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UNCERTAINTIES IN LCA

Life cycle assessment of the environmental influence of wooden and concrete utility poles based on service lifetime

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Abstract
Purpose Many applications of life cycle assessment do not consider the variability of the service lifetime of different structures, and this may be a relevant factor in an environmental impact assessment. This paper aims to determine the influence of the service lifetime on the potential environmental impacts of wooden and concrete poles in the electricity distribution system.
Methods The estimation of service lifetime was conducted using the factorial method. The life cycle assessment was applied using SimaPro software and considered the entire life cycle of utility poles, from the extraction of raw materials to the final disposal. Then, an evaluation of the environmental impacts using the CML IA baseline method was performed. The study included the analysis of uncertainty using the Monte Carlo method.
Results and discussion In general, the wooden poles had a lower potential environmental impact compared to the concrete poles. The result of the sensitivity analysis considering the variability of the chromated copper arsenate wood preservative retention rate suggests that the frequency of maintenance affects the service lifetime. Often, the comparison of products in the LCA perspective is carried out by considering similar useful lifetime services for the different alternatives, and this study shows that the environmental performance of products or services is directly proportional to the lifetime. It is a crucial parameter that has to be clarified in order to reduce uncertainty in the results.
Conclusions Thus, some factors such as material quality, design adjustments and routine maintenance extend the service lifetime of a product or process and are shown to be effective ways to reduce environmental impacts. Therefore, the service lifetime has a significant influence on the development of the life cycle assessment. Comparative LCA studies are often sensitive to parameters that may even change the ranking of selected impact categories. All in all, from the sensitivity analysis highlighted in this study, the variability of lifetime service has proven to be one of the most prominent factors influencing comparative LCA results.

Keywords Factorial method · Life cycle assessment · Life span · Maintenance · Wooden pole

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1 Introduction

Service lifetime has the potential to influence life cycle assessment (LCA) results, especially when it is used to compare products or services (Rauf and Crawford 2015; Aktas 2012). The LCA results may be biased if using smaller life estimates for the less desired products and greater ones for the preferred products.

Utility poles, like many other products, represent a considerable investment worldwide, necessitating the examination of the structural reliability and probability-based management optimisation (Ryan et al. 2014).

Poles are subjected to environmental stresses from climatic loads and degrading processes, which may lead to mechanical failure and power outages. Considering the large number of poles deployed in a power system infrastructure, their management is important to the economy of distribution utilities.

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Poor management and/or design strategies have led to the substantial accumulation of costs because of repairs and disrupted service (Gustavsen and Rolfseng 2005).

To bring consistency to this complex area, LCA practitioners are increasingly using the ISO 15686 series of standards (factorial method) on service life planning (Aktas 2012). Thereby, instead of assuming typical values, the use of high-quality data on the service lifetime of the products could improve the results of the LCA.

Service life planning is increasingly linked with sustainable development and entire life value. Moreover, there may be opportunities to considerably improve the operating cost in the case of high lifetime variability (Kouki and Jouini 2015).

When materials and components demonstrate recognised durability, the elements have a longer-use phase and the environmental impacts caused by maintenance are thereby diminished (De Castro et al. 2014). Increasing the service life of structures is also a determining factor in reducing the energy consumption and environmental impacts of products (Emídio et al. 2014).

Utility pole service life varies greatly and is often a function of proper inspection and maintenance (Bolin and Smith 2011). One of the main causes of poles' deterioration in coastal areas is the maritime atmosphere, which is extremely aggressive to engineering materials (Cerqueira et al. 2012). In locales like these, more resources are required due to the higher frequency of maintenance, and the environmental impacts are greater.

Depreciation of goods in the electrical sector is considered at the tariff applied by companies on their customers in order to ensure a financial balance between the invested capital and the provided return (McDermott 2014; Cossent et al. 2009).

In Brazil, the regulatory agency Agência Nacional de EnergiaElétrica (ANEEL), in Portuguese, established a lifetime of 26 years for assets in the electricity sector, including the utility poles, basing this estimation on the manufacturers' experience, as well as on international and national consultation with agents of the sector (Hage and Rufin 2016).

However, Vidor et al. (2010) found that wooden poles often do not achieve even the minimum lifetime of 15 years established by the Brazilian Association of Technical Standards (ABNT) NBR 8456 1984. On the other hand, the Brazilian standard ABNT NBR 8451:1998 establishes a minimum lifetime of 35 years for reinforced concrete poles, which may also not be achieved, especially in aggressive atmospheres (Aït-mokhtar et al. 2013).

In contrast, in North America and Europe, there are reports of wooden poles with lifetime service of over 70 years (Lebow et al. 2015; Datla and Pandey 2006; Gustavsen and Rolfseng 2005; Pope 2004; Morrell 2008), and concrete poles are also assumed to have a long lifetime service of around 60 years (Künniger and Ritcher 1995; Bolin and Smith 2011).

This difference between the durability of the utility poles can be explained by several factors, including climatic variability, wood preservative type and wood species (Ali et al. 2011; Palanti et al. 2011; Brischke et al. 2014; Plaschkies et al. 2014).

Even though pine species are widely used for utility poles in many countries (Erlandsson et al. 1992; Künniger and Ritcher 1995; Bolin and Smith 2011), in Brazilian conditions, planted forest areas are composed of around 74% eucalyptus, 22% pine and 4% other species (IBGE 2015). Pinus species have been used mainly by companies in southern Brazil, especially in Paraná and Santa Catarina states, since they are considered more tolerant to frost damage than eucalyptus species (de Gonçalves et al. 2013).

Comparatively, eucalypts have been highlighted around the country due to their high growth rates, multiple uses (e.g. raw material, energy wood, timber and paper) and adaptability to different soils and climates (de Gonçalves et al. 2013; Silva et al. 2016; Stape et al. 2010; Campoe et al. 2016).However, the use of fast-growing eucalyptus species is probably one of the most important aspects for the shorter service lifetime observed in utility poles compared to other countries (Vidor et al. 2010).

1.1 LCA of utility poles

One of the first studies comparing the utility poles in an electricity distribution network was conducted by Erlandsson et al. (1992) and examined the use of wooden poles treated with creosote or chromium, copper and arsenic (CCA); aluminium poles; and reinforced concrete.

Künniger and Ritcher (1995) conducted an LCA of utility poles in Switzerland, comparing different types of treated wood, based on copper, chrome and fluorine or based on copper, chromium and boron, as well as utility poles of reinforced concrete and steel. The steel poles had the worst results in 9 of the 11 evaluation parameters, mainly due to the effects of steel production.

An estimate made by Sedjo (2001) on the effect of replacing steel poles with wooden poles within 1 km of a network in Switzerland revealed the possibility of the elimination of 34,436 kg of CO_2 equivalent, a metric used for quantifying the greenhouse effect.

Bolin and Smith (2011) compared the life cycle of wooden poles treated with pentachlorophenol with that of concrete poles and steel poles, also evaluating opportunities to reduce the environmental impact of utility poles. Greenhouse gases, fossil fuel usage, acidification, water use and ecotoxicity showed lower impact values for wooden poles treated with pentachlorophenol than those obtained for the concrete and steel poles.

Even though some LCAs of utility poles consider the service lifetime variation in the section on sensitivity analysis (Bolin and Smith 2011; Künniger and Ritcher 1995), it is important be clear how relevant it is to the results of the environmental impact assessment and also compare this influence with other potential results of the sensitivity analysis.

Given this context, this study investigates the life cycle environmental impacts of CCA-treated utility poles compared to concrete poles used for electricity distribution, considering the variation in service lifetime identified by the factorial method.

2 Methods

The LCA, as standardised by ISO 14040 (2006) and ISO 14044 (2006), was applied using SimaPro software 8, considering the entire life cycle of the utility poles, from the extraction of raw materials to the final disposal.

The databases of ecoinvent v3 were used for the demand for materials and processes included in the life cycle inventory (LCI). Uncertainty analysis was applied using a pedigree matrix and the Monte Carlo method, considering a lognormal data distribution curve.

The CML baseline method of impact assessment developed by the Centre of Environmental Science of Leiden University was selected. The reference year 2000 for global coverage was chosen, including long-term emissions. The first version of this method dates back to the beginnings of the development of LCA, and it has been updated for the validation of the classification factors, which translate the resource extractions and associated emissions with the life cycle of the product into contributions to a number of environmental problem types, such as resource depletion, global warming, ozone depletion and acidification. It provides an analysis for European or global contexts (Gabathuler 2006; Guinée et al. 1993).

The material extraction stage is related to the impacts of extracting the raw materials consumed for manufacturing and constructing the systems. The use and operation stage include the modelling of the transport and output emissions of wooden poles (leaching). The final disposal of the systems considers the scenarios of landfill, reuse and recycling.

The utility poles of an aerial distribution network of medium voltage (15 and 34.5 kV) were analysed, considering a *Corymbia* (*Eucalyptus*) *citriodora* wooden pole treated with CCA-C and a double tee concrete pole.

The functional unit adopted was 1 km of distribution network, supporting medium voltage power distribution for a period of 50 years. Utility poles of 11 m in length and a resistance of 400 kgf were considered, with a distance of 40 m between them.

Figure 1 shows the scope of the study for both scenarios analysed. In these scenarios, the consumption of materials, water and energy for the construction of the systems as well as the emissions to the air, soil and water were considered. The maintenance of the systems includes the distances and masses of transport, and the end use includes portions of reutilisation, recycling and landfill disposal.

2.1 Life cycle inventory analysis—eucalyptus cultivation

Eucalyptus cultivation data were taken from a company with a total planted area of 600 ha. The supplies are mainly consumed in the first 3 years of cultivation, so that only manual maintenance and agricultural management with tractors, with negligible inputs, are performed in the following years.

\It was assumed that the cutting age of the trees for the purpose of poles must be no less than 9 years (reaching up to 19 years, depending on the required diameter). One hectare of cultivation under these conditions generates approximately 20 m^3 $year^{-1}$ of wood. The wood density was assumed to be 800 kg m^{-3}.

In 1 ha, approximately 1500 seedlings are planted. Subsoiling on soil (which also comprises the aeration process) and maintaining firebreaks using tractors were used for the preparation of the land.

The application of 200 kg ha^{-1} of fertilizer under the planting (superphosphate inserted into the pit) and 100 kg ha^{-1} 1 year after the planting was considered. Both are purchased in plastic bags containing 50 kg of fertilizer. On average, 120 kg ha^{-1} was considered to be applied before planting.

Seven days after planting, the fertilisation is completed with 300 kg ha^{-1} of NPK 6–30–6, and after 60 days, 270 kg ha^{-1} of NPK 11–05–18 is applied.

Approximately 20% of the total nitrogen used suffer volatilisation as ammonia, another 20% are emitted into the water through leaching (or seepage) and runoff and approximately 2% are emitted as N_2O by denitrification. It was also considered that approximately 5% of the total phosphate fertilizer applied flow into the water.

For the application of lime, according to IPCC (2006), we assumed that 13% of the total consumed lime are released into the atmosphere as carbon. For the use of herbicide (glyphosate), an average of 4 kg $ha^{-1}$was considered, applied in the first and second years. For the use of insecticide, an average application of 2.5 kg ha^{-1} was considered until the third year.

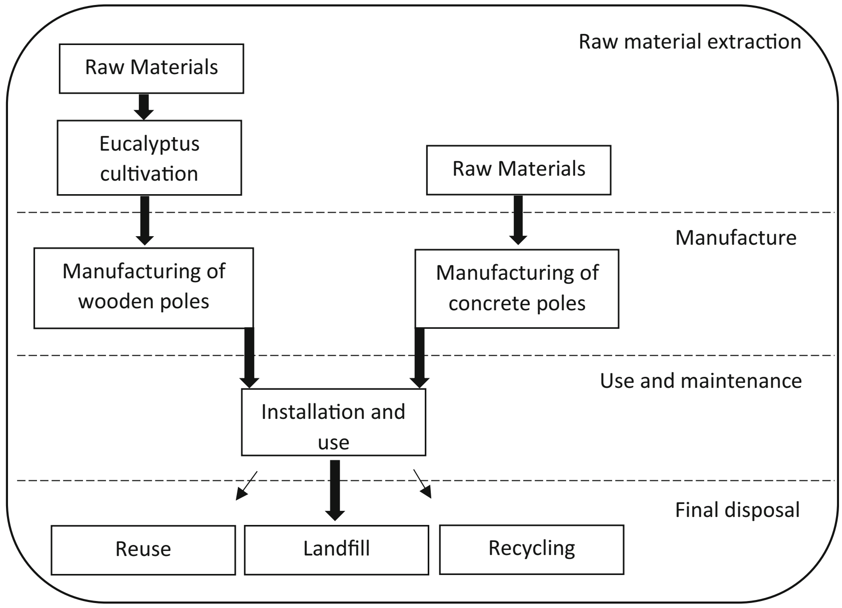
It was assumed that the entire amount of pesticide applied (herbicide and insecticide) eventually reached the environment by emissions to the ground. The packaging of products along with the packaging of fertilizers is according to the National Institute for the Processing of Empty Packaging in Conceição do Jacuípe, Bahia, Brazil.

The amount of CO_2 sequestered by the trees during their growth was estimated according to the IPCC (2006). The carbon stored in the branches and roots was disregarded, and only the quantity stored in the trunks of the trees was estimated using Eq. (1).

$$\mathrm{CS} = V \times D \times \mathrm{CF} \times \frac{44}{12} \tag{1}$$

where “CS” is the carbon storage ($t\mathrm{CO}_2$), “V” is the wood volume (m^3), “D” is the density of eucalyptus (t/m^3), “CF”

Fig. 1 System boundaries



is the fraction of carbon in dry matter equal to 0.47 and 44/12 is a conversion factor from C to CO_2.

Thus, the wood volume of *Eucalyptus citriodora* generated per hectare in a 9-yearperiod is 180 m^3. Considering that approximately 2% of this volume are represented by the bark and branches and that these parts are deposited in the same locale as cultivation for ground cover, this material undergoes fast decomposition and returns the carbon sequestered to the atmosphere. Thus, this portion was not considered in the calculation of the carbon stock. Therefore, considering the density of 800 kg m^{-3}, the value of CS in 1 ha of *E. citriodora* for a 9-year period is 243 t of CO_2.

It has been recorded that the cultivation of 1 ha of eucalyptus for 9 years can produce around 144,000 kg of wood, considering a wood production of 20 m^3 year^{-1}. Higher rates of productivity can be obtained using irrigation or fertilisation techniques (Stape et al. 2010). This estimated wood mass is equivalent to just over 400 utility poles with dimensions of 11 m of length and 342 kg of weight. It follows that for the production of one utility pole, an area of approximately 25 m^2 is needed.

For cutting eucalyptus trees, the use of two chainsaws working for approximately 8 h per day for 2 days was considered to cut 1 ha. The trunks are peeled manually on the ground, and the branches are removed.

A tractor is used to carry the trunks to the dispatch location, where they are stacked and loaded onto trucks by means of a crane. The trunks are not exposed on the ground without proper treatment to minimise the risk of their deterioration. Table 1 shows the inventory of eucalyptus cultivation for wooden pole manufacturing.

2.2 Life cycle inventory analysis—manufacturing wooden poles

The manufacture of wooden poles was quantified by primary sources, obtained from technical visits to a company with an

Table 1 Inventory of agricultural inputs/outputs (1 ha per 9 years) for eucalyptus cultivation

Input/output flows	Amount	Unit	SD
Inputs			
Carbon dioxide in air	240	t	1.32
Seedlings	103	kg	1.30
Single superphosphate	880	kg	1.22
Limestone	120	kg	1.22
Glyphosate	4	kg	1.22
Insecticide	2.5	kg	1.22
Urea, as N	105	kg	2.01
Potassium chloride, as K_2O	110	kg	2.01
Fertilizer	1	ha	1.22
Tillage	1	ha	1.22
Chainsawing	32	h	1.24
Outputs to air			
Ammonia	7.2	kg	1.32
Dinitrogen monoxide	0.96	kg	1.53
Carbon dioxide	57	kg	1.33
Outputs to water			
Nitrogen, total	9.6	kg	1.62
Phosphorus	5.2	kg	1.62
Outputs to soil			
Glyphosate	4	kg	1.38
Insecticides	2.5	kg	1.38
Wood waste	2900	kg	1.31

average annual production of 7500 m^3 of treated wood, located in Camaçari, Bahia, Brazil. At an early stage in manufacturing wooden poles, the top and bottom of the trunks are cut off with a chainsaw for height adjustment, removing approximately 7 kg of wood per pole (2% of volume). This material is forwarded to bakeries and other places that use wood-fired ovens, being considered the combustion of wood as fuel. After drying the utility poles in the open air for approximately 60 days to a moisture level of approximately 30%, they are drilled according to the specifications of buyers and then subjected to chemical treatment. For the wooden pole treatment, according to the retention rate recommended by ABNT NBR 8456 (1984), there is a consumption of CCA-C of approximately 9.6 kg m^{-3}. Additionally, a small amount of creosote (approximately 50 g per pole) is used to paint the top and bottom of the utility poles to reduce the deterioration. Table 2 shows the inventory of wooden pole manufacturing.

2.3 Life cycle inventory analysis—raw material extraction and manufacturing concrete poles

The manufacture of concrete poles was quantified by primary sources, obtained from technical visits to a company with an average annual production of 22,000 concrete poles, located in Jacuipe, Bahia, Brazil. The data for extracting the raw materials for concrete poles were estimated based on the quantitative identification of materials in the manufacturing process.

Manufacturing the materials for concrete poles primarily uses a mixture of sand, cement, water and gravel. First, the steel armour is assembled using electricity. The average steel consumption is 61 kg per pole, and the average consumption of concrete is approximately 1024 kg.

For the production of concrete, the materials are agitated by mixing or vibration. Both processes resulted in an average electric energy consumption of 2.8 kWh per utility pole. It was assumed that each utility pole generates approximately 10 kg of concrete waste. Table 3 shows the inventory for concrete pole manufacturing.

2.4 Life cycle inventory analysis—use and maintenance

In the use and maintenance stage of each 1 km of network running over a period of 50 years, the replacement of the utility poles was considered only when they reached the end of their service lifetime. No other inputs were considered besides the transport of poles in use and the maintenance step. However, leaching from the CCA to the soil was estimated over time, as generated during the use of wooden poles. The amount of preservative that leaches out depends on certain conditions, such as the rate of rainfall and the temperature of the site. These emissions were estimated according to Hillier et al. (1997), with leaching rates over the pole lifetime of 2.4% of the Cu, 0.36% of the Cr and 9.45% of the As.

2.5 Life cycle inventory analysis—final disposal

The data for final disposal for both pole types were estimated based on the experience of a Brazilian electric power company.

Approximately 35% of the volume of wooden poles are discarded at the end of the service life, without the possibility of reuse, representing the part that has deteriorated. It is sent to a landfill.

The remaining 65% of the volume of wooden poles are used as hedges on farms at the end of their service life. It is expected to reduce the impacts of final disposal by the recycled wood. The distance of 30 km of transport was accounted.

In the case of concrete poles, at the end of their service life, the steel is sent for recycling, representing 5% of the volume,

Table 2 Inventory of wooden pole manufacturing (one unit)

Input/output flows	Amount	Unit	SD
Inputs			
Water	30	l	1.22
Eucalyptus wood	350	kg	1.15
CCA-C	2.1	kg	2.01
Creosote	50	g	1.58
Steel, low-alloyed	100	g	1.32
Aluminium	10	g	1.32
Electricity, medium voltage	0.7	kWh	1.24
Outputs to air			
Wood (dust)	20	g	1.56
Outputs to treatment			
Wood incineration	7	kg	1.15

Table 3 Inventory for concrete pole manufacturing (one unit)

Input/output flows	Amount	Unit	SD
Inputs			
Water	75	l	1.24
Reinforcing steel	61	kg	1.24
Gravel	530	kg	1.24
Sand	270	kg	1.24
Cement, Portland	150	kg	1.24
Electricity, medium voltage	2.8	kWh	1.24
Outputs to air			
Particulates	150	g	1.63
Outputs to final disposal			
Steel waste	40	g	1.63
Concrete waste	10	kg	1.32

and the concrete is destined for a landfill representing 95% of the volume. It was accounted the energy for crushing and material separation, estimated in 38 MJ per pole.

2.6 Transport

Transportation was considered at all stages of the life cycle of the utility poles. In the inventory of the eucalyptus cultivation stage, the displacements of seedlings, fertilizers and limestone were evaluated, considering the weights of the loads in tons and the distances in kilometres.

The seedlings were purchased in Inhambupe, Bahia, and transported by a truck capable of carrying an average of 30,000 seedlings (approximately 2 t). The nitrogen, phosphorus and potassium (NPK) and single superphosphate fertilizers are manufactured in Camaçari, Bahia, approximately 30 km from the site of cultivation.

Limestone is produced in Alagoinhas, Bahia, a distance of approximately 83 km from the planting location. The displacement of empty product packaging used in eucalyptus cultivation equivalent to an adequate final disposal was also considered.

During the step in which the wooden poles are manufactured, which follows eucalyptus cultivation and cutting, the trunks are transported from the planting site to the factory approximately 30 km away (in the region of Camaçari Bahia). The truck's load capacity is 24 t.

The cement for concrete poles is produced in Candeias, Bahia, approximately 280 km from where the poles are manufactured. The sand and gravel is extracted in the metropolitan region of Salvador, approximately 60 km from where the cement is made.

Throughout the manufacturing process, we use a tractor to transport the materials and to stack the utility poles, which drives fossil fuel consumption.

Table 4 shows the transport considerations used in the steps associated with the raw material extraction and manufacture of utility poles. These data were obtained from technical visits and may vary depending on the situation analysed. The nearer the centre of distribution of inputs is, the lower the environmental impact of this step is.

The displacement considered in the use and maintenance stage refers to the installation of the poles and the replacements required. The distance, estimated at 30 km, was the same for the wooden and concrete poles. It was also considered that five poles can be transported in the truck per trip.

The total distance travelled in this stage was quantified based on the number of substitutions required for each type of pole. Moreover, the displacement of the loaded truck to the final disposal site was considered.

2.7 Limitations

The infrastructure (buildings and equipment) was considered to be outside the scope of this LCA. Considering the plastic packaging of the consumed products was also outside the scope of the analysis. The use of lubricating oils that are consumed indirectly in the transport steps was also not considered. The volume of water for irrigation was not considered, as this is not necessary at the Camaçari location (the techniques and quantities of inputs for eucalyptus cultivation can vary depending on the location and species considered).

Table 4 Transport used in the extraction of raw material and for the manufacture of utility poles

Step	Product	Transported distance (km)	Vehicle type	Load carried (t)
Eucalyptus cultivation	Eucalyptus seedlings	120	Truck	2
	Fertilizer (single superphosphate)	30	Truck	6
	NPK 6–30-6	30	Truck	6
	NPK 11–5-18	30	Truck	6
	Limestone	83	Truck	6
	Herbicide (packaging disposal)	100	Passenger car	–
	Insecticide (packaging disposal)	83	Passenger car	–
Wooden pole production	Eucalyptus trunks	30	Truck	24
	CCA–C	2000	Truck	16
	Internal movement	0.1	Tractor	0.342
Concrete pole production	Sand	60	Truck	6
	Crushed stone	60	Truck	6
	Cement	280	Truck	16
	Internal movement	0.1	Tractor	1.085

Primary data were not obtained to evaluate the variability of the lifetime of the poles of the electric power distribution system. Nevertheless, the factorial method was effective for the purpose of this study by generating values that demonstrate compatibility with national and international data (Bolin and Smith 2011; Datla and Pandey 2006; Gustavsen and Rolfseng 2005; Künniger and Ritcher 1995; Lebow et al. 2015; Morrell 2008; Pope 2004; Vidor et al. 2010).

2.8 Factorial method

The use of the factorial method, included in the class of deterministic methods, to estimate the service lifetime of construction components is proposed by ISO 15686 (2011), which states that the factors that affect the durability are the quality of components (A), level of design (B), work execution level (C), indoor environment (D), outdoor environment (E), in-use conditions (F) and maintenance level (G).

The implementation of the factorial method is possible because the materials used to manufacture the utility poles are commonly used in construction, and the factorial method allows for the assessment of the isolated components of the buildings, as reported in Emídio et al. (2014). Only the D factor was not applicable in this case study, which corresponds to the characteristics of the indoor environment. The estimated service life by the factorial method is provided by using Eq. (2).

$$\mathrm{ESL} = \mathrm{RSL} \times A \times B \times C \times D \times E \times F \times G \tag{2}$$

where ESL is the estimated service life of a component or product and RSL is the reference service life of a component or product. So, for the implementation of the factorial method, it is necessary to define the value of the reference service life (RSL). In this study, the RSL value is 26 years for both pole types, as suggested by the Brazilian electricity regulatory agency ANEEL (Hage and Rufin 2016).

Table 5 shows the influence of the factors in the life of the utility poles, determined through a literature review. Each factor has an influence on the lifetime of the poles, ranging from 0.8 (for a negative influence) to 1.2 (for a positive influence) with respect to the RSL. Some factors are the same for wooden and concrete poles because the type of material does not influence the factor. The RSL is then multiplied by all the possible combinations of factors that influence the life of the poles. The statistical analysis of this step was aided by *R-project* software.

2.9 Factor A—quality of components

In the case of wooden poles, the quality of the material, amongst other factors, is the result of the good management of the eucalyptus, which is very important because it highlights the situation of the raw element in the process. The influencing factors on cultivation, such as humidity, soil conditions and growth space, can result in considerable variability in the material properties (Stape et al. 2010).

The pruning of branches and the node control should be done without unnecessary removal of healthy wood to preclude the accumulation of water on the cut point. For over 30 years, a number of practises have been applied in timber quality assurance, including the proportions of heartwood and sapwood, size of the pieces, selected species, cutting age, strength, presence of defects and care in handling (ABNT-NBR 8456 1984).

It has also been long known that improving the quality of the wood by genetic improvement is desirable, including optimizing factors such as high lignin content, high density (providing greater mechanical resistance) and low shear stress (decreasing cracks) (Rockwood 1984). In general, clones exhibit less disease damage (Costa e Silva et al. 2013).

The manufacturer of concrete poles must perform quality control testing on the materials used during the manufacture step. Moreover, the concrete has properties like porosity, permeability, capillary absorption, ion migration and diffusion that are influenced by the use of additives. These factors result in the further refinement of the concrete pores, providing greater protection against the penetration of aggressive agents and leading to better performance. In aggressive atmosphere environments, a concrete covering of 20-mm thickness over the steel reinforcement is suggested (more than the usual thickness of 15 mm).

2.10 Factor B—level design

After cutting down the tree trunks and peeling them, drying in the open air (elevated off the soil to prevent biological attack) is performed for 3 to 6 months to achieve a 30% moisture level for further processing. This step is important for the expected quality in the treatment process (Pirasteh et al. 2014).

The treatment of the poles is essential for their durability, but in certain cases, the retention of CCA-C is not achieved as recommended. The correct fixing of the wood preservative depends on the processing conditions and after treatment. The time required for the substance to impregnate the wood (depending on the room temperature) must be provided, and if the treated wood is placed into service before the necessary reactions have been completed, it is susceptible to the leaching of the preservative and consequent decrease of the service lifetime (Morrell 2012; Barton 2014). Moreover, the need for higher preservative retentions in hardwoods than in softwoods has been observed, since the type and amount of

Table 5 Factors influencing the useful life of the poles

	Factor	Characteristics	Applicable index
A	Conditions of eucalyptus cultivation[a]	Great	1.2
		Good	1.0
		Bad	0.8
	Genetic improvement of eucalyptus seedlings[a]	Absent	1.0
		Present	1.2
	Material quality[a,b]	Completely in ideal conditions	1.0
		Partially in ideal conditions	0.8
	Armour covering[b]	20-mm concrete thickness	1.2
		15-mm concrete thickness	1.0
	Additives to concrete[b]	Absent	1.0
		Present	1.2
B	Drying process[a]	Correct	1.0
		Incorrect	0.8
	Fixing the wood preservative[a]	Correct	1.0
		Incorrect	0.8
	Higher preservative retention than usual[a]	Present	1.2
		Absent	1.0
	Base protection[a]	Absent	1.0
		Present	1.2
	Trials to verify the characteristics of the poles[b]	Good condition	1.0
		Defective condition	0.8
	Transport of the poles[b]	Correct	1.0
		Incorrect	0.8
C	Labour qualification[a,b]	Labour qualified and experienced	1.2
		Labour qualified	1.0
		Labour unskilled and inexperienced	0.8
	Inspection[a,b]	Present or effective	1.0
		Absent or ineffective	0.8
D	Not applicable	–	–
E	Solar radiation[a,b]	Unexposed	1.2
		Partial shade	1.0
		Directly exposed	0.8
	Humidity[a,b]	Low rate	1.0
		High rate	0.8
	Salinity[a,b]	Not littoral region	1.0
		Littoral region	0.8
	Wind[a,b]	Low rate	1.0
		High rate	0.8
	Atmospheric pollution[a,b]	Low rate	1.0
		High rate	0.8
	Rate of burning[a,b]	Low rate	1.0
		High rate	0.8
F	In-use conditions[a,b]	Conform to design conditions	1.0
		Do not conform to design conditions	0.8
	Interference during use[a,b]	Low levels of vandalism and car accidents	1.0
		High levels of vandalism and car accidents	0.8
G	Maintenance frequency[a,b]	Up to 3 years	1.2
		Up to 10 years	1.0
		Absent	0.8
	Retreatment of the base[a]	Present	1.2
		Absent	1.0

[a] Wooden poles

[b] Concrete poles

lignin present influence the CCA performance (Preston and Jin 2005).

The service lifetime of wooden poles can be prolonged by the presence of a physical protection to the base, which is the part most susceptible to fungal attack (from the part of the soil that contains oxygen). Thus, the use of a physical barrier, such as polyurethane, reduces the contact of the timber with degradation agents present in the soil, and the moisture level is decreased (Morrell 2012).

During the manufacturing stage, some characteristics of the concrete poles are evaluated, such as the elasticity, tensile strength, coatings, removal of armour and water absorption. Even the production of the concrete should be uniform because materials often segregate due to their different densities. Moreover, the drying of concrete must occur slowly to avoid cracking.

With regard to the transport of concrete poles, the following recommendations should be observed: (a) whenever possible, larger vehicles should be used to transport the poles; (b) the lower poles should be securely fixed; (c) the vehicle must be loaded and unloaded using a winch; (d) to avoid cracks, the poles must not suffer sudden impacts, which are often imperceptible, so during transport, the driver should avoid high speeds, sudden braking and sudden lateral movements.

2.11 Factor C—work execution level

Factor C for the wooden and concrete poles refers to the quality of the production of the poles. The qualification of the workforce and the presence of supervision during the manufacturing process of the poles, with the promotion of training and greater safety efforts at work, allow for improvement in the production conditions, influencing the quality of the products (Hertig and Davies 2008).

2.12 Factor D—indoor environment

Factor D refers to the characteristics of the indoor environment, and this factor does not apply in this study.

2.13 Factor E—outdoor environment

Factor E refers to the characteristics of the external environment, influenced by degradation agents. Solar radiation, humidity, salinity, wind, air pollution and forest fires were considered in this study. Sites protected by natural or anthropogenic barriers (e.g. hills, buildings and bridges), as well as other locations with a lower incidence of sunlight, are less affected by solar radiation aggression.

Humidity is in the air and on the ground. In both cases, a high index was applied because of the potential to damage the poles. Soil conditions where the pole is installed can be a very influential factor in the service lifetime, especially if the soil is saturated, when the rate of deterioration is even greater. High humidity, and even the precipitation rate, usually generates a loss of resistance in the poles over time. In the case of concrete poles, this factor is especially aggravated when part of the steel reinforcement is exposed (Yuan and Jiang 2012). For wooden poles, the rain leads to leaching of the wood preservative into the soil and the consequent reduction of the service lifetime.

Other factors may also be relevant, such as salinity, which is directly related to the proximity to the sea. Moreover, some regions are more prone to wind aggression than others. Metropolitan and industrial areas are more susceptible to atmospheric pollution aggression. Regions with high rates of fire, combined with factors such as drought and the proximity to forests, can adversely affect the potential for burning aggression.

2.14 Factor F—in-use conditions

Utility poles can often be used incorrectly. Overloading poles with equipment beyond their project capacity may be a relevant factor. Another factor that reflects in-use conditions of the utility poles is interference from vandals or car accidents.

2.15 Factor G—maintenance level

The maintenance performed over the lifetime of the poles usually generates a high probability of extended durability (Gustavsen and Rolfseng 2005).

An alternative method of increasing the durability of wooden poles is called “curative” (retreatment), which consists of the use of toxic chemicals to prevent or interrupt biological decay. This process is different from the preservative treatment. The products are applied to wooden poles in service and are limited to the region of critical deterioration (from approximately 20 cm above the outcrop line to a maximum of 50 cm below this line). The products used can be based on boron and fluoride, impregnating not only the outer portion of the pole but also its heart (Schiopu and Tiruta-Barna 2012).

3 Results and discussion

According to the factorial method, considering the reference service life of 26 years and data from Table 2, the lifetime of the wooden poles varies between 9 and 44 years, and that of the concrete poles varies between 8 and 40 years.

These data present three scenarios. In scenario I, the lowest lifetime was estimated for wooden poles, and a longer lifetime was found for concrete poles, 9 and 40 years, respectively. In scenario II (baseline scenario), mean values of 26 years were used for both pole types. Scenario III represents the reverse of scenario I, with a longer lifetime found for the wooden poles and a shorter time for the concrete poles, that is, 44 and 8 years, respectively. The

Table 6 Service lifetime and number of poles needed to support the network for 50 years

Scenario	Wooden poles		Concrete poles	
	Lifetime (years)	Number of poles km^{-1}	Lifetime (years)	Number of poles km^{-1}
I	9	139	40	31
II	26	48	26	48
III	44	28	8	156

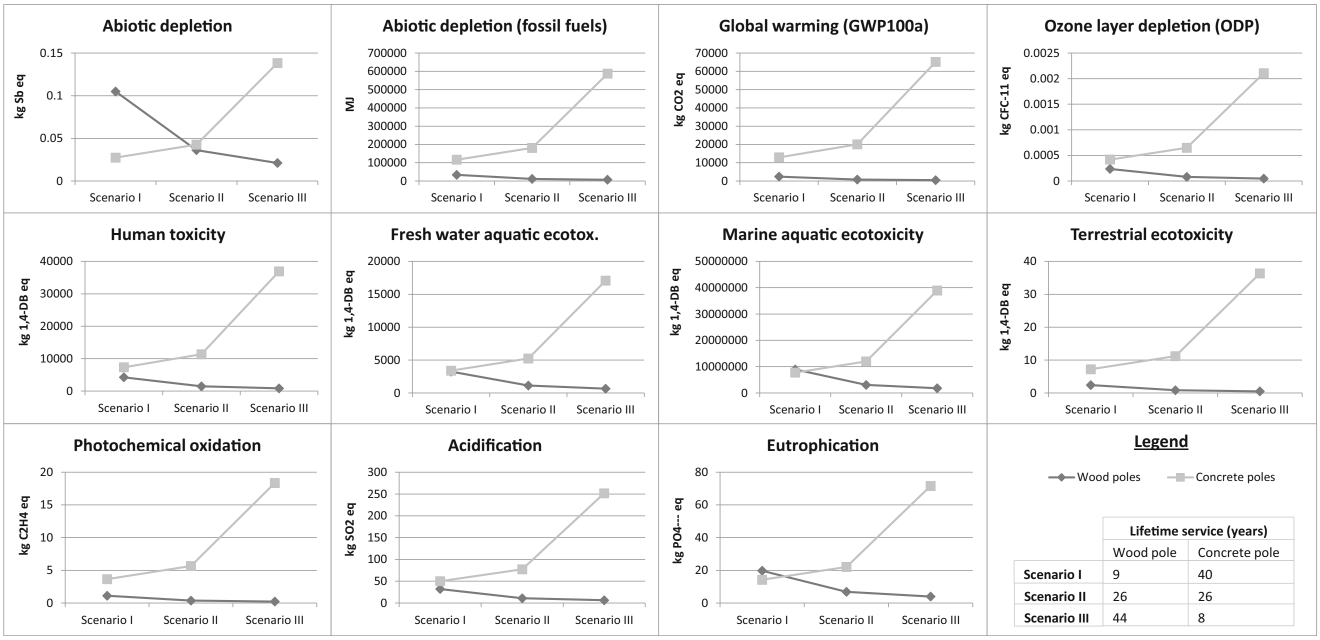


Fig. 2 Influences of the environmental impacts of the utility poles by the variation of the service lifetime (CML-IA baseline)

objective of these scenarios is to evaluate the intermediate and extreme conditions for each scenario separately.

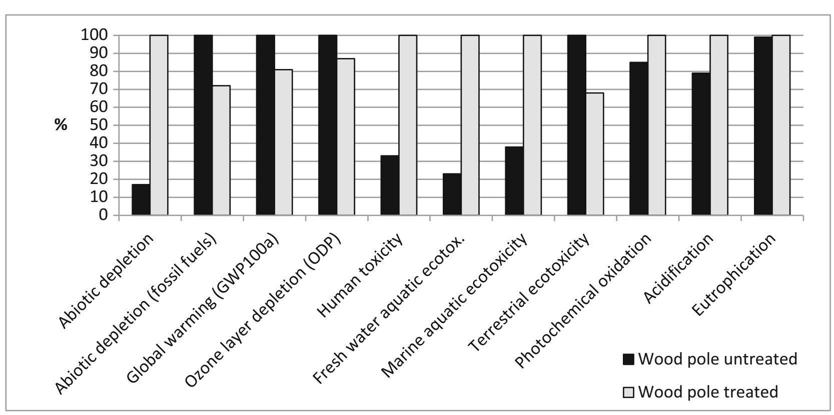
Therefore, every scenario assumes a value corresponding to the service lifetime, and consequently, a certain number of poles are needed to support the network for 50 years, as shown in Table 6. Figure 2 shows the environmental impact of the poles in the three scenarios analysed, based on the variation of the lifetime.

In scenario I, the wooden poles show a higher environmental impact just for the category of abiotic depletion. For the other impact categories in this scenario, it is not clear with 95% probability which pole type has higher or smaller environmental impacts. This probability is also not reached for the abiotic depletion category in scenario II, but the environmental impacts of the concrete poles are higher than the wooden poles in all other environmental impact categories in the same scenario. In scenario III, the environmental impacts of the concrete poles are clearly higher than the wooden poles in all environmental impact categories.

The results of the LCA show that the use of wooden poles, in comparison with the use of concrete poles, provides lower potential environmental impacts. If a pole lasts for a longer time, fewer resources are consumed, and therefore, the environmental impacts will be reduced. Thus, the longer the service lifetime is, the lower the potential environmental impact is and vice versa.

The sensitivity analysis considering the variation of lifetime service of the poles showed that this parameter can influence the environmental impacts of the poles by 160% in the case of the abiotic depletion category, varying the "ranking" amongst the alternatives for this category. Other environmental impact categories are influenced by this parameter in the following proportions: eutrophication (117%), marine ecotoxicity (108%), freshwater aquatic ecotoxicity (91%), acidification (63%), human toxicity (55%), ozone layer

Fig. 3 Sensitivity analysis of the use of CCA-C on wooden poles and frequency of maintenance



depletion (53%), terrestrial ecotoxicity (32%), abiotic depletion fossil fuels (28%), photochemical oxidation potential (28%) and global warming potential (17%).

In addition, through a sensitivity analysis, it is possible to identify some improvements in the environmental performance of the poles. In this case, we considered the baseline scenario in which the lifetime mean of 26 years was used for both pole types, as exposed below.

In the step of final disposal of concrete poles, it was considered that the concrete waste, instead of being destined for landfill, would be recycled, such as for use in asphalt pavement in the form of crushed stone. This change results in a variation of up to 12% in reducing the potential impact of the marine ecotoxicity and freshwater ecotoxicity categories.

By reducing clinker use in cement production with alternative constituents, an environmental improvement of up to 3% is provided for the concrete poles.

The sensitivity analysis also shows that at the end of life of the wooden pole, if the reuse rate of wooden poles as fences on farms does not occur, the environmental impacts of the wooden post against the concrete pole rise to 9% for the terrestrial ecotoxicity category.

The retention rate of the CCA-C chemical preservative directly influences the service lifetimes of wooden poles, but for this component, the impact of the abiotic depletion category is greater in scenario I. So, purely increasing the CCA-C retention rate is not the most suitable method to increase the lifetime of the wooden poles, as this would imply the use of an input directly related to potential environmental impacts.

Thus, a sensitivity analysis considering wooden poles free of chemical treatment was conducted. In such a situation, untreated pole networks required approximately twice as many maintenance-based pole replacements to sustain the same level of reliability, which typically involve pole inspection to ascertain the remaining load carrying capacity, and pole replacement when the capacity is found to be inadequate (Ryan et al. 2014). Figure 3 shows a comparison of the life cycles of poles treated with CCA-C and untreated poles, considering that the untreated scenario has double the required transport but half the lifetime service. This measure presents environmental benefits for the categories of abiotic depletion (fossil fuels), global warming, ozone layer depletion and terrestrial ecotoxicity.

4 Conclusions

The study contributes to the identification and analysis of the environmental impacts of wooden and concrete poles. It was observed that, depending on the service lifetime, the potential environmental impacts can be reduced or increased at a rate that depends on the values assigned to the analysed processes.

Thus, extending the lifetime of a product or process through factors such as material quality, design adjustments, and routine maintenance is an effective way to reduce environmental impacts.

A reliable estimate of the service lifetime in accordance with reality is vital to performing a life cycle assessment. However, the lifetime values of products and processes are often simply assigned, with no cross-checks with the characteristics of the region, such as climate or soil type, or the performance of periodic maintenance.

Finally, some opportunities for the improvement of the environmental performance of the utility poles were observed, such as reducing transport rates or reducing inputs related to the eucalyptus cultivation.

Comparative LCA studies are often sensitive to parameters that may even change the ranking of the selected impact categories. All in all, in the sensitivity analysis highlighted in this study, the variability of lifetime service has proven to be one of the most prominent factors influencing the comparative LCA results.

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