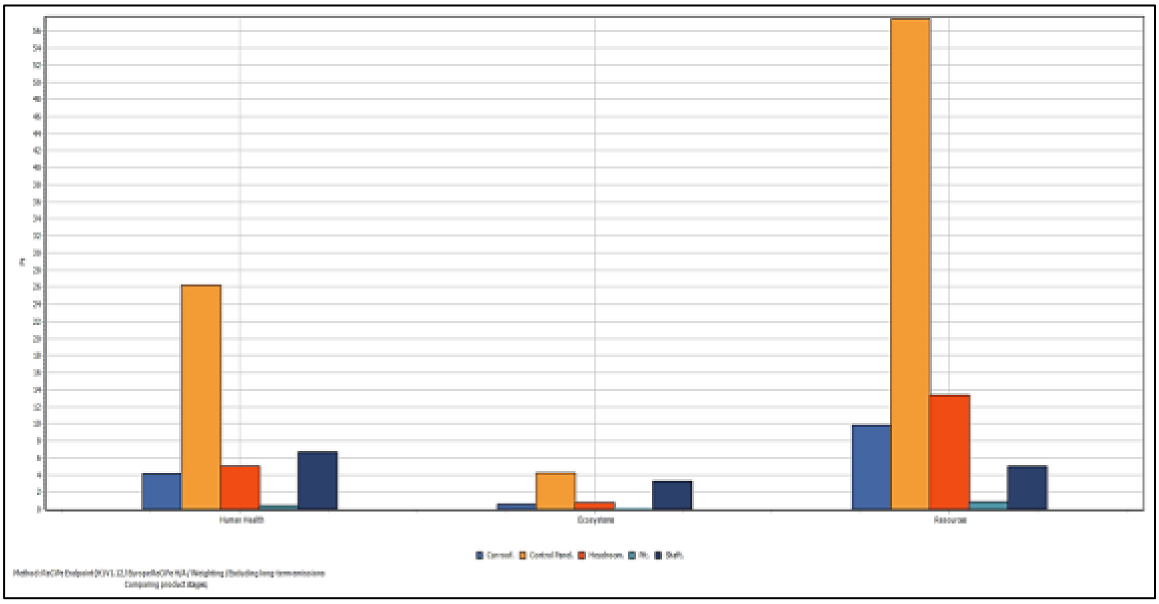


Figure 10: Comparative weighting assessment of the evaluated cable infrastructure sub-assemblies.

The weighting analysis of the individual midpoint categories additionally indicates that metal depletion represents one of the dominant environmental contributors within the evaluated cable infrastructure. This result is directly associated with the high environmental significance of copper extraction and refining processes included within the life cycle inventory model. Climate change, fossil depletion, human toxicity and particulate matter formation also contribute substantially to the overall weighted environmental profile.

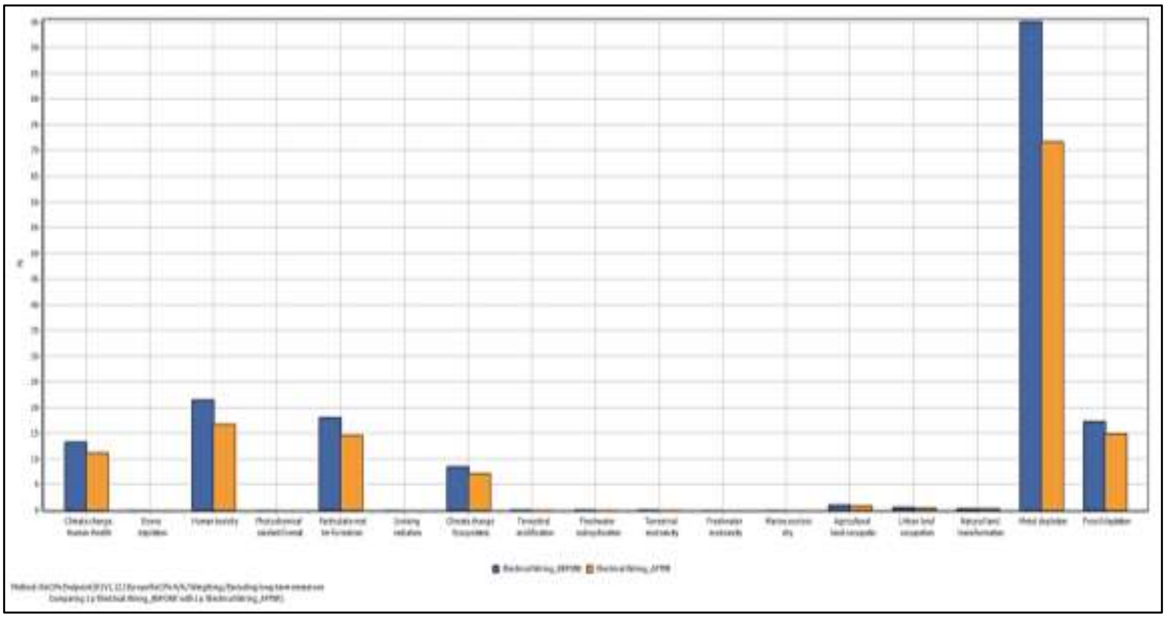


Figure 11: Comparative weighted midpoint environmental impact assessment of the reference and optimized cable infrastructure configurations.

Furthermore, the contribution analysis of the evaluated sub-assemblies demonstrates that the control panel area represents the most significant contributor to the overall environmental impact due to the concentration of cable infrastructure and associated installation materials within this subsystem.

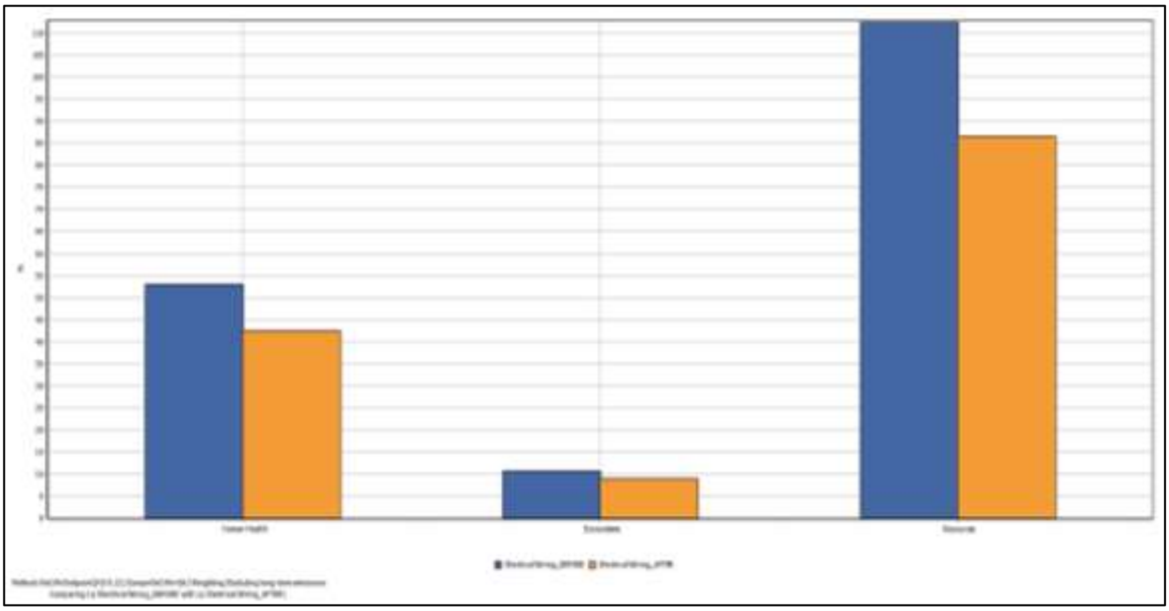


Figure 12: Weighted endpoint environmental damage categories before and after optimization.

Overall, the weighting results confirm that the implementation of optimized routing methodologies and standardized cable calculation practices contributes substantially to the reduction of the overall environmental footprint of the evaluated cable infrastructure.

6.5. Single Score

In order to compare the overall environmental performance of the evaluated configurations and identify the most significant environmental “hot spots,” the environmental impacts are weighted and aggregated into a single indicator known as the Single Score. The Single Score represents the overall environmental burden of the evaluated system by combining all environmental impact categories into a common unit.

The comparative results demonstrate that the optimized cable infrastructure configuration presents a substantially lower overall environmental impact compared to the reference configuration. More specifically, the total single score is reduced by approximately 20–22% following the implementation of the optimized cable routing and material reduction methodology.

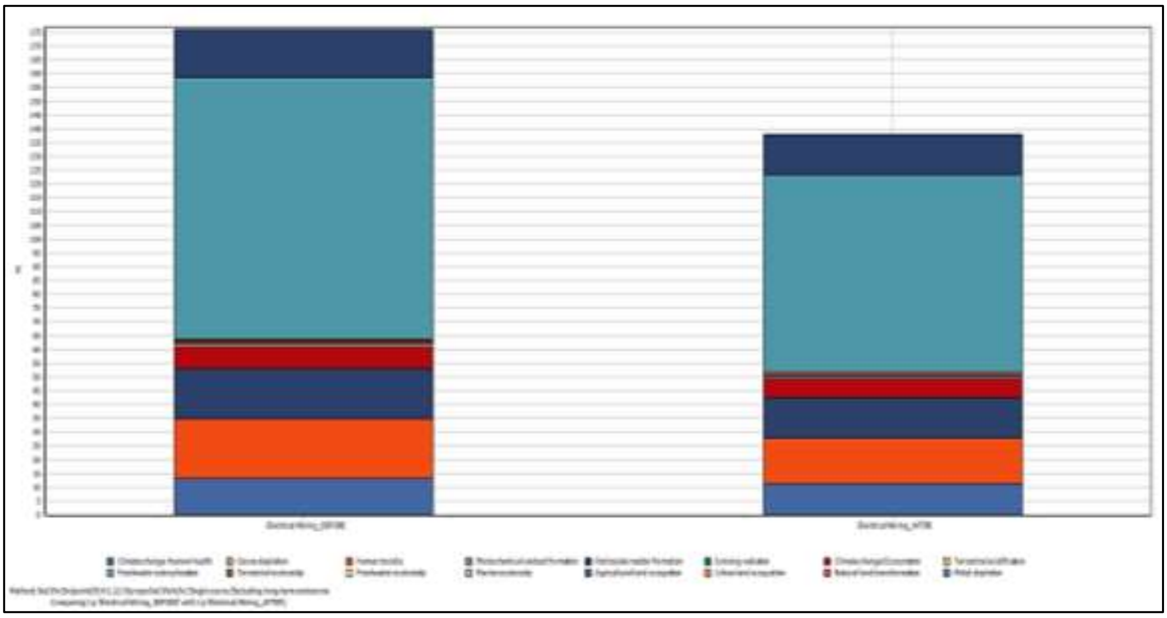


Figure 13: Comparative single score assessment of the reference and optimized cable infrastructure configurations by impact category.

The contribution analysis indicates that the Resources category represents the dominant environmental contributor within the evaluated cable infrastructure. This result is mainly associated with copper consumption and the upstream energy-intensive processes required for copper extraction, refining and polymer production related to cable manufacturing activities. Human Health impacts also contribute significantly to the overall environmental profile, while Ecosystem-related impacts represent a comparatively smaller contribution.

The breakdown by environmental impact category additionally demonstrates that:

- Climate change and Human Health-related impacts remain among the dominant contributors to the overall environmental profile
- Human toxicity and particulate matter formation categories contribute significantly to the total single score due to upstream material production activities
- Metal depletion represents one of the most important environmental hot spots, directly associated with copper consumption within the cable infrastructure
- Fossil depletion impacts are also significant due to the upstream energy demand associated with cable and polymer production processes

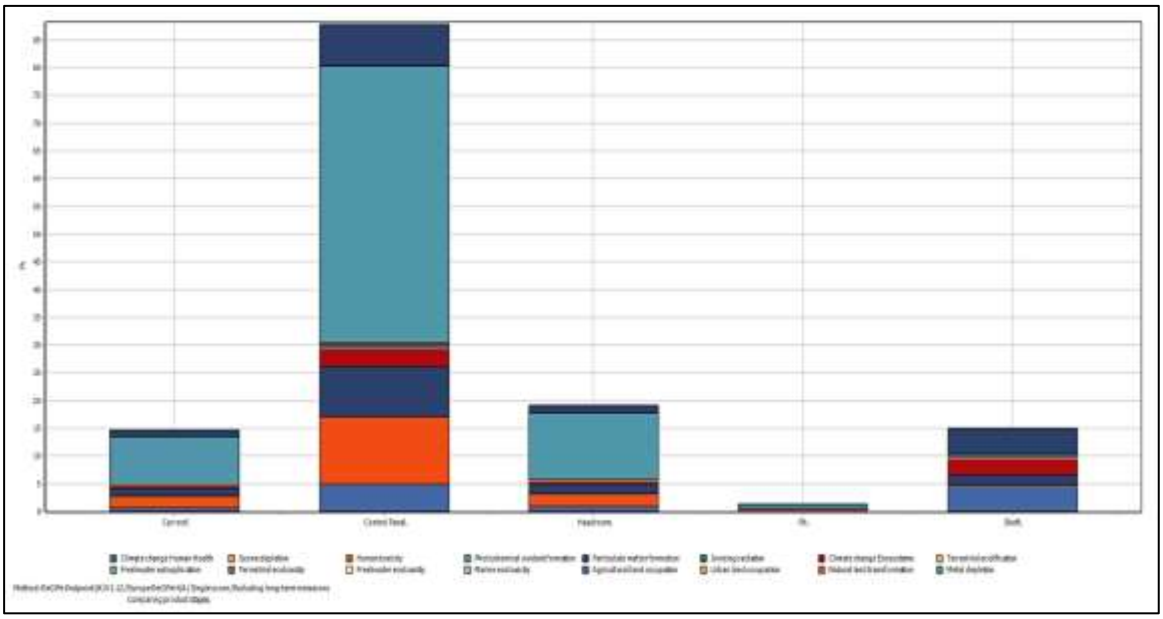


Figure 14: Contribution analysis of the evaluated installation areas to the overall single score.

The subsystem contribution analysis demonstrates that the Control Panel area represents the most environmentally significant subsystem among the evaluated installation areas. This is mainly due to the concentration of cable infrastructure and associated installation materials within this subsystem. The Shaft and Headroom installation areas also contribute noticeably to the overall environmental profile, whereas the Pit area presents comparatively limited environmental impact due to the lower quantities of installation materials involved.

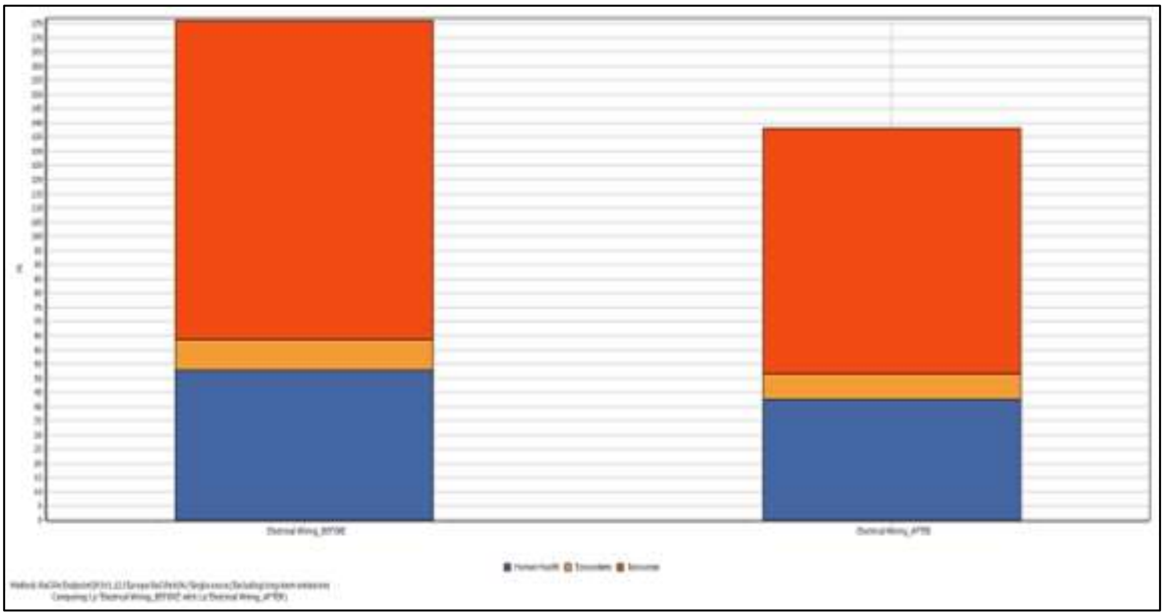


Figure 15: Overall environmental single score assessment for the reference and optimized cable infrastructure configurations.

Overall, the Single Score assessment confirms that the implementation of routing-based cable calculation methodologies and standardized installation practices contributes substantially to the reduction of the overall environmental burden associated with the evaluated cable infrastructure.

Land use impacts are expressed in units of Potentially Disappeared Fraction (PDF) × m^2 × year/m^2. The extraction of raw materials is quantified based on the surplus energy required per kilogram of minerals, while excess fossil fuel use is expressed as energy per extracted megajoule (MJ), kilogram, or cubic meter (m^3).

7. General Conclusions

The comparative life cycle assessment performed for the evaluated cable infrastructure demonstrates that the optimized wiring architecture achieves a consistently lower environmental impact across nearly all evaluated environmental categories. The implementation of routing-based cable calculation methods and standardized installation practices resulted in substantial reductions in material consumption and corresponding environmental burdens associated with cable production and upstream manufacturing activities.

Key conclusions of the present study include:

- Across Midpoint Categories: The optimized configuration achieves significant impact reductions, generally ranging from approximately 8% up to 25%, in categories such as climate change, human toxicity, particulate matter formation, ecotoxicity, metal depletion and fossil depletion. These improvements are mainly associated with reduced copper consumption, lower polymer material requirements and reduced upstream energy demand related to cable manufacturing processes.
- At Endpoint Level: The optimized configuration demonstrates reductions of approximately 20% in Human Health-related impacts, 15–16% in Ecosystem-related impacts and up to 23–24% in Resources-related impacts, confirming the environmental benefits of the optimized cable routing methodology.
- Normalization Results: Even when normalized against average European environmental loads, the optimized configuration maintains lower environmental burdens across the majority of the evaluated categories, particularly in metal depletion and fossil depletion, highlighting the importance of material reduction strategies in cable infrastructure optimization.
- Weighted Impact (Pt): Using the ReCiPe Endpoint weighting methodology, the optimized configuration presents an overall environmental impact reduction of approximately 20–22%. Human Health and Resources remain the dominant environmental categories due to the environmental significance of copper extraction, polymer production and associated upstream electricity generation processes.
- Single Score Analysis: The optimized wiring architecture demonstrates a substantially lower overall environmental single score compared to the reference configuration. The Control Panel installation area represents the most significant environmental contributor among the evaluated sub-assemblies due to the concentration of cable infrastructure and associated installation materials within this subsystem.

Overall, the results confirm that targeted eco-design actions focusing on wiring architecture optimization, standardized cable routing methodologies and material reduction strategies can contribute substantially to the environmental optimization of elevator cable infrastructure installations. The study additionally highlights the importance of life cycle assessment methodologies and eco-design principles in supporting environmentally responsible product development and engineering decision-making processes.

To allow additional comparison between different environmental impact assessment methods, supplementary evaluations were also carried out using EPD, IPCC and CML methodologies. The corresponding results are presented in the following table.

Table 3: Comparative environmental impact results obtained using EPD, IPCC and CML assessment methods for the reference and optimized cable infrastructure configurations

Impact category	**Unit**	**EPD**		**IPCC**		**CML**	
		BEFORE	AFTER	BEFORE	AFTER	BEFORE	AFTER
Acidification	***kg SO_2 eq***	11.4	9.19			12.9	10.3
Eutrophication	***kg PO_4--- eq***	3.6	2.82			3.6	2.82
Global warming (GWP100a)	***kg CO_2 eq***	481	405	487	412	481	405
Photochemical oxidation	***kg C_2H_4 eq***	0.517	0.414			0.517	0.414
Ozone layer depletion (ODP)	***kg CFC-11 eq***	0.000128	0.000108			0.000128	0.000108
Abiotic depletion	***kg Sb eq***	0.162	0.126			0.162	0.126
Abiotic depletion (fossil fuels)	***MJ***					7270	6230

NOTE: If required, additional environmental impact assessments using alternative impact assessment methodologies beyond the ReCiPe Endpoint (Hierarchist version) approach can also be carried out for further evaluation and comparison purposes.

The continuous development of products based on the principles of life cycle assessment, environmental impact evaluation and eco-design constitutes a fundamental element for the sustainable evolution of products and engineering solutions. This approach contributes to the development of environmentally responsible products while supporting resource efficiency, material optimization and reduced environmental impact throughout the product life cycle.

Appendix

Acidification potential: Phenomenon by which atmospheric rainfall has a pH which is lower than average. This may cause damage in forests and cultivated fields, as well as in water ecosystems and objects in general. This phenomenon is due to the emissions of SO_2, of NO_x, and NH_3, which are included in the Acidification Potential (AP) index expressed in masses of SO_2 produced.

Eutrophication potential: Enrichment of the watercourses by the addition of nitrates and phosphates. This causes imbalance in water ecosystems due to the overdevelopment encouraged by the excessive presence of nourishing substances, so is increased the growth of aquatic plants and can produce algal blooms that deoxygenate water and smother other aquatic life. In particular, the Eutrophication Potential (EP) includes phosphorous and nitrogen salts and it is expressed in grams of oxygen (kg O_2).

Global warming potential (GWP100): Phenomenon by which the IR irradiation emitted by the earth's surface are absorbed by the molecules in the atmosphere, as a result of solar warming, and then re-emitted in the form of heat, thus giving rise to a process of global warming of the atmosphere. The indicator used for this purpose is GWP (Global Warming Potential). This mainly includes the emissions of carbon dioxide, the main greenhouse gas, as well as other gases with a lower degree of absorption of infrared rays, such as methane (CH_4), nitrogen protoxide (N_2O), chlorofluorocarbons (CFC), which are expressed according to the degree of absorption of CO_2 (kg CO_2).

Ozone depletion potential (ODP): Degradation and depletion of the ozone layer in the stratosphere, which has the property of blocking the UV components of sunlight thanks to its particularly reactive compounds, originated by chlorofluorocarbons (CFC) or by chlorofluoromethanes (CFM). The substance used as a point of reference for assessing the ODP (Ozone Depletion Potential) is trichlorofluoromethane, or CFC-11. ODPs are calculated as the change that would result from the emission of 1kg of a substance to that from emission of 1 kg of CFC-11 (a Freon).

Photochemical oxidation: The index used to translate the level of emissions of various gases into a common measurement to compare their contributions to the change of ground-level ozone concentration. POCPs are calculated as the change that would result from the emission of 1 kg of a gas to that from emission of 1 kg of ethylene.

Depletion of abiotic resources: Two impact categories: Abiotic depletion (elements, ultimate reserves) and abiotic depletion (fossil fuels). Abiotic depletion (elements, ultimate reserves) is related to extraction of minerals due to inputs in the system. The Abiotic Depletion Factor (ADF) is determined for each extraction of minerals (kg antimony equivalents/kg extraction) based on concentration reserves and rate of deaccumulation. Abiotic depletion of fossil fuels is related to the Lower Heating Value (LHV) expressed in MJ per kg of m^3 fossil fuel. The reason for taking the LHV is that fossil fuels are considered to be fully substitutable.

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