

Energy consumption in the life cycle of plumbing fixtures

A. Kalbusch and E. Ghisi

ABSTRACT

The main objective of this paper is to propose a method for quantifying the energy consumption in the life cycle of different plumbing fixtures. The method can be used to estimate the energy consumption in the production, use and disposal phases of plumbing fixtures. This allows for the comparison between the performances of different plumbing fixtures and the identification of the share of each phase on the energy consumption over the life cycle. The method was applied in a case study in Southern Brazil to quantify the energy consumption in the life cycle of two types of taps installed on a university campus. The total energy consumption in the life cycle of ordinary and self-closing taps used in the study was respectively, 177.71 MJ and 164.11 MJ over 4 years. Production accounted for 33% of the energy consumption share of the ordinary tap, while the use phase accounted for 65% and the disposal phase for 2%. For the self-closing tap, the production phase accounted for 46% of the energy consumption share, the use phase for 52% and the disposal phase for 2%. Therefore, considering the energy consumption in the life cycle, self-closing taps should be preferred over ordinary taps.

Key words | energy consumption, life cycle assessment, plumbing fixtures, taps, water consumption

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INTRODUCTION

The concern with the environment and the role of the construction industry in the generation of environmental impacts are topics that have been widely discussed (Geng *et al.* 2017). The environmental evaluation of products or systems enables the specification of materials in order to promote environmental and economic improvements at various stages of the life cycle. Life cycle assessment (LCA) is a method applied to evaluate the environmental effects of a system or product throughout its life span (Andrew & Vesely 2008; Godskesen *et al.* 2010). The results may be employed for different purposes, such as the selection of relevant environmental indicators, support decision making in product design (or redesign) processes, and the improvement of environmental performance of products (ISO 2006).

Thus, LCA is a method that supports decision making and can be used for developing or improving processes. The results can also be used for the comparison of different

products that fulfill exactly the same function according to their goal and scope definitions (Buyle *et al.* 2013). The method provides information on the potential environmental impacts at each stage of the life cycle of a product and can also be used as a tool for performance improvement (UNEP 1996; Tukker 2000; Tsai *et al.* 2011).

LCA is a method that can be used to identify opportunities in order to reduce potential impacts and resource consumption (Pieragostini *et al.* 2012). Moreover, the energy issue is crucial for planning assumptions based on sustainability (Kaygusuz 2012; Rae & Bradley 2012). The relevance of energy consumption to compare materials and products in terms of environmental impacts, especially in the civil engineering area, has been widely studied (Abey-sundara *et al.* 2009; Bribián *et al.* 2009; Verbeeck & Henz 2010; Tsai *et al.* 2011). Scientific studies on energy consumption in buildings are important to promote the development

and use of energy conservation technologies in the sector (Zheng *et al.* 2009).

Devkota *et al.* (2013) developed a life cycle based model to evaluate economic and environmental impacts due to the use of rainwater and composting toilets in buildings. Anand & Apul (2011) presented a comparative LCA study on technologies that require less or no potable water use in toilets. The method was used to estimate cost, energy demand and global warming potential for production and use phases.

Lee & Tansel (2012) developed a study which includes energy consumption in the life cycle of three residential water-using appliances. The authors analysed energy requirements for manufacturing and disposing of toilets, washing machines and showers. In the use phase, the electricity consumption to operate the appliances and energy consumption for water heating, supply and wastewater treatment were considered. Energy requirement for water supply and drainage were also considered in the research conducted by Zheng *et al.* (2009) on energy conservation in buildings using LCA. These studies highlight the importance of evaluating the energy consumption of devices designed for water savings. Water savings are extremely relevant, but other environmental impacts should not be neglected.

Fidar *et al.* (2010) explained the need for the development of studies on environmental impacts of water efficient end uses. The application of the concept of LCA in Brazilian studies is also important since a large part of the studies involving LCA in the built environment are undertaken in developed countries (Cabeza *et al.* 2014).

OBJECTIVE

The objective of this paper is to evaluate the energy consumption over the life cycle of taps in a university building in Southern Brazil.

METHOD

The method proposed in this paper consists of applying the concept of LCA to assess energy consumption during the life

cycle of any plumbing fixture. In this paper it is employed in a study on taps in particular. The analysis considers energy consumption from the extraction of raw materials to the disposal of plumbing fixtures. Energy consumption is related to water consumption since, in order to provide water to any plumbing fixture, there are energy requirements such as embodied energy. And it is necessary to consider the energy consumption related to all phases of the life cycle of such plumbing fixtures.

A life cycle inventory considers the energy consumption during each phase of the plumbing fixture life cycle, measured in Mega Joules (MJ). The data collected must be calculated or obtained through field research, academic literature or reliable databases. The calculation of the total energy consumption takes into account the various phases of the life cycle of the plumbing fixture as shown in Equation (1).

$$EC = EE_{pr} + EC_u + EC_{di} \quad (1)$$

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

Embodied energy in 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 (Equation (2)).

$$EE_{pr} = EE_{rm} + EE_{rc} + EE_p \quad (2)$$

where EE_{pr} is the embodied energy for plumbing fixture production (MJ), EE_{rm} is the embodied energy for extraction and processing of raw materials (MJ), EE_{rc} is the embodied energy for the acquisition and processing of recycled materials (MJ), and EE_p is the embodied energy for manufacturing plumbing fixtures (MJ).

In the production phase, the type of transport used and its energy consumption should be considered taking into account the percentage (by mass) of the material compared to the total load transported. For the extraction and transportation of raw materials used in the production of plumbing fixtures, this study considers the mass of the

material and transport distances from extraction to manufacturing (Equation (3)).

$$EE_{rm} = \sum_{i=1}^n (M_{rmi} \times EC_{ei} + D_{rmi} \times Pc_i \times EC_{ti}) \quad (3)$$

where EE_{rm} is the embodied energy for extraction and processing of raw material (MJ), n is the number of materials, M_{rm} is the mass of the material (kg), EC_e is the energy consumption for extraction and processing the material (MJ/kg), D_{rm} is the distance of raw material transportation (km), Pc is the percentage (by mass) of the raw material compared to the total load transported (%), and EC_t is the energy consumption for transportation (MJ/km).

If recycled materials are employed, the energy consumption should be considered according to Equation (4).

$$EE_{rc} = \sum_{i=1}^n (M_{rci} \times EC_{ri} + D_{rci} \times Pc_i \times EC_{ti}) \quad (4)$$

where EE_{rc} is the embodied energy for the acquisition and processing of recycled materials (MJ), n is the number of materials, M_{rc} is the mass of the recycled material (kg), EC_r is the energy consumption for recycling and processing the material (MJ/kg), D_{rc} is the distance of recycled material transportation (km), Pc is the percentage (by mass) of the recycled material compared to the total load transported (%), and EC_t is the energy consumption for transportation (MJ/km).

Finally, in the production phase, the energy consumption required for manufacturing and transporting the plumbing fixture should be considered according to Equation (5).

$$EE_p = M_{pf} \times EC_m + D_p \times Pc_i \times EC_t \quad (5)$$

where EE_p is the embodied energy for manufacturing the plumbing fixtures (MJ), M_{pf} is the mass of the plumbing fixture (kg), EC_m is the energy consumption at the plant responsible for the manufacturing, per mass of the plumbing fixture (MJ/kg), D_p is the transportation distance (km), Pc is the percentage (by mass) of the plumbing fixture compared to the total load transported (%), and EC_t is the energy consumption for transportation (MJ/km).

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. Energy requirements for water pumping systems must also be considered. These should be estimated taking into account the number of users in the building and the characteristics of the plumbing systems. The method can be used to evaluate the performance of plumbing fixtures concerning energy consumption related to water savings. A plumbing fixture that enables water savings over its use phase will require lower energy consumption for water heating and pumping. Energy consumption for water treatment and supply, as well as collection and treatment of sewage should be considered. Equation (6) shows the proposed method for calculation of energy consumption for use and maintenance of the plumbing fixture.

$$EC_u = EC_{ut} \times LS + EC_h + (EC_{pu} + EC_{ws} + EC_s) \times (WC_{pf} \times LS) + EC_m \quad (6)$$

where EC_u is the energy consumption for use and maintenance of the plumbing fixture (MJ), EC_{ut} is the annual energy consumption of the plumbing fixture (MJ/year), LS is the life span (years), EC_h is the energy consumption for heating water (MJ), EC_{pu} is the energy consumption for pumping water (MJ/m³), EC_{ws} is the energy consumption for potable water treatment and supply (MJ/m³), EC_s is the energy consumption for collecting and treating sewage (MJ/m³), WC_{pf} is the annual water consumption of the plumbing fixture (m³/year), and EC_m is the energy consumption for maintenance (MJ).

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 land-filling of the materials, the energy consumption considered in this study is the one 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 transportation is necessary for disposal in open-loop recycling, the transport distances and the corresponding energy consumption should also be considered according to Equation (7).

$$EC_{di} = M_{di} \times EC_d + D_{di} \times Pc_i \times EC_t + M_{re} \times EC_{re} + D_{re} \times Pc_i \times EC_t \quad (7)$$

where EC_{di} is the energy consumption for disposal and recycling (MJ), M_{di} is the mass of the discarded material (kg), EC_d is the energy consumption for material disposal (MJ/kg), D_{di} is the transport distance to the plumbing fixture disposal site (km), P_c is the percentage (by mass) of the material compared to the total load transported (%), EC_t is the energy consumption for transportation (MJ/km), M_{re} is the mass of the recycled material (open-loop) (kg), EC_{re} is the energy consumption for recycling and processing the material (MJ/kg), and D_{re} is the transportation distance for recycling (km).

In order to apply the method in a case study, the assessment of energy consumption during the life cycle of two types of taps was conducted. The water consumption of ordinary and self-closing taps installed in a block of classrooms of Santa Catarina State University campus in Joinville, Southern Brazil, was measured. The two-storey block has 18 classrooms and four bathrooms. The measurements were performed daily using water meters in each tap.

For the production phase, the data were obtained from literature review and by consulting the main suppliers of raw materials. The distances from the material production site to the plumbing fixture production site was also considered. In the manufacturing phase, industry data were used. For the calculation of the energy consumption to transport the plumbing fixture, the distance from the factory to the application site was also considered. In the scope of this particular case study, recycling was not considered. In view of the typology of the building and aspects such as durability and maintenance of the plumbing fixtures on the campus, the life span of the taps was considered as 4 years. Over the use phase of the taps, it is recommended that the water consumption measurements are taken *in situ*. For the disposal phase, the energy consumption considered in this study refers to transportation. The distances from the building where the plumbing fixtures are installed to the landfill site were obtained from the local environmental authorities.

In order to account for discrepancies, a sensitivity analysis was performed. Some variables such as transport distances and number of users were modified in order to assess the influence of these factors on the final results. As transport distances in Brazil are fairly long, the location of the factory affects the results of embodied energy for

extraction and transformation of the raw materials which the taps are made of. Similarly, as the energy consumption over the use phase of taps is directly related to water consumption, the sensitivity analysis aimed to determine how the number of users of the building affects the results.

RESULTS AND DISCUSSION

The consumption of water in the building was measured in two stages: with ordinary taps and with self-closing taps in the 14 lavatories installed in the building. The school days (from Monday to Saturday) were considered, excluding Sundays and holidays. The water consumption in lavatory taps can be seen in Figure 1. The consumption index represents the consumption per user per day. This index was applied because the population that uses the building during the week is variable. The average water consumption rates for the ordinary and self-closing taps are, respectively, 0.538 litre/user per day and 0.396 litre/user per day.

Considering all plumbing fixtures installed (lavatory taps, toilets, cleaning taps, drinking fountains and urinals), the average water consumption index is 3.020 l/user per day over the period. For calculation purposes, it is considered that 1 year has 223 teaching days and the building shelters an average of 921 users per day. As the population that uses the building during the week is variable, the standard deviation was calculated as 328 users over the period.

Embodied energy in the production phase

Data on material composition of both ordinary and self-closing taps were collected from a manufacturer of plumbing fixtures in Brazil. Information concerning the composition of the two taps and the transport distances considered can be seen in Table 1.

Data available in the literature were used for the calculation of energy consumption for the extraction and transformation of the materials that compose the taps. Energy consumption for the production of polyoxymethylene was not found either in the literature or industry reports. In this case, energy consumption data obtained from a production plant in Brazil were considered. The

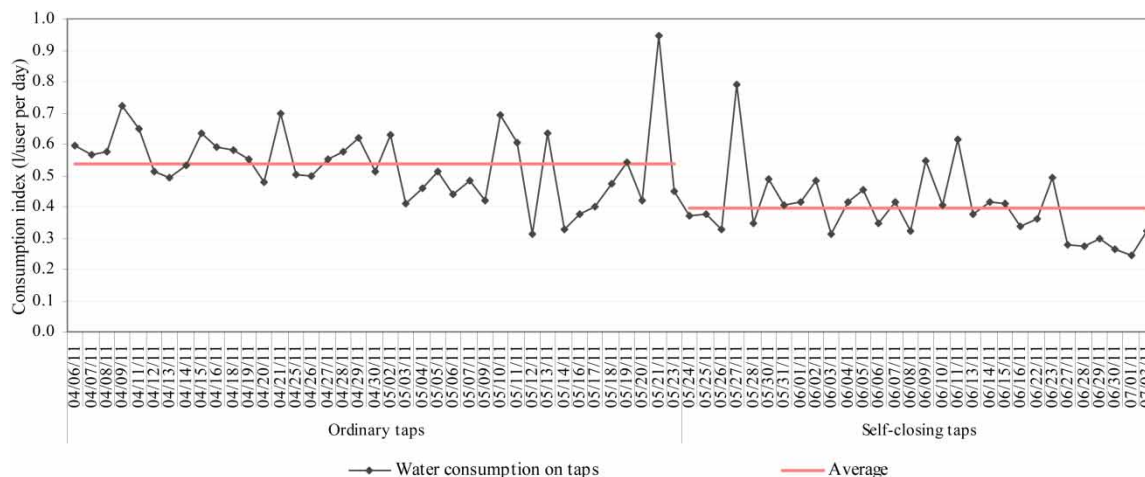


Figure 1 | Water consumption index for ordinary and self-closing taps.

Table 1 | Composition of the two taps and transport distances

Tap composition	Copper		Zinc		Polyoxymethylene		Rubber	
	Mass (kg)	Distance (km)	Mass (kg)	Distance (km)	Mass (kg)	Distance (km)	Mass (kg)	Distance (km)
Ordinary tap	0.445	2,938	0.191	1,850	0.002	1,076	0.005	1,422
Self-closing tap	0.566	2,938	0.243	1,850	0.007	1,076	0.009	1,422

plant uses 0.4 kWh to produce 1.0 kg of polyoxymethylene. For the transformation of brass, the data are related to a Brazilian factory (confidential source) that uses 7 kWh per kg of brass.

For the quantification of the inputs involved in the transport of materials, road transport by truck was considered in this paper. Road transport is widely used in Brazil; thus it was considered that raw materials were transported by heavy trucks in this study. The performance of heavy trucks was considered as 2.6 km per litre of diesel (Souza *et al.* 2013). Table 2 shows the energy consumption for extraction, processing and transportation of raw materials to the industry that manufactures the ordinary and self-closing taps. For transportation the percentage by mass of the raw material compared to the total load transported was considered. Energy consumption for extraction and transformation of the raw materials that compose the ordinary and self-closing taps are, respectively, 34.47 MJ and 44.29 MJ.

The embodied energy in copper and zinc (including brass transformation) represents the major contribution in

the total embodied energy for extraction and transformation of raw materials that compose both ordinary and self-closing taps. Embodied energy for brass transformation as well as for copper and zinc extraction and transformation are 97% and 98% of the total embodied energy for extraction and transformation of raw materials for the self-closing tap and for the ordinary tap, respectively. The mass of brass

Table 2 | Embodied energy for extraction and transformation of raw materials that compose the ordinary and self-closing taps

Raw material	Ordinary tap		Self-closing tap	
	Mass (kg)	Embodied energy (MJ)	Mass (kg)	Embodied energy (MJ)
Copper (includes brass transformation)	0.445	19.14	0.566	24.35
Zinc (includes brass transformation)	0.191	14.49	0.243	18.44
Polyoxymethylene	0.002	0.01	0.007	0.03
Rubber	0.005	0.83	0.009	1.47
Total	–	34.47	–	44.29

corresponds to 98% in the composition of the self-closing tap and 99% in the composition of the ordinary tap.

In the production phase, the plumbing fixture manufacturer reported a consumption of 4.238 kWh of electricity and 0.0303 kg of liquefied petroleum gas per kilogram of plumbing fixtures produced. Table 3 shows the energy consumption for manufacturing the taps and transporting them to the university campus using light trucks. The fuel consumption for the light truck was considered as 3.9 km per litre of diesel (Souza *et al.* 2013). The embodied energy for manufacturing the ordinary tap is 24.45 MJ, and 31.39 MJ for the self-closing tap.

Energy consumption in the use phase

As the method is proposed to be applied to assess energy consumption during the life cycle of any plumbing fixture, the equations may contain terms that do not apply to the plumbing fixtures under analysis. The taps used in this particular case study, for example, do not present direct energy consumption for their operation. Also, the building under analysis does not have any water heating system (which nullifies the term EC_h in Equation (6) in this particular case).

The method considers the energy consumption related to water consumption (water supply, pumping system and sewage treatment). Therefore, the greater the volume of water consumed by the fixture in the use phase, the greater the energy consumption. In the case study it was considered that the power of the pump system is equal to 0.25 HP and

its operation period is equal to 2 hours per day. The total water consumption in the building is equal to 2.78 m³/day. Thus, the energy consumption for pumping water was estimated as 0.547 MJ/m³.

Another issue to consider is the energy consumption for potable water supply and subsequent collection and treatment of sewage. According to the National Information System on Sanitation (Brasil 2015), the energy consumption index for potable water supply systems in the city of Joinville is 1.656 MJ/m³ and the energy consumption index for sewage systems is 1.440 MJ/m³.

In the city of Joinville the sewage treatment system is based on anaerobic, facultative and maturation ponds. For taps maintenance, only cleaning the tap aerators every 6 months by maintenance staff was considered. It was also considered that this activity does not lead to a significant energy consumption. The consumption in each of the 14 lavatory taps was calculated using the consumption index shown in Figure 1, considering 223 days and 921 users. The energy consumption in the use phase is 115.01 MJ for the ordinary tap and 84.65 MJ for the self-closing tap (Table 4).

Energy consumption in the disposal phase

The energy consumption for the disposal phase considered in this study is due to the transportation to the landfill site. The distance considered from the campus to the landfill site was 5.90 km. In this case, it was considered that a light truck carries the 14 taps installed in the building at

Table 3 | Energy consumption for manufacturing the taps

Tap	Mass (kg)	Electricity (MJ/kg)	LPG (kg/kg)	Distance (km)	% truck load	Energy consumption for transport (MJ/km)	Embodied energy (MJ)
Ordinary	0.643	15.257	0.303	596	0.2572	8.97	24.45
Self-closing	0.826	15.257	0.303	596	0.3030	8.97	31.39

Table 4 | Energy consumption in the use phase of the taps

Tap	Water consumption index (l/user/day)	Users	Days per year	Number of taps	Water consumption over 4 years (m ³)	Energy consumption (MJ/m ³)			
						Pump	Water supply	Sewage treatment	Energy consumption in the use phase (MJ)
Ordinary	0.538	921	223	14	31.57	0.547	1.656	1.440	115.01
Self-closing	0.396	921	223	14	23.24	0.547	1.656	1.440	84.65

the end of the life span. The energy consumption for transportation presents the same value described in the quantification of the embodied energy in the production phase. The energy consumption required for transportation is divided among the 14 taps. The energy consumption for both ordinary and self-closing taps is equal to 3.78 MJ (Table 5).

Comparison of energy consumption in the life cycle of the taps

The total energy consumption in the life cycle of the ordinary tap is 177.71 MJ, i.e., 33% in the production phase, 65% in the use phase and 2% in the disposal phase. For the self-closing tap, the total energy consumption in the life cycle was estimated as 164.11 MJ (46% in the production phase, 52% in the use phase and 2% in the disposal phase). The production phase includes energy consumption for raw material extraction and transformation, and tap manufacturing. The use phase includes energy consumption to allow the use of water in the building and also sewage treatment (water treatment and supply, collection and treatment of sewage, and pumping system). Considering the entire life cycle, the energy consumption of the self-closing taps is lower than that of the ordinary taps.

Sensitivity analysis

As the case study presented in this paper is based on some assumptions, a sensitivity analysis was performed in order to account for discrepancies. In the production phase, for both ordinary and self-closing taps the transportation distances considered a particular manufacturer plant. A variation of 100 km in the plant location produces a variation of $\pm 0.30\%$ on the embodied energy (production phase) for the ordinary tap and $\pm 0.31\%$ for the self-closing tap (Figure 2).

Table 5 | Energy consumption in the disposal phase of the taps

Tap	Distance (km)	Number of taps transported	Energy consumption in the disposal phase (MJ)
Ordinary	5.90	14	3.78
Self-closing	5.90	14	3.78

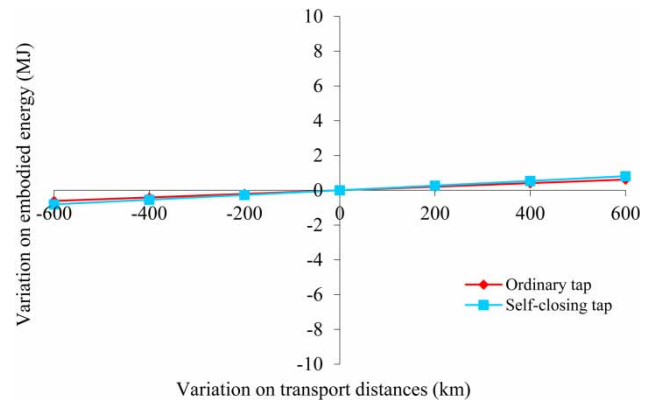


Figure 2 | Sensitivity analysis on the transportation distances (raw materials) of the two types of taps.

In the use phase, it was considered that 1 year has 223 school days and the building average population is 921 users per day. The standard deviation was calculated as 328 users over the study period. Figure 3 shows the variation on energy consumption in the use phase of the taps according to the population variation around the average of 921 users per day. A single user per day (added or subtracted) consuming water during the 4-year period represents an increase or decrease on energy consumption equal to 0.12 MJ in the use phase of the ordinary tap and 0.09 MJ on the use phase of the self-closing tap.

The results of the sensitivity analysis show the importance of the use phase for the determination of the energy consumption over the life cycle of the taps. The energy consumption in the use phase of the taps includes energy for pumping water and energy to allow the operation of the

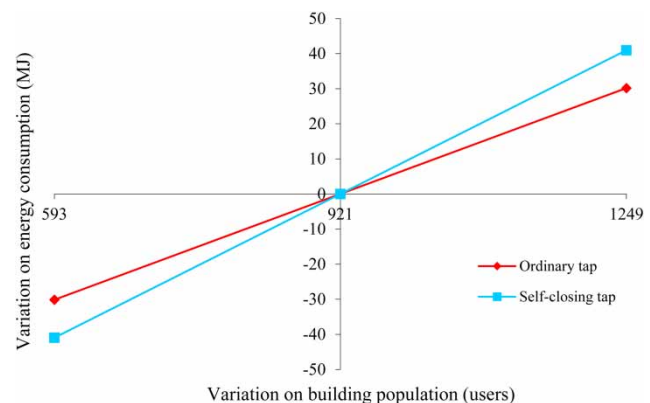


Figure 3 | Sensitivity analysis on the number of users of the two types of taps.

sewage system. The use phase is responsible for a significant share of the energy consumed over the life cycle of the taps and this result reinforces the importance of water savings as a means to reduce other environmental impacts, such as energy consumption.

CONCLUSIONS

This paper presented a method for choosing between different plumbing fixtures that perform the same function through the quantification of energy consumption in their life cycle. The method considered the consumption of water over the life span of the fixtures and how the consumption of water resulted in differences in energy consumption over the use phase.

The energy consumption in the production phase of the ordinary tap is lower than the energy consumption during the production phase of the self-closing tap, as the first one uses less material in its composition. In the use phase, the situation is reversed because the ordinary tap presents higher water consumption and, consequently, higher energy consumption. Overall, the self-closing tap has a lower energy consumption compared to the ordinary tap. Energy consumption is one of the significant effects of the utilization of plumbing fixtures. LCA studies are highly relevant because they show the potential for environmental improvement and allow comparisons between different products, as presented in this case study.

As a general conclusion, the results showed that the water-saving tap, in addition to water saving aspects in the use phase, presented lower energy consumption in a cradle to grave analysis. The method proposed herein can be used to evaluate the energy consumption of different plumbing fixtures, which is already being developed by the research teams of the authors. It is expected, therefore, to contribute to the promotion of environmental sustainability in water use in the built environment.

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