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Sustainable consumption in mobility from a life cycle assessment perspective

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ABSTRACT

The shift toward the adoption of sustainable lifestyles may be achieved with the support of environmental indicators, such as those obtained from Life Cycle Assessment (LCA). The aim of this paper was to perform a Consumer LCA of the potential environmental impacts of mobility habits of a generic consumer. This study also proposed a methodology for analyzing life cycle impact assessment (LCIA) results called Marginal Variation on Impact Assessment (MVIA). Mobility habits in lifestyles were modeled considering transportation to short and long-distance travels. The mobility alternatives considered were travel on foot, by bicycle, car (private and shared), bus, and airplane. Linear regression was applied to identify the marginal variation in aggregated single score results of transportation habits. Mobility with a private car had the highest environmental impact, whereas the use of a bus, bicycle and walking were the most sustainable alternatives. The results exhibited sensitivity to car-sharing. Taking flights for long-distance travels resulted in higher environmental impacts than other alternatives. Marginal Variation on Impact Assessment indicated that the consumer may find the greatest potential to change behavior and reduce impacts in mobility habits related to short-distance travels as well as by reducing the frequency of long-distance travels. The proposed MVIA methodology fits as a tool to support environmental life cycle impact assessment.

1. Introduction

The transport sector is a hotspot accounting for about 14% of greenhouse gas emissions (IPCC, 2014) and 24% of carbon dioxide emissions from fuel consumption (IEA, 2017). Nonetheless, there is still a growing demand for passenger commuting and alternatives of mobility, especially in developing countries (Dalkmann and Huizenga, 2010). In addition, there is a need for more sustainability in transportation, which is determined by factors like the availability of appropriate transportation infrastructure (Chiou et al., 2013), the promotion of sustainable consumer policies (Thøgersen, 2005), and a shift on transportation habits by consumers (Young et al., 2010). In turn, decision-makers are faced with the challenge of ensuring a larger capacity of transport systems, as well as to meet the consumer demands for more sustainable alternatives of mobility (United Nations Environment Programme, 2016).

How lower would be individual environmental impacts by sharing a car when going to work? If doing so rather than taking a bus, would a consumer increase his or her own environmental footprint? In this sense, a consumer might wonder: what mobility alternatives would be more sustainable? The aim of this study is to perform a Life Cycle Assessment (LCA) to analyze the potential environmental impacts of mobility habits of a generic consumer. Therefore, we aim to provide real consumers with information supporting a more sustainable change in lifestyles, as well as to back-up decision-makers to evaluate more precisely what aspects should be prioritized when formulating policies for sustainable

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consumption. This study also proposes an innovative methodology to support the analysis of life cycle impact assessment (LCIA) results called Marginal Variation on Impact Assessment (MVIA), aimed to identify and quantify variations on environmental impact of lifestyles, given certain changes in consumer behavior.

LCA is an ISO-standardized environmental management method (International Organization for Standardization, 2006) widely used in mobility studies, especially to its comparative nature and multi-indicator approach (Heijungs, 2014). This four-phased method can identify potential environmental impacts associated with products and services as well as indicate opportunities for improvements in the environmental performance of specific processes or whole life cycles (Finnveden et al., 2009; Van Hoof et al., 2013). Objective and scope are defined in the first phase of an LCA study. Inputs and outputs of environmental aspects within the settled system boundaries are then quantified (life cycle inventory phase, also LCI) and translated into environmental impacts related to a functional unit, in the LCIA phase. Finally, hotspots, trade-offs, uncertainties and other results can be interpreted and presented to stakeholders (Pennington et al., 2004; Rebitzer et al., 2004).

Originally, LCA was used only for the environmental assessment of products and services, indicating their environmental performance. From the more complex situations that emerged from the increasing concern for sustainability in decision-making processes (Zamagni et al., 2013), the method has been improved to be applied with different approaches. Nowadays, there are a number of studies assessing environmental impacts from consumption activities, and methods such as LCA and Carbon Footprint (CF) have extensively been used. For instance, Jansen and Thollier (2006) compared impacts due to household consumption in Belgium, and Saner et al. (2013) assessed environmental impacts from housing and land-based mobility demands of households in a small community. Difference in impacts between diet baskets have been estimated by Tukker et al. (2011), while sustainability of tourism activities was target by Castellani and Sala (2012). From such studies, and many others applying LCA and CF, the interest on evaluating environmental impacts from consumer behavior and lifestyle patterns has greatly increased, with several studies applying either top-down, bottom-up or hybrid approaches. This emerging branch within the LCA framework has been known as Consumer LCA (Hellweg and Milà I Canals, 2014).

Consumer LCA analyzes consumption patterns and lifestyles (Hellweg and Milà I Canals, 2014), sorting products and services in consumption categories, which enables the analyst to indicate hotspots and opportunities of improvement within these groups. Consumption categories such as food, mobility, and housing have already been identified in previous studies as responsible for the largest share of environmental impacts in consumption activities. Thus, these groups are commonly targeted in consumption-related LCA investigations.

For instance, Frostell et al. (2015) verified the average household expenditure related to impacts of energy use, global warming potential, and nitrogen oxides. In turn, Roibas et al. (2017) examined the carbon footprint of all production and consumption activities in the Spanish region of Galicia. A few more studies targeted a wider group of consumption categories through LCA. Huysman et al. (2016) calculated impacts from household activities of food, consumer goods, mobility, shelter and services through a top-down approach and midpoint LCA categories. Kalbar et al. (2016) associated Consumer LCA to the concept of personal metabolism, focusing on estimates of impacts from the consumption habits of an individual consumer. More recently, Matuštík and Kočí (2019) identified the segments of personal consumption contributing most to a consumer environmental impact by an approach similar to Kalbar et al. (2016).

Similar to the scope of the present paper, other studies focused on impacts from transportation. François et al. (2017) evaluated urban mobility through assessments of the transportation system and travel habits based on midpoint impact categories. Carbon footprint was the indicator selected to verify the impacts from transportation of the academic community in a Brazilian university (Barros et al., 2019). This same indicator was used to scrutiny transportation habits of tourists and other activities during holidays (Cadarso et al., 2016; Pereira et al., 2017). Environmental assessments of car-sharing (Nijland and Van Meerkerk, 2017) and vehicle performance (Bauer et al., 2015) were also performed. In common, these studies presented an association of fossil fuels use and low vehicle occupancy with higher environmental impacts.

All the literature referenced above greatly contributed to the improvement of studies on consumption and environmental impacts, through LCA and CF. Our study has the aim to support scientific advancement in this area, and the contribution presented is twofold. First, information, *i.e.*, scientific data is presented for decision-makers to develop effective policies for sustainable consumption, as well as knowledge is available for consumers to reduce environmental impacts in transportation activities. In addition, these benefits borrow strength from a bottom-up approach and results aggregated on a single score, rather than midpoint or endpoint results, which may ease the comprehension by a wide audience (Van Hoof et al., 2013). Second, methodological, *i.e.*, the proposed MVIA methodology fits as a tool to clearly identify impact variations on the means, and not only on the ends, a function not verified very often. Moreover, this paper enhances the value of Consumer LCA for studies on mobility activities, modeling real-world situations faced by people on everyday life.

2. Materials and methods

2.1. Transportation scenarios

Four mobility habits of a generic consumer were considered in this study: departing from the place of residence to the workplace (WK), business trips (BS), a vacation trip (VA) and other unspecified places (OT), such as to the supermarket or the mall (henceforth, denominated "others"). This mobility could be practiced using five mobility alternatives: on foot (ft), by bicycle (bike), private car (car), public bus (bus), or airplane (air). The functional unit (FU) considered was the mobility of one consumer to four destinations using one alternative of transportation for each location for a period of one year. This FU refers to the impacts of adopting a lifestyle with particular mobility habits. The system boundary shown in Fig. 1 comprises routes from the consumer's residence to the four destinations. Each vehicle was also considered within the system boundary (see list of unitary processes in Supplemental Material A).

The most realistic transportation habits were considered for each route. For example, it was not possible for the consumer to take an airplane for a short-haul travel or go by bicycle to a distant destination. The occupancy of the transportation modes varied when an automobile was adopted: with the driver only (car-1); driver plus one passenger (car-2); and driver plus two passengers (car-3). The increase in mass from the additional passengers was not considered, as well as the differences in impact between vehicle use in urban areas (home/work and home/others) and mixed areas (home/vacation and home/business).

Every union between four different round-trip routes, a transportation mode, and a number of repetitions created a combination (denominated transportation lifestyle) represented by symbols (Table 1). The variable "repetition" refers to the number of times a round-trip route is completed by the consumer in one year.

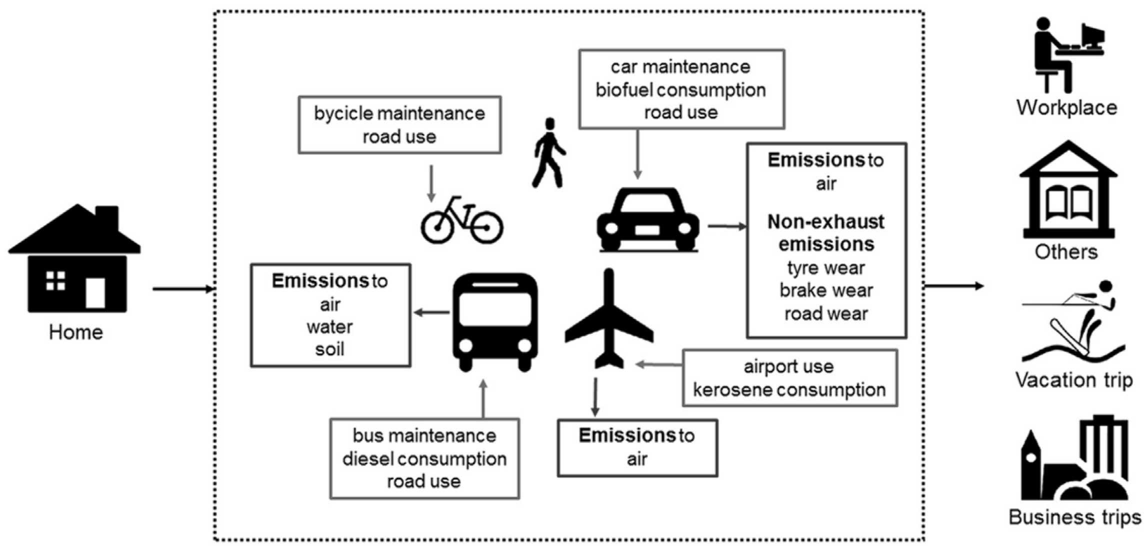

Fig. 1. System boundary highlighting inputs and outputs of four transportation modes from home to four different destinations.

Table 1
Setup of mobility habits.

Route		Transportation mode	Repetitions to meet FU	Symbol	Round-trip distance (km)
From	To				
Home	Workplace	On foot	249	WK-ft	5
		Bicycle		WK-bike	
		Car 1		WK-car-1	
		Car 2		WK-car-2	
		Car 3		WK-car-3	
		Bus		WK-bus	
	Others	On foot	200	OT-ft	1.6
		Bicycle		OT-bike	
		Car 1		OT-car-1	
		Bus		OT-bus	
	Vacation	Car 3	1	VA-car-3	446
		Bus		VA-bus	
		Airplane		VA-air	342
	Business	Car 3	3	BS-car-3	1542
		Bus		BS-bus	
		Airplane		BS-air	1230

The following geographic coordinates were adopted for each location: home (27°48′49″S 50°19′19″W); workplace (27°48′20″S 50°18′17″W); others (27°49′05″S 50°19′35″W); vacation room (27°35′44″S 48°33′32″W); business office (23°31′34″S 46°40′45″W). When air travel was adopted, only the flight distance between the Lages (LAJ) and São Paulo (GRU) airports were considered for business trips and only the flight distance between the LAJ and Florianópolis (FLN) airports was considered for the vacation trip. The 249 repetitions of WK corresponded to the average number of working days in a year in Brazil. The 200 repetitions of OT represented an annual number of days a consumer would go shopping. The repetitions of BS meant a business trip taken every four months. VA was set to 1, considering the consumer to travel on vacation once a year.

2.2. Life cycle assessment (LCA)

This study was conducted using a Consumer LCA with a bottom-up approach. SimaPro v. 8.3.0.0 (PRé Consultants, 2016) and secondary inventory data from the ecoinvent database v. 3.3 (Wernet et al., 2016) – cut-off modeling – were used for the life cycle impact assessment, along with the ReCiPe endpoint method v. 1.12 (World ReCiPe H/A) (Goedkoop et al., 2009).

We considered the endpoint level damage categories of human health (HH), ecosystems (ECO) and resources (RES). Since specific damage categories might generate opposing results (*e.g.*, one option may be the best for HH, but the worst for ECO), we focused on the single score results measured in Ecopoints (Pt) to facilitate the understanding of decision-makers and consumers. The environmental impact values of the endpoint categories were weighted according to the set of values from ReCiPe endpoint, *i.e.*, 400, 400, and 200 for HH, ECO, and RES, respectively.

Datasets representing a combination of mobility habits in lifestyles were adapted in SimaPro using the rest-of-the-world (RoW) feature. The fuel input for the automobile was adjusted to the percentages of gasoline (78%) and anhydrous ethanol (22%) similar to the composition of Brazilian gasoline (Alvarenga and Dewulf, 2013). Fuel-dependent emissions (carbon dioxide, carbon monoxide, and nitrogen oxides) were then adjusted according to data from a major Brazilian environmental health agency (CETESB, 2004). The same unit processes were used for short-distance and long-distance bus travel. The addition of biodiesel to the fuel used in buses was not considered.

Finally, the life cycle impact assessment was conducted by multiplying the number of mobility habits to form combinations of four elements. Each of the 216 resulting combinations represented the impact of mobility habits according to the route taken by the consumer, transportation mode, and number of annual repetitions.

2.3. Marginal Variation on Impact Assessment (MVIA)

This study proposes a methodology for analyzing LCIA results called MVIA. A linear regression was performed with the aid of SPSS Statistics v. 25 (IBM Corp, 2017) to identify the marginal variation in environmental impacts from any transportation habit over another without changing the frequency or destination. The estimated single score values of the initial set combinations were calculated (Eq. (1)) from binary variables (dummy variables) and the ordinary least squares (OLS) method. Dummy regression estimates the means of the system when a given variable enters the equation, enabling the estimation of the marginal increase of the change of each transport habit.

$$Y = \beta_0 + \beta_1 WK_{bike} + \beta_2 WK_{car\text{-}1} + \ldots + \beta_{12} BS_{air} + \mu \quad (1)$$

In which:

Y: dependent variable and indicates the estimated single score (Pt) of combinations, consisting of the sum of the estimated coefficients (βnXn) of *four* transportation habits (WKn, OTn, VAn, BSn);
$\boldsymbol{\beta_0}$: estimated coefficient of the combination from the initial set with the lowest single score value (65.340 Pt), corresponding to the transportation lifestyle (WK-ft, OT-ft, VA-bus, BS-bus);
$\boldsymbol{\beta_{1 \ldots 12}}$: coefficient of the estimated parameters (Pt);
$\boldsymbol{X_{1 \ldots 12}}$: set of independent variables (WKn, OTn, VAn, BSn) composed of mobility habits. X is binary and assumes $X = 1$ when the consumer adopts a given mobility habit and assumes $X = 0$ when the consumer does not adopt it;
$\boldsymbol{\mu}$: statistical error.

In the model of Eq. (1), $X = 1$ only for four simultaneous variables (transportation habits), while the other twelve simulated mobility habits are equal to zero. This is it because each combination comprises no more than four transportation habits simultaneously. For example, it is not possible for BS-air to occur at the same time as BS-bus. After the linear regression, the basic assumptions of the OLS were verified and confirmed through the following tests:

a. Autocorrelation checking: Durbin-Watson statistic to check autocorrelation from a regression analysis. Condition: $dL < d < (4 - dL)$, in which d is closest to 2.00.
b. Multicollinearity checking: test to check the degree of correlation between independent variables. Given:
   Condition Index (CI): the lowest from 10.
   Tolerance (TOL): the lowest from 1.00.
   Variance Inflation Factor (VIF): the lowest from 10.
c. Homoscedasticity checking: Goldfeld-Quandt test to check heteroscedasticity in regression analysis. Condition: λ (SSE_1/SSE_2) < $F_{critical}$ for 0.05 significance.

2.4. Sampling and analysis of results

The set of 216 combinations was analyzed in SimaPro and the results were exported to Excel 2016 (Microsoft Corp, 2016) spreadsheets. The combinations were graphically analyzed to check the occurrence of clusters of similar environmental impact values. The 17 clusters identified were dissociated into 24 layers (six layers per endpoint category plus six layers on the single score) and the combination of median values was extracted from each layer. Median combinations that occurred more than once were discarded. The 20 combinations remaining out of the initial set of 216 are presented in Table 2.

This sampling process was performed in order to optimize the analysis of mobility habits in lifestyles, reducing the number of combinations from 216 to 20 (approximately 10% of the initial set).

3. Results

This section presents the results of the LCIA of mobility habits in lifestyles in the context of other findings from the literature. Results from the application of the MVIA methodology are also presented. The debate and implications of these findings can be found in the discussion section.

3.1. Single score uncovered

This study presents an assessment of multiple midpoint and endpoint categories of a commonly used LCIA method in an aggregated form (single score). Conversely, LCA-based studies regarding mobility activities usually focus on energy demand and greenhouse gas emissions to assess impacts or to evaluate sustainability of transportation systems (Frostell et al., 2015; Ornetzeder et al., 2008; Pereira et al., 2017; Roibas et al., 2017; Saner et al., 2013). In addition to such methodological differences, many specificities from one study to another, *e.g.*, the system boundaries, functional unit, and inventory data, difficult direct comparisons between results from different sources. Such issues were taken into account at the time of the ISO 14040 series elaboration (International Organization for Standardization, 2006). Whenever an LCA analyst was willing to declare a product more environmentally preferable than another, all assumptions in the comparison (especially regarding the functional unit) should be equivalent between both studies.

Despite the ministration of all these issues, some assumptions can still be made in the sense of the general meanings from different studies. In the present case, Fig. 2 shows the single score of the sampled transportation lifestyles in terms of the absolute contribution from each midpoint level impact category.

Table 2
Combinations sampled for impact assessment.

Combination	Transportation habits			
1	WK-ft	OT-ft	VA-bus	BS-air
2	WK-ft	OT-bus	VA-car-3	BS-bus
3	WK-ft	OT-bus	VA-air	BS-car-3
4	WK-bike	OT-bike	VA-air	BS-car-3
5	WK-bike	OT-car-1	VA-bus	BS-car-3
6	WK-bike	OT-bus	VA-car-3	BS-bus
7	WK-car-1	OT-bike	VA-car-3	BS-car-3
8	WK-car-1	OT-bike	VA-bus	BS-car-3
9	WK-car-1	OT-car-1	VA-car-3	BS-car-3
10	WK-car-1	OT-bus	VA-car-3	BS-bus
11	WK-car-1	OT-bus	VA-bus	BS-car-3
12	WK-car-1	OT-bus	VA-air	BS-bus
13	WK-car-2	OT-ft	VA-bus	BS-air
14	WK-car-2	OT-bike	VA-car-3	BS-car-3
15	WK-car-2	OT-car-1	VA-car-3	BS-car-3
16	WK-car-2	OT-bus	VA-car-3	BS-bus
17	WK-car-2	OT-bus	VA-bus	BS-air
18	WK-car-3	OT-bike	VA-air	BS-car-3
19	WK-bus	OT-bike	VA-bus	BS-car-3
20	WK-bus	OT-car-1	VA-car-3	BS-air

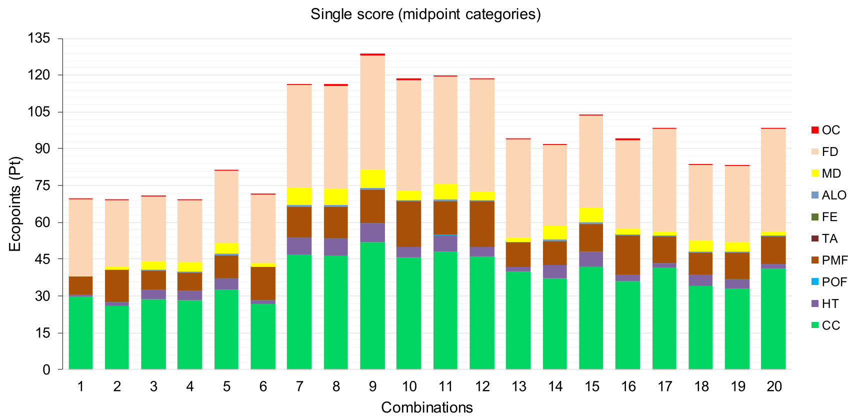

Fig. 2. Single score (Pt) of transportation lifestyles from the perspective of midpoint categories – ReCiPe endpoint. **Note: CC:** climate change; **HT:** human toxicity; **POF:** photochemical oxidant formation; **PMF:** particulate matter formation; **TA:** terrestrial acidification; **FE:** freshwater eutrophication; **ALO:** agricultural land occupation; **MD:** metal depletion; **FD:** fossil depletion; **OC:** other midpoint categories.

The midpoint categories climate change (CC: 37%–43%), fossil depletion (FD: 36%–45%), and particulate matter formation (PMF: 11%–19%) were the highest contributors to the environmental impacts of all transportation lifestyles, similar to Kalbar et al. (2018). Exhaust emissions (54%) and car production (20%) accounted for the largest share of impact from private car use in CC, along with the impact of biofuel production (72%) on FD, as well as the impact of car production (42%) and biofuel production (34%) on PMF. Bus use had the highest absolute impact on PMF, mostly from exhaust emissions (71%) and diesel production (13%). Kerosene production and its combustion during airplane use accounted for most of the impacts from this transportation mode.

Fig. 3 presents the single score from endpoint level impact categories, considering the weighting set from the ReCiPe endpoint method (World ReCiPe H/A).

The greatest contribution to the single score was from the endpoint category human health (HH: 51%–55%), with greater weight from business trips made by bus and lower weight when made by airplane. The ECO category had little influence on the single score (3%–4%), while the RES category represented 41%–45% of impacts from transportation habits.

Castellani and Sala (2012) found that individual private car use was responsible for the greatest impact in the three areas of protection, as indicated in Fig. 3, with an even greater relative impact in comparison to airplane use. In the study cited and the present investigation, as also verified by (Pereira et al., 2017), the greater number of passengers that an airplane can transport might explain these results. Both studies also presented midpoint categories fossil fuels, respiratory inorganics (including particulate matter formation) and climate change as the most contributing to the impact of car use (Fig. 2).

Fig. 4 presents the contribution of mobility habits to the overall potential environmental impact within different transportation lifestyles.

In general, mobility with a private car had the highest environmental impacts for mobility, whenever used in short-haul travels. This was similar to Kalbar et al. (2018), who found this transportation habit as strongly related to high environmental burdens. Conversely, the use of a bus, bicycle, and walking were the alternatives with the lowest environmental impacts, as also identified by Barros et al. (2019) and Cuéllar et al. (2016). Similarly to found by Ornetzeder et al. (2008), taking flights for long-distance travels resulted in higher environmental impacts than the other alternatives available. Car-sharing (also carpooling) contributed for lowering individual environmental impacts. Nijland and Van Meerkerk (2017) found a 13–18% reduction in CO_2eq emission due to car-sharing and variations in car ownership. We identified a similar effect, given that impacts from emissions were equally shared among all passengers, thereby offsetting impacts related to an individual consumer.

3.2. MVIA of the single score

Fig. 5 shows the marginal variation of each mobility habit on the

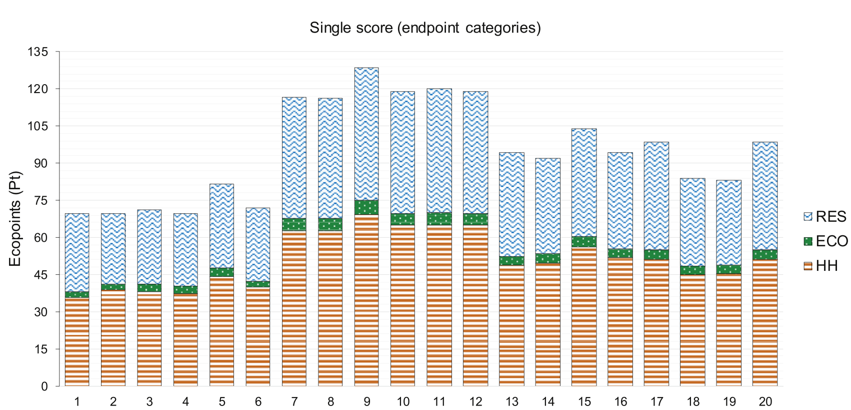

Fig. 3. Single score (Pt) of transportation lifestyles from the perspective of endpoint categories – ReCiPe endpoint. **Note: HH:** human health; **ECO:** ecosystems; **RES:** resources.

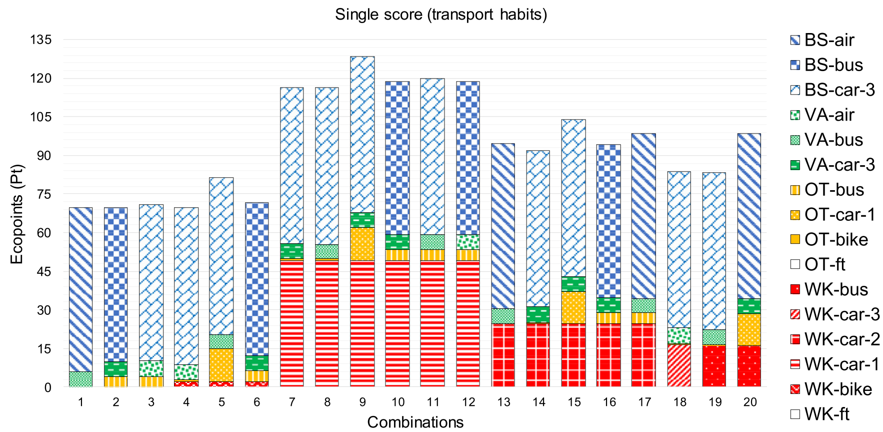

Fig. 4. Single score (Pt) of transportation lifestyles using bottom-up approach on transport habits – ReCiPe endpoint. **Note:** Routes: **WK:** workplace; **OT:** others; **VA:** vacation trip; **BS:** business trips; Transportation modes: **ft:** on foot; **bike:** bicycle; **car-1:** car with 1 occupant; **car-2:** car with 2 occupants; **car-3:** car with 3 occupants; **bus:** bus; **air:** airplane. WK-ft and OT-ft blocks are null due to mobility "on foot" present an empty inventory.

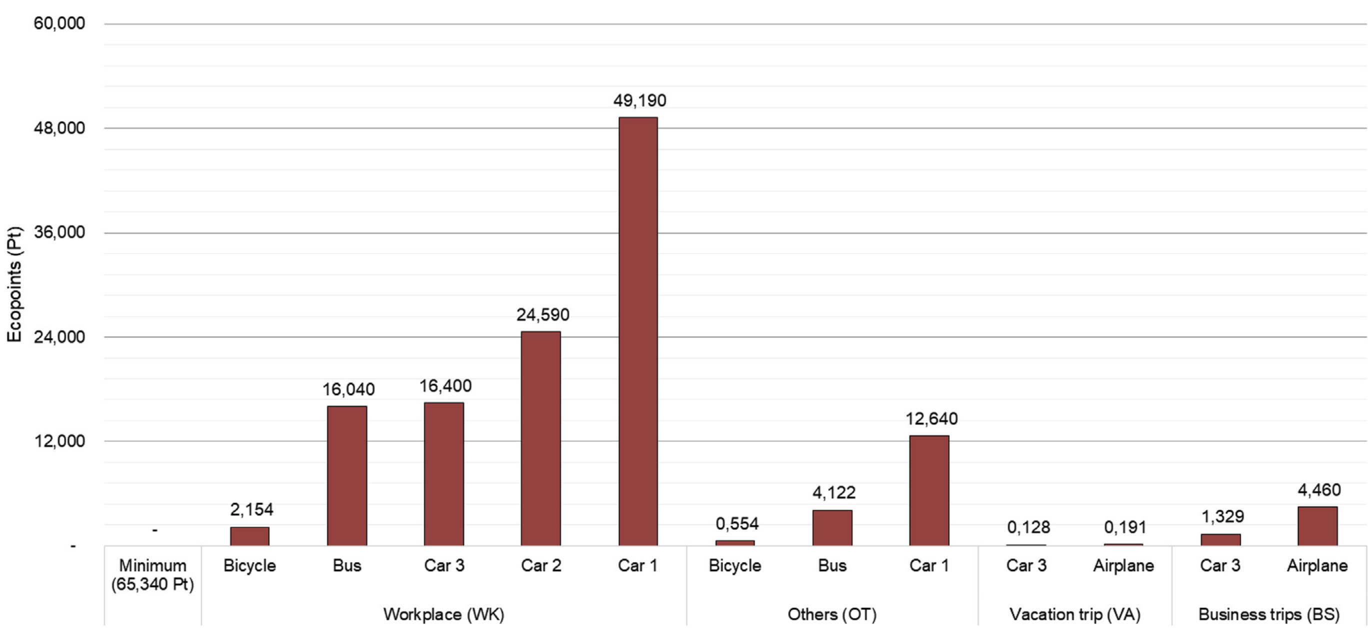

Fig. 5. Marginal contribution of transportation habits to single score value of the set of combinations from a bottom-up approach – ReCiPe endpoint.

single score from the established impact threshold of 65.340 Pt (minimum). The columns indicate how much each mobility habit *adds* to the *minimum* if such a habit were practiced in substitution to WK-ft, OT-ft, VA-bus, or BS-bus. The minimum variable comprises 0.000 Pt from WK-ft, 0.000 Pt from OT-ft, 5.750 Pt from VA-bus, and 59.590 Pt from BS-bus. The inventory of habits WK-ft and OT-ft was considered empty and the impact was therefore equal to zero, due to the consumer go to nearby places on foot, as also considered by Barros et al. (2019).

From Fig. 5, mobility to "others" was the second group of transportation habits that most varied the potential impact. The variables behaved alike those found for the home/work route, which was the group of habits whose transportation alternatives most varied. Habits related to the vacation trip exhibited little potential to vary the environmental impact caused by this type of activity. The impact of taking flights or driving a shared car was higher than going by bus for business trips. The absolute potential impact of using airplane for business trips was the highest among all transportation habits (64.050 Pt), representing nearly the same as the minimum threshold alone (65.340 Pt).

The results obtained from the application of the MVIA methodology enable a consumer to identify how much each mobility habit contributes to his or her own environment footprint. For instance, WK-bike contributes 2.154 Pt additional; OT-car-1 contributes 12.640 Pt additional; VA-air adds 0.191 Pt; BS-car-3 contributes 1.329 Pt; and so on. If the consumer replaced the transportation habit WK-bike with WK-car-2 (a car shared between two people), the effect of this replacement on the environment would be an additional damage of 22.436 Ecopoints (24.590 Pt minus 2.154 Pt). On the other hand, if the consumer were willing to mitigate the marginal impact and decided to go by bicycle to "others" instead of car, there would be a 12.086 Pt decrease in the impact (12.640 Pt minus 0.554 Pt).

We attempted to validate the results obtained from the MVIA methodology with results already published in other studies. There are several articles analyzing environmental impacts under different approaches, scenario drawings, and diverse impact categories, even applying statistical references. However, to the best of our knowledge, there has been no study undertaken applying a similar methodology on LCIA results. This situation might be explained by the novelty presented by the MVIA methodology. Thus, further discussion on this subject will proceed within the framework of LCA method itself, based on applications to consumer lifestyle analysis, policy development and other study areas.

4. Discussion

The functional unit of this study, referred as the mobility of one consumer to four destinations using one alternative of mobility for each location for a period of one year, was not limited solely to the quantification of impacts from the use of means of transportation. Neither was it aimed to quantify burdens from a vehicle itself. The modeling from the defined FU enabled to assess environmental impacts of transportation lifestyles, *i.e.*, the verification of impacts from the entire transportation routine of consumers within the timeframe analyzed.

4.1. Sustainability of transportation lifestyles

Mobility habits carried out with a private car had the highest environmental impacts among all alternatives considered in the present study. Conversely, mobility habits performed on foot or by bicycle were the alternatives with the lowest environmental impacts. Considering the option for a motor vehicle, the use of bus was the habit with the lowest impact. The major contributions to impacts have been shown as those originated from the use phase (Nesheli et al., 2017). Given so, sharing a car was the attitude that most contributed for lowering the consumer's environmental impact, whenever one chooses by an automobile. Moreover, a greater use of shared cars, rather than keep the single-occupancy, could not only reduce environmental impacts, but also contribute to a lower frequency of vehicle substitution, as well as greater road durability (Chester et al., 2010; Trigaux et al., 2017).

In our study, mobility habits of short-distance travels demonstrated considerable high potential to vary the environmental impact of a transportation lifestyle without significantly changing the *frequency* of travels. Thus, the feasibility of environmental impact reduction would depend mostly on consumer behavior and transportation alternatives.

Business trips contributed most to the single score in absolute terms, which suggests that the frequency of travel is relevant in a consumer's environmental footprint. Indeed, three business trips per year were considered in the simulation stage in this study. Supposing that a consumer reduces the travel frequency to once or twice a year, the decrease in impact could be presumed as reducing as well. Frostell et al. (2015) confirm this finding, suggesting that videoconference meetings could be an option to replace such activities.

A similar reasoning from business trips fits on vacation trips. Tourism activities generates an increasing share in greenhouse gas emissions worldwide (Adamiak et al., 2016). Therefore, replacing vacation trips in far destinations for leisure activities at nearer places may be a measure to reduce one's environmental impact on holidays (Frostell et al., 2015). However, this task might not be so straightforward due to the fact that even environmentally conscious consumers might prefer to externalize the reduction in environmental impacts rather than to reduce the number of flights on vacation trips (Barr et al., 2010). Actually, studies have shown that consumers in general are concerned with the environment, but do not necessarily translate these concerns into behavioral changes (Terlau and Hirsch, 2015).

Although frequency of travels could reduce absolute environmental impacts, transportation habits related to long-distance travels did not exhibit much variation among themselves, which indicates that the way the consumer chooses to travel for business or holidays changes little to the overall environmental impact. Such a potential in reducing environmental impacts was diagnosed by Polizzi di Sorrentino et al. (2016), who also highlighted the importance of adding the behavioral component into LCA studies and recognized the need of modeling usage scenarios considering individual variations in consumption habits.

This study also supports the idea of encouraging urban environments to be more compact, which opposes urban sprawling, a phenomenon that increases the consumer's dependence upon private cars (Sanne, 2002). The promotion of urban sprawling as a means of development and long-lasting urban infrastructure tend to direct transport users to a particular transportation mode (Dijst, 2013). This *status quo* ends up by locking-in consumers who live in distant locations, either into private cars (Sanne, 2002), or modes of public transportation, which may not be available with a desirable frequency (Marique and Reiter, 2012). Shorter distances to any destination translate to less need for the use of motor vehicles, thereby decreasing environmental impacts. Thus, public policies should focus on low-carbon mobility, such as bike lanes, safe and accessible pathways for pedestrians, whilst encouraging the use of high-capacity public transportation and avoiding urban sprawling. While this knowledge is already established in many advanced economies, it is yet to be widely applied in Brazilian cities.

4.2. General value of the MVIA methodology for (bottom-up) LCA

Most of studies related to consumption patterns are based on a top-down approach. Top-down studies indicate the main drivers of environmental impacts from diverse economic sectors with support of environmentally extended input-output analysis with statistics provided by national offices (Feng et al., 2011; Saner et al., 2013). Conversely, in the present study we modeled consumption in transportation at a bottom-up approach and used dummy variables for environmental impact analysis. A bottom-up approach considers all relevant life-cycle stages of a product within the system boundaries (Feng et al., 2011; Jansen and Thollier, 2006), which enables the analyst to determine what processes present the greatest potential of impact reduction. Thus, hotspots for the implementation of policy efforts may be identified (Hellweg and Milà I Canals, 2014).

Only from such bottom-up approach that it was possible to determine the marginal variation in impacts from transportation habits with high precision, which is quite innovative in the field. Even the particular contribution of a unitary process or the variation of an input parameter could be identified, *e.g.*, the fuel type, occupancy rate, composition of materials, so as existing synergies and interrelations (Jansen and Thollier, 2006).

In addition, the marginal variation was examined from the aggregated values of the midpoint or endpoint impact categories of the ReCiPe endpoint method (single score). This aggregated format presents benefits and risks to the target audience of an LCA study. On the one hand, results aggregated on a single score allow an easier understanding of the magnitude of environmental impacts by consumers not familiar to terms such as impact category, weighting or LCA (Van Hoof et al., 2013). On the other hand, aggregation adds uncertainty and subjectivity into the analysis (Weidema, 2019). The authors of this work, aware of this trade-off, have chosen to present the MVIA results in a single score. As presented by Kägi et al. (2016), it is crucial that decision-makers and consumers understand the practical significance of environmental impacts, in order to recommendations from LCA to be implemented. Moreover, the MVIA methodology has the flexibility to be applied to results of individualized midpoint and endpoint categories, if so the analyst aims.

The MVIA methodology is supposed to be applied *after* LCIA results are generated. This approach enables the method to be used no matter the scenario specificities considered in the phases of objective and scope definition and life cycle inventory. For instance, the application of the MVIA in the present work allowed to identify the degree of variation of the impact between different mobility habits. This approach can be extended to other consumption categories. Once the results are presented in single score values, the impacts from different lifestyles, whether related to food, housing, health and education expenses, etc., could be quantified. Thus, consumers can to target specific hotspots to change in consumption habits, promoting a behavior-driven transformation in urban environment (Polizzi di Sorrentino et al., 2016). Nonetheless, explicit considerations in the normative framework of LCA should still be maintained in order to ensure comparability between studies.

Although MVIA shows suitability to any LCA study aiming to analyze processes, scenarios and obviously, lifestyles, opportunities of improvement still remain in the methodology. A major challenge for the applicability of this methodology to top-down studies might be the issue of disaggregation data from input-output tables (IO-tables) to the individual consumer level. Also, the MVIA methodology relies on results built upon inventory data from datasets of processes representing different geographical regions, technology levels, and temporal ranges, which brings up variability to the results. All these sources of uncertainty have long been known (Huijbregts, 1998), and could be properly quantified by the analyst.

5. Conclusions

The aim of this paper was twofold. First, to perform a Consumer LCA to analyze the potential environmental impacts of mobility habits of a generic consumer. Second, to propose a methodology for analyzing LCIA results called Marginal Variation on Impact Assessment (MVIA). Both objectives were defined aiming to support consumers toward a change more sustainable in their lifestyles, as well as to back-up decision-makers when formulating policies for sustainability in consumption.

The impact assessment performed corroborated findings from several previous studies, but with a level of precision only achieved by modeling transportation habits from a bottom-up approach and by implementing the MVIA methodology. The group of transportation habits characterized by short-distance travels repeated many times a year, that is, to the workplace and other places in general, presented the greatest *variation* in environmental impacts. This might suggest that the consumer may find the greatest potential reduce impacts in transportation activities by changing his or her behavior on short-distance travels. On the other hand, long-distance travels (vacation trip and business trips) did not exhibited much potential for variation in environmental impact. However, diminishing the frequency of long-distance travels could significantly reduce the *absolute* environmental impact of a transportation lifestyle.

The proposed MVIA methodology fitted as a tool to support environmental life cycle impact assessment given the flexibility of the method, which may be applied both to results of midpoint and endpoint impact categories. In addition, there is an opportunity for the analyst to identify alternatives of improvement of sustainability in lifestyles without a sudden or an impractical change in consumer's habits.

Finally, a few scientific challenges are left by our study. First, is the adaptation of the MVIA methodology to data obtained from IO-tables and hybrid models is recommended. Second, in order to know the whole consumption profile of consumers from a Consumer LCA study, this methodology may be applied to other relevant consumption categories, such as food, housing, and water consumption. And last, uncertainties of data and sensitivity analysis to variations in modeling parameters may also be explored.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2019.06.203.

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