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EcoLabware: Assessing the carbon footprint of single-use plastic ware versus reusable glassware

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EcoLabWare calculator[1] aims at comparing the carbon footprint and the water scarcity footprint (method AWARE) of reusable and single-use labware items, either pipettes, tubes or conical flasks (Erlenmeyer). The analysis concerns the labware item itself, but not its use. For single-use labware items, this includes manufacturing, sterilization (optional), decontamination (optional), transport and end-of-life. For reusable glassware, this includes manufacturing, decontamination (optional), soaking, manual wash (optional), machine wash, sterilization (optional), transport and end-of-life. If default values are provided for most of the activity data (described in this note), few ones need to be entered by the user.

This technical note is organized as follows. In section 1, we first define the notation for all activity data and emission factors needed to compute the footprint of glassware. Then we detail, for each steps listed above, how to compute the corresponding impacts and we give the mathematical formula. Section 2 concerns the computing of the footprint of plastic ware, and has the same structure than the previous section. Finally, we put in appendix the default values used for activity data and detail some less straightforward issues.

1 Reusable glassware

1.1 Activity data and emission factors

Activity data provided by the user

- p_v is the weight of the glassware (in kg),
- τ is the autoclave filling rate,
- the manufacturing geographical zone z_v of the glass material (Europe, Asia or America),
- N_v is the number of times a glassware item is reused (31 by default),
- n_g is the number of pairs of protective gloves used per reuse (1 by default),
- n_a is the number of times the autoclave is used per week (10 by default),
- L is the number of liters of hot water (37°C) used for glassware manual wash.

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[1] `https://shinyproxy-dev.migale.inrae.fr/app/EcoLabWare`

Fixed activity data ; unless specified, their values are given in Table 1.

- q_a^{deio} is the quantity of deionized water used by a 600L autoclave per autoclaving,
- N_a is the total number of times the autoclave is used: it is the product of n_a times 52 weeks times 20 years (the average lifetime of an autoclave considered here),
- E_a^{man} is the footprint of the manufacturing of an autoclave, it depends on its size (or weight),
- k_a is the electric consumption of the autoclave per labware item, it depends on the type of glassware (see Table 2),
- C_a is the default autoclave capacity (number of glassware items that can be placed into a 600L autoclave), it depends on the type of glassware (see Table 3),
- C_a^{user} is the autoclave capacity calculated from the autoclave characteristics eventually supplied by the user. It depends on the type of glassware.
- C_w is the capacity of washer (number of items per washer), it depends on the type of glassware (see Table 3),
- N_w is the total number of times the washer is used,
- E_w^{man} is the footprint of the manufacturing of the washer,
- K_w is the electric consumption of the washer per machine wash,
- q_s^{det} is the quantity of detergent used per glassware item in the soaking step, it depends on the type of glassware,
- q^{det} is the quantity of detergent used per glassware item in the manual wash step, it depends on the type of glassware,
- q_w^{det} is the quantity of detergent used per machine wash,
- q_s^{water} is the volume of tap water used in the soaking step,
- q_w^{water} is the volume of tap water used per machine wash,
- q_w^{deio} is the volume of deionized water per machine wash,
- e_{hot}^{water} is the amount of energy required to heat 1 liter of water from 15°C to 37°C, considering 35 % of loss in boiler and distribution,
- E_g is the footprint of a pair of single-use nitrile gloves,
- α is the number of glassware items that can be manually scrubbed in one hour

Emission factors ; have been calculated and provided by Ecovamed (https://www.ecovamed.com). Each term below corresponds either to a carbon emission factor, expressed in kg CO2eq (method IPCC 2021 AR6), or to a water scarcity factor, expressed in m3 world eq (Available Water Remaining (AWaRe) model). All calculations are the same for both impacts, only the values and units of the emission factors change.

- $f_v^{man}(z_v)$ is for the glass manufacturing in zone z_v (either Europe or out of Europe)
- f_v^{end} is for the end of life of glass
- f_{small}^{t} is for the transportation by middle size lorry
- f_{big}^{t} is for the transportation by large lorry

- f^t_{sea} is for the transportation with container ship
- f^{water}_{tap} is for the production of tap water
- f^{water}_{deio} is for the production of deionized water
- f^{det} is for the manufacturing of detergent for soaking
- f^{det}_w is for the manufacturing of detergent for machine wash
- f^{home} is for the commuting of personnel by car (mean for French citizen)
- f^{elec} is for the production and distribution of electricity, it depends on the country selected by the user
- f^{gas} is for the production of energy with natural gas

1.2 Manufacturing

The impacts E^{man}_v of the manufacturing of the glassware are given by

$$E^{man}_v = \frac{p_v f^{man}_v}{N_v} \tag{1}$$

where p_v is the weight of the glassware, f^{man}_v is the emission factor of laboratory glassware manufacturing (it depends on the country of production) and N_v is the number of times the glassware is reused. The default value of the later was obtained as follows. For each type of item, a ratio was obtained by dividing the number of items washed per year by the number of items bought per year in Micalis unit (average purchases over 5 years); N_v is the mean of these ratios.

1.3 Transport

The impacts $E^{transport}_v$ of the transport of the glass material are given by

$$E^{transport}_v = \frac{p_v t}{N_v} \tag{2}$$

where p_v is the weight of the glassware (in kg), N_v is the number of times the glassware is reused, and t is the footprint generated to transport 1kg of labware (from factory to lab and from lab to incinerator). t depends on the geographic zone of manufacturing entered by the user (see the appendix for the details of its computation).

1.4 Autoclaving

The impacts of autoclaving $E^{autoclave}_v$ result from the following activities: the use of deionized water, commuting of the personnel, manufacturing of the autoclave and the electric consumption of the autoclave. All these parts vary with the type of glassware considered, as the number of glassware items τC_a that can be placed in an autoclave depends on the type of glassware. The part related to the manufacturing of the autoclave may depend on parameters entered by the user, which explains the use of C^{user}_a in the formula below; if the user does not provide any autoclave characteristics, then one should replace C^{user}_a by the default capacity C_a of the autoclave. We hypothesized that the quantity of water and personnel working time per item does not vary with the size of the autoclave. The amount of time required for loading and unloading a 600L autoclave is hypothesized to be one hour. The mean of electrical consumption per glassware item k_a was found to vary little with the size of the autoclave (see the appendix), and is therefore a constant per type of item. It corresponds to a classical sterilization program (120°C for 20 minutes). The formula is

$$E^{autoclave}_v = \frac{q^{deio}_a f^{water}_{deio} + f^{home}}{\tau C_a} + \frac{\frac{E^{man}_a}{N_a}}{\tau C^{user}_a} + k_a f^{elec} \tag{3}$$

1.5 Soaking

The impacts of soaking E_v^{soak} result from two activities: the use of tap water and the use of detergent, leading to

$$E_v^{soak} = q_s^{water} f_{tap}^{water} + q_s^{det} f^{det} \tag{4}$$

where q_s^{water} and q_s^{det} are the quantities of water and detergent used (they depend on the type of glassware, see Table 1), and f_{tap}^{water} and ^{det} are the emission factors for the production of water and detergent.

1.6 Manual wash

The impacts of manual wash $E_v^{man\_wash}$, if any, result from the following activities: the use of tap water, the heating of the water (either with natural gas or electricity), the use of detergent and the employee's commuting, which is proportional to the manual wash duration. All these parts appear explicitly in the formula below:

$$E_v^{man\_wash} = \frac{f^{home}}{\alpha} + L\, f_{tap}^{water} + q^{det}\, f^{det} + L\, e_{hot}^{water}\, f^{energy} \tag{5}$$

where α is the number of glassware items that can be manually scrubbed in one hour (it has been evaluated to 120 for tubes and 60 for Erlenmeyer flasks), f^{energy} is equal to f^{elec} or f^{gas}, depending on the energy used to heat the water, and q^{det} is the amount of detergent used. The later depends on the type of material and is given in the appendix Table 1.

1.7 Machine wash

The impacts of machine wash E_v^{wash} result from the following activities: the use of tap water, the use of the deionized water, the use of detergent, the employee's commuting, the manufacturing of the washer, the eventual gloves used and the electric consumption of the washer. All these parts vary with the type of item. They have been determined from the analysis of the water and electricity consumption of 7 washers of different brand and sizes, that showed a linear correlation between capacity and consumptions. All these parts appear explicitly in the formula below:

$$E_v^{wash} = \frac{1}{C_w}\left(q_w^{water} f_{tap}^{water} + q_w^{deio} f_{deio}^{water} + q_w^{det} f_w^{det} + f^{home} + \frac{E_w^{man}}{N_w} + n_g E_g + K_w f^{elec}\right) \tag{6}$$

1.8 End of life

The impacts E_v^{end} of the end of life of the glassware are given by

$$E_v^{end} = \frac{p_v f_v^{end}}{N_v} \tag{7}$$

where p_v is the weight of the glassware, N_v is the number of times the glassware is reused, and f_v^{end} is the emission factor of the end of life by incineration with energy recovery of glass.

1.9 Total impacts

Finally, the total carbon footprint and water scarcity footprint E_v of the reusable glassware are the sum of 8 activities: (1) manufacturing, (2) transport, (3) sterilization, (4) soaking, (5) manual wash, (6) machine wash, (3) decontamination and (7) end-of-life. The impacts of decontamination and sterilization are equal to the impacts of autoclaving.

$$E_v = E_v^{man} + E_v^{transport} + E_v^{soak} + 2\, E_v^{autoclave} + E_v^{man\_wash} + E_v^{wash} + E_v^{end}$$

2 Single-use plastic ware

2.1 Notations and constants

Activity data provided by user

- the plastic type p among polypropylene, polystyrene or polycarbonate
- p_p is the weight of the plasticware item (in kg)
- the manufacturing zone z_p of the plasticware among Europe, Asia and America

Fixed activity data

- e^{ebeam} is the amount of energy to sterilize by e-beam 1kg of plasticware (kWh/kg)
- K_a is the electricity consumption of a 600L autoclave for a classical decontamination program,
- C_{waste} is the quantity of plastic waste that can be placed in a 600 L autoclave (in kg).

Emission factors required for the computation; their values have been determined and provided by Ecovamed.

- $f_p^{prod}(z_p)$ is for the plastic manufacturing in one of the 2 zones (z_p =Europe or out of Europe), and for the 3 types of plastic p
- $f_p^{mould}(z_p)$ is for the injection moulding in one of the 2 zones (z_p =Europe or out of Europe), and for the 3 types of plastic p
- f_p^{end} is for the end of life, it depends on the type of plastic p.

2.2 Manufacturing

The impacts of manufacturing E_p^{man} result from 3 different activities: the production of plastic raw material, the injection moulding to create the plasticware item and finally its sterilization, if any. All these parts appear explicitly in the formula below:

$$E_p^{man} = p_p \left(f_p^{prod} + f_p^{mould} + e^{ebeam} \times f^{elec} \right) \tag{8}$$

where p_p is the weight of the plastic labware item, f_p^{prod} and f_p^{mould} are the emission factors corresponding respectively to the production of plastic raw material and the injection moulding (they depend on the production zone) and e^{ebeam} is the amount of energy required for sterilization by e-beam.

2.3 Decontamination

The impacts of decontamination by autoclaving $E_p^{autoclave}$, if any, result from the use of deionized water, commuting of the employee, manufacturing of the autoclave and the electric consumption of the autoclave. The calculations are based on the use of a 600L autoclave, but can be transposed to any type of autoclave, as the amount of energy consumed per unit of internal volume varies little with the size of the autoclave. The amount of time required for loading and unloading the autoclave is hypothesized to be 15 minutes. It gives

$$E_p^{autoclave} = \frac{p_p}{C_{waste}} \left(q_a^{deio} \times f_{deio}^{water} + 0.25 f^{home} + \frac{E_a^{man}}{N_a} + K_a \times f^{elec} \right) \tag{9}$$

2.4 Transport

The footprint $E_p^{transport}$ related to the transportation of the plastic ware is given by

$$E_p^{transport} = p_p t \tag{10}$$

where p_p is the weight of the plastic ware and t is the footprint generated by the transport of 1 kg of plastic labware (from factory to lab and from lab to incinerator; see appendix for its computation).

2.5 End of life

The footprint E_p^{end} related to the end of life of plasticware is given by

$$E_p^{end} = p_p f_p^{end} \tag{11}$$

where p_p is the weight of the item (in kg) and f_p^{end} is the emission factor of plastic's end of life.

2.6 Total footprint

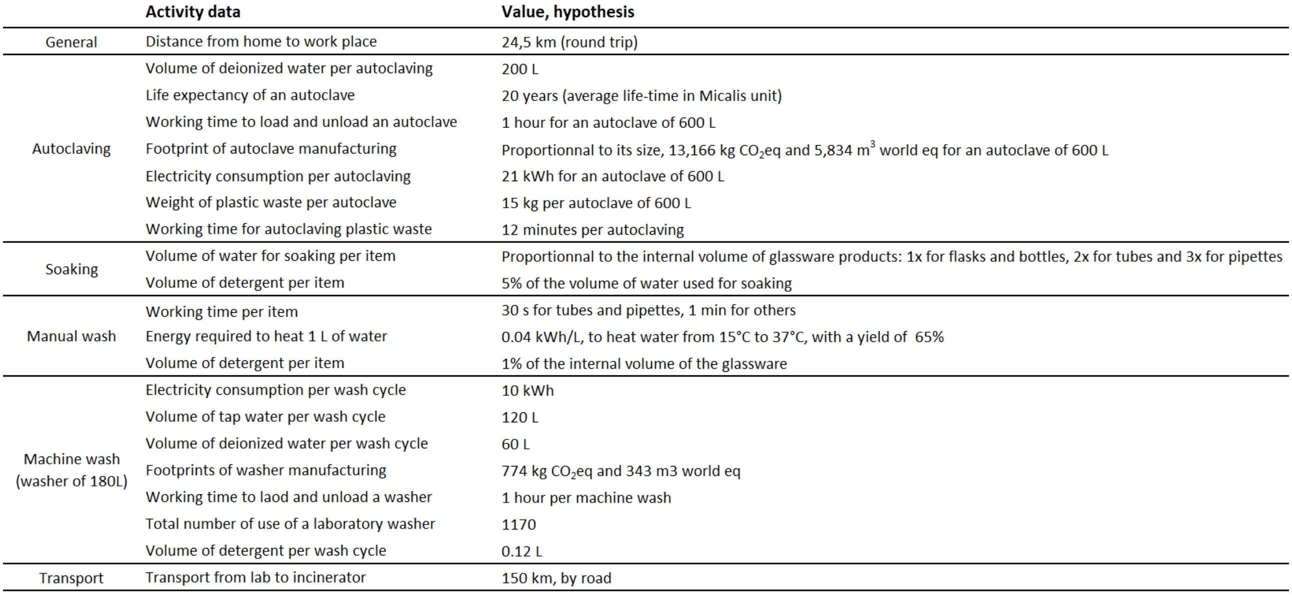
Finally, the total footprints of the single-use plastic ware are the sum of 4 activities: (8) for the manufacturing, (10) for the transport, (9) for the decontamination and (11) for the end of life:

$$E_p^{man} + E_p^{transport} + E_p^{autoclave} + E_p^{end}.$$

Appendix

Activity data

Table 1 gives the value or hypothesis regarding fixed activity data.

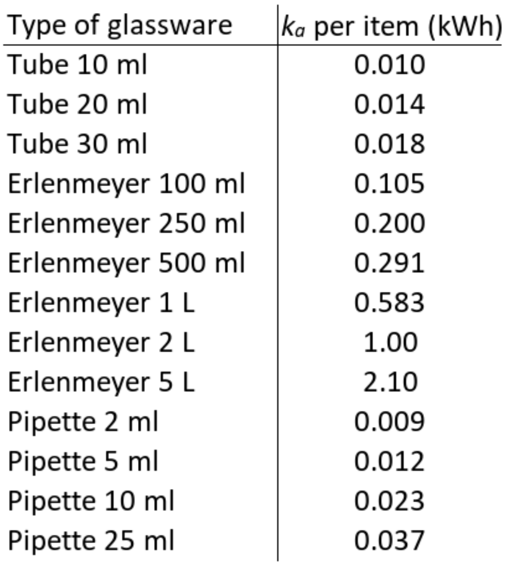


	Activity data	**Value, hypothesis**
General	Distance from home to work place	24,5 km (round trip)
Autoclaving	Volume of deionized water per autoclaving	200 L
	Life expectancy of an autoclave	20 years (average life-time in Micalis unit)
	Working time to load and unload an autoclave	1 hour for an autoclave of 600 L
	Footprint of autoclave manufacturing	Proportionnal to its size, 13,166 kg CO_2eq and 5,834 m^3 world eq for an autoclave of 600 L
	Electricity consumption per autoclaving	21 kWh for an autoclave of 600 L
	Weight of plastic waste per autoclave	15 kg per autoclave of 600 L
	Working time for autoclaving plastic waste	12 minutes per autoclaving
Soaking	Volume of water for soaking per item	Proportionnal to the internal volume of glassware products: 1x for flasks and bottles, 2x for tubes and 3x for pipettes
	Volume of detergent per item	5% of the volume of water used for soaking
Manual wash	Working time per item	30 s for tubes and pipettes, 1 min for others
	Energy required to heat 1 L of water	0.04 kWh/L, to heat water from 15°C to 37°C, with a yield of 65%
	Volume of detergent per item	1% of the internal volume of the glassware
Machine wash (washer of 180L)	Electricity consumption per wash cycle	10 kWh
	Volume of tap water per wash cycle	120 L
	Volume of deionized water per wash cycle	60 L
	Footprints of washer manufacturing	774 kg CO_2eq and 343 m3 world eq
	Working time to laod and unload a washer	1 hour per machine wash
	Total number of use of a laboratory washer	1170
	Volume of detergent per wash cycle	0.12 L
Transport	Transport from lab to incinerator	150 km, by road

Table 1: Summary of fixed activity data

Estimation of k_a, the amount of kWh per item for autoclaving

We compiled the electric consumption per item, based on the assumption that the autoclave if filled with a single type of glassware, of nine models of autoclave: Tuttnauer 2840EL, 3850 EL, 3870 EL, 5050 EL, 5075 EL, 2840 ELV, 3850 ELV and 5050 ELV models, and Steam A-line 600 model. The internal volume of these autoclaves ranges from 28 L to 600 L. The number of items that can be placed in an autoclave was obtained either from the documentation of the manufacturer for Erlenmeyer flasks, or for measurements on a smaller number of models (Tuttnauer 2840EL and 5050WEL and A-Line 600) for tubes and pipettes. We found that the amount of kWh per item is relatively independent of the autoclave model. We therefore defined k_a as the median of the values (in kWh/item) obtained for the 9 autoclaves. k_a values for each type of item are given in Table 2.



Type of glassware	k_a per item (kWh)
Tube 10 ml	0.010
Tube 20 ml	0.014
Tube 30 ml	0.018
Erlenmeyer 100 ml	0.105
Erlenmeyer 250 ml	0.200
Erlenmeyer 500 ml	0.291
Erlenmeyer 1 L	0.583
Erlenmeyer 2 L	1.00
Erlenmeyer 5 L	2.10
Pipette 2 ml	0.009
Pipette 5 ml	0.012
Pipette 10 ml	0.023
Pipette 25 ml	0.037

Table 2: Electricity consumption per item and per autoclaving

Capacity calculation

The default C_a corresponds to the number of items of a given type that can be placed into a Steam A-line 600 autoclave. The user capacity τC_a^{user} is calculated by first determining the volume required per item for each type of glassware across the 9 previously described autoclave models. The average volume was then calculated, and the user's entered autoclave volume is divided by this average to obtain τC_a^{user}. If the weight is entered, the τC_a^{user} is calculated similarly, by first multiplying the weight by 1.66 to obtain the volume of the autoclave. C_{wash} corresponds to the number of items that can be placed into a 180 L laboratory washer (Lancer Ultima 1300LX). C_a, τC_a^{user} and C_{wash} values are given in Table 3.

Transport calculation

t corresponds to the footprint generated by the transport of 1kg of labware from the geographical zone of manufacturing (Europe, Asia or America) to France[2], both from factory to lab, and lab to incinerator:

- Assumption for transport from factory to laboratory: Europe: 500km factory-warehouse by road with a trailer truck and 500 km warehouse-lab by delivery truck; Asia: 500km factory-port by road with a trailer truck, 20,000km by sea, 500km port-warehouse road by trailer truck, 500km warehouse-lab by delivery truck; Americas: 1000km factory-port by road with a trailer truck, 10,000km by sea, 500km port-warehouse road by trailer-truck, 500km warehouse-lab by delivery truck)
- Assumption for transport from lab to incinerator: 150km lab-to-incinerator route by delivery truck.

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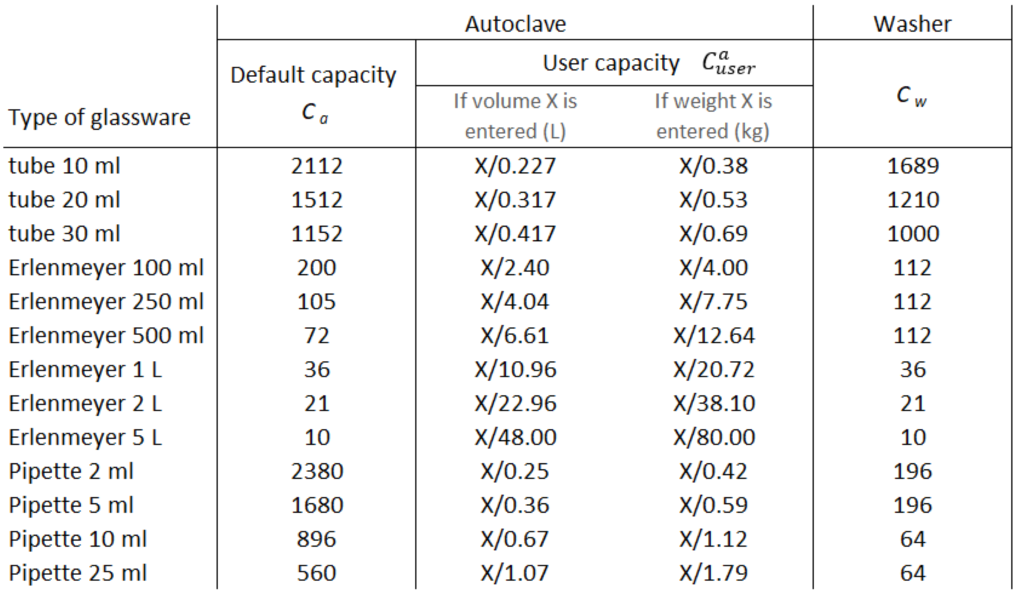
[2] For more generality, one should also consider the case where the user is not in France; this is part of future development



Type of glassware	Autoclave			Washer
	Default capacity C_a	User capacity C^a_{user}		C_w
		If volume X is entered (L)	If weight X is entered (kg)	
tube 10 ml	2112	X/0.227	X/0.38	1689
tube 20 ml	1512	X/0.317	X/0.53	1210
tube 30 ml	1152	X/0.417	X/0.69	1000
Erlenmeyer 100 ml	200	X/2.40	X/4.00	112
Erlenmeyer 250 ml	105	X/4.04	X/7.75	112
Erlenmeyer 500 ml	72	X/6.61	X/12.64	112
Erlenmeyer 1 L	36	X/10.96	X/20.72	36
Erlenmeyer 2 L	21	X/22.96	X/38.10	21
Erlenmeyer 5 L	10	X/48.00	X/80.00	10
Pipette 2 ml	2380	X/0.25	X/0.42	196
Pipette 5 ml	1680	X/0.36	X/0.59	196
Pipette 10 ml	896	X/0.67	X/1.12	64
Pipette 25 ml	560	X/1.07	X/1.79	64

Table 3: Autoclave and washer capacities per item (number of items per machine)

It leads to:

$$1000t = \begin{cases} 500f^t_{big} + 500f^t_{small} + 150f^t_{small} & if \quad zone = \text{Europe} \\ 500f^t_{big} + 20000f^t_{sea} + 500f^t_{big} + 500f^t_{small} + 150f^t_{small} & if \quad zone = \text{Asia} \\ 1000f^t_{big} + 10000f^t_{sea} + 500f^t_{big} + 500f^t_{small} + 150f^t_{small} & if \quad zone = \text{America} \end{cases}$$

Autoclave and washing machine manufacturing footprint calculation

Washing machine The footprints (both carbon and water scarcity) of the manufacturing of a laboratory washer was calculated proportionally to its weight, using the footprints of the household dishwasher Kitchen Aid KDTM354ESS [1].

Autoclave The footprints of an autoclave manufacturing is similarly calculated proportionally to its weight, using the carbon footprint that has been calculated for the GSS-P 91413 Gettinge autoclave: 34 220 kg CO2e [2]. To get the water scarcity footprint, we used the same ratio between CO2eq and m3 world eq for the autoclave and the washer.

Estimation of detergent quantity

The amount of detergent used for soaking glassware is one twentieth of the volume of water required for soaking, which is one fold the internal volume of labware for flasks and bottles, twice the internal volume for tubes and three times the internal volume for pipettes.

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[2] Hella and Madhusoodhanan (2022). Life Cycle Assessment (LCA) of a GSS-P 91413 Autoclave Produced in the Getinge Factory, Master's thesis in Mechanical Engineering, Halmstad University, `http://hh.diva-portal.org/smash/record.jsf?pid=diva2%3A1673121&dswid=-325`