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Comparative life-cycle assessment of ordinary and water-saving taps

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ABSTRACT

The replacement of plumbing fixtures is a regular practice in the implementation of water conservation programmes in existing buildings. However, even though such programmes aim at reducing water consumption, it is necessary to understand the environmental implications of the replacement of ordinary plumbing fixtures with water-saving versions. The feasibility of such a practice, in terms of environmental aspects, should be evaluated in order to verify its effectiveness. This paper describes the application of a methodology to evaluate the environmental impacts involved in the replacement of ordinary taps with water-saving ones based on life-cycle assessment. The method quantifies inputs and outputs in the production, use, and disposal phases of the plumbing fixtures under analysis. The impact categories considered are global warming potential, depletion of the ozone layer, human toxicity, acidification, water consumption, and energy consumption. In order to assess the economic impacts, Life Cycle Cost methodology was applied. The method was applied in a water conservation programme of a university campus in Southern Brazil. The results indicate that the use phase of both ordinary and water-saving taps present strong influence in four impact categories (global warming potential, depletion of the ozone layer, water consumption, and energy consumption). Life Cycle Cost was estimated as R$245.99 and R$316.20 for the ordinary and water-saving taps, respectively. Such results show that the adoption of water-saving taps is not economically feasible without incentives from the public sector. On the other hand, the environmental performance of the water-saving tap was superior for all environmental impact categories analysed herein. The results indicate that the replacement of ordinary taps with water-saving taps would reduce water consumption by 26.2%, energy consumption by 13.6%, human toxicity by 4.6%, acidification by 0.2%, global warming potential by 14.8% and depletion of the ozone layer by 15.8%. Although the replacement of ordinary taps is not economically feasible, the use of water-saving taps is recommended on the campus where the study was conducted based on the environmental impacts in the life cycle.

1. Introduction

Water conservation is defined as the optimization of water consumption, which can be achieved through demand management, with the planning and implementation of actions to reduce misuse and loss (Marinho et al., 2014). Studies on the implementation of water conservation programmes (WCP) in buildings are generally structured to integrate the following steps: general diagnosis, leak detection, water consumption diagnosis, leak repair, installation of sub-metering systems, replacement of ordinary plumbing fixtures with water-saving versions, assessment of water reuse systems, promotion of educational campaigns, and evaluation of potable water savings (Cheng and Hong, 2004; Marinho et al., 2014; Velazquez et al., 2013).

In a WCP, the plumbing fixture replacement phase should occur in a systemic way, and the stages of the WCP should not be detached or applied without integrated planning (Marinho et al., 2014). The general diagnosis should be the basis for the verification of the water end-uses where water consumption can be optimised (Cheng and Hong, 2004). Studies on the technical feasibility of installing the available technology are also necessary, and in this regard, it is important to have data on water consumption both for ordinary and water-saving plumbing fixtures. In addition, the environmental implications of the actions applied to promote water efficiency must be verified (Fidar et al., 2010; Lee and Tansel, 2012).

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A study by Clarke et al. (2009) demonstrated the importance of water conservation in the reduction of greenhouse gas emissions. The authors mention water saving due to the use of taps, but assert the need for further research involving this particular plumbing fixture. Fidar et al. (2010) proposed a methodology to evaluate the energy consumption and carbon emissions associated with water-efficient devices. The authors focused on the use phase of the plumbing fixtures and found that certain carefully selected strategies to save water promote energy savings and carbon emissions reduction. The study conducted by Racoviceanu and Karney (2010) compared the use of water-efficient devices and rainwater harvesting as strategies for water saving, as well as the energy use and greenhouse gas emissions associated with those strategies. As a conclusion, the study reiterates the importance of water-saving measures in energy conservation for the residential sector. Lee and Tansel (2012) also concluded that significant reduction in environmental impacts is observed by applying water conservation practices in buildings.

Life cycle assessment (LCA) is a method that has been widely used to evaluate the potential environmental impacts of products or systems (ISO, 2006). In the building industry, studies have been conducted in order to incorporate the concept of LCA in the selection of construction methods and for choosing materials. Studies in several areas related to the construction industry have demonstrated that the scope of LCA application is vast (Asif et al., 2007; Cabeza et al., 2014), though few published LCA studies applied within the building sector include water consumption as environmental impact (Ortiz et al., 2009).

The practice of LCA is well recognised, and some studies have confirmed the importance of replacing plumbing fixtures with more efficient devices in WCPs. Marinho et al. (2014) reported results for a WCP in Brazil and indicated plumbing devices as one of the main factors that influence water consumption in buildings. The importance of adopting water-saving plumbing fixtures has also been assessed in studies conducted by Silva et al. (2005) and Velazquez et al. (2013). Such studies have investigated the water consumption resulting solely from the use phase of ordinary and water-saving devices. Thus, life-cycle environmental impacts were not considered.

Few LCA studies reported in the literature evaluate water-saving strategies in buildings and are concentrated in the residential sector (Clarke et al., 2009; Fidar et al., 2010; Lee and Tansel, 2012; Racoviceanu and Karney, 2010). Also, the results demonstrate that significant impacts resulting from the use phase of plumbing fixtures are due to water heating (Fidar et al., 2010; Lee and Tansel, 2012). Such studies exclusively analysed energy consumption and CO_2 emissions, and the results reported do not apply to non-residential buildings or cold water taps.

As the main objective of a WCP is to obtain water savings, the planning of actions to promote water conservation and the selection of products should be based on water consumption in the life cycle of the products involved, as well as on other environmental aspects. Thus, the life-cycle environmental impacts due to the replacement of ordinary plumbing fixtures (that is, those in operation with higher water consumption when compared with water-saving plumbing fixtures) must be assessed.

The objective of this paper is the application of a method to assess the life-cycle environmental impacts (including water consumption) of ordinary and water-saving taps in a case study conducted on a university campus in Southern Brazil. Also, Life Cycle Cost methodology is applied in order to assess economic performance of ordinary and water-saving taps. The frequent replacement of taps due to damage and the fact that many ordinary taps leak due to malfunctioning or inappropriate closing motivated the selection of self-closing taps for analysis herein.

2. Method

In order to assess the environmental impacts, it is important to define the inputs and outputs of the system under study (Finnveden et al., 2009). In this case, for the life cycle of plumbing fixtures, the inputs considered include water flow, energy, and raw materials, and the outputs considered include emissions to air, soil, and water. The impact categories analysed are water consumption, energy consumption, global warming potential, depletion of the ozone layer, human toxicity, and acidification.

The selection of such categories was based on their environmental importance and application in previous LCA studies in the building sector (Bribián et al., 2009; Ortiz et al., 2009). Moreover, global warming potential, depletion of the ozone layer, human toxicity, and acidification are internationally recognised impact categories (Guinée, 2002). Energy consumption has also been assessed in previous LCA studies within water-saving strategies (Fidar et al., 2010; Lee and Tansel, 2012; Racoviceanu and Karney, 2010). There has also been some research stating the importance of considering water consumption in LCA studies (Bribián et al., 2009; McCormack et al., 2007).

Global warming potential and depletion of the ozone layer are global scale impacts while acidification and human toxicity are considered regional and local scale impacts (Hermann et al., 2007). In this study, each category is proposed to be analysed separately. Furthermore, there is no recognised ideal method for weighting them (Soares et al., 2006).

The starting point of the study was the definition of the role played by the plumbing fixture in the building under assessment. First, the functional unit was determined (ISO, 2006), and consequently, the ordinary and water-saving plumbing fixtures, which perform the same function for analysis (Finnveden et al., 2009). This action required the collection of information on the building under study, the water pipe systems, and the existing plumbing fixtures. Through this diagnosis associated with ascertaining the requirements and expectations of the building users and the water consumption profile, the definition of the requirements concerning the replacement of plumbing fixtures was possible. The next step was to define the limits to be considered, such as the boundaries of the system under study and the phases of the life cycle of products to be included (Finnveden et al., 2009). A life-cycle inventory considers the inputs and outputs during each stage of the plumbing fixture life cycle in order to quantify the indicators of the environmental impact categories as presented in the following section.

2.1. Calculation of the indicators of the environmental impact categories

The calculation of water consumption, proposed in this paper, takes into account the total volume of water consumed, including the contributions at various stages of the life cycle of the plumbing fixtures and their transportation, according to Eq. 1:

$$WC = WC_{pr} + WC_{u} + WC_{di} \tag{1}$$

where WC is the total water consumption (m^3), WC_{pr} is the water consumption for the production of the plumbing fixture (m^3), WC_u is the water consumption during the life span (use and maintenance) of the plumbing fixture (m^3), and WC_{di} is the water consumption for disposal of the fixture (disposal and recycling) (m^3).

Water consumption in the fixture production phase includes the water required for the extraction and processing of raw materials, the acquisition and processing of recycled materials, and the manufacturing of plumbing fixtures (McCormack et al., 2007). In the use phase, the total volume of water consumed during the life span of the plumbing fixture should be considered (Peuportier, 2001). Maintenance is also considered by adding the water consumed during the life cycle of any spare part of the fixture and its transportation using the proposed method.

The calculation of the water consumption during the disposal phase takes into account the volume of water consumed for the disposal and recycling of the plumbing fixture and the volume consumed for transportation (Wu et al., 2009).

The impact category energy consumption evaluates the inputs in regards to the total energy consumption in the phases of the life cycle of plumbing fixtures. This includes transportation, production, and material disposal, as well as the energy required to operate the device, to provide potable water to the building, and to treat subsequent effluents (Fidar et al., 2010; Lee and Tansel, 2012; Racoviceanu and Karney, 2010). The inputs are computed in the units of MJ according to Eq. 2:

$$EC = EE_{pr} + EC_u + EC_{di} \tag{2}$$

where EC is the energy consumption (MJ), EE_{pr} is the embodied energy for plumbing fixture production (MJ), EC_u is the energy consumption during the life span (use and maintenance) of the plumbing fixture (MJ), and EC_{di} is the energy consumption during the disposal phase (disposal and recycling) (MJ).

Embodied energy during the production phase includes the energy required for extraction and processing of raw materials, acquisition and processing of recycled materials, and manufacturing of plumbing fixtures (Anand and Apul, 2011). In the use phase, it is important to determine the direct energy consumption of plumbing fixtures, energy consumption for heating water, and energy consumption for maintenance requirements (Fidar et al., 2010; Racoviceanu and Karney, 2010). Energy requirements for water pumping systems must also be considered (Lee and Tansel, 2012). This method intends to evaluate the performance of plumbing fixtures concerning energy consumption related to water savings. A plumbing fixture that enables water savings in its use phase will require lower energy consumption in the building water heat and pumping systems. Other data considered are the energy consumption for treatment and potable water supply and the collection and treatment of effluents (Anand and Apul, 2011).

The calculation of the energy consumption during the disposal phase takes into account the energy resources consumed for the disposal and recycling of the plumbing fixture and for transportation. For the landfilling of the materials, the energy consumption considered in this study was the energy necessary for transportation. For material recycling, the amount of recycled material used in the production of the plumbing fixture must be taken into account in the calculations related to the production phase. If there are transportation needs related to disposal in open-loop recycling, the transport distances and the consequent energy consumption should also be considered.

The calculation of the acidification indicator was performed based on the output data of the emissions to air, according to Eq. 3 (Heijungs et al., 1992):

$$I_A = \sum_{i=0}^{n} AP_i \times AE_i \tag{3}$$

where I_A is the acidification indicator (kg SO_2 eq), n is the number of analysed substances, AP is the acidification potential of the substance (kg SO_2 eq/kg), and AE is the substance emission to air (kg).

For global warming potential, the emissions of greenhouse gases to air were analysed in kg of CO_2 equivalent using the method developed by the Intergovernmental Panel on Climate Change for a 100-year time horizon (Eq. 4) (Heijungs et al., 1992).

$$I_{GWP} = \sum_{i=0}^{n} GWP_i \times AE_i \tag{4}$$

where I_{GWP} is the global warming potential indicator (kg CO_2 eq), n is the number of analysed substances, GWP is the global warming potential of the substance (kg CO_2 eq/kg), and AE is the substance emission to air (kg).

Eq. 5 estimates the indicator for the depletion of the ozone layer, which evaluates the direct ozone depletion effect of emissions to air in kg of CFC-11 equivalent (Heijungs et al., 1992).

$$I_{DOL} = \sum_{i=0}^{n} ODP_i \times AE_i \tag{5}$$

where I_{DOL} is the depletion of the ozone layer indicator (kg CFC-11 eq), n is the number of analysed substances, ODP is the ozone depletion potential of the substance (kg CFC-11 eq/kg), and AE is the substance emission to air (kg).

The human toxicity impact category assesses the impact of toxic substances emitted to soil, water, and air on human health in the units of kg 1,4-dichlorobenzene equivalent (Guinée, 2002) (Eq. 6).

$$I_{HT} = \sum_{i=0}^{n} (HTPa_i \times AE_i + HTPw_i \times WE_i + HTPs_i \times SE_i) \tag{6}$$

where I_{HT} is the human toxicity indicator (kg 1,4-DB eq), n is the number of analysed substances, HTPa is the human toxicity potential of the substance emitted to air (kg 1,4-DB eq/kg), AE is the substance emission to air (kg), HTPw is the human toxicity potential of the substance emitted to water (kg 1,4-DB eq/kg), WE is the substance emission to water (kg), HTPs is the human toxicity potential of the substance emitted to soil (kg 1,4-DB eq/kg), and SE is the substance emission to soil (kg).

2.2. *Life cycle cost*

In order to assess the economic profile of the two taps, Life Cycle Cost (LCC) methodology is applied. The criterion utilized to compare the alternatives is the Net Present Value (NPV). NPV consists to discount to the current moment all the future cash flows (Morera et al., 2015) and is one of the most important economic indicators associated with LCC (Danthurebandara et al., 2015). NPV is calculated according to Eq. 7.

$$NPV = \sum_{t=0}^{n} \frac{C_t}{(1+r)^t} \tag{7}$$

where NPV is the Net Present Value, t is the time of the cash flow, n is the lifespan of the plumbing fixture, C_t is the cash flow at time t, and r is the discount rate.

2.3. *Application of the method in a case study*

The method was employed to investigate the implementation of a WCP in the Centre of Technological Sciences, on the campus of Santa Catarina State University in Joinville, Southern Brazil. The campus is composed of fourteen buildings located over an area of approximately 62,000 m^2.

In the case study, two models of lavatory taps, installed in the toilets of a classroom building, were analysed to determine the water consumption during the use phase. For the production phase of the taps, distances from the material production site to the plumbing fixture production site were considered. In the manufacturing stage, industry data was used. For the calculation of the environmental impacts associated with the transport of the plumbing fixture, the distance from the place of manufacture to the application site, i.e., the university campus under investigation, was also considered. In the scope of this particular case study, material recycling was not considered, and the calculations were performed using the software SimaPro v. 7.3.

The acquisition of regional and reliable data aimed to contribute to the proper calculation of the impact categories; furthermore, the data should preferably originate from Brazilian sources. Cabeza et al. (2014) analysed published life-cycle assessments and life-cycle energy analyses of buildings and concluded that most of them are conducted in developed countries. In this study, data from academic studies performed in other countries and from the database of the Ecoinvent Centre (2010) were used only when there was no reliable national data available. According to Islam et al. (2015), in recent LCA studies, the utilization of region-specific life-cycle inventory data is preferred.

For extraction and processing of the materials used in the production of the taps, input data were calculated and inserted in SimaPro version 7.3 considering the Brazilian energy matrix, available in the database of the Ecoinvent Centre (2010).

Water consumption for the production of polyoxymethylene was not found either in the literature or industry reports. In this case, water consumption data, obtained for a production plant in Brazil from January 2010 to June 2011, were considered. The plant uses 0.70 m^3 of water to produce 1000 kg of polyoxymethylene. According to data provided by the company, the energy consumption for the production of polyoxymethylene is 0.40 kWh of electricity per kilogram of polyoxymethylene. For the transformation of brass, the data are related to a production plant in Brazil that uses 7.0 kWh of electricity and 1.38 L of water per kg of brass processed, which was added, respectively, to the embodied energy and water consumption for extraction and processing of copper and zinc materials available in the literature. For the quantification of the inputs and outputs involved in the transport of materials, road transport by truck was considered in this paper.

In view of the type of the building and aspects such as durability and maintainability of the plumbing fixtures on the campus where the study was conducted, the life span for the taps was considered as four years. This figure is within the life span established in the Brazilian standard NBR 15575-6 (ABNT, 2010) for plumbing fixtures. In the use phase of the plumbing fixtures, it is recommended that the water consumption measurements are taken *in situ*.

To allow for a comparison of the performance of the taps, the water consumption of all lavatory taps of the building under study was measured in two stages: with ordinary taps and water-saving taps installed. The measurements were performed daily using water meters in each tap from April 6 to July 3, 2011. For the disposal phase, the distances from the building where the plumbing fixture under analysis was installed to the landfill site were obtained from the local environmental authorities.

For Net Present Value calculation, a discount rate of 10% per year was considered (Börner et al., 2010). The initial investment (purchase of the tap) and expenditures with water and energy in the building (to enable the tap operation) over the life span was considered. In the disposal phase, expenditures related to landfilling and transportation were also considered. The analysis is based on the same assumptions adopted in the environmental assessment.

The method enables the evaluation, from the environmental and economic perspectives, of the implications of plumbing fixture replacement on a WCP. The plumbing fixture replacement aims at reducing water consumption, but other environmental implications of this action must not be neglected. The limitations of the case study have been indicated in the previous paragraphs. These limitations enable opportunities, such as the implementation of studies considering other regional contexts or the analyses of plumbing fixtures other than taps. The results are presented in the following section.

3. Results and discussion

The water consumption in the building under analysis was measured in two stages: with ordinary taps and with self-closing taps. The measurement results for water consumption can be seen in Tables 1 and 2. The consumption index represents the consumption per user per day. This index was applied because the population that uses the building over the week is variable. The average water consumption rates for the ordinary and water-saving taps are, respectively, 5.38E-01 L/user per day and 3.96E-01 L/user per day.

To calculate emissions, material, energy, and water consumption in the production phase of both ordinary and water-saving taps, the material composition data were collected from one of the largest manufacturers of plumbing fixtures in Brazil. Information concerning the composition of the two taps can be seen in Table 3.

For the transportation of materials, road transport by truck was considered in this paper. Road transport is a means widely used in Brazil, and in this study, the performance of heavy trucks was considered as 3.0 km per litre of diesel (Holmberg et al., 2014; Huai et al., 2006) and the volume of water required to produce diesel as 0.469 L/bhp-h (Sheehan et al., 1998). Table 4 shows the distances considered from the raw material extraction and production site to the area in which the taps are manufactured.

Table 1
Water consumption and consumption index using ordinary taps.

Ordinary tap parameters	Average	Minimum	Maximum
Water consumption (litre/day)	4.62E + 02	1.92E + 02	7.24E + 02
Number of users per day	876	426	1342
Consumption index (litre/user per day)	5.38E-01	3.12E-01	9.46E-01

Table 2
Water consumption and consumption index using water-saving taps.

Water-saving tap parameters	Average	Minimum	Maximum
Water consumption (litre/day)	3.83E + 02	1.43E + 02	9.31E + 02
Number of users per day	980	426	2234
Consumption index (litre/user per day)	3.96E-01	2.42E-01	7.89E-01

Table 3
Composition of the two taps analysed.

	Ordinary tap		Water-saving tap
Raw material	Mass (g)	Raw material	Mass (g)
Brass	614.5	Brass	591.4
Ceramics	3.4	Stainless steel	14.1
Polyoxymethylene	81.5	Polyoxymethylene	60.7
Rubber	1.5	Rubber	3.1
Paper	8.2	Paper	88.5
Total	709.1	Total	757.8

Note: It was considered that brass is composed of 70% copper and 30% zinc.

Table 4
Origin and distance considered for raw material transportation.

Raw material	Origin	Destination	Distance considered (km)
Copper	Camaçari, BA	Joinville, SC	2440
Zinc	Três Marias, MG	Joinville, SC	1361
Stainless steel	Timoteo, MG	Joinville, SC	1314
Ceramics	Criciúma, SC	Joinville, SC	349
Plastic	Suzano, SP	Joinville, SC	575
Rubber	Barretos, SP	Joinville, SC	896
Paper	Timbó, SC	Joinville, SC	112

The Brazilian government data for emissions into water, air, and soil were used, as well as the data available in the database of the Ecoinvent Centre (2010). For the transportation needs, emissions to air were provided by the Brazilian Ministry of Science and Technology (MCT, 2006). Table 5 presents the emission of gases in heavy road transport in Brazil.

In the production phase, according to data provided by the company, the volume of water used to manufacture one tap per square decimetre of external surface of the tap, is 4.60 L.

The external surface areas of the self-closing and ordinary taps under study are 3.32 dm^2 and 2.30 dm^2, respectively. Thus, the total volume of water needed for manufacturing the water-saving tap is 15.27 L, and the total volume of water needed for manufacturing the ordinary tap is 10.58 L. Energy consumption for the manufacturing of taps is 5.41 kWh/kg of equipment produced according to data provided by the company.

In the production phase, the emission of SO_x was estimated as 2.56E-02 kg of SO_x per kg of plumbing devices produced in the factory. Data regarding emissions to water during the manufacturing process of the taps were also provided by the manufacturer. These data are presented in Table 6.

The calculation of water consumption in the use phase, ideally, involves the determination of the consumption profile of the building. Thus, the water consumption resulting from the operation of ordinary and water-saving plumbing fixtures should reflect the reality of the building analysed. In this study, measurements were taken during two periods, that is, with the use of ordinary taps and water-saving taps, as shown in Tables 1 and 2. The water savings due to the use of water-saving taps was 1.42E-01 L/user per day, i.e., approximately 26%. This corresponds to an annual savings of 2.08 m^3 of water per tap (considering the 14 taps installed in the building, 223 teaching days, and an average of 921 users per day).

For the plumbing fixtures on campus, considering a life span of four years, there are no major needs related to plumbing fixture maintenance. The only recommendation is the cleaning of the aerators every six months, which would not require a substantial level of water consumption for this study. Thus, the annual water consumption in the use phase based on the data presented in this section was estimated as 7.90 m^3/year for the ordinary tap and 5.81 m^3/year for the self-closing tap installed in the campus building.

Energy consumption for pumping water in the building was calculated as 0.55 MJ/m^3. Regarding the energy consumption for the provision of potable water and effluents disposal, according to the National Sanitation Information System (Brasil, 2007), energy consumption in Brazilian water supply and sewage systems are, respectively, 1.91 MJ/m^3 and 0.65 MJ/m^3.

Landfilling is the disposal scenario considered in this case study, as described in Section 2.3. However, the consideration of scenarios including the recycling of different materials is suggested for future studies using the proposed method. In this case study, the distance from the campus to the landfill site is 5.90 km. For the quantification of the inputs and outputs involved in the landfill transport, the same data used in the calculations in the production phase were used (Ecoinvent Centre, 2010; Holmberg et al., 2014; Sheehan et al., 1998). It was considered that the 14 lavatory taps are transported to the landfill site at the end of their life span. Thus, the water and energy consumption for disposal is the same for both ordinary and water-saving taps, i.e., 1.27E-03 m^3 and 5.16 MJ, respectively, per tap.

Table 7 and Figs. 1–6 show the results calculated for both ordinary and water-saving taps for the impact categories of acidification, global warming potential, depletion of the ozone layer, human toxicity, water consumption, and energy consumption. The results are presented for each stage of the life cycle (production, use, and disposal).

The production phase of the taps has the largest share of the environmental impact category acidification (Fig. 1). This is mainly due to the emission of SO_x on the factory plant. For global warming potential, the largest share of contribution, in kg CO_2 equivalent, was attributed to the use phase of the taps as a function of energy consumption to enable the use of water at

Table 5
Gas emissions per litre of diesel used in heavy road transport in Brazil (MCT, 2006).

Emission (g/l)						
Gas	CO_2	CO	CH_4	NOx	N_2O	NMVOC
Emission	2.80E + 03	6.05E + 01	1.82E-01	7.76E + 01	2.20E-03	1.47E + 01

Table 6
Emissions to water for the manufacturing of taps per kg of plumbing devices produced.

Emission (g/kg)			
Substance	Phosphorus	Nickel	Sulfides
Emission	1.45E-03	2.63E-03	1.45E-04

Table 7
Environmental impact categories for both taps.

	Environmental impact category	Production	Use (4 years)	Disposal	Total
Ordinary tap	Acidification (kg SO_2 eq)	3.26E-02	8.21E-03	5.70E-03	4.65E-02
	Global warming potential (kg CO_2 eq)	3.45E + 00	6.41E + 00	4.80E-01	1.03E + 01
	Depletion of the ozone layer (kg CFC-11 eq)	1.61E-07	4.34E-07	8.72E-08	6.82E-07
	Human toxicity (kg 1,4-DB eq)	2.55E + 01	1.45E + 00	3.99E-02	2.70E + 01
	Water consumption (m^3)	4.46E-02	3.16E + 01	1.27E-03	3.16E + 01
	Energy consumption (MJ)	5.04E + 01	1.03E + 02	5.16E + 00	1.58E + 02
Water-saving tap	Acidification (kg SO_2 eq)	3.46E-02	6.05E-03	5.70E-03	4.64E-02
	Global warming potential (kg CO_2 eq)	3.61E + 00	4.72E + 00	4.80E-01	8.81E + 00
	Depletion of the ozone layer (kg CFC-11 eq)	1.68E-07	3.19E-07	8.72E-08	5.75E-07
	Human toxicity (kg 1,4-DB eq)	2.46E + 01	1.07E + 00	3.99E-02	2.57E + 01
	Water consumption (m^3)	8.56E-02	2.33E + 01	1.27E-03	2.33E + 01
	Energy consumption (MJ)	5.59E + 01	7.55E + 01	5.16E + 00	1.37E + 02

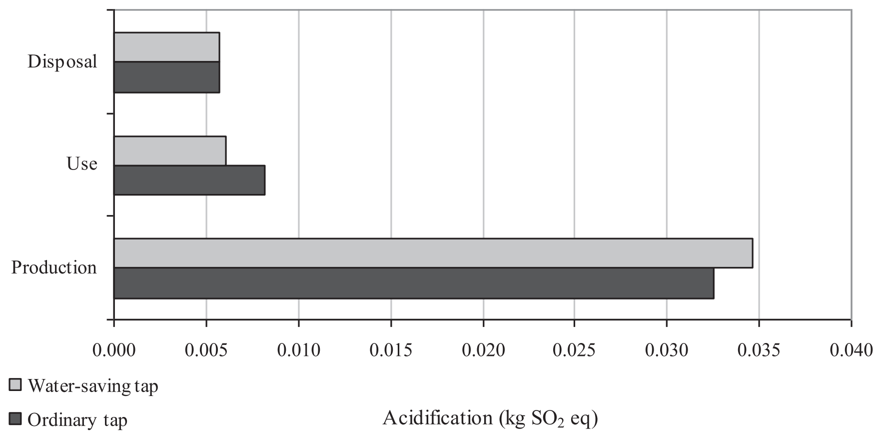

Fig. 1. Acidification for ordinary and water-saving taps.

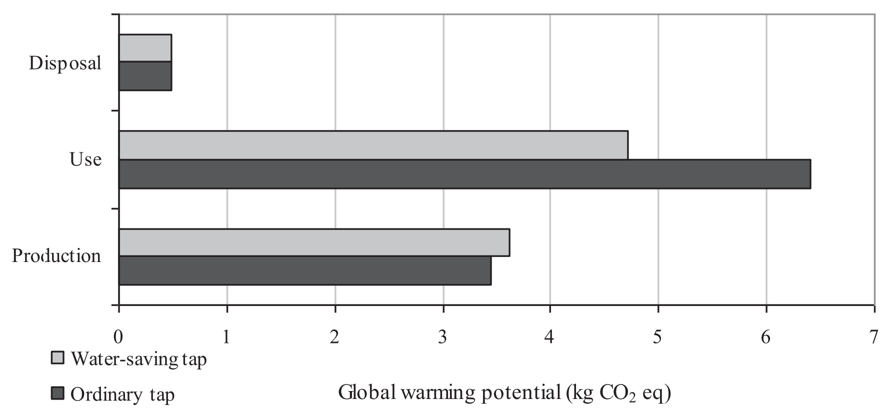

Fig. 2. Global warming potential for ordinary and water-saving taps.

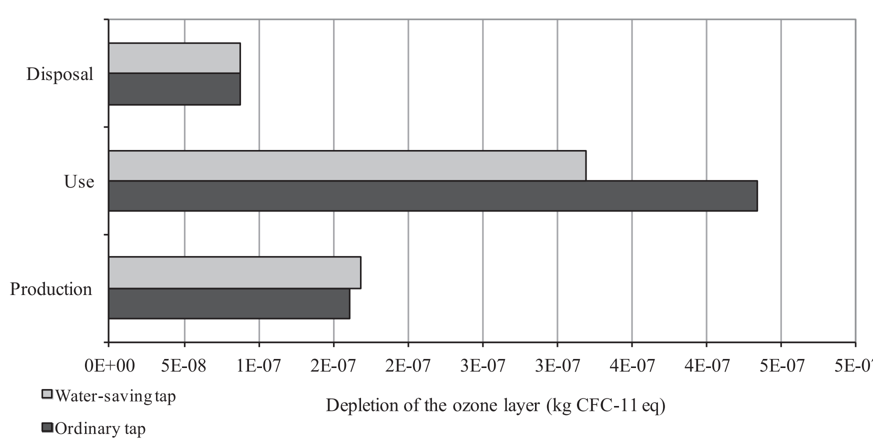

Fig. 3. Depletion of the ozone layer for ordinary and water-saving taps.

the building (pumping, water and effluent treatment) (Fig. 2). As the ordinary tap presents higher water consumption, the global warming potential is higher when compared to the water-saving tap.

For depletion of the ozone layer, the largest share of the environmental impact was attributed to the use phase of the taps (Fig. 3). The main contribution of the use phase is due to emissions to air caused by energy use associated with water consumption. For human toxicity, the graph (Fig. 4) is plotted on logarithmic scale since there is a great difference amongst impacts during the production, use, and final disposal of the taps. The use and disposal phases present minor contributions related to water and energy consumption and to the transportation needs. The production phase presents 94.4% and 95.7% of the life-cycle environmental impact for the ordinary and the water-saving taps, respectively.

The water consumption for both taps is shown on a logarithmic scale in Fig. 5. The largest share of the contribution lies in the use phase of the taps, i.e., 31.6 m^3 over four years for the ordinary tap and 23.3 m^3 for the water-saving tap. Fig. 6 shows the energy consumption for the production, use, and disposal phases in the life

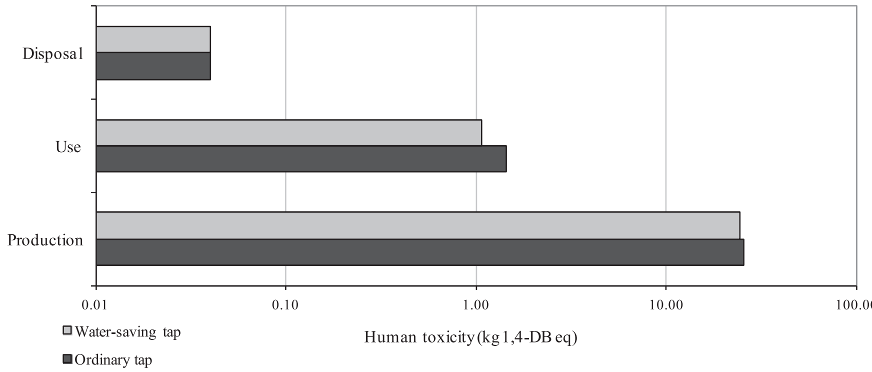

Fig. 4. Human toxicity for ordinary and water-saving taps.

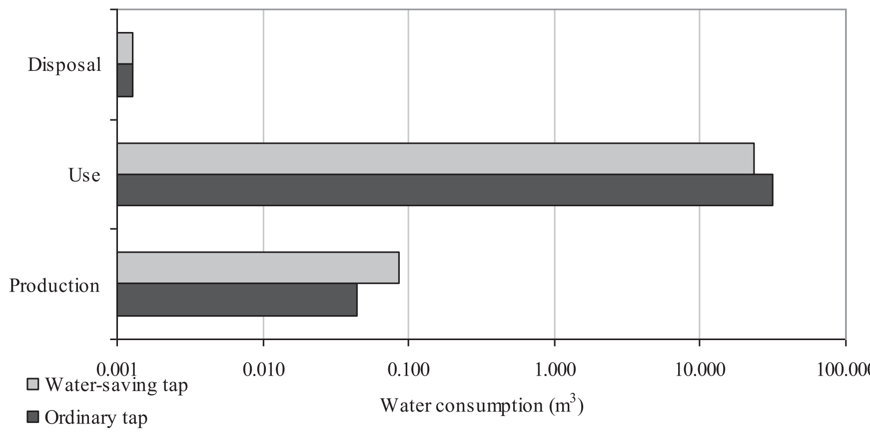

Fig. 5. Water consumption for ordinary and water-saving taps.

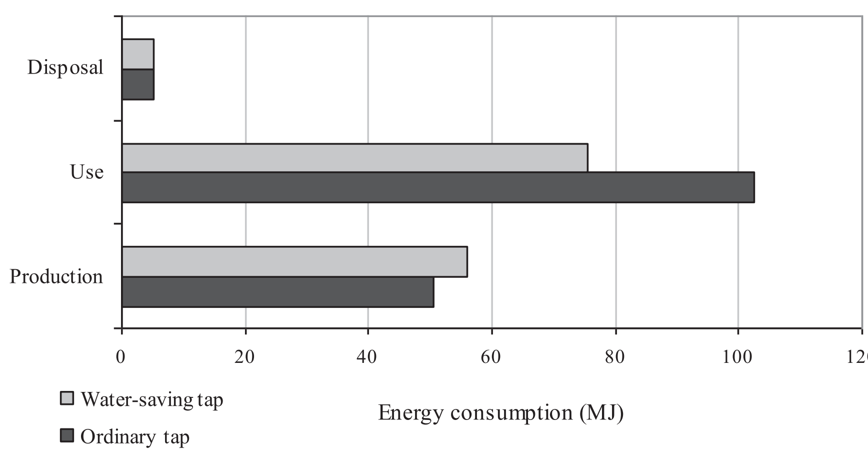

Fig. 6. Energy consumption for ordinary and water-saving taps.

cycle of the taps. The energy consumption to enable the use of water at the building is responsible for the most significant contribution in this environmental impact category.

In conclusion, the water-saving tap presents lower environmental impacts when compared to the ordinary tap for all impact categories. For acidification, the results for both taps are very similar. The water-saving tap provides a major contribution in the production phase, but this situation is reversed in the use phase; thus, the acidification results are 4.65E-02 kg of SO_2 equivalent and 4.64E-02 kg of SO_2 equivalent for ordinary and water-saving taps, respectively. Fig. 7 shows the comparison of the impact categories for ordinary and water-saving taps.

Thus, by performing an environmental assessment of two models of taps, based on a method that considers the impact categories acidification, global warming potential, depletion of the ozone layer, human toxicity, water consumption, and energy consumption, the conclusion is that the use of water-saving taps is recommended instead of ordinary taps.

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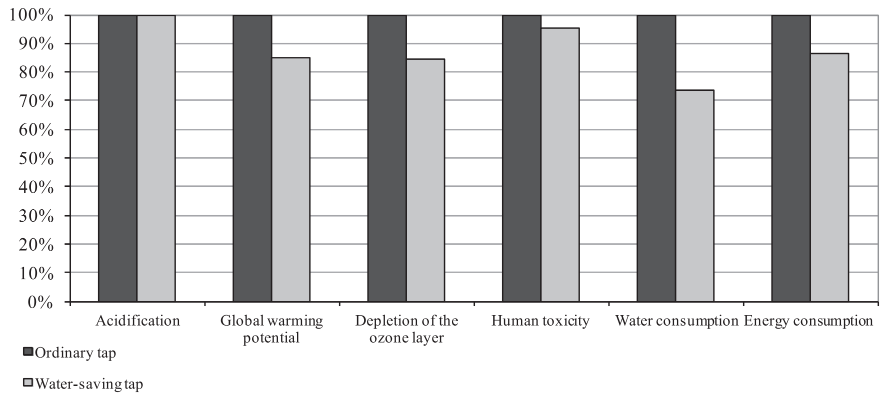

Fig. 7. Comparison of the impact categories for ordinary and water-saving taps.

The results indicate that the replacement of ordinary taps with water-saving taps would reduce, among other environmental impacts, energy consumption and global warming potential over the life cycle of these plumbing fixtures. This was confirmed for other water fixtures (toilets, clothes washers, and showerheads) in the study conducted by Lee and Tansel (2012) in residential buildings.

The results have also confirmed that significant energy consumption and carbon emissions are attributed to water consumption in the use phase of plumbing fixtures (Fidar et al., 2010). Fidar et al. (2010), however, estimated energy use related to water heating as the main contributor to the results in the use phase. In this study, the most significant fraction of water-related energy use and carbon emissions are due to water supply since the taps installed in the campus buildings are provided with cold water only.

The results for the impact categories show that the use phase has a higher share of contribution in four environmental impact categories (global warming potential, depletion of the ozone layer, water consumption, and energy consumption). Thus, water savings in the use phase of plumbing fixtures is not only crucial to the preservation of this resource, but also presents a significant bearing on the performance of these devices when considering other environmental impacts.

The LCC analysis is based on the same assumptions adopted in the LCA study. For Net Present Value calculation, the initial investment is R$87.00 for the ordinary tap and R$199.00 for the water-saving tap. A discount rate of 10% per year was considered. Expenditures with water are based on water tariffs for the public sector, which includes the campus under study (R$6.28/m^3). Energy requirements to enable water provision in the lavatory taps were calculated as 0.55 MJ/m^3 and expenditures were also based on energy tariffs for the public sector in Brazil (R$0.34/kWh). In the disposal phase, expenditures related to landfill tariffs and transportation fuel consumption were also considered.

The NPV indicates life cycle costs of R$245.99 and R$316.20 for the ordinary and water-saving taps, respectively. This result is driven mainly by the initial investment on the water-saving tap which is high compared to the money savings due to water savings.

Thus, based only on monetary factors, the use of water-saving taps is not cost-effective in the case study since the current purchase price of the water-saving taps is more than twofold the current purchase price of ordinary taps. In addition, the cost of one cubic metre of water for the public sector represents only 3% of the average price of a water-saving tap. The study indicates that the adoption of water-saving taps on the campus area is not economically feasible without public economic incentive. However, the environmental implications cannot be disregarded. These statements are also supported by the study conducted by Velazquez et al. (2013) on urinals installed on a university campus. The authors proposed that decisions should be made considering the efficiency-benefit ratio, which takes into account the impact generated in other areas, such as the environmental area.

4. Conclusions

The objective of this paper was the application of a method to verify the environmental impacts in the life cycle of plumbing fixtures. The impact categories considered were global warming potential, depletion of the ozone layer, human toxicity, acidification, water consumption, and energy consumption. This method was used to compare the performance of ordinary and water-saving taps installed in a university building in Southern Brazil. The application of the method was shown to be effective in the case study and to fulfil the objective of the study.

The water-saving tap result in lower environmental impacts when compared to the ordinary tap. Based on these results, it can be concluded that the use of water-saving taps is recommended, and it is worth replacing ordinary taps with water-saving taps on the university campus under study.

Significant reduction in environmental impacts has been observed by applying water-saving taps. Since the cost of water-saving taps in Brazil is much higher than the cost of ordinary taps, incentive strategies for replacing ordinary devices could be provided in order to reduce water consumption and other environmental impacts. Moreover, as the purchase of products by the public sector in Brazil is based on the lowest price, the specifications should allow the purchasing of water-saving taps only.

The method proposed herein can also be used by the plumbing fixture manufacturers in order to improve industry processes or to change procedures for selection of raw material suppliers.

In the case study, measurements were performed *in situ* to determine the water consumption for taps installed in the building under analysis. Thus, it is important to emphasize that the water consumption in the building, and therefore, the results of the impact categories also depend on user behaviour. In the scope of the case study, recycling was not considered, only simple disposal (landfill). The consideration of recycling is a suggestion for future studies using the proposed method. The application of this method in the life-cycle assessment of plumbing fixtures other than taps is also suggested.

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