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Prioritisation of modelling parameters of a free-floating car sharing system according to their sensitivity to the environmental impacts

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Relying on life cycle assessment (LCA) to evaluate product-service systems (PSSs), and more specifically car sharing systems, involves many challenges. Car sharing services include free-floating car sharing, which enables users to take and leave vehicles anytime and anywhere within a limited service area. This paper proposes a model of a free-floating electric car sharing system in which eight parameters that influence environmental impacts may be identified. Among these parameters are the rate of use of the vehicles, standard trip representative of the service's actual use, vehicle model used within the service, and electric mix used to charge the vehicles. Adapting the life cycle assessment methodology to the studied system makes it possible to link the studied parameters to the indicator values of the service's environmental impact. The environmental indicators considered are global warming potential (GWP), photochemical oxidation potential (POCP), eutrophication potential (EP), and abiotic resource depletion potential (ADP). As a result, by using a design of experiments, it is possible to prioritise the eight system parameters according to their influence on the four environmental impact indicators. More specifically, the experiment demonstrates that the electricity mix has a major influence on the GWP and POCP indicators. With regard to the ADP indicator, the vehicle model used in the service is the most influential parameter by far. The use rate and trip type parameters have significant effects on the four environmental indicators. Finally, the experiment also shows that the results heavily rely on the study's methodological choices.

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Keywords: Free-floating car sharing; product-service system; life cycle assessment; modelling.

Table 1 List of main parameters

Parameters	Units
Study period T	Years (or minutes)
Trip demand (number of type-trip made) N	No unit
Standard trip time t	Minutes
Standard trip distance d	Kilometres
Use rate τ	%
Number of vehicles in service (during T) n	No unit
Distance traveled by one vehicle (during T) D	Kilometres
Allocation coefficient α	%

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1. Introduction

The automotive industry is undergoing a revolution. Tackling the energy transition, appropriating technological advances to increase their competitiveness and the attractiveness of their products, and having to anticipate new uses for them, car manufacturers must adapt quickly (Delhi, 2016). Among the new uses of vehicles are innovative mobility services, such as car sharing and carpooling (Kamargianni et al., 2016). With the arrival of these new services, most car manufacturers are responding by offering their own mobility services (Gao et al., 2016). One of the most common is car sharing. There are several types of car sharing, including the B2C (business-to-consumer) free-floating car sharing that is currently being developed in large cities (Becker et al., 2017).

The environmental performance of automotive vehicles is gradually becoming a design criterion for manufacturers. More specifically, current regulations call for exhaust emission thresholds that must not be exceeded under financial penalties for carbon dioxide emissions (Regulation, 2009) or a market ban (Parliament and Union, 2007). It seems likely that these regulations will eventually apply over the entire life cycle of products (Manfredi et al., 2012) and even organisations themselves (Pelletier et al., 2012). Also, customers are increasingly sensitive to issues related to global warming and the environment in general. It is legitimate to think that it will soon become essential to also analyse and optimise the environmental performances of new mobility solutions through a life cycle approach, as is essential today for the use of personal vehicles. Car manufacturers will have to stand out from the competition by offering services with the best possible environmental performances. While these different services are often presented as virtuous for the environment (Katzev, 2003), few studies have undertaken their environmental analysis. This is mainly due to a lack of methods and tools to analyse the environmental performances of the services. Indeed, methodologies such as life cycle assessment in compliance with ISO 14040 standards (Finkbeiner et al., 2006) are not directly applicable to these product-service systems (PSSs) or car-sharing services (Doualle et al., 2015). It is, therefore, necessary to develop methodologies to analyse and optimise these services from an environmental perspective. To our knowledge, there are only a few studies in the literature that attempt to demonstrate the environmental benefits of new mobility solutions as compared to traditional solutions such as private vehicle use (Luna et al., 2020). Concerning the environmental analysis and quantification of the impacts of these services, there is a real gap that this paper seeks to address.

This paper presents an original approach to modelling a free-floating car sharing system to which a life cycle assessment methodology was adapted. System parameters are based on this modelling. By adapting the LCA methodology, these parameters may be linked to the output values of environmental indicators. Four environmental indicators are considered: global warming potential (GWP), photochemical oxidation potential (POCP), eutrophication potential (EP), and abiotic depletion potential (ADP). These are the four environmental indicators most commonly observed by automotive manufacturers (Garcia et al., 2015). GWP is an indicator that aims to group under a single value the added effect of all the substances contributing to the increase in the greenhouse effect. Conventionally, we are limited for the moment to direct greenhouse gases (GHGs), that is to say, the six gases (CO₂, CH₄, N₂O, CFC, HFC, SF₆) taken into account in the Kyoto protocol. This indicator is expressed in “CO₂ equivalent” because, by definition, the greenhouse effect attributed to CO₂ is set at 1 and that of other substances relative to CO₂. POCP is one indicator of the possible contribution of an organic compound to the formation of ground-level ozone; EP indicator represents the modification and degradation of an aquatic environment linked to an excessive supply of nutrients, in particular nitrogen and phosphorus. Finally, ADP refers to the measure of the use of non-renewable sources for energy production.

80 In the literature, there are few studies on the environmental assessment of PSS. The objective of this paper is to propose a modeling of a car-sharing PSS allowing an environmental assessment based on the traditional methodology of vehicle LCA. Thanks to this modelling, it will be possible to prioritise the identified system parameters according to their influence on the environmental impact indicators of the service by using a design of experiments. The results obtained can help in decision-making to design the business model of a car-sharing service to minimize these environmental impacts.

85 **2. Background**

2.1 Free-floating car sharing product-service system

90 Car sharing is part of the product-service systems (PSSs) in automotive mobility category. The concept of PSS is neither new nor exclusive to the automotive sector. For the past two decades, many authors have tackled PSSs, and there are several definitions in the literature. Mont (2002) explains that a PSS should be defined as a system of products, services, networks, and supporting infrastructure designed to be competitive, meet customer needs, and have less environmental impact than traditional business models. In contrast to traditional business models based primarily on selling products to customers, a PSS focuses on offering a *function* to the customer and, more specifically, a combination
95 of products and services to meet customer needs (Goedkoop, 1999). Three types of PSSs encompass all PSS offerings (Tukker, 2004):

- Product-oriented services where ownership of the tangible product is transferred to the consumer;
- 100 • Usage-oriented services where ownership of the physical product is retained by the service provider, which sells the functions of the product through modified distribution and payment systems, such as sharing, pooling, and leasing;
- Results-based services in which products are replaced by services. As a result, there is no pre-determined product comparable to the first two types of PSSs.

105 The article focuses mainly on user-oriented services and car-sharing services in particular. Car sharing is a vehicle rental model in which people rent cars for short periods, often on a time basis (Katzev, 2003). Today, there are different business models for car-sharing services. Among these models, free-floating car-sharing services are mainly found in large metropolises with high population density. This type of service does not operate charging stations (for services with electric vehicles). The business model enables users to take and leave (mainly electric) vehicles anywhere in a given (and limited) area
110 through a smartphone application. Operators take care of moving the vehicles to charge and reposition them in strategic locations. This paper focuses exclusively on B2C car sharing in a free-floating service. Table 2 below shows the main characteristics of this type of car sharing based on a benchmark of free-floating car-sharing services.

Table 2 Free-floating car sharing characteristics

Criterion	Definition	B2C free-floating service
Service deployment area	The area in which the service is usable	Limited area (city)
Trip type	Characteristics of a trip representative of the real use of the service	- One way - Simple and uniform use of the service: urban and peri-urban use
Location of available vehicles	Places where vehicles can be found	Spread over the service deployment area
Composition of the fleet	Types of vehicles available	Usually only one electric vehicle model
Vehicle use rate	The ratio of the use duration of the same vehicle by service users over the total duration	Between 8 and 15%
Vehicles renewal	Duration or maximum distance travelled by vehicles in service before replacement	Based on the service business model
Infrastructure	Elements that enable the service to operate (other than vehicles)	No charging stations/charging station for electric vehicles in hangars by operators/digital infrastructure (website and smartphone app)

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2.2 Environmental benefits of car-sharing services

The development of car-sharing is aimed at reducing environmental impacts and reducing the number of cars on the road. Numerous studies have been carried out to analyze the environmental benefits of these alternative car mobility solutions. First of all, car-sharing could reduce the number of motorized vehicles in a city's or country's vehicle fleet (Martin et al., 2010). A study showed that in the Netherlands, car sharers own 30% fewer cars and drive 15% to 20% fewer car kilometres than prior to car-sharing (Nijland and van Meerkerk, 2017). This study shows also that the shared car mostly replaces a second or third car. Rydén and Morin (2005) estimate that a vehicle in service is 17% more efficient than a private vehicle. Despite all these benefits, Briceno et al. (2005) stressed the importance of taking into account the rebound effects of car-sharing. Indeed, the savings achieved through carpooling can lead to new household expenditures that may be linked to new environmental impacts. A study in Beijing used the methodology of cycle LCA to compare the environmental benefits of several types of car-sharing services (Ding et al., 2019). It highlights that the different types of services do not have the same potential on the modal shift from the use of private cars to the use of these services. Regarding the case of free-floating car-sharing, a case study in Basel (Switzerland) showed that 6% of free-floating car-sharing customers reduce their ownership of private vehicles (Becker et al., 2018). To conclude, there are many studies on the analysis of the environmental benefits of car-sharing services but to our knowledge, there is a lack of research about the intrinsic environmental analysis or optimization of these services.

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2.3 LCA: from private vehicle to car sharing PSS

Life cycle assessment (LCA) is widely used in industry to evaluate the environmental impacts of a product throughout its life cycle. The ISO 14040 and ISO 14044 standards (Finkbeiner et al., 2006) describe the essential characteristics of LCA and good practices to conduct this type of study and provide a methodological framework to conduct a product LCA. Many vehicle manufacturers use LCA to compare a vehicle model and its successor from an environmental perspective (Mayyas et al., 2012). The stages in a vehicle's life cycle considered here are manufacturing, logistics, use, maintenance, and end of life. The life cycle assessment provides an overview of the impacts of vehicles throughout their life cycle. Before they began using this method, car manufacturers only focused on emissions during the use phase of vehicles. In this phase, the electric vehicle seems ideal because it releases zero emissions (Hawkins et al., 2013). However, the LCA methodology reveals that the manufacturing phase has a high impact due to the extraction of the rare metals required to build the vehicles' batteries and permanent magnet motor (Speirs et al., 2014). Also, the electricity production phase when electric vehicles charge can have a significant impact depending on the country in which the electricity is produced (Faria et al., 2013). Today, most car manufacturers have mastered the life cycle assessment applied to vehicles. The method has been adapted to private vehicles used exclusively by their owners. For example, a functional unit used by some car manufacturers to conduct an LCA of a car is the *transportation of people and goods over a distance of 150 000 kilometres over 10 years* (Nordelöf et al., 2014).

The introduction of new forms of mobility and, above all, new uses of vehicles, suggests new challenges for the use of LCA in the automotive sector. Indeed, a shared vehicle is not used in the same way as a private vehicle, and the use of a service consisting of a fleet of vehicles is much more complex than the use of a single-vehicle by its owner. These innovative uses make it interesting to change the paradigm from the LCA of a private vehicle to the LCA of a shared vehicle and car-sharing services. Few articles in the literature explore LCA applied to PSSs and even fewer consider LCA for PSSs for automotive mobility. It is relevant to ask whether this methodology, in compliance with ISO 14040 and ISO 14044 standards, is adaptable to the case of PSSs. According to the authors who have studied the question, many challenges complicate the use of LCA for PSS and therefore also for car-sharing services (Table 3).

Table 3 Challenges when adapting LCA to PSSs (literature review)

Authors	Challenges to adapt LCA to PSSs
(Dal Lago et al., 2017)	<ul style="list-style-type: none"> - Focus on the environmental assessment of physical unit products - Lack of guidelines and frameworks for stroke practitioners to conduct PSS assessments - Intangible assets in PSSs
(Amaya et al., 2014)	<ul style="list-style-type: none"> - The use phase of a product in a PSS is much more complex than that of a product introduced through a standard economic model.
(Maussang et al., 2009)	<ul style="list-style-type: none"> - In a PSS, the product will be used more frequently and by several users.
(Corti et al., 2016)	<ul style="list-style-type: none"> - The lack of a general PSS LCA procedure is also due to the multitude of PSS offers, which are combined with products of very different natures. - The development of a single generalizable method for all PSSs is very complex.
(Dal Lago et al., 2017)	<ul style="list-style-type: none"> - Determining system boundaries and the inventory phase of the LCA is more complex for a PSS. - The infrastructure (total amount of equipment used to operate the PSS) must be taken into account in the LCA of a PSS.

170 Despite the challenges presented above, some authors have attempted to provide guidelines to adapt stroke methodology to PSS. Kjaer et al. (2016) explain that LCA may be applied to a PSS in three relevant fields of application: (1) analysis and optimisation of a PSS; (2) comparison of a PSS and alternative solution; and (3) analysis of the consequences of implementing a PSS. The main challenges are the determination of the reference system, functional unit, and system boundaries (Dal Lago et al., 2017; Kjaer et al., 2016).

175 To our knowledge, there is a real lack of LCA methodologies to analyze the environmental performances of car-sharing services and support the ecodesign of these services. In this article, the LCA methodology as it is currently applied by the automotive industry will be adapted to the free-floating car-sharing system using several assumptions and conventions that are presented in the following paragraphs.

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3. Modelling and methodologies

3.1 System boundaries

185 In this paper, the studied business model is the free-floating car sharing service presented earlier. Figure 1 is a map of the system and its constituting elements.

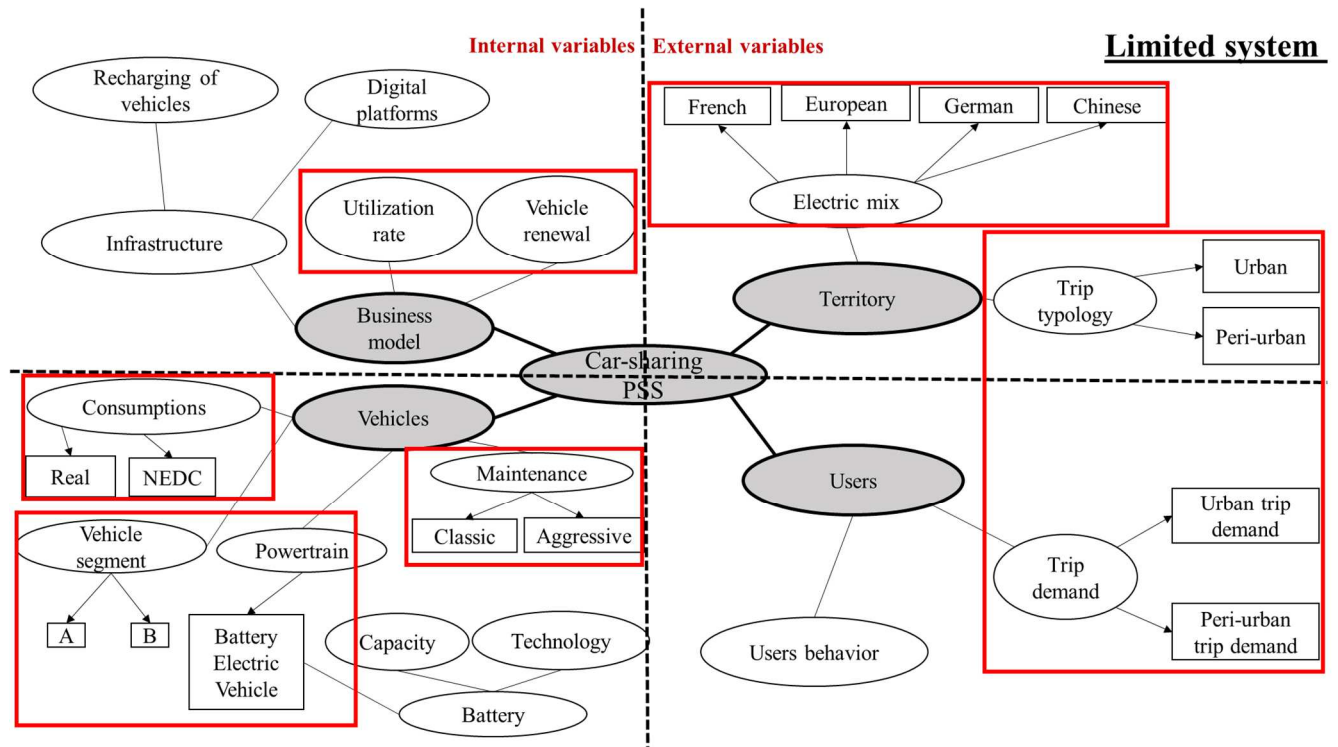


Figure 1 Representation of the complete system

The complete system is divided into four sub-systems: territory, users, business model, and vehicles.

- In the business model subsystem, three elements related to profitability have been identified: vehicle use rate, maximum distance of vehicles in the service, and service infrastructure.
 - A vehicle's use rate is defined as the ratio of the duration of use of the same vehicle by service users over the total duration (duration of use of the vehicle by users +

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duration of immobilisation of the vehicle + duration of use of the vehicle by service operators).

195 - The vehicle-renewal is related to the maximum distance a vehicle can travel in service over the study period. This constraint is linked to vehicle-renewal to maintain the attractiveness of the service by offering vehicles that are in good condition.

200 - Two types of infrastructure are identified in this business model: infrastructure related to the charging of electric vehicles and digital platforms that enable the service to operate. The traditional solution to charge vehicles in free-floating services consists of moving the electric vehicles (by service operators) to a shed to charge them at charging stations and then placing them back on the road in strategic locations. In this study, we consider that the impacts linked to platforms are negligible compared to the impacts of vehicles. Also, it is considered that the movement of vehicles for recharging is included in the use of vehicles.

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- In the vehicle subsystem, there are powertrains and vehicle segments (generally categorized by vehicle size or use). Concerning the vehicle segments, only segment A or B vehicles are considered. Segment B includes multi-purpose city cars (or sub-compact cars) while segment A includes small city cars. Only predefined models of electric vehicles are considered in this study. Parameters related to the dimensioning of the vehicle battery pack are therefore not included. This subsystem also includes the type of maintenance applied to the vehicles (conventional or aggressive) as well as the type of consumption values assigned to the vehicles: NEDC ("New European Driving Cycle," 2020) or real.

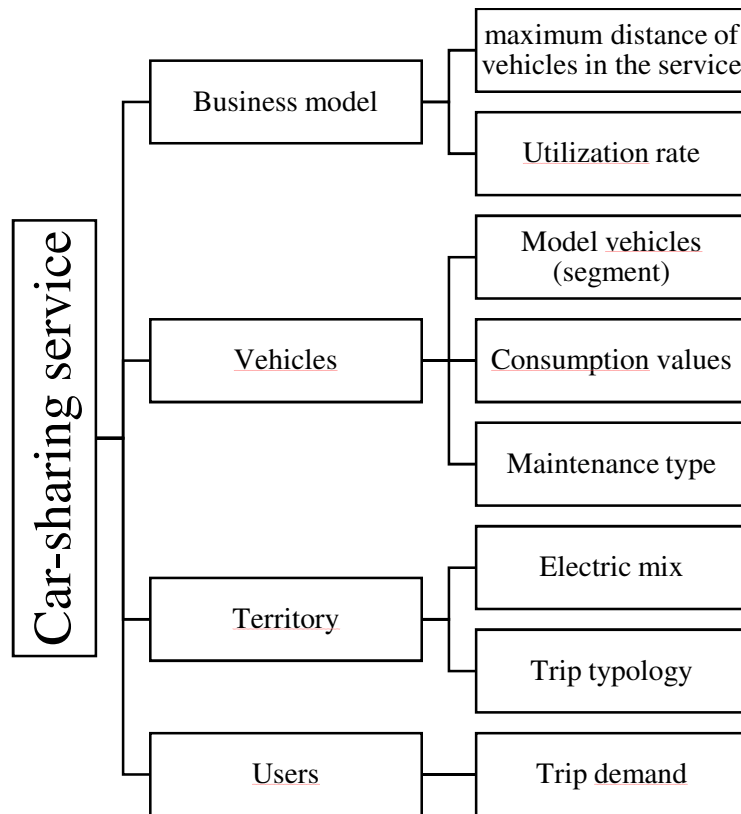
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- In the territory subsystem, four different electrical mixes may be used to charge the electric vehicles. There is also a route typology. Free-floating car-sharing services are set up on territories where trip types are essentially city (urban) or road (peri-urban) trips.

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- Finally, in the "users" subsystem, the elements represented are user travel demand and user behavior. The influence of user behavior (the type of driving or use of heating or cooling) on the impacts of the service is not studied here.

The mapping (Figure 1) illustrates the eight remaining blocks shown in Figure 2.



225 Figure 2 Identification of the main system elements

3.2 Modelling assumptions

To carry out the experimentation to study the influence of system parameters on the environmental impacts, it was necessary to model the system and identify the system parameters to be analysed. In this session, the LCA methodology adapted to the system will make it possible to establish the relationships between the parameters and environmental indicators chosen for the study. To model the different system blocks, simplifying hypotheses were used:

- Study duration T is the time during which the service is used. The objective of the environmental assessment is to study the impacts of the service on duration T . This duration is imposed as an input. In our study, we consider $T = 2$ years.
- The use of the service is modelled based on the completion of a single standard trip (type-trip): an urban standard trip or a peri-urban standard trip. It is assumed that all the trips are made within the limited service area without considering the spatial distribution of the trips in this area.
- The standard urban trip is considered to be an 8-km (d) urban trip completed in 20 min (t), and the standard peri-urban trip is a 25-km (d) road trip completed in 20 min (t).
- The number of trip requests (associated with the urban type-trip or peri-urban type-trip) over study period T by service users is imposed as an input. The number of trip requests is considered to be equal to the number of trips made N . The temporal distribution of trips is not taken into account. Only the total value of trips made N over time T is used.
- The service fleet consists of one vehicle model only.
- The homogeneous use of the vehicles in the fleet is considered, meaning that each vehicle in the fleet has the same usage data over the study period. The use rate of fleet τ is, therefore, the same as that of all the vehicles in the fleet. It is assumed that this use rate is between 5 and

250 15%, which is representative of the actual use of a free-floating car-sharing service.
Equation 1 is used to calculate the rate of use of the service τ :

$$\tau = \frac{N \cdot t}{n \cdot T} \quad (1)$$

N : the number of standard trips made during the study period T

t : the duration of the standard trip

n : the number of service vehicles used during study period T

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- Two types of maintenance are considered: standard maintenance (replacement of parts according to the maintenance logbook for conventional use of a vehicle) and aggressive maintenance for which 10% is added to the impact value associated with vehicle maintenance compared to conventional maintenance.
 - We consider four electric mixes: French, European, German, and Chinese.
- 260
- Two electric vehicle models will be tested: a low-end A-segment vehicle and a high-end B-segment vehicle.
 - Two types of vehicle consumption values will be used as input data: actual consumption values and consumption values obtained on a mixed NEDC cycle.
 - The maximum distance that each vehicle can travel in the service is defined. This distance is necessarily lower than the theoretical end-of-life distance of the vehicles. It is considered that
- 265 this maximum distance varies between 100 000 and 200 000 km.

From these modelling hypotheses, nine parameters are obtained: eight associated with the eight blocks of the system and duration of the study. These parameters are associated with value ranges or discrete values depending on the type of parameter (see Table 4).

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Table 4 Modelling parameters

Parameters	Options
Standard type	Urban / peri-urban
Trip demand	Constant (imposed as input)
Vehicle model	Electric segment B/ electric segment A
Use rate (%)	[5;15]
Maximum distance of service vehicles (km)	[100 000; 200 000]
Electric mix	French / European / German/ Chinese
Maintenance type	Standard / Aggressive
Type of consumption values	Actual / NEDC
Study period	2 years (imposed as input)

3.3 Adapted LCA methodology: assumptions and conventions

275 In the automotive industry, life cycle assessment is used to evaluate the environmental impacts of vehicles throughout their life cycles. In this article, we present a model to calculate the environmental impacts of a car-sharing service over a specific study period. The aim of adapting the LCA methodology to the car-sharing system is to obtain the mathematical relationships between the system parameters and output environmental impact indicators.

280 Four environmental indicators are considered: global warming potential (GWP), photochemical oxidation potential (POCP), eutrophication potential (EP), and abiotic depletion potential (ADP). The model seeks to calculate the values of these indicators for a free-floating car-sharing service over a defined study period for an input-imposed trip demand. Below are the assumptions and conventions used to calculate the environmental impacts of the service over the study period.

285 • The impacts of the service are limited to the impacts of the service vehicles since the infrastructure is considered to be beyond the scope of the study.

290 • The impacts of service vehicles over the study period correspond to the sum of the impacts throughout the vehicle's life cycle phases: manufacturing, maintenance, in-service use, and end of life (for each indicator).

295 • The impact of vehicle use is directly related to the use of service vehicles during the study period (for the N trips). It is equal to the sum of the well-to-tank and tank-to-wheel impact (Edwards et al., 2011) related to the use of service vehicles. The tank-to-wheel (TtW) impact corresponds to the exhaust emissions after fuel combustion, and the well-to-tank (WtT) impact corresponds to the impacts of fuel (or electricity) production to power the vehicle. The value of the distance travelled by the service vehicles over the two years and consumption values of the vehicles make it possible to calculate these impacts.

- Impacts related to out-of-service use of vehicles (outside the study period) are not attributed to the impacts of service over the study period.
- The impacts related to the maintenance of the service vehicles are proportional to the distance travelled by the service vehicles. The value of the impact of the conventional maintenance of a vehicle (one value per vehicle model) that travels 150 000 km over 10 years (results of Groupe PSA life cycle assessment) was used as input data.
- A theoretical distance travelled by each vehicle model is also defined for the duration of its operation (before it is considered to be out of use). In the study, the distance is defined as 200 000 km for all vehicle models.
- The manufacturing and end-of-life impacts of vehicles are attributed to the service on a linear basis according to the distance travelled by the service vehicles. The purpose is to calculate only the impacts of the service, and thus the vehicles, during the study period. While a vehicle may be used outside the study period, it is considered that it was designed in part for the service during the study period. It is for this reason that part of the manufacturing and end-of-life impacts are directly allocated to the service. The allocation is carried out by introducing the allocation coefficient α . This coefficient is defined by the percentage of the service vehicle's manufacturing and end-of-life impacts allocated to the service from the vehicle's initial use as part of the service. This coefficient is only used in the initial condition (Equation 2) to determine the vehicle manufacturing (and end-of-life) impact value allocated to the service according to the distance travelled by the vehicle. The remainder of the impacts (manufacturing and end-of-life) are attributed to the service linearly based on the distance travelled in the service. It is, therefore, logical to consider that 100% of the manufacturing and end-of-life impacts are attributed to the service if the vehicle travels 200 000 km in service (i.e. if the vehicle is only used in service during its total operating life (Equation 4)). It is assumed that the allocation coefficient varies between 0.25 and 0.75. The subjective choice of this coefficient justifies its wide range. For example, if the coefficient is equal to 0.25, this means that 25% of the manufacturing and end-of-life impacts of the vehicles are attributed to the service from their initial use. This choice corresponds to the case in which the vehicles are considered to have not been exclusively designed for the service. A relatively long after-service use is projected for vehicles in this case. For an allocation coefficient value of 0.75, it is considered that the vehicles were designed specifically for use in a car-sharing service. Equations 2 and 3 (below) are the boundary conditions for the vehicle manufacturing impact value allocated to the service. These two conditions are therefore sufficient to determine the expression of the impact value (Equation 4) as a function of vehicle distance (travelled at the end of the study period), as this is an affine function (based on the above assumptions).

$$I(D = 0+) = n \cdot \alpha \cdot I1 \quad (2)$$

$$I(D = 200\ 000) = n \cdot I1 \quad (3)$$

$$I(D) = \left[\frac{(1 - \alpha)}{200\ 000} \cdot n \cdot D + n \cdot \alpha \right] \cdot I1 \quad (4)$$

I : Impact of fleet vehicle manufacturing attributed to service (or end of life)

α : Allocation coefficient

n : Number of vehicles in the service fleet

D: Distance traveled per vehicle at the end of the study period (two years)

340 I1: Vehicle manufacturing impact (or end of life) as input data

- The impact values of electric vehicles for the manufacturing, end-of-life, and maintenance stages are obtained using ADEME (French environmental agency) data (Warburg et al., 2013) for the segment A vehicle, and Groupe PSA life cycle assessment databases using Gabi software (<http://www.gabi-software.com/>,” 2017) for the segment B vehicle. In the
345 experiment, the real consumption values and NEDC cycle values of the Groupe PSA vehicles are also used.

4. Design of experiments

4.1 Identification of system parameters (factors)

350 By adapting the LCA methodology to the system, two new parameters are introduced: the allocation coefficient α and theoretical end-of-life distance of vehicles. These two parameters are in addition to the nine parameters derived from the system modelling, thus yielding eleven modelling parameters, three of which are fixed parameters. As input data, a study duration of two years and a fixed trip demand over this duration are imposed. It is also assumed that the distance travelled by the vehicles
355 (regardless of model) at the end of their life cycles is 200 000 km. Regarding the allocation coefficient, it is assumed that its value varies between 0.25 and 0.75. The influence of the eight parameters on the environmental impact indicators of the service remains to be studied: rate of use of the vehicles, standard trip (type-trip) as part of the service, electric mix used to recharge the vehicles, type of maintenance, type of electric consumption values of the vehicles, vehicle model, maximum
360 distance travelled by the vehicles in the service and impact allocation coefficient.

Based on a configuration of these parameters (combination of eight values of these parameters), the model presented here makes it possible to obtain a value for the studied environmental indicator and, therefore, a value for each of the four environmental indicators considered in the study. The design of experiments method (Kuehl and Kuehl, 2000) was used to understand the influence of the system
365 parameters on the different environmental indicators, thus making it possible to rank the system parameters with a reduced number of tests (simulations).

4.2 Choice of factor levels and design of experiments

370 Firstly, concerning the choice of design of experiments, it would be possible to carry out a complete factorial experimental design for which the responses (indicator values) are calculated for all factor level combinations. However, with eight factors at two levels, this would require 2^8 simulations (i.e. 256 tests) for each of the four studied environmental indicators. This is why it is preferable to use Taguchi's design of experiments (Roy, 2001), which reduces the number of simulations to be carried
375 out with sufficient robustness. Using XLSTAT software (XLSTAT | Logiciel Statistique pour Excel, n.d.), we were able to use the L32 (2^8) design of experiments to perform only 32 simulations (tests) to study the effects of factors on the value of an environmental indicator. The same design of experiments (Appendix 1) is used for each indicator. The model was built so that there is no interaction between the eight parameters which justifies the choice of this orthogonal experimental
380 design. For each simulation (32 in total per indicator), the model was used to calculate the value of each indicator for the parameter configuration. A total of 128 values (32 x 4 environmental indicators) are therefore filled to start the analysis of the design of experiments for each indicator.

385 In a second step, it is essential to choose the two levels of each factor to correctly prioritise the eight factors according to their influence on the values of the environmental indicators with a reduced number of tests. To obtain the two levels of a factor, it is necessary to choose the two values of the range of variation (possible values) of the factor for which the difference between the two calculated indicator values (associated with the two values of the factor) is the widest.

390 In the case of discrete parameters with only two possible values, there is no other option than to take both values as factor levels. This is the case for three types of factors: type of trip, type of consumption values, and type of maintenance. Similarly, two electric vehicle models belonging to two different segments are studied and will therefore consist of the two levels of the vehicle model factor. For the continuous parameters of our study (i.e., use rate, allocation coefficient, and maximum distance travelled by the vehicles in service), the choice of levels consists of taking the limits of the ranges of variation. Indeed, verifying that the four service impact indicators are monotonic functions of these three parameters is a simple task. The impacts are minimised by taking the maximum values of the use rate and maximum distance (of vehicles in service) and the minimum value of the allocation coefficient. This justifies the choice of levels for these three factors. The choice of levels for the electricity mix factor is based on carbon intensity: of the four, the electricity mix with the least impact is the French mix, while the mix with the highest carbon footprint is the Chinese mix, which still heavily relies on coal (Ou et al., 2010). The two levels for this factor are therefore the French mix and the Chinese mix. In the end, two levels per factor could be retained in this phase of the experimental design. They are set out in Table 5 below.

Table 5 Identification of factor levels

Factors (parameters)	Level 1	Level 2
Standard type (discrete parameter)	Peri-urban	Urban
Vehicle model (discrete parameter)	Electric segment B	Electric segment A
Use rate (%)	5	15
Maximum distance of service vehicles (km)	100 000	200 000
Allocation coefficient (%)	0.25	0.75
Electric mix (discrete parameter)	Chinese	French
Maintenance type (discrete parameter)	Aggressive	Classic
Consumption values type (discrete parameter)	NEDC	Actual

405 5. Results

The order of the levels of the eight factors detailed in Table 5 is used to present the results. To study the influence, calculations of averages over balanced (i.e. orthogonal) sets of results are used. This is the notion of effect. The effect of a factor associated with a level is defined by the arithmetic difference between the mean of the indicator values associated with the factor level in question (mean

of 16 values for this design of experiments) and the overall mean calculated from all the indicator values of the design of experiments (mean of the 32 values of the design). The values of the effects of the two levels of a parameter are therefore symmetrical, making it sufficient to compare the absolute values of the effects of the eight parameters and rank them according to their influence on the global warming indicator. The process is the same for the other three indicators, using each indicator's 32 calculated values.

Table 6 below (first two lines) shows the 16 averages calculated from the GWP values of the design of experiments simulations. Each average is calculated from all the indicator values associated with a level of factors (16 values, see Appendix). For example, in the first box of the table (row 1, column 1), there is the average of the GWP indicator values for all the simulations using a peri-urban standard trip as the standard service trip. The result is therefore the average of the 16 indicator values obtained for the first 16 combinations of parameters in the design of experiments. In the second row of the table is the average of the indicator values associated with the other level of the factor (in this case, the standard urban trip factor). In the third row are the values of the effects of each factor. In the fourth row are the effects of each factor expressed in percent (%) with the effect of the allocation coefficient parameter as a reference (100%) to present the results of the four indicators. This choice is justified by the significant value of the parameter's effect on the four indicators. The effects (in percentage) of the other parameters are therefore calculated with this reference. Figure 3 shows the graphic representation of the effects of each parameter (%) on the four studied environmental indicators: global warming potential (GWP), photochemical oxidation potential (POCP), eutrophication potential (EP), and abiotic resource depletion potential (ADP). The effects of the allocation coefficient parameter on each indicator therefore serve as a reference when reading the table (100% effect value).

Table 6 Parameter effect values on environmental indicators

	Trip	Vehicle model	Use rate	Maximum distance of service vehicles	Allocation coefficient	Electric mix	Maintenance type	Consumption values type	
GWP	level 1 average	2.52E+06	3.99E+06	4.12E+06	3.67E+06	2.69E+06	4.31E+06	3.38E+06	3.36E+06
	level 2 average	4.10E+06	2.86E+06	2.50E+06	3.24E+06	4.16E+06	2.54E+06	3.47E+06	3.49E+06
	factor effect (kg CO2-eq)	6.78E+05	5.62E+05	6.93E+05	1.85E+05	7.37E+05	8.89E+05	4.19E+04	6.04E+04
	factor effect (%)	92%	76%	94%	25%	100%	121%	6%	8%
POCP	level 1 average	1.16E+03	1.45E+03	2.00E+03	1.76E+03	1.25E+03	2.00E+03	1.69E+03	1.59E+03
	level 2 average	1.99E+03	1.82E+03	1.15E+03	1.54E+03	2.02E+03	1.27E+03	1.58E+03	1.68E+03
	factor effect (kg ethylène-eq)	3.59E+02	1.89E+02	3.61E+02	9.72E+01	3.88E+02	3.66E+02	5.05E+01	4.40E+01
	factor effect (%)	93%	49%	93%	25%	100%	94%	13%	11%
EP	level 1 average	9.28E+02	1.54E+03	1.58E+03	1.40E+03	9.98E+02	1.56E+03	1.28E+03	1.29E+03
	level 2 average	1.58E+03	1.06E+03	9.26E+02	1.22E+03	1.60E+03	1.04E+03	1.32E+03	1.31E+03
	factor effect (kg phosphate-eq)	2.79E+02	2.44E+02	2.81E+02	7.55E+01	3.02E+02	2.62E+02	2.06E+01	1.43E+01
	factor effect (%)	92%	81%	93%	25%	100%	87%	7%	5%
ADP	level 1 average	1.53E+02	4.27E+02	3.26E+02	2.80E+02	1.73E+02	2.54E+02	2.26E+02	2.63E+02
	level 2 average	3.29E+02	8.06E+01	1.57E+02	2.34E+02	3.34E+02	2.54E+02	2.81E+02	2.44E+02
	factor effect (kg	7.52E+01	1.73E+02	7.24E+01	2.00E+01	8.06E+01	7.14E-02	2.72E+01	9.21E+00

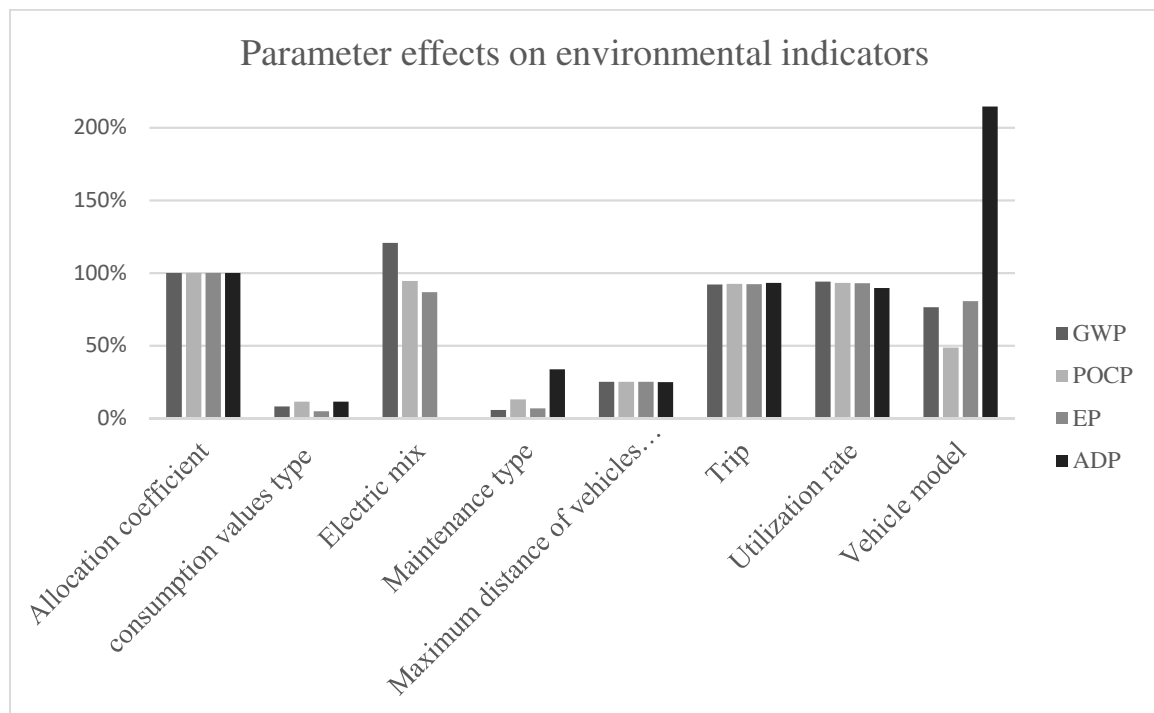


Figure 3 Parameter effects (%) on environmental indicators

In a full factorial design, all parameter combinations (256) are tested to obtain the most complete information. In this experiment, by carrying out only 32 simulations, a fortiori information is lost. Efficiency and robustness depend on the choice of tested combinations (i.e. on the levels assigned to the different factors during the tests). The design of experiments method, therefore, does not provide the exact value of the means and effects that would be obtained by carrying out the 256 simulations for each indicator but does yield a value close enough for the needs of the study. Indeed, the objective is not to precisely determine the influence of each of the parameters on the environmental indicators but to compare their influence and be able to rank them.

Given the results, it is possible to draw conclusions on the influence of the eight study parameters on the environmental impacts of the service by comparing the value of the parameter effects for each indicator. Table 7 outlines the sensitivity analysis matrices for the eight parameters. The first matrix shows the influence of each parameter with the influence of the reference parameter (maximum effect value for each indicator), thus making it possible to compare the influence of the different parameters. In the second matrix are the ranks of each of the parameters according to their effect values on each of the four indicators.

Table 7 Sensitivity analysis matrices of parameters

Parameters	GWP	POCP	EP	ADP
Trip	76%	93%	92%	43.46%
Vehicle model	63.28%	48.66%	80.70%	100%
Use rate	77.95%	93.08%	92.85%	41.83%
Maximum distance of service vehicles	20.79%	25.06%	24.99%	11.57%
Allocation coefficient	82.92%	100.00%	100.00%	46.61%
Electric mix	100.00%	94.40%	86.82%	0.04%

Maintenance type	4.72%	13.01%	6.82%	15.73%
consumption values type	6.80%	11.33%	4.74%	5.33%

	90-100%
	80-90%
	60-80%
	40-60%
	20-40%
	10-20%
	0-10%

455

Parameters	GWP	POCP	EP	ADP
Trip	4	4	3	3
Vehicle model	5	5	5	1
Use rate	3	3	2	4
Maximum distance of service vehicles	6	6	6	6
Allocation coefficient	2	1	1	2
Electric mix	1	2	4	8
Maintenance type	8	7	7	5
consumption values type	7	8	8	7

6. Discussion

460 It is important to emphasize that these results are based on the study's methodology and assumptions. Indeed, the allocation coefficient parameter ranks among the most influential parameters for each environmental indicator. The strong influence of this parameter is related to its wide range of variation (between 0.25 and 0.75). Seeing as the choice of the coefficient value is subjective, it seemed necessary to select a broad range. Indeed, the value of this coefficient reflects the share of the manufacturing impacts of vehicles that is directly attributed to the service from the initial use. In the case of vehicles designed specifically for use in a car-sharing service, there would be a tendency to maximise the value of this coefficient. As the vehicles do not reach the end of their life at the end of two years (the theoretical distance at the end of the vehicle's life is imposed at 200,000 km), the part of the vehicle manufacturing impacts attributed to the service depends strongly on the value of this allocation coefficient. As the vehicle manufacturing impacts correspond to a major part of the service impacts for each indicator, it explains that this coefficient has a major influence on the service impacts.

475 The electricity mix has a major influence on the GWP and the POCP while it does not have a great influence on the EP and ADP indicators. This is because according to our input data used, electricity production in China emits 13 times more kg CO₂-equivalent and 25 times more kg of Ethylene-equivalent than in France. For the EP indicator, the ratio is 9 between the electrical mixes, and for the ADP indicator, it is close to 1. As the impacts of vehicle use represent, as for manufacturing, a major part of the impacts attributed to the service, it is logical that this parameter also has a major influence on the impacts for the GWP and POCP indicators. The deployment of a free-floating electric car-sharing service in a city should depend on the electric mix used to recharge vehicles. When this type of service is set up in Paris or Berlin, for example, its impacts will be very different.

480 However, concerning the type of maintenance, its influence on the impacts is not significant. This is simply justified by the fact that the share of service impacts related to maintenance is very low compared to impacts related to the manufacture and use of vehicles. Likewise, concerning the type of

485 consumption values, the difference between the theoretical value of the consumption of vehicles in the NEDC cycle and the values of actual consumption in urban or peri-urban trips is not large enough to have a major influence on the difference in service impacts after two years.

490 Regarding the vehicle model, it is the most influential parameter on the ADP indicator. This is because the production of electric vehicles represents the largest share of the impacts of this indicator. The depletion of critical abiotic energy and non-energy resources and the future availability to meet their demand appears to be a potential limit to the expansion of the electrified vehicle industry due to the use of their components and especially lithium-ion batteries (Hernandez et al., 2017). The B-segment model has a lithium-ion battery that has twice the capacity of the A-segment model. Then there is also a major difference in mass and trim level between these two models. These elements explain that the parameter of the vehicle model has a major influence on the ADP indicator. It seems relevant to offer 495 low-end A-segment vehicles in this type of service as long as this does not significantly deteriorate the attractiveness of the service.

7. Conclusion

500 This study ranks the various parameters according to their influence on the values of the four indicators of the service's environmental impacts. The loss of accuracy of the results due to the use of the design of experiments may, in some cases, postpone the prioritisation of the parameters. However, it is still possible to draw interesting conclusions from the results. First, the importance of the choice of allocation coefficient, which has a major influence on the results (for all four indicators), must be 505 stressed once again. Concerning the study's other parameters, the electricity mix also has a significant influence on the GWP and POCP service impact indicators. The rate of use of the service vehicles, as well as the standard trip, significantly influence the four indicators of the service's impacts. Increasing the use rate of the service increases its profitability and environmental performance. In terms of a standard trip, the results show that the impacts are lower when the service's trips are only road trips 510 (peri-urban). In reality, the type of trip depends on the area in which the service is deployed. If the area favours mainly urban trips, a vehicle model suitable for urban use (segment A or B vehicle) must then be put in service. Finally, the choice of vehicle model (segment, level of range, finish) has a major influence (far more than other parameters) on the abiotic depletion potential (ADP) indicator, which is logical considering the vehicle manufacturing phase.

515 The results obtained in the study therefore make it possible to rank the selected parameters of the free-floating car-sharing system. However, this study has certain limitations. First, in terms of the testing method, the choice of a design of experiments with 32 simulations had a negative impact on the accuracy of the results. To increase the robustness of the experiment, it would be possible to carry out the 256 simulations (for each indicator) of complete factorial design for eight factors at two levels. 520 This would require more time and the optimisation of the calculation process. The methodology also has limitations due to the lack of guidelines to apply the LCA methodology to product-service systems and car-sharing services in particular. Several of the assumptions and conventions in the study affect the results. In the future, applying LCA to other case studies would support the development of guidelines and standards to facilitate the approach. In this paper, eight parameters from the system with the limitations presented here are analysed. It would be interesting to extend the system's limits 525 by integrating several elements of a free-floating car-sharing system, such as service infrastructure (related to electric vehicle charging), user behaviour (type of driving, use of heating/cooling), or battery size (for electric vehicles). Additional parameters may also have a significant influence on environmental impacts. Also, considering a more detailed scale of the service (e.g. size of the battery pack in electric vehicles) would make it possible to enhance the service's environmental optimization. 530

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640 9. Appendix
 9.1 Appendix 1: Design of experiments used

Observations	Trip	Vehicle model	Use rate	Maximum distance of service vehicles	Allocation coefficient	Electric mix	Maintenance type	Consumption values type
Obs1	1	1	1	1	1	1	1	1
Obs2	1	1	1	1	2	2	1	1
Obs3	1	1	1	2	1	2	1	2
Obs4	1	1	1	2	2	1	1	2
Obs5	1	1	2	1	1	2	2	1
Obs6	1	1	2	1	2	1	2	1
Obs7	1	1	2	2	1	1	2	2
Obs8	1	1	2	2	2	2	2	2
Obs9	1	2	1	1	1	2	2	2
Obs10	1	2	1	1	2	1	2	2
Obs11	1	2	1	2	1	1	2	1
Obs12	1	2	1	2	2	2	2	1
Obs13	1	2	2	1	1	1	1	2
Obs14	1	2	2	1	2	2	1	2
Obs15	1	2	2	2	1	2	1	1
Obs16	1	2	2	2	2	1	1	1
Obs17	2	1	1	1	1	2	2	2
Obs18	2	1	1	1	2	1	2	2
Obs19	2	1	1	2	1	1	2	1
Obs20	2	1	1	2	2	2	2	1
Obs21	2	1	2	1	1	1	1	2
Obs22	2	1	2	1	2	2	1	2
Obs23	2	1	2	2	1	2	1	1
Obs24	2	1	2	2	2	1	1	1
Obs25	2	2	1	1	1	1	1	1
Obs26	2	2	1	1	2	2	1	1
Obs27	2	2	1	2	1	2	1	2
Obs28	2	2	1	2	2	1	1	2
Obs29	2	2	2	1	1	2	2	1
Obs30	2	2	2	1	2	1	2	1
Obs31	2	2	2	2	1	1	2	2
Obs32	2	2	2	2	2	2	2	2