LCA OF A LUXURY MECHANICAL WATCH

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Executive Summary

The luxury watch industry is composed by many actors, mainly located in Switzerland whose values are precision, refinement and quality. For the vast majority, they are settled for almost a century in this field, producing watches always more complex but whose essence remained the same. With the evolution of environmental consciousness, the science of life cycle assessment has made its way to this industry in order to give a new vision of the impacts and future challenges.
The present LCA is comparing the environmental impact of two luxury mechanical watches different only by the material composing their bracelets, one made of rubber and the other of steel. The goal is to identify specific indicators that are relevant in this field and compare the different outcomes based on the materials. Further sensitivity analysis are introduced to assess for instance the benefits that can be obtained by recycling scrap generated during the production phase. In this way, what is commonly called hot-spots can be identified in order to raise questions on how to make such a watch more eco-friendly. Data is provided by the companies in the consortium with confidential clause. Also, the study is solely for internal use in the consortium. No disclosure is to be made except in the closed range of the academic framework (ENV-510 course, EPFL).
In the meantime, the Ecoinvent database is put to a test in describing materials and processes specific to the micro technology industry (watchmaking), a domain poorly served by LCA tools up to now, even though a rising interest is observed, boosted in particular by few smart watch studies. In the framework of a larger project commissioned by a consortium of watch making companies, this study should also “pave the way” for watch oriented LCA tools, trying to understand whether Ecoinvent is sufficient for watch LCA or needs to be fed with new processes.
The results shows that the rubber bracelet is better in almost all the environmental impacts than the basic steel one, as extraction and metal working has great impacts. The results are a bit nuanced when adding additional assumptions: if a serious effort is put on recycling scraps, the rubber bracelet is not the best anymore for impacts like eco-toxicity. At last, the location of services plays an important role. A swiss watch may return to Switzerland for its maintenance ans as expected it will have a far greater impact than a maintenance in the local shop.
Many assumptions needed to be made to treat properly the subject such as transport or recycling. The most impacting ones are studied in three different sensitivity analysis: the processes not modelled in Ecoinvent, the modelling of tungsten and the quantity of scraps. When the first two does not play a great role in our results, the impact of the last is very significant.
To conclude, we show that our study permitted to make a sustainable choice between rubber and steel bracelet. However, the many uncertainties shows that there still is some work to be done in order to make the precise life cycle assessment of a watch.

Contents

1 Environmental issues in the Watch industry

Mechanical watches are mainly made up of metals like steel, aluminium or nickel alloys. Several rare metals such as gold or platinum are also present in some components. The impact of the extraction of all these metals is huge, in terms of CO2 produced but also in the management of resources, the impact on ecosystems or on human health. The article of Sabah Abdul-Wahab and Fouzul Marikar [3] gives an example of the pollution in water stream and soil, and by consequence on the ecosystem in larger scale and on the health of the surrounding population, caused by gold mines.

The Swiss watch industry is known for its very high precision micro technology. This industry is however expensive in terms of energy. Many manufacturing processes are often very precise and the production of a piece takes a lot of time and therefore energy. The requirements in terms of precision are also very high, which can induce a greater rejection in the production. The first goal of this project is to assess the environmental impact of all the steps of the watch's life cycle to establish where an effort can be made to reduce this impact. The steps are, as for all products, the materials extraction, the pieces production, the assembly, the transportation, the distribution, the packaging, the maintenance, the use and the end of life (recycling and/or landfill).

This project is also about the comparison of different bracelets for the watch. It can be made of metal or rubber. The impact of these two materials is very different, as well as their lifespan and maintenance. For example, the CO2 impact production of rubber is lower than that of steel but poses other problems such as deforestation, as shown in the article of Perapong Tekasakul and Surajit Tekasakul [4].

2 Review of similar LCA studies

The only study found of LCA on watches is from Huynh Quang Nguyen Vo, et al. on a Samsung Galaxy watch, made in January 2020 at Aalto university [5]. They analyse in their study the energy usage, the carbon footprint and the water consumption of the material extraction, the manufacture, the consumer use during three years of life and the end of life. They found that the total manufacturing process of the watch impact is of 8.88kg of CO_2 and represents around 95% of the final impact of the whole life cycle product. They don't take into account the assembly of the product, the transportation, distribution and packaging. They also affirm that a potential recycling of the watch can compensate 15% of the total life cycle CO_2 emissions.

This study is about an electronic smartwatch, which is quite different from a mechanical watch. First the manufacture, with no electronic devices like batteries in a mechanical watch, then the use, the fact that there is no need to charge a mechanical watch. Finally, the life expectancy is around 10 times smaller in a electronic watch. Similarities between the two studies are maybe the extraction of the materials, the watch case and strap, and a potential recycling of the elements. It is also desirable to take into account the assembly, transportation and packaging phases, in order to establish an impact comparison between all the different processes.

3 Project objectives

The present LCA has been commissioned by a consortium of several companies, namely

- Azurea Technologie Horlogere SA
- Panatere SA
- Kering SA
- Manufactures Cartier Horlogerie, Branch of Richemont International SA
- La Fabrique du Temps Louis Vuitton SA
- 109 degrees

This project aims at comparing the environmental impact of two variants of the same watch. One has its bracelet made of steel while the other has it made of rubber, all remaining components and parts being the same between the two products. Additionally, since watchmaking is an industry using very specialized processes in its production phase, it represents also the opportunity to put to test an existing database (Ecoinvent) for that specific industry: among the many manufacturing processes identified, some will be properly identified in the database while (many) others will be only approached by the existing closest ones. In fact, the study at hand is part of a larger project dedicated to the creation of an environmental database of the processes and materials of the micro-technology. In this context, a work in parallel is led by the University of Applied Sciences Northwestern Switzerland to precisely study watchmaking manufacturing processes and gather data to implement them in LCA models. Consequently, the following pages serve also as an introduction of the LCA science in a domain such as watchmaking where previous studies are extremely rare or not brought to the general public.
The present LCA study is meant solely in the framework of the presented project: the intended audience is internal with exception of the academic framework (course ENV-510 at EPFL) but not public. Correspondingly, the study will not be used to support comparative claims disclosed to the public.

4 Product system description

The two product systems to compare will be watches only different from each other in the material their bracelets are made of, as mentioned in the previous section: one is made of metal, while the other one is made of rubber. The movement (*mouvement* in french, basically the driving parts allowing the watch to function and to break down time into units - seconds, minutes, hours[4]) of the watches as well as the rest of the casing (*habillage* in french) remain the same, but as a part of the goal of the study is to understand if current databases are complete enough to describe the manufacture of a watch, the study will be as comprehensive as possible for all the parts of the watch. Thus, most of the processes will be modelled gate-to-gate. Only the raw materials, transport and manufacturing processes will be implemented cradle-to-gate.

[4] https://www.lepage.fr/fr/blog/les-mouvements-d-une-montre--n37

One can easily imagine that the product system of a mechanical watch can get extremely dense considering all the parts required for its fabrication and watchmaking specific processes. In fact, the watch studied is composed by 165 movement components and about 70 casing components. These components can't be treated individually considering the complexity that they would generate on the software used for the LCA. Furthermore, many components show similarities in their conception or material, this is why it has been decided to group movement components in 12 groups. The groups are the following :

- pinions
- plates
- wheel (pinion + plate)
- simple pinion
- bridge(bar)/disk
- screw
- flat items
- mass segment
- bridge(bar)/disk assembly
- jewel
- tenon/pin
- Movement others

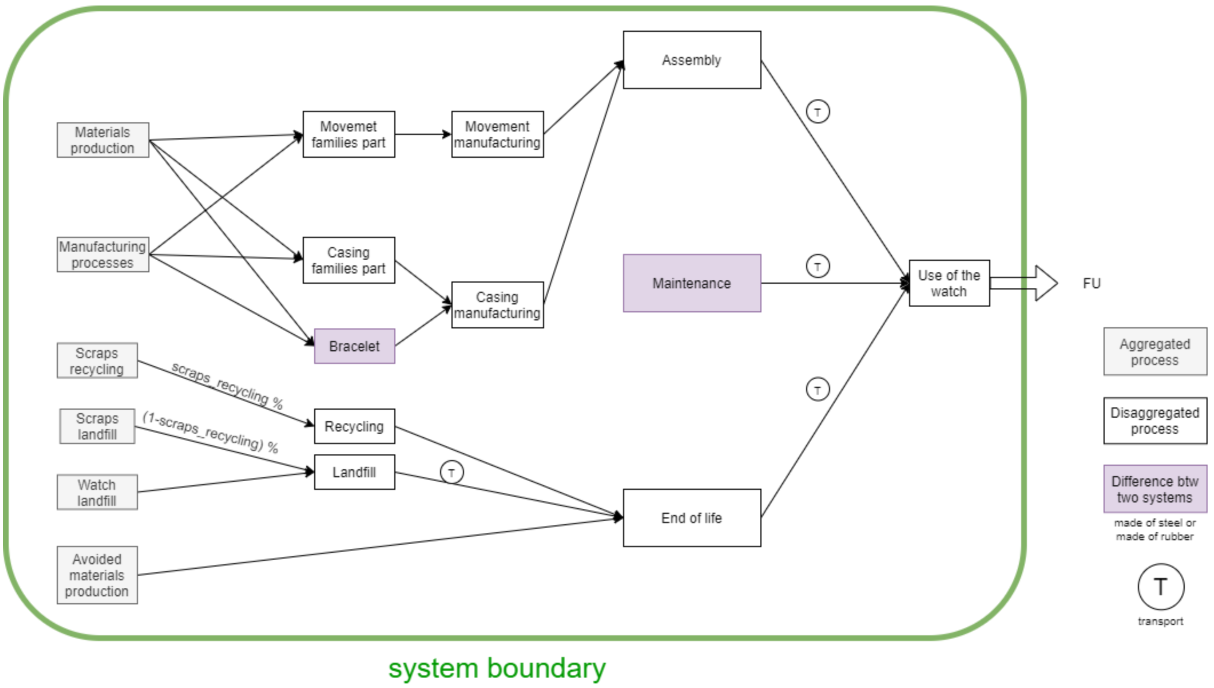

Figure 1: Process tree of the two product systems, mechanical watch with steel bracelet and mechanical watch with rubber bracelet

These groups will be used to gather components as well as assemblies. Each group comes with a series of processes associated with it, that are applied to its components. In the case of components, the production of raw material will be added to the inputs, whereas for assembly groups only assembly processes that are recurrent will be set as inputs.

The same categorisation work has been conducted for the casing and bracelet. Components fall into 8 categories :

- hands
- dial/collar
- steel components
- sapphire
- plastic components
- indexes
- bracelet

The process tree retained is presented above, in a simplified version. A detailed version regarding the family groups organization can be found in the appendix Figure 11. Many choices lead to such a representation, for the sake of simplicity. First of all, material is not explicitly shown as they would complexify even more the process tree. Still, some component groups that are all made of the same material are specified. Then, in order to have clear and handy economic fluxes, it has been decided to regroup everything in movement manufacturing and casing (*habillage*) manufacturing. Finally, to highlight the changing part in this process tree, the bracelet process is shown as being plastic or metal manufactured depending on the case.

5 Function and functional unit

The primary function of the mechanical watch system is to tell the time. Additionally, one could also involve a function of style, but of negligible importance here. The function is then formulated as follows:

"Mechanical luxury time telling for personal and portable use in 2021"

As such, the product system is strictly electricity free in its functioning (as opposed to increasing popular smart watches, see previous studies about the topic). Accordingly, the functional unit (FU) is

"Mechanical luxury time telling for personal and portable use in 2021 in the world for 80 years"

The specific time duration of 80 years corresponds to typical lifetime of such luxury watches which are kept for one's life, sometimes even longer and passed to other generation.

6 Product system boundaries

The process tree (see Figure 1) presented in section 4 aims at illustrating the boundaries, unit processes and reference flows of the systems. The two product systems only differ on the bracelet side, as mentioned previously, which is considered to be made out of steel for one and of rubber for the other. Recycling and end of life is a sensible topic of concern when it comes to luxury watches [2]. First of all, luxury watches are designed to last in time. In the ideal case they are eternal since the maintenance that should take place every 5 to 10 years is taking care of making the watch work until the next maintenance. These maintenance could imply major component changes or just a simple lubrication. Furthermore, customers pay a consequent price to acquire them and therefore are more likely to keep them in time. However, at a certain point in time, one can assume that they will reach their end of life.

The end of life recycling approach is the one retained here. As such, the primary materials are assumed 100% primary, an assumption in accordance with the information given by our reference person: very few data are available regarding the origin or not of the materials from a recycling sector. Effectively, during the manufacturing processes lots of components are made by removing metal from raw materials which results in a huge amount of scraps that can be recycled. As such, only these scraps were modelled in the recycling approach by extending the system boundary while the watch itself at end of life was considered 100% land filled. For the movement families, specific data values were given regarding the amount of scraps generated for each part. For the casing however, no data were given and as such, a parameter (copeaux = 4) was introduced to represent the part of recycled scraps. It must be noticed that in terms of mass, the movement part represent only about 6% (steel bracelet) to 10% (rubber bracelet) of the total watch mass while the casing takes the remaining proportion i.e. more than 90%. That supports the application of the scrap parameter only on the casing parts which represent nearly the watch total mass. Also, the value of 4 was chosen such as to represent the high mass proportion of scraps (here corresponds to 80%, since the copeaux parameters multiplies the final part mass to compute scrap mass, see section 7 for more details).

7 Reference flows and key parameters

As suggested by the process tree presented above, the following reference flows have been already identified: assembly, maintenance and end of life. The reference flows listed previously directly serve as input for the functional unit. The assembly flow represents the watch ready to be delivered to the customer. It is clear here that only one watch is needed to fulfil the functional unit, the key parameter being 1.

Accordingly, the following key parameters will be used: lifespan of the watch and maintenance occurrence. Watch lifespan key parameter is useful to characterise the end of life reference flow, whereas maintenance occurrence is used for maintenance reference flow. Since the functional unit covers the whole lifespan of the watch, key parameter for end of life will be one, as only one EoL process is needed per watch. The maintenance occurrence is less trivial since, a watch will be serviced on a regular basis that is inferior to the 80 years of lifespan of the watch. The value of this key parameter can be explained in section 8.

Consequently, equations referring the key parameters to calculate the reference flows are quite trivial, of the simple form.

$$\#Watch = 1(for\ 80\ years) \tag{1}$$

$$\#Maintenances = \#Maintenances\ per\ year\ \times\ 80\ years \tag{2}$$

$$\#EoL\ process = 1(for\ 80\ years) \tag{3}$$

8 Assumptions

Many assumptions were made in order to model the present system product, some already provided in the data made available, others formulated in the model framework on openLCA. All these have been summarized in four families of assumptions according to their domain/processes of application for organization and clarity purpose. They are presented in the following lines.

8.1 Transport

Hypothesis	**Value**	**Process concerned**	**Flow concerned**
Number of maintenances	11 [-]	Use of the watch	Watch serviced
Packaging factor	1.5 [-]	Use of the watch	transport, freight, lorry, unspecified
			transport, freight, aircraft, unspecified
		Maintenance	transport, freight, lorry, unspecified
Land transport distance	417 [km]	Use of the watch	transport, freight, lorry, unspecified
Air transport distance	6023 [km]	Use of the watch	transport, freight, airfract, unspecified

Table 1: Transport related assumptions

Life span of the watch has been defined to 80 years to match the average life expectancy of a human. Knowing that technically a watch could work for more than 80 years thanks to the maintenance and parts replacement, it was decided that maintenance would only take care of the visual aspect (surface treatment). The number of total maintenance is based on a seven years of after sales services. Even though, the manufacturer recommends maintenance every 5 years, it is observed that customers tend to be less regular, thus 7 years. In order to match the FU, 11 maintenance will be required. The packaging factor represents the mass increase due to the conditioning and packaging of the watch, for both sale and after sales services. The on land distance corresponds to the distance travelled by small trucks/lorries for selling purpose and was already provided while the air distance travelled by freight airplane, already provided as well, is an average made thanks to data from the *Fédération horlogère*. Based on different regions of export (Europe, Africa, Middle East, etc.), the distance was weighted on the number of pieces sold per year.

8.2 Manufacturing

The watchmaking manufacturing industry has many specific unique manufacturing processes which are not listed in the Ecoinvent database used. As such, these were approximated using general metal working process (general steel working process when steel was concerned) with a parameter $manf\_proc\_unknown$ to weight that unknown. With that parameter being 0, the n not found manufacturing processes for the family part were replaced by a single general metal working process. With 1, the n not found manufacturing processes were replaced by n general metal working processes, correspondingly meaning the amount of material worked being multiplied by n. Also, no precise information was given regarding the time duration of laser machining for the synthetic sapphire and ruby. As a gross estimation, a duration of five minutes was used.

Hypothesis	Value	Process concerned	Flow concerned
Not found manufacturing processes	1, 0	Pignon	metal working, average for metal product manufacturing
		Plates	
		Simple pinion	
		Bridge/diska assembly	
		Screw	
		Flat items	
		Mass segment	
		Jewel	
		Tenon/pin	
		Simple pinion	
		Wheel	
		Movement others	
		Hands	
		Dial/collar	
		Steel components	
		Sapphire	
		Indexes	
Laser machining approximation	5[min]	Jewel	aluminium oxide, non-metallurgical
		Sapphire	

Table 2: Manufacturing related assumptions

8.3 Materials

Most of the precise alloys used in the watch industry are not modeled in Ecoinvent, so a few assumptions were made to replace the precise metals used by metals existing in OpenLCA. We replaced different types of steel by chromium steel, unalloyed or low-alloyed steel, according to the type of alloy. We tried to replace other alloys by its dominant metal.
The case of tungsten (also not modeled in Ecoinvent) is special: the corresponding component has a relatively important mass (10 g) compared to the total watch mass and tungsten is a rare material, which extraction is not negligible. Based on an analysis by *France Stratégie* [1], we assumed that the impact of tungsten is comparable to the one of titanium and we did the corresponding replacement. A sensitivity analysis will be made on this assumption, by changing the choice of replacement metal. The matching between all watch materials and Ecoinvent ones is given in appendix Table 5.

8.4 Recycling

Hypothesis	Value	Process concerned	Flow concerned
Scraps estimation casing	4	Bracelet steel	steel, chromium steel, 18/8
Scraps estimation casing	4	Bracelet steel	chromium steel removed by turning, average, conventional
Scraps estimation casing	4	Steel components	steel, chromium steel, 18/8
Scraps estimation casing	4	Steel components	titanium, primary
Scraps estimation casing	4	Steel components	brass
Scraps estimation casing	4	Steel components	chromium steel, removed by turning, average, conventional
Collection & recycling yield	0.8, 0.6, 0.7	End of life	brass
Collection & recycling yield	0.8, 0.6, 0.7	End of life	steel, chromium steel, 18/8
Collection & recycling yield	0.8, 0.6, 0.7	End of life	titanium, primary
Collection & recycling yield	0.8, 0.6, 0.7	End of life	aluminium oxide, non-metallurgical
Collection & recycling yield	0.8, 0.6, 0.7	End of life	steel unalloyed
Collection & recycling yield	0.8, 0.6, 0.7	End of life	steel low-alloyed
Collection & recycling yield	0.8, 0.6, 0.7	End of life	copper scrap, sorted, pressed
Bronze scraps	-	Recycling	bronze scrap, post-consumer
Bronze scraps	-	Recycling	bronze

Table 3: Recycling assumptions

Since an end of life recycling approach is considered, only primary materials are used. The watch is assumed to be landfill, as represented by the process tree. A recycling of the watch at end of life could be consider, but taking into account its life span and status (luxury watch), this hypothesis is unlikely and also, scraps recycling has more importance considering the mass they represent. Consequently, the recycling of the watch itself was not considered. In this study, the use of material will play an important role in determining different impacts. Therefore, one should be really accurate in assessing the quantity of mass of scraps produced for each part. Concerning the movement parts, which represent the mass majority of the watch, data about scraps generation for each part were given: this number was extrapolated by imagining the square or cylindrical convex hull of the component and taking its mass minus the mass of the component and provided in the data. However, for the casing parts, no information were given and as such, it was advised by the reference person to consider a scraps mass equals to four times the component mass, what we implemented using $copeaux = 4$ parameter. During the project, more accurate data was given, showing that scrap mass could sometimes by 1000% (!) of the components' mass.

In order to obtain a realistic scenario, efficiencies for sorting and recycling of the scraps were introduced. For the baseline scenario, 60% of recycling rate ($scraps\_recy\_rate = 0.6$), 80% collection yield ($collection\_yield = 0.8$) and 70% recycling yield ($scraps\_recy\_yield$) were assumed. These parameters were then tuned to create three different scenarios of recycling, low, medium and high recycling situation, see section 10. Also, it must be noted that for the collection and recycling, considering the multiplicity of materials considered for scraps (brass, titanium, aluminium oxide, unalloyed steel, low-alloyed steel), the two processes were modelled using brass as a gross assumption since only the corresponding processes for copper were found and the amount of scraps per watch is not enormous in absolute (we are talking about grams but relative to the mass of the watch itself, it is quite big).

8.5 Others

Aesthetic : Luxury watches also have to comply in a certain way to the aesthetic standards of clients that invest considerable amount of money to purchase these pieces. To this extent, a particular care is given to the visual aspect of the watch and details are conscientious. Purely functional components are coated with gold or nickel even though it is not essential for the good operation of the watch. In order to simplify this aspect of the watch making, it will be assumed that each component that in reality is coated for its visual appearance, will be in the frame of this LCA coated with nickel.

Rubber bracelet : Explanations are required for bracelet lifespan. A steel bracelet is considered as the rest of the watch, thus lasting the whole 80 years, needing to be simply serviced according to maintenance occurrence. On the contrary, a rubber bracelet does not last 80 years. Firstly it wears and potentially cracks. It must therefore be replaced and this is included in the maintenance. In the case of a watch with rubber bracelet, maintenance process will include the production of a new bracelet. The assumption being that the rubber bracelet has a lifespan equal to the maintenance occurrence.

9 Data sources

In order to make a precise life cycle assessment of a watch, an important amount of data is required, on all the mechanical parts of the watch, even the smallest ones.
109 Degrees in collaboration with Louis Vuitton have worked to provide a very complete nomenclature of one of its watches, under a confidentiality clause. This document provides a vast range of information on the casing and the movement. Firstly, it provides exploded view for both casing and movement with a precise legend of each component. These latter will only be used to visualise how the watch is assembled and in which order.
Secondly, two additional tables thoroughly list all the components of the watch and casing with excessive amount of data for the purpose of this LCA. It gathers information about density, surface, mass, volume, scrap mass, scrap volume and much more for each component. For the scope of this LCA, only mass and scrap mass will be relevant. In addition, for each component, it is given its material, number of pieces in a watch and identification numbers.
Thirdly, a last table provides a list of processes that are used in order to manufacture each part and assemble them together. Each family of components for the movement and the casing is associated with a series of processes applied to its components. As these processes are utterly specific to watch manufacturing and also provided in French, a work of translation and characterisation has been conducted with 109 Degrees.

10 Impact assessment results and interpretation

The two main ideas to reduce the impact of a mechanical watch are the recycling and using rubber instead of steel for the bracelet. The indicators retained here are the climate change, long term since mechanical watches have a long lifetime, the human toxicity non cancer because a watch is in direct contact with the human skin, the freshwater eco-toxicity due to the fact that some watches are made to be submerged and the mineral resources use since that a watch needs these resources to be produced.

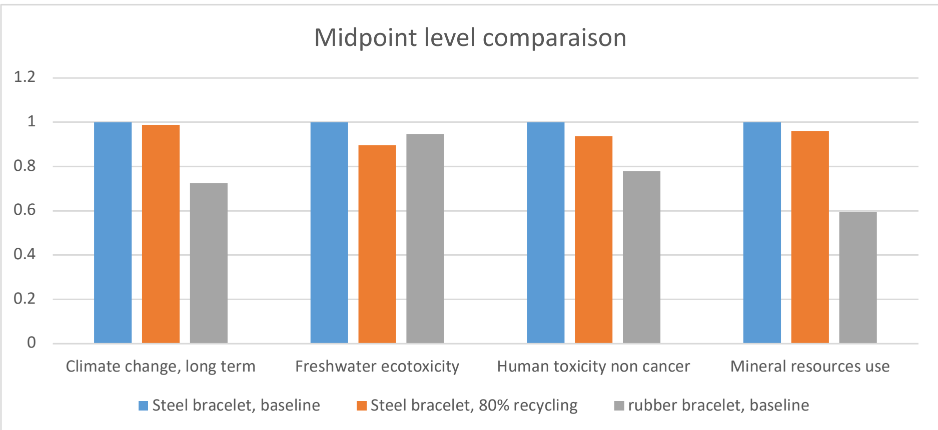

Figure 2: Midpoint analysis with maintenance travel by plane

The figure above shows that for the fresh water eco-toxicity, the rubber bracelet is a little bit higher in terms of impact than the recycled case with the steel bracelet. However the rubber is lower in the other case with a significant difference in the climate change and the mineral resources use. For the results above the number of services was set to eleven in accordance with the previous assumptions and they are supposed to be made in Switzerland, so the watch travels back and forth by plane.
However the same analysis can be done assuming that the watches are serviced locally, *ie* in the country of the client, so when they get serviced they are travelling only by lorry and on a much smaller distance. This may reduce the impact of the steel bracelet because it is heavier.

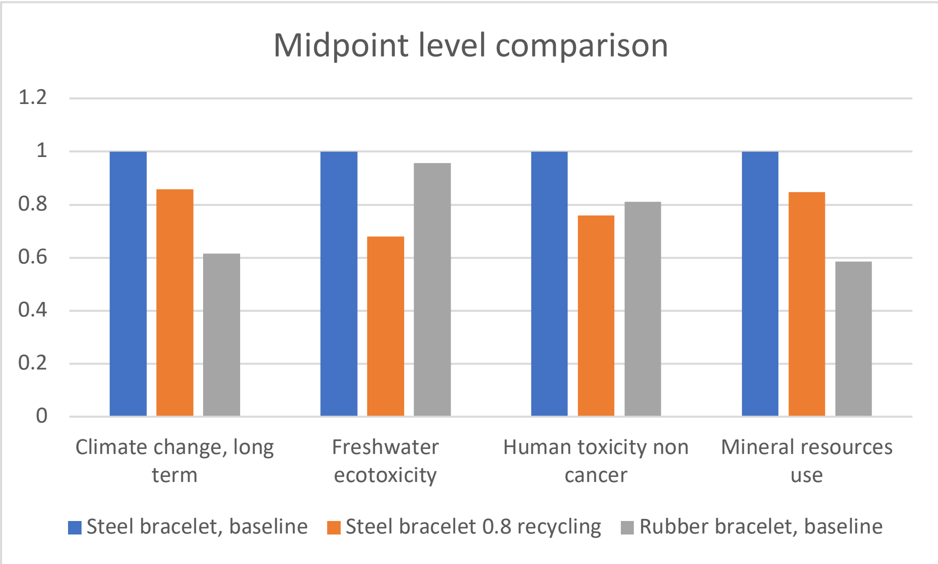

Figure 3: Midpoint analysis with maintenance travel by lorry

Here the lower impact for freshwater eco-toxicity is without doubts for the recycling scenario. As expected, the reduction of transport benefits to the heavier steel bracelet. Then, the rubber bracelet becomes less "ideal" in the impacts where rubber plays a significant role: eco- and human toxicity. The impact between the rubber and the high recycling are now close to each other for the human toxicity and there is still a significant lower impact for the rubber for the climate change and the mineral resources use.
In the Figure 4, it can be observed that the main processes contributing to the climate change are linked with the chromium steel. This material is used for many components of the case and in particular for the steel version of the bracelet. That is why removing this material by using a rubber bracelet decreases so much the impact on the climate change, indeed the mass of the steel bracelet corresponds almost to half of the total chromium steel used.
From an environmental damage perspective, the Figure 5 shows that the main damages categories for the three scenarios are the climate change and the freshwater ecotoxicity. This is comforting the choice of retained midpoints made before.
If the elementary flows are analysed it is clear from the biggest part of carbon dioxide emitted that the impact on climate change is important. The other important flow is aluminium which contributes to increase the impact of freshwater ecotoxicity, when all other flows are negligible.

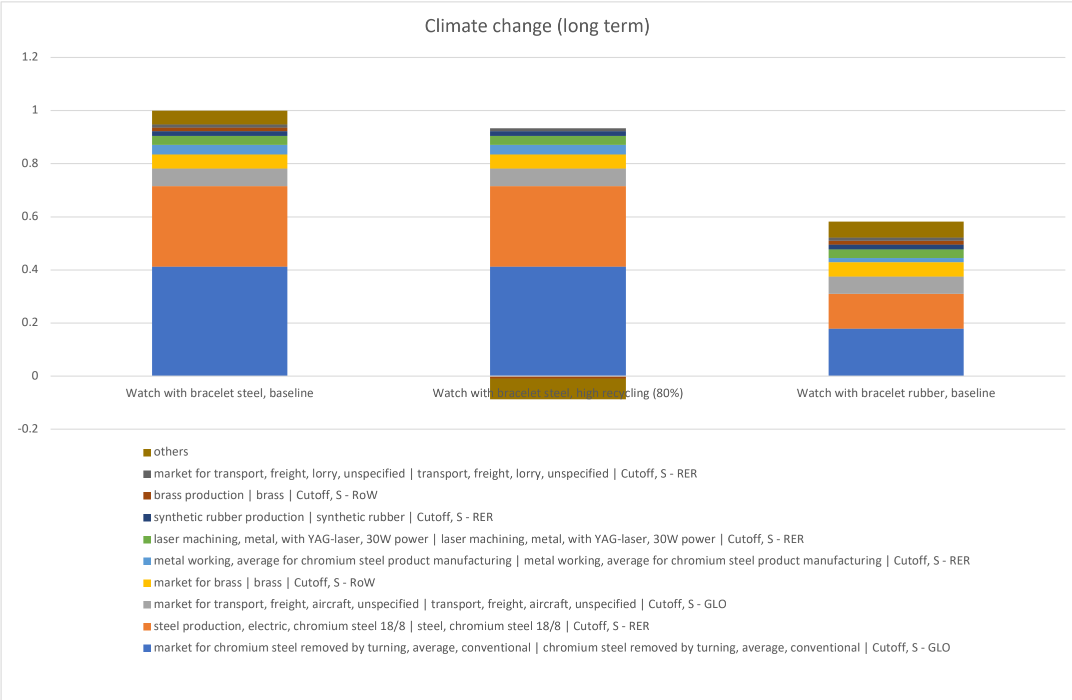

Figure 4: Elementary process contribution

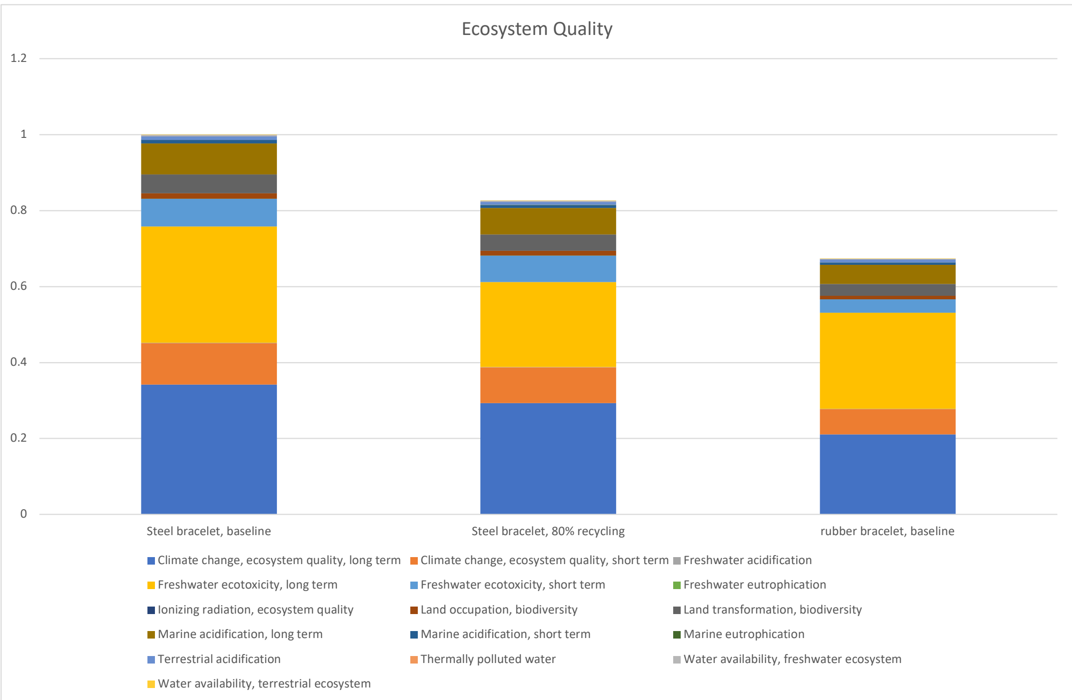

Figure 5: Ecosystem quality analysis with 11 services

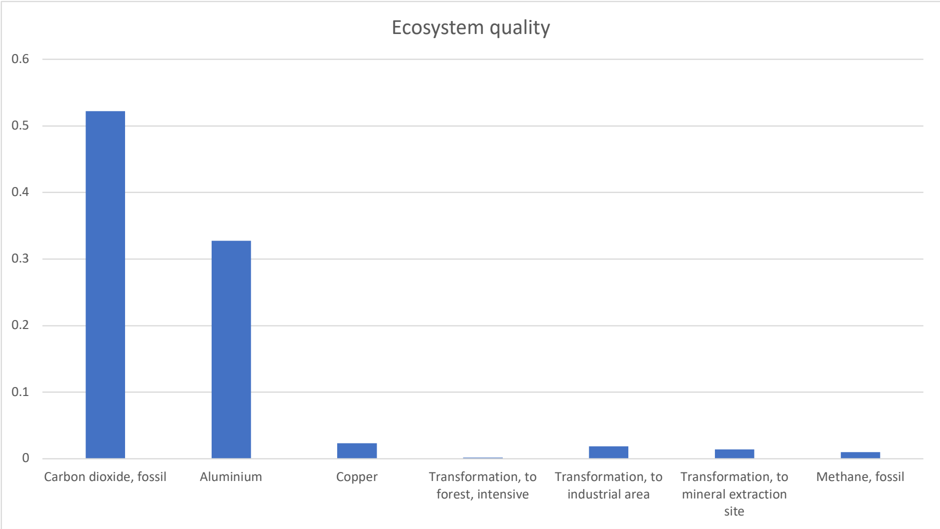

Figure 6: Elementary flow to Ecosystem quality for the steel bracelet, baseline with 11 services

11 Sensitivity and scenario analyses

11.1 Unknown metal working processes

As mentioned in subsection 8.2, many watch manufacturing processes are not modelled in Ecoinvent, so they were replaced by an average process of metal working. Because we didn't know how many "average metal working processes" were corresponding to a given unknown processes, when a component of the watch was going through several not found processes, we considered two main alternatives:

- to replace all these processes by one process of metal working (*manf-proc-unknown*= 0)

- to replace each process by one process of metal working (*manf-proc-unknown*= 1)

To see the relative impact of the unknown processes, we then made an analysis by changing the variable *manf-proc-unknown* from 0 to 1.

The quantity of metal working processes does not have any impact on the relative performance of the rubber and the steel bracelets, rubber is still as better as before.

However, when focusing on the impact of the processes (Figure 8), we can see that as *manf-proc-unknown* increases, the impact of the related processes (colored in the diagram) become less and less negligible. It appears that the margin of error coming from this processes is of the order of 10%, which is reasonnable but still relatively important (see Figure 12 for the increase in the impacts with *manf-proc-unknown*).

Thus, the implementation of the missing processes in Ecoinvent is not a priority, as they are not the most impacting in the watch making process. However, this implementation is needed in order to assess more precisely the life cycle of a watch, as the relative impact is of the order of 10%.

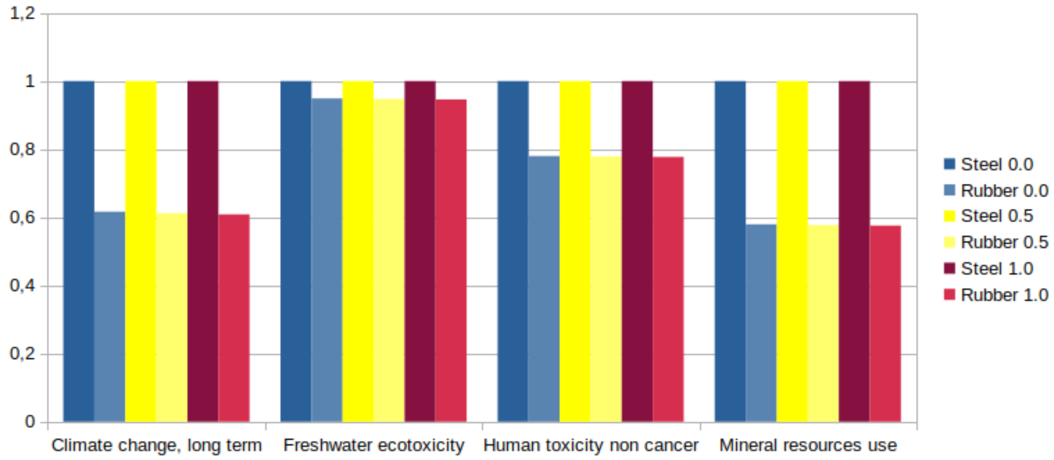

Figure 7: Impact of the metal working processes on the midpoints impact. *manf-proc-unknown* takes the values 0 (blue), 0.5 (yellow) and 1 (magenta)

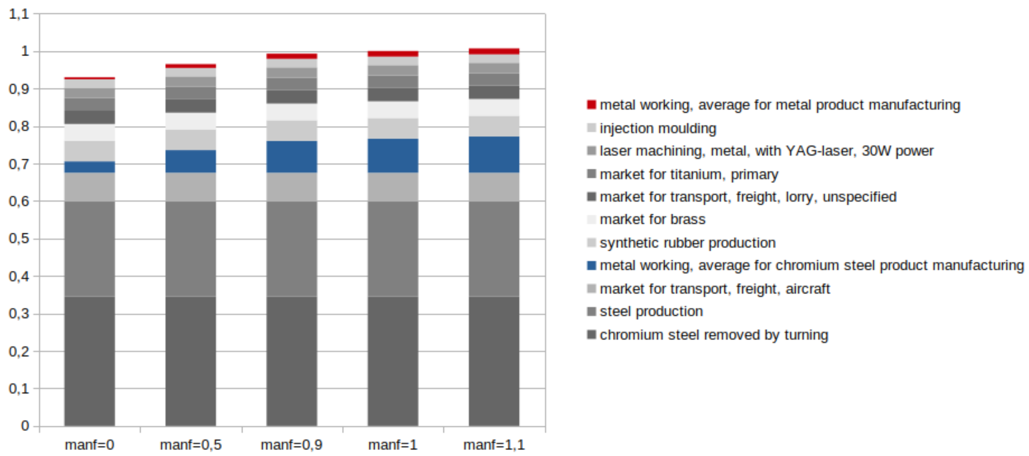

Figure 8: Impact of the metal working processes on the Long term climate change (midpoint)

11.2 Tungsten replacement

As tungsten is a rare metal, its extraction has an important impact on the environment, as shown in [1]. Moreover, the weight of the tungsten is quite heavy, as it is the piece that allows the watch to wind itself thanks to its inertia. As such, the impact of tungsten on the life cycle assessment of the watch is certainly not negligible. Based on the production of carbon dioxide per tonne of metal from the report by *France Stratégie*, we replaced tungsten by titanium as their impact is very close: respectively 29 and 30 tonnes of C02 per tonne of metal.

However, testing the sensitivity of the choice of metal was important. Especially since this piece is often visible and participate in the design of the watch, it can be in more precious metal as gold or platinum in other watch models, so it was also interesting to see the impact of that choice.

And this impact is far from being anecdotal. As precious metals as gold and platinum are much more problematic for the environment than basic metal, the carbon footprint of the watch explodes, as shown below.

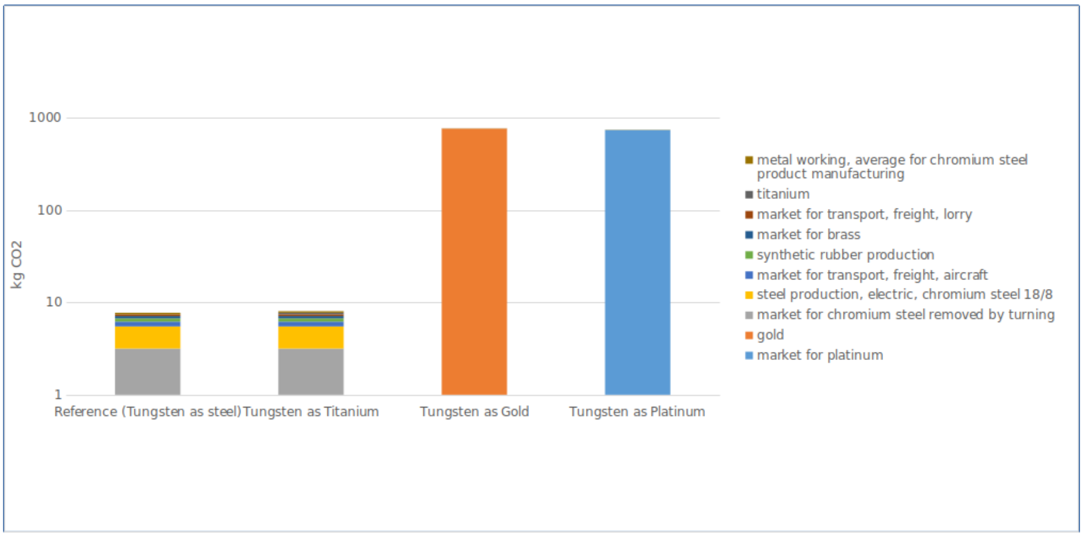

Figure 9: Midpoint impact of long term Climate Change. Pay attention to the fact that vertical axis is in logarithmic scale.

When replacing tungsten by steel or titanium doesn't change significantly the result, replacing by gold or platinum multiply the impact by 100. This fact does not totally disqualifies the relevance of our study, as the assumption made (Tungsten as steel) is legitimate and justified by a rigorous study. However, it shows two important things:

- for the watch industry, the choice of metal for this piece must be made very carefully in order to minimize the impact of the watch, 10 grams of gold are not a small detail.
- if one wants to make a precise life cycle assessment of a watch, the modelling of the process of tungsten production will be one of the main priorities.

11.3 Quantity of scrap

A very common process in the watch industry is machining by removing material. In fact, many components are obtained by a succession of machining operation such as turning or milling operated on an initial piece of material. Depending on the final shape, the initial piece of raw material can be cylindrical or a slab. Therefore, to obtain a component ready to be assembled to the movement, a consequent amount of scrap will be produced. This amount can vary largely depending on the complexity of the component. For instance, some small wheels are machined from big cylindrical slabs due to the machine's constraints. Such wheels can represent only 1% of the weight of the initial processed material. Referring to section 8, it was assumed that average ratio of scrap production is 4 times the mass of the component.
Acknowledging the variation of scrap quantity that takes place in the reality, a sensitivity analysis on this topic turned out to be relevant. This sensitivity analysis was conducted on the rubber version of the watch since the steel bracelet is not concerned by this issue. In fact, bracelets links are fairly big components

in comparison with the scale of the watch that can be machined without production of more than 4 times of scrap. Furthermore, rubber bracelet is not concerned by scrap assumptions since it is produced by injection. The results are observed below. Midpoint indicators are chosen as in the previous sections. From a general point of view with the four visions provided, every indicator follows the same increase pattern with increasing scrap quantity.

First of all, the mineral resources use is easily understandable. From the x10 assumption to the x40, the indicator was also multiplied by 4. This observation is less relevant from x4 to x10 as plastic materials come into play. Plastic being lighter than metals has a small influence at this scale, but as soon as scrap quantity increases, its influence diminishes.

Secondly, from the climate change perspective, going from the classical assumption (x4) to the x40 one, CO2 quantity released is multiplied by 4. This impact is massive, knowing that it is very likely that the x4 assumption is underestimating the reality. The x40 assumption cannot be considered as the worst-case scenario because as seen previously, this number can take values such as x100. However, in average on all components x40 assumption is a good upper-bound.

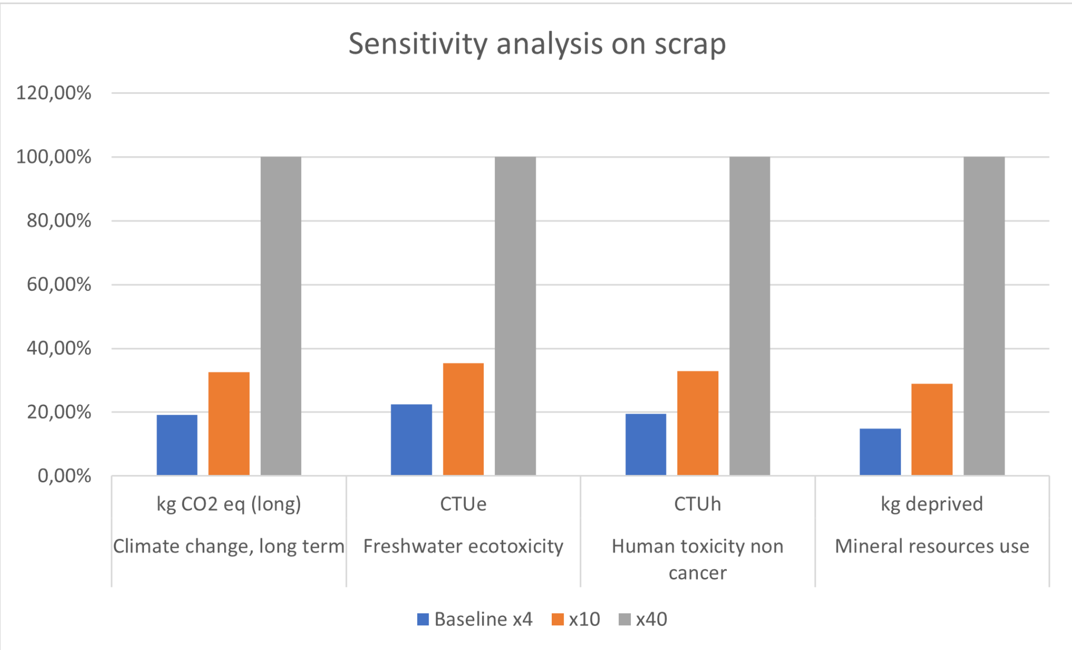

Figure 10: Impact of the quantity of scrap produced to machine a component, midpoint impact

In conclusion, manufacturers should focus on finding appropriate machines to work in their components and optimise their processes. In general, the size of the initial machined slab doesn't influence the final result. One could think of transferring the knowledge from the science of processing precious materials to alloys and steel.

12 Uncertainties and limits

12.1 Uncertainties and limitations

In general, uncertainties in LCA can be divided into two categories: variability (stochastic uncertainty) and uncertainty (epistemic uncertainty). Unlike sensitivity analysis that estimates the effects that have the data and the choices of methods on results, uncertainty analysis considers the propagation of uncertainty of all the data input.

Variability includes temporal, spatial and object variability. In this study, the variability in the transport, the maintenance, the watch lifetime, or fluctuations linked to different manufacturing processes, are the main sources of this type of uncertainty. These sources of variability are inherent variations in the real world and thus cannot be reduced.

On the other hand, the epistemic uncertainty is caused by the lack of knowledge of real quantities. It can theoretically be reduced by a more in-depth research, more time or more data collected. It is divided in three categories: parameter uncertainties, model uncertainties and scenario uncertainties.

The representativeness of the parameters used in this study can be considered good, as the data come directly from the manufacturer of the watch on which this study is based. The reliability is more difficult to measure, parameters like transport come from statistical averages so can be considered quite good. Other parameters such as maintenance or the origin of materials delivered by suppliers, are much more difficult to measure by the manufacturer. It is therefore here that the main parameter uncertainties are concentrated.

The main sources of model uncertainty clearly come from the lack of data on watch manufacturing processes. Indeed, the Ecoinvent database has turned out to be very poorly suited to the precision microtechnology industry. Many assumptions have had to be made, such as the process crap rate, the recycling rate or even the replacement of certain rare materials by others existing in the database. This inevitably leads to great model uncertainty. Another source of uncertainty comes from the fact that the assembly is done mainly by hand and with resources (energy, tools, oils ...) difficult to quantify, which makes this part very difficult to model.

The first scenario uncertainty is the functional equivalence of steel and rubber bracelet, and this is an assumption and is certainly not the case for questions of convenience and for the fashion aspect. Secondly, only one set of impact method and weighting method is applied. To reduce this uncertainty, further investigation on the completeness and correlation of covered impact categories in the domain of watch making is needed. The exclusion of infrastructures, the exclusion of long-term impact due to precious metal pollution or the hypothesis of land-filling regarding the end of life are other scenario uncertainties sources that can be stated.

12.2 Data quality assessment

The data quality of this study is summarized in the table below. A score of 4 represents the worst reliability and representativeness. A × means that element is judged as priority and ✓ is judged as no priority or completed.

Step Lifecycle	Data Quality		Contribution	Collection
	Reliability	Representativeness	Climate change	
Materials extraction	3	3	38-42%	×
Manufacturing processes	3	4	48-60%	×
Transport/distribution	2	1	5-10%	✓
Maintenance	3	3	1-5%	×
End of life	3	3	1-2%	✓

Table 4: Data quality summary

The steps which have a collection marked with a "×" means that, regarding of their current reliability, representativeness and contribution to the overall impact, it is recommended to make deeper research to find more reliable / representative data. Indeed their lack of quality is currently expected to induce high uncertainties in this LCA study.
The representativeness is globally good, from the fact that data and assumptions came from the watch maker or from discussion with their represented person. However, it is less the case for the reliability, mainly for two reasons. First the lack of data for the origin of materials, the maintenance or the end of life. Second, the lack of recognition of the database towards processes and rare materials. Even if the end of life have low score, as its contribution is very weak ,it was judged that it is not a priority to collect better data about it. Indeed, in the professional domain, data collection and verification is time and money consuming, therefore it is a better practise to highlight and focus on processes and parameters which matter the most and not on all of them.

13 Recommendations

According to the impact results, sensitivity analysis and uncertainties mentioned in previous sections, some recommendations can be stated:

- First, with the comparison of the two bracelets, it came out that the rubber bracelet is better, from an environmental and human health point of view, than the steel bracelet, and this for all indicators. Replacing all steel bracelets with rubber bracelets would reduce the impact of the watch by around 40%. Obviously, the impact of a watch can be reduced by greater recycling of the metal in it. However, despite the effort of 80% recycling, the impact still will be greater than that of a rubber bracelet except for one impact that is ecotoxicity. If the number of services is increased from 3 to 10, this benefits of the rubber bracelet is clearly reduced, so the recommendation is also to make a rubber bracelet with the longest lifespan possible.

- It has been observed that the impact of tungsten can potentially play a very important role in the overall impact of the watch. It is therefore advisable to clearly establish what its real impact is and that if it is closer to that of gold or platinum, to change materials or to put pressure on suppliers in order to reduce this enormous impact.

- *A priori*, the Ecoinvent database is not totally suited for the LCA of a mechanical watch or not. Indeed, the uncertainties remain great after our analysis. More than 80% of the micro-technology processes were not found in the database. In addition, the sensibility analysis showed very variable results, for example depending on the impact of the tungsten or the scrap content of the different processes. It is therefore recommended that watch manufacturers create a better environmental database dedicated to micro-technology industry in order to better establish the impacts and potentially improve them.

- Finally a recommendation for further LCA on mechanical watches. It was found that particular efforts should be made in determining manufacturing process and the weight of each components, the scrap content of each processes, the upstream and downstream transport, the details on maintenance and the lifetime of the watch and its components. Indeed these are key features to obtain reliable and convincing conclusion about the impact of the product. Recommendations for other sensitivity analysis could be the type of transport, component scrap rate, location and frequency of after-sales service or even lead-free steel or brass.

14 Conclusion

The first conclusion made is the fact that a bracelet in rubber is considerably less impacting, for most of the indicators, than a steel bracelet, and this even if the steel comes from 80% recycled materials. In the scope of the assumptions made, the results give a diminution of around 40% of the middle impact of the watch. Obviously, the environmental aspect is not the only parameter in the choice of the material of the bracelet, questions of utility or the visual aspect certainly play a much more important role, but maybe this result could tip the choice of clients undecided on that of rubber. It was also observed that the steps which weigh the most in the overall impact were the market for chromium steel removed by turning, the

steel production and the transport. It is therefore on this that efforts must be made as a priority in order to reduce this impact.
The very many assumptions that have been made and the various sensitivity analyses clearly show that the reliability of our study is not high. Indeed, many manufacturing processes and some materials such as tungsten were unknown to the database. In addition, certain parameters such as the scrap rate or the origin of the materials have shown a significant sensitivity in the final result. Discussions, especially with the reference person, and bibliographical research have made it possible to obtain results as close as possible to reality. However, these choices remain subjective and potentially significant sources of uncertainty.
The global objective of this project was to determine if the Ecoinvent database proves to be suited for micro-technology industry or not. Today's society is increasingly sensitive to environmental issues and climate change. So in order to obtain effective strategies for reducing the impacts of this watch industry and more precise answers to customers, the answer is that the database is too imprecise. The creation of a database dedicated to the micro-technology industry would be more suited to current environmental challenges.

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A Process tree

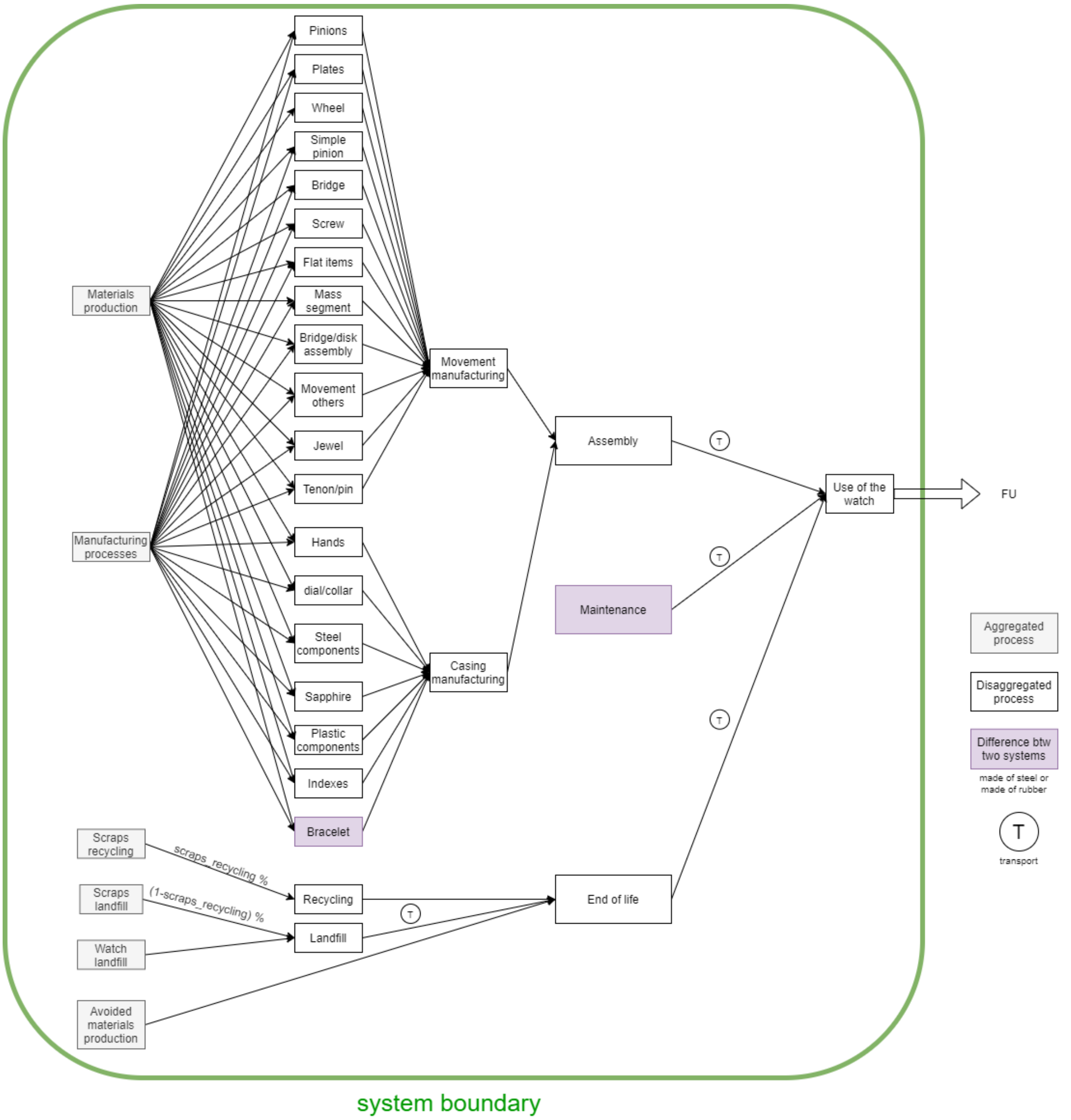

Figure 11: Detailed process tree of the watch product system

B Sensitivity analysis

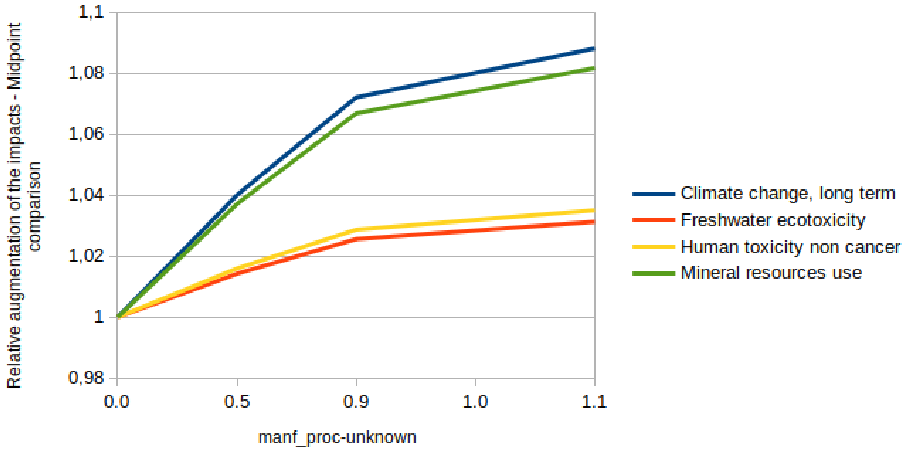

Figure 12: Relative evolution of 4 impacts when changing the quantity of unknown "average metal working" process

C Materials assumptions

Watch materials	**Ecoinvent materials**
Steel 20AP	Steel unalloyed
Steel durnico	Steel low-alloyed
Steel 1-4435 and 316S	Chromium steel
$CuBe_2$	Copper
Tungsten	Titanium
Synthetic ruby and sapphire	Aluminium oxide
Super LumiNova	Aluminium sulfate
Nitrile	Synthetic rubber
HYTREL, GRILAMID TR90 and POLYAMID	Polyester resin

Table 5: Material replacements

D Results

Name	Impact result	Unit
Climate change, long term	7.00	kg CO_2 eq
Freshwater ecotoxicity	1.32E+06	CTUe
Human toxicity non cancer	9.92E-06	CTUh
Mineral resources use	0.09	kg deprived

Table 6: IMPACTWORLD+ Midpoint, steel bracelet baseline

Name	Impact result	Unit
Climate change, long term	3.97	kg CO_2 eq
Freshwater ecotoxicity	1.25E+06	CTUe
Human toxicity non cancer	7.71E-06	CTUh
Mineral resources use	0.05	kg deprived

Table 7: IMPACTWORLD+ Midpoint, rubber bracelet baseline

Tungsten as		gold	platinum	titanium
Name	**Unit**	**Impact result**	**Impact result**	**Impact result**
Climate change, long term	kg CO_2 eq	772.21	745.06	7.29
Freshwater ecotoxicity	CTUe	4.36E+08	1.4E+08	1.32E+06
Human toxicity non cancer	CTUh	1.10E-03	3.46E-03	9.97E-06
Mineral resources use	kg deprived	1.54	2.28	9.26E-02

Table 8: IMPACTWORLD+ Midpoint, baseline steel bracelet, tungsten variations

manf_proc_unkown **equals**		0	0.5	1
Name	**Unit**	**Impact result**	**Impact result**	**Impact result**
Climate change, long term	kg CO_2 eq	8.05	8.37	8.69
Freshwater ecotoxicity	CTUe	1.33E+06	1.35E+06	1.37E+06
Human toxicity non cancer	CTUh	1.00E-05	1.03E-05	1.04E-05
Mineral resources use	kg deprived	9.75E-02	1.01E-01	1.05E-01

Table 9: IMPACTWORLD+ Midpoint, baseline steel, unknown manufacturing processes

manf_proc_unkown **equals**		0	0.5	1
Name	**Unit**	**Impact result**	**Impact result**	**Impact result**
Climate change, long term	kg CO_2 eq	4.96	5.13	5.29
Freshwater ecotoxicity	CTUe	1.26E+06	1.28E+06	1.30E+06
Human toxicity non cancer	CTUh	7.87E-06	7.98E-06	8.09E-06
Mineral resources use	kg deprived	5.65E-02	5.84E-02	6.03E-02

Table 10: IMPACTWORLD+ Midpoint, baseline rubber, unknown manufacturing processes

baseline		steel	rubber
Name	**Unit**	**Impact result**	**Impact result**
Climate change, long term	kg CO_2 eq	23.67	17.17
Freshwater ecotoxicity	CTUe	1.35E+06	1.28E+06
Human toxicity non cancer	CTUh	1.17E-05	9.16E-06
Mineral resources use	kg deprived	0.15	6.21E-02

Table 11: IMPACTWORLD+ Midpoint, airplane maintenance

copeaux **equals**		10	40
Name	**Unit**	**Impact result**	**Impact result**
Climate change, long term	kg CO_2 eq	8.46	25.95
Freshwater ecotoxicity	CTUe	1.99E+06	5.61E+06
Human toxicity non cancer	CTUh	1.33E-05	4.03E-05
Mineral resources use	kg deprived	0.11	0.38

Table 12: IMPACTWORLD+ Midpoint, baseline rubber, scraps influence

E Ecoinvent processes and flows mapping

Unit processes	Flow type	Flow
Use of the watch	Intermediary flows-outputs	Time telling for 80 years
	Intermediary flows-inputs	Assembled watch
		Watch serviced
		End of life
		transport, freight, lorry, unspecified
		transport, freight, aircraft, unspecified
Maintenance	Intermediary flows-outputs	Watch serviced
	Intermediary flows-inputs	Injection moulding
		synthetic rubber
		transport, freight, lorry, unspecified
Assembly	Intermediary flows-outputs	Assembled watch
	Intermediary flows-inputs	Mouvement
		Habillage
Habillage manufacturing	Intermediary flows-outputs	Habillage manufactured
	Intermediary flows-inputs	Aiguilles
		All habillage steel compounds
		Bracelet
		Cadran réhaut
		Index
		Plastics compounds
		Saphir
Mouvement manufacturing	Intermediary flows-outputs	Mouvement manufactured
	Intermediary flows-inputs	Movement autres
		Pièces plates acier
		Pierres
		Pignon
		Pignon sans taillage
		Pignon simple
		Planche
		Pont platine
		Roue (pignon+planche)
		Segment mass tungstène
		Tenons, goupilles, pieds-vis
		Vis

Figure 13: Ecoinvent processes Part 1

Unit processes	Flow type	Flow
Pignon	Intermediary flow-outputs	Pignon
	Intermediary flow-inputs	steel, unalloyed
		steel removed by turning, average conventional
		metal working, average for metal product manufacturing
Planche	Intermediary flow-outputs	Planche
	Intermediary flow-inputs	brass
		sheet rolling, copper
		steel, low-alloyed
		deep drawing (étampé)
		metal working, average for metal product manufacturing
Pignon simple	Intermediary flow-outputs	Pignon simple
	Intermediary flow-inputs	steel, unalloyed
		steel removed by turning, average, conventional
		metal working, average for steel product manufacturing
Pont platine	Intermediary flow-outputs	Pont platine
	Intermediary flow-inputs	brass
		steel, low-alloyed
		steel removed by millding, small parts
		metal working, average for metal product manufacturing
Vis	Intermediary flow-outputs	Vis
	Intermediary flow-inputs	steel, unalloyed
		steel removed by turning, average, conventional
		metal working, average for steel product manufacturing
Pièces plates acier	Intermediary flow-outputs	Pièces plates acier
	Intermediary flow-inputs	steel, low-alloyed
		steel, unalloyed
		steel, unalloyed
		sheet rolling, copper
		brass
		deep drawing, steel, 650 kN press, automode
		metal working, average for metal product manufacturing
Segment de masse	Intermediary flow-outputs	Segment mass tungstene
	Intermediary flow-inputs	steel, unalloyed
		metal working, average for steel product manufacturing
		steel, removed by turning, average, conventional
Pierre	Intermediary flow-outputs	Pierres
	Intermediary flow-inputs	aluminium oxide, non-metallurgical
		laser machining, metal, with YAG-laser, 30W power
		metal working, average for metal product manufacturing

Figure 14: Ecoinvent processes Part 2a

Pierre	Intermediary flow-outputs	Pierres
	Intermediary flow-inputs	aluminium oxide, non-metallurgical
		laser machining, metal, with YAG-laser, 30W power
		metal working, average for metal product manufacturing
Tenons, goupilles, pied-vis	Intermediary flow-outputs	Tenons, goupilles, pied-vis
	Intermediary flow-inputs	brass
		sheet rolling, copper
		steel, unalloyed
		steel, low-alloyed
		steel removed by turning, average, conventional
		metal working, average for metal product manufacturing
Pignon sans taillage	Intermediary flow-outputs	Pignon sans taillage
	Intermediary flow-inputs	steel, unalloyed
		metal working, average for steel product manufacturing
Roue	Intermediary flow-outputs	Roue (pignon+planche)
	Intermediary flow-inputs	steel, unalloyed
		metal working, average for steel product manufacturing
Mouvement autres	Intermediary flow-outputs	Mouvement autres
	Intermediary flow-inputs	sheet rolling, copper
		Brass
		metal working, average for copper product manufacturing
		metal working, average for metal product manufacturing

Figure 15: Ecoinvent processes Part 2b

Unit processes	Flow type	Flow
Aiguilles	Intermediary flow-outputs	Aiguilles
	Intermediary flow-inputs	brass
		deep drawing, steel, 650 kN press, automode
		metal working, average for metal product manufacturing
Cadran+réhaut	Intermediary flow-outputs	Cadran_réhaut
	Intermediary flow-inputs	brass
		deep drawing, steel, 650 kN press, automode
		metal working, average for metal product manufacturing
Steel compounds habillage	Intermediary flow-outputs	all habillage steel compounds
	Intermediary flows-inputs	steel, chromium steel, 18/8
		titanium, primary
		steel, chromium steel, 18/8
		brass
		chromium steel removed by turning, average, conventional
		metal working, average for metal product manufacturing
		metal working, average for chromium steel product manufacturing
Saphir	Intermediary flow-outputs	Saphir
	Intermediary flow-inputs	aluminium oxide, non-metallurgical
		metal working, average for aluminium product manufacturing
Plastic compounds for habillage	Intermediary flow-outputs	Plastic compounds habillage
	Intermediary flow-inputs	synthetic rubber
		polyester resin, unsaturated
		polymer foaming
		Injection moulding
Index	Intermediary flow-outputs	Index
	Intermediary flow-inputs	aluminium sulfate, powder
		Brass
		steel removed by milling, small parts
		metal working, average for metal product manufacturing
Bracelet	Intermediary flow-outputs	Bracelet
	Intermediary flow-inputs	Bracelet rubber
		Bracelet steel
Bracelet rubber	Intermediary flow-outputs	Bracelet rubber
	Intermediary flow-inputs	Injection moulding
		synthetic rubber
Bracelet steel	Intermediary flow-outputs	Bracelet steel
	Intermediary flow-inputs	chromium steel removed by turning, average, conventional
		metal working, average for chromium steel product manufacturing
		steel, chromium steel, 18/8

Figure 16: Ecoinvent processes Part 3

Unit processes	Flow type	Flow
End of life	Intermediary flows-outputs	End of life
	Intermediary flows-inputs	Landfill
		Recycling
		brass
		steel, chromium steel, 18/8
		steel, chromium steel, 18/8
		titanium, primary
		aluminium oxide, non-metallurgical
		steel, unalloyed
		steel, low-alloyed
		copper scrap, sorted, pressed
		Landfill
		Recycling
		transport, freight lorry, unspecified
Landfill	Intermediary flows-outputs	Landfill
	Intermediary flows-inputs	process-specific burdens, inert material landfill
		transport, freight, lorry, unspecified
Recycling	Intermediary flows-outputs	Recycling
	Intermediary flows-inputs	Collection of materials scraps
		Recycling of collected scraps materials
Collection of materials scraps	Intermediary flows-outputs	Collection of materials scraps
	Intermediary flows-inputs	Bronze scrap, consumer
Recyling of collected scraps materials	Intermediary flows-outputs	Recycling of collected scraps materials
	Intermediary flows-inputs	Bronze scrap, consumer

Figure 17: Ecoinvent processes Part 4