KU LEUVEN

Life Cycle Assessment of Wooden and Mechanical Pencils: A Comparative Study

Applied Sustainability Assessment

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1 Introduction

As a writing utensil pencils have been around the world since the invention of the modern pencil in 1795 (Norman 2024). Worldwide there are two commonly used casings for pencils; wood and mechanical which are mostly made from plastic. The manufacturing process involves various stages and requires a wide range of resources such as graphite, clay, ferrule, eraser, wood and plastic, all of which are carefully processed to make a material that is still used every day by people of all ages.

Through the use of Life Cycle Assessment (LCA), this report will evaluate the environmental impact associated with pencil production processes including raw material, manufacturing, distribution, use and final disposal. The study will provide an overview of the production process and materials involved in both pencil options. In the assessment, key environmental indicators are considered which are climate change, ionizing radiation, freshwater eutrophication, freshwater eco-toxicity, and fossils.

In general pencils, despite their small size and simple nature their production involves complex procedures. Yet, they are often overlooked when it comes to assessment of their environmental footprint even though they are common everyday products. To date, limited research has been conducted on this topic. Realizing this gap, more investigation is needed to assess the sustainability of this common utensil. The comparison in this study will give insight into the environmental effect of the alternative materials and provide actionable recommendations for reducing their environmental impact.

2 Functional unit and "goal and scope"

2.1 Goal of the Study

For students, pencils are essential in their everyday life. Wooden pencils used to be the only choice for them but the emergence of mechanical pencils brings a competitive alternative. With its reusable plastic pencil case, the mechanical pencil seems to be a greener option.

Based on the background, this LCA study is carried out to compare the environmental impacts of wooden pencils and mechanical pencils. The results and analysis can be used for purposes as follows:

- The environmental impact indicators of the products' Life Cycle Assessment can be used as a basis for comparing resource and environmental benefits for pencil producers
- The report can be used for assessing different environmental impacts caused by different materials and means of transport, assisting green designs of pencil products.

2.2 Scope of the Study

Functional Unit

The functional unit for this study is the amount of mixed graphite used by a student in a typical school year in Leuven, Belgium. Various kinds of wooden pencils and mechanical pencils can be found on the market. To control the irrelevant variables through the production process, the manufacturing corporation BiC was chosen for the study. BiC is a French company producing both wooden pencils and mechanical pencils, the headquarter of which is in Clichy, France. In this study, wooden pencils and mechanical pencils produced by this company in Clichy and used in Leuven, Belgium, are chosen as benchmarks.

Then we assess the amount of mixed graphite used in wooden pencils:

Mass of mixed graphite in 1 pencil = (volume of mixed graphite)*density

=π*r^2*length*density of mixed graphite

=3.14*(0.12cm)2*19cm*1.71g/cm^3

=1.46g

Mass of mixed graphite in 12 pencils=12*1.47g

=17.61g

As for the mechanical pencil, the total number of equivalent sticks of graphite were calculated as follows:

Mass of 1 stick of 0.7mm mixed graphite=0.057g

Equivalent sticks of graphite = 17.61g/0.057g/1 stick

= 309 sticks

This is taken to be a pack of 12 BiC wooden pencils, or 309 sticks of 0.7 mm lead for a BiC mechanical pencil. It was assumed that one mechanical pencil would be continuously reused for the duration of a year. As for the impacts of lead refills, it was also assumed that packs of 500 lead stick refills were used in the distribution stage.

System Boundaries

A “cradle-to-grave” life cycle assessment is adopted in this study, from the extraction of raw materials to the disposal of the products. Main procedures are as follows:

1. Raw material production (Graphite, clay etc.);
2. Energy production (Electricity, etc.);
3. Transport (Raw material transportation and product distribution);
4. Pencil production;
5. Use phase of the product;
6. Recycle, disposal of the product after use.

General description

As shown below in Figures 1.1 and 1.2, the lifecycle of the pencils begins with the production of the raw materials that go into their manufacturing, including their transport, transformation and packaging. The packed pencils are then delivered to students in Leuven then discarded after use.

The foreground system includes the raw materials, manufacture, distribution, use and end-of-life cycle stages.

Raw materials generally include graphite and clay mixing, and eraser processing. Depending on different types of raw materials, the following processes are included:

- Graphite and clay mixing: Mixing graphite and clay according to a ratio of 63:31 by mass to create mixed graphite;
- Eraser processing: Making polyvinyl chloride into eraser tips;
- Wood cutting and shaping: Making slat wood from softwood;
- Plastic molding: Molding high impact polystyrene into pencil case;
- Metal processing: Shaping the chromium steel into springs;

The manufacturing phase includes various stages at the pencil production site (BiC's factory in Clichy). It therefore includes assembly with glue, painting, ferrule and eraser assembly and final assembly for wooden pencils while the mechanical pencil needs just assembly. Both types of pencils are then packed in corrugated cardboard boxes for distribution.

The distribution subsystem includes the transport of the pencils from the production sites to students in Leuven.

Finally, the use phase includes students writing with pencils, which has no environmental impact. The end-of-life phase includes the disposal of used wooden pencils and mechanical pencils and the recycling of corrugated board boxes used for packaging.

The background system includes activities related to resource supply. The supply refers to water, electricity, etc, including the extraction, processing of the natural resources and the various transport used to move them to the factories.

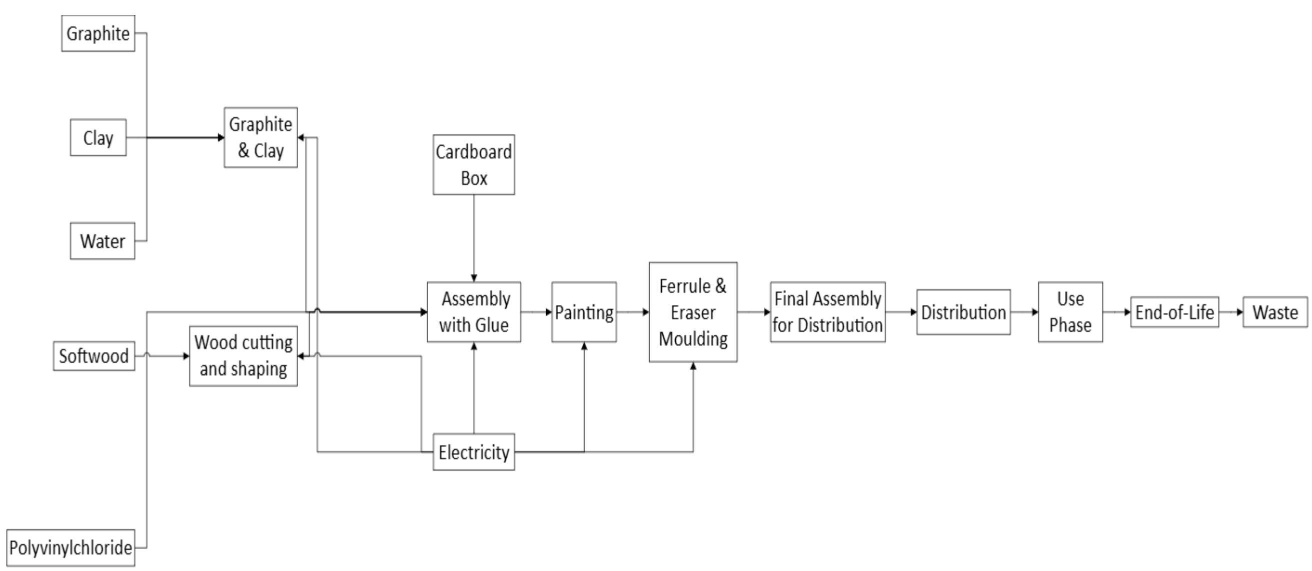


Figure 1.1 LCA system boundaries for wooden pencil production

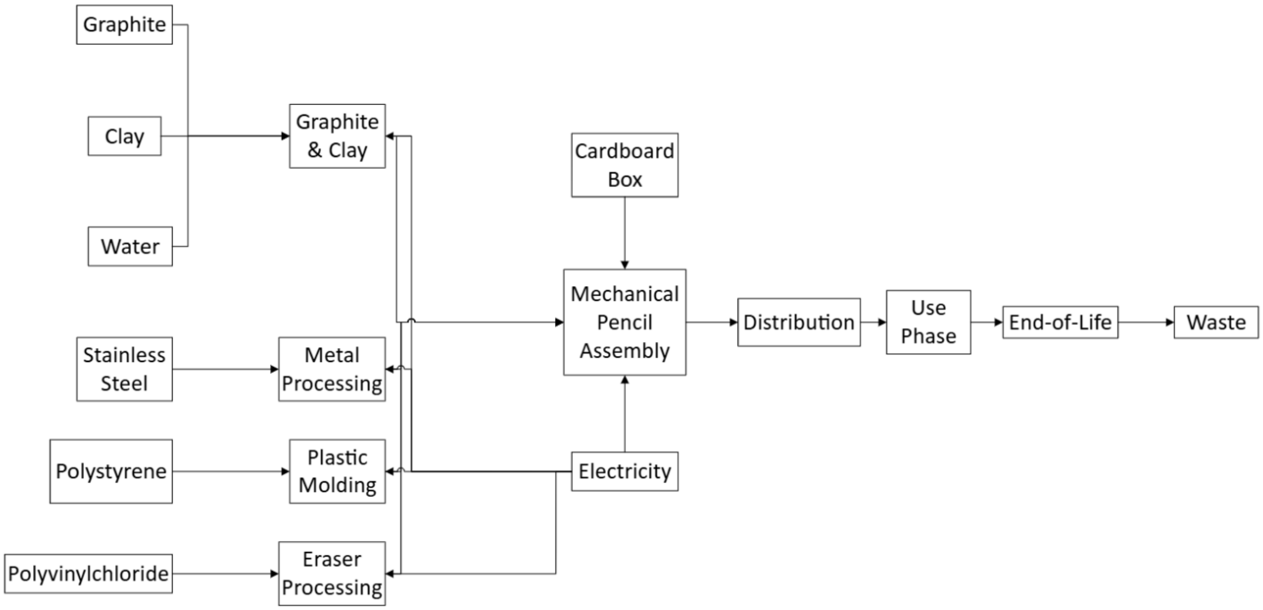


Figure 1.2. LCA system boundaries for mechanical pencil production

Cut-off Criteria

No cut-off criteria (based on mass, energy or environmental relevance as suggested by the ISO standards) was used when modeling the systems to exclude processes from the boundaries, all available information was used.

Multi-functionality

Multi-functionality occurs when one process produces more than one functional flow. In this study, system expansion is applied to the recycling of cardboard processes specially. This approach expands the system boundaries to include the additional functions that recycling brings, ensuring that the environmental impacts of reusing materials are fully accounted for.

For the rest of the processes, an allocation approach is applied. Allocating the impacts by mass provides a consistent and practical way to address multi-functionality.

2.3 General Assumptions

The sub-section presents the general assumptions pertaining to the studied systems.

- No pencil loss was assumed during the distribution;
- The lorry transport during the distribution of the pencils was modeled as weight-limited;
- The average transport distance of the pencils by road transport from Clichy to Leuven was assumed to be 409 km (based on Google Maps);
- The wooden pencils are assumed to be discarded after 85% is used, while the plastic case for the mechanical pencil is assumed to be reused throughout the whole year and then discarded;

- All the corrugated boards are assumed to be recycled.

3 Inventory

After defining the goal and scope, inventory or data collection is the second phase of the LCA process. This step presented a significant challenge because of the availability of sufficient data. Life cycle inventories for the production of wooden and mechanical pencils were gathered from different sources. The sources include; peer-reviewed publications, LCA reports and relevant websites which are listed in detail in Table 3.1 and Table 3.2. To obtain primary data, the products were dismantled to weigh the individual components which are presented in Figure 3.1. Additionally, FTIR (Fourier Transform Infrared Spectroscopy) was used to identify the plastic material for the mechanical pencil as shown below in Figure 3.1.

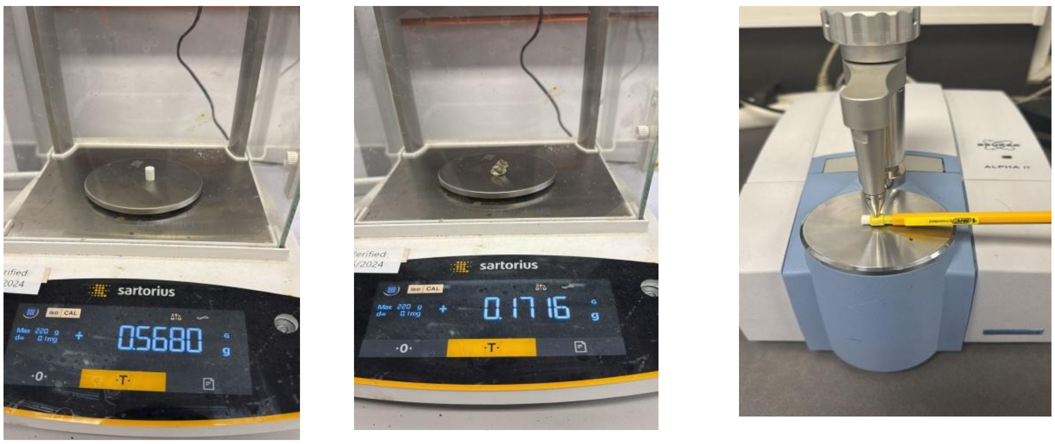


Figure 3.1: Primary Data: Scale Measurement and FTIR (Fourier Transform Infrared Spectroscopy)

Table 3.1: Life cycle inventory (LCI) data for Mechanical Pencil

Material		Mass(g)	Process	Source
Processed Graphite	Graphite	17.61	Graphite & Clay Process	Anyanwu and Li, 2017
	Clay	6.798	Graphite & Clay Process	Anyanwu and Li, 2017
	Tap Water	5.25	Graphite & Clay Process	Australian Government Initiative: Science Week, 2021
Steel Parts	Chromium Steel	0.5	Metal Processing	Shane, 2024
Pencil Plastic	High Impact Polystyrene	5	Plastic Molding	Leibenluft , 2008
Eraser Tip	Polyvinylchloride	0.4	Eraser Processing	American Chemical Society, 2002
Corrugated Cardboard Box	Cardboard	590 for 1000 pencils	Mechanical Pencil Assembly	Pitafi , 2023

Energy		Amount(kWh)	Process	
Graphite & Clay Process	Electricity	0.7107	French Mix	Purwaningsih et al., 2020
Metal Processing	Electricity	0.000025	French Mix	Norgate et al., 2004
Plastic Processing	Electricity	0.011	French Mix	Plastic Europe, 2005
Eraser Processing	Electricity	0.0053	French Mix	Purwaningsih et al., 2020
Mechanical Pencil Assembly	Electricity	0.005	French Mix	Purwaningsih et al., 2020
	Transport	**Amount(km)**		
Factory to shop	lorry	409	16-32t, Euro 5	Distance from Google Maps

Table 3.2: Life cycle inventory (LCI) data for Wooden Pencil

		Material	Mass(g)	Process	Source
Mixed Graphite		Graphite	1.47	Graphite & Clay Process	Anyanwu and Li, 2017
		Clay	0.38	Graphite & Clay Process	Peter, 2021
		Tap Water	730	Graphite & Clay Process	Australian Government Initiative: Science Week, 2021
Slat Wood		Soft Wood	3.32	Wood Cutting and Shaping	Wu Jerome (n.d.) 2024
		Tap Water	200	Wood Cutting and Shaping	Purwaningsih et al., 2020
Assembled Pencil with Glue		Ethylene	0.009	Assembly with Glue	Purwaningsih et al., 2020
Paint		Acrylic Binder	0.005	Painting	Purwaningsih et al., 2020
Finished Pencil	Aluminum	Aluminum Alloy	0.172	Ferrule and Eraser Molding	Primary Data
	Eraser	Polyvinylchloride	0.57	Ferrule and Eraser Molding	Primary Data
Corrugated Cardboard Box		Cardboard	590 for 1000 pencils	Final Assembly for Distribution	Pitafi , 2023
Energy		**Type**	**Amount(kWh)**	**Process**	
	Graphite & Clay Process	Electricity	0.06	French Mix	Purwaningsih et al., 2020
	Wood Cutting and Shaping	Electricity	0.00013	French Mix	Hossain and Poon (2018)
	Assembly with Glue	Electricity	0.004	French Mix	Purwaningsih et al., 2020
	Painting	Electricity	0.002	French Mix	Purwaningsih et al., 2020
	Ferrule and Eraser Molding	Electricity	0.0085	French Mix	Purwaningsih et al., 2020

Transport	Type	Amount(km)		
Factory to shop	lorry	409	16-32t, Euro 5	Distance from Google Maps

4 Environmental impact analysis

In this project, for the implementation of the impact assessment and overall LCA modeling, Environmental Footprint (EF) 3.0 and Umberto 11 were used. EF 3.0 method was implemented because it is an internationally accepted and recommended approach to be used for all LCA studies in the EU (Commission Recommendation EU 2021/2279). It is indicated that the EF methodology is structured in similar steps as ISO 14040 , and provides a high degree of robustness, reproducibility and comparability (Damiani et al., 2022). In this study, the assessment takes into account 16 impact categories to communicate the environmental impact of two alternative pencil types using the mid-point method. The mid-point assessment was selected because it allows a more detailed insight into the problem at hand.

The detailed results of LCA related to the production and use of wooden and mechanical pencils are shown in detail in Annex 1. Figure 4.1 and Figure 4.2 below respectively show the normalized values for the 16 impact categories for mechanical and wooden pencils.

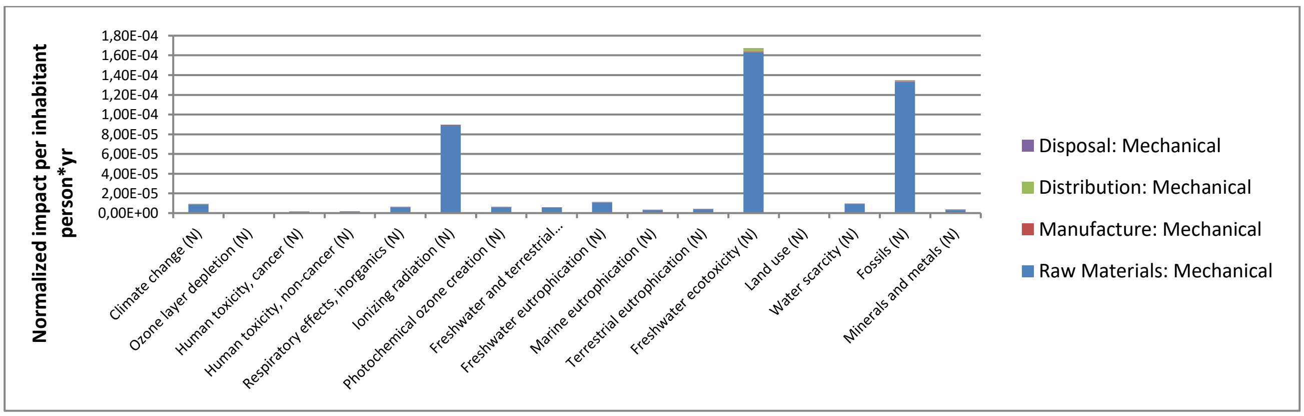


Figure 4.1: Normalized Impact of Mechanical Pencil over 16 Impact Categories

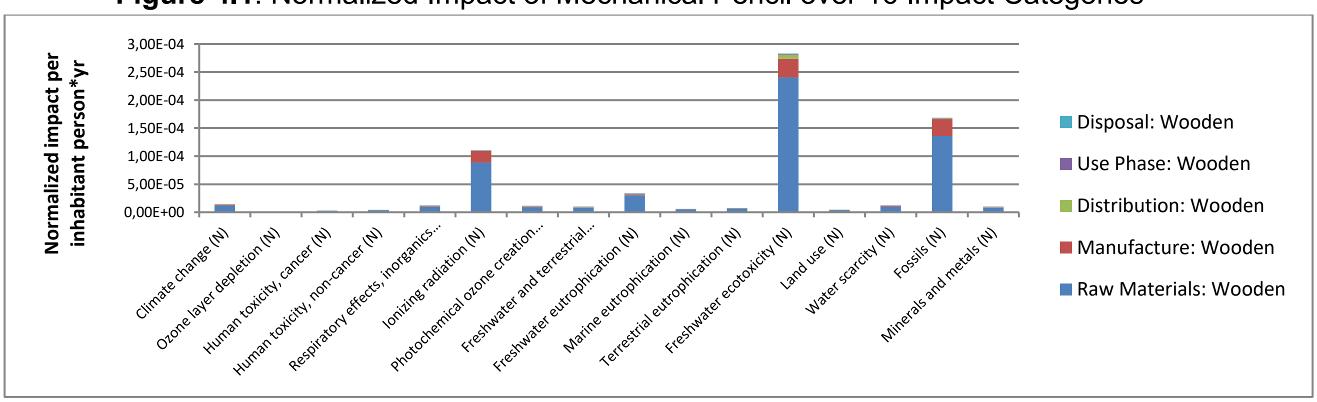


Figure 4.2: Normalized Impact of Wooden Pencil over 16 Impact Categories

The above figures indicate the total result per impact category as well as the breakdown of impact per life cycle stage for mechanical and wooden pencils. For each alternative, raw material, manufacture, distribution and disposal stages are included in the results. It is important to note that in the assessment, the impact categories should not directly be compared on the basis of the characterized indicator units. Therefore, in order to analyze the result of the impact assessment the normalized values were used, and five major impact categories were selected for further analysis which include climate change, ionizing radiation, freshwater eutrophication, freshwater eco-toxicity, and fossils based on their contribution.

Furthermore, to analyze the influence of each phase, the numbers for each impact category are converted to percentages of the total impact and displayed in a bar graph shown in Figure 4.3 and Figure 4.4. The bar graph shows the percentage distribution of wooden and mechanical pencil lifecycle to the total impact of the five major categories.

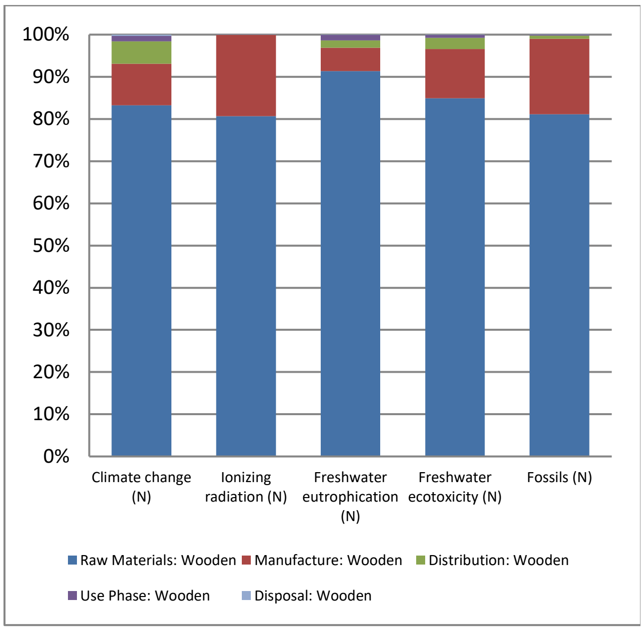


Figure 4.3 Percentage contribution impact categories wooden pencil

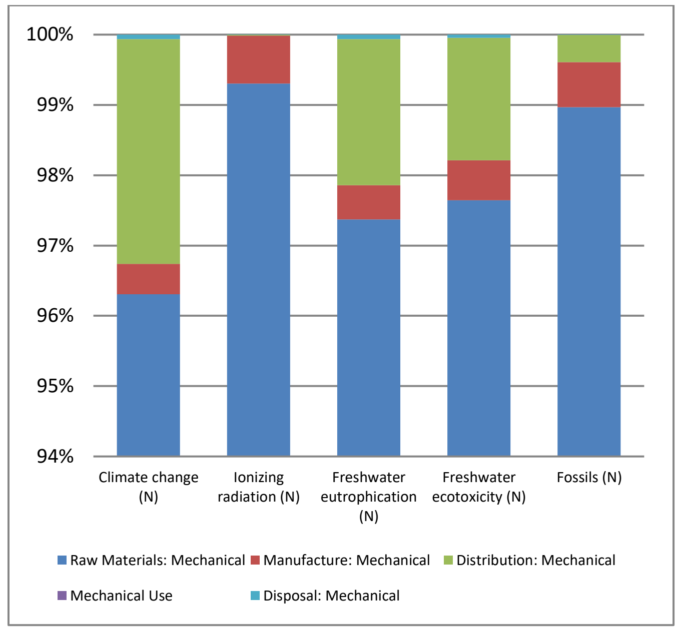


Figure 4.4 Percentage contribution impact categories Mechanical pencil

From the figures above, it can be noted that the greatest contribution in almost all impact categories is attributed to the raw material process, followed by the manufacturing of wooden pencils and the distribution of mechanical pencil production. The contribution of the raw material process is more than 80% and 90% for the wooden pencil and the mechanical pencil respectively. This effect is also clearly indicated in Figure 4.5 where the raw material process shows a disproportionally high contribution in comparison with other life cycle stages. This result underlines that enough attention should be given to this stage in order to improve the sustainability of these products.

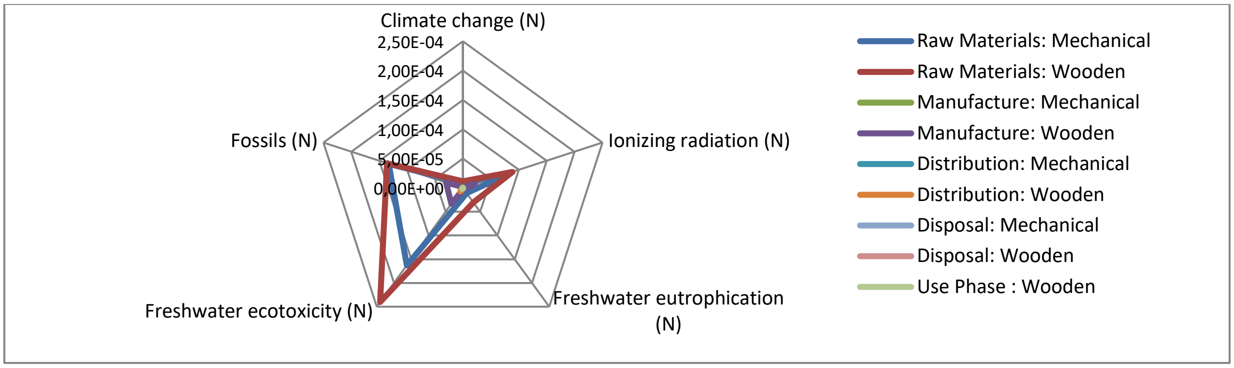


Figure 4.5: Contribution of Phases

A breakdown of a comparison between the two alternatives, based on different phases of the life cycle is shown from Figure 4.6 to Figure 4.9 for climate change, ionizing radiation, freshwater eutrophication, freshwater eco-toxicity, and fossils impact categories. The figures give a general insight into the contribution to the impact of the two pencil alternatives for each phase. As can be seen from the figures, the mechanical pencil which is indicated in blue color has a comparable contribution to the wooden pencil in the raw material stage. However, the wooden pencil is shown to have a greater impact in the manufacturing, distribution, and disposal phases of the life cycle. In the following section of the report, a detailed analysis of each impact category will be provided for two pencil options.

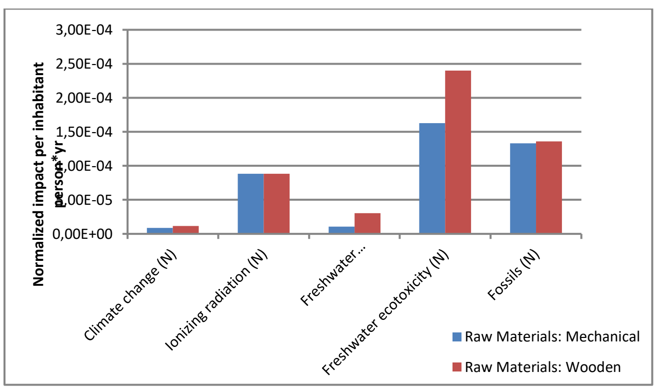


Figure 4.6: Impact: Raw Material

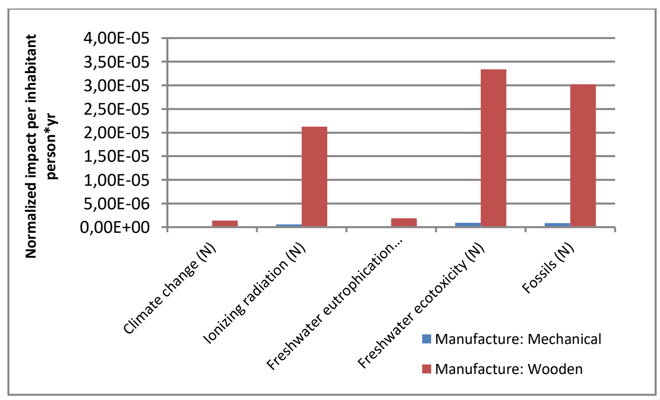


Figure 4.7: Impact: Manufacture

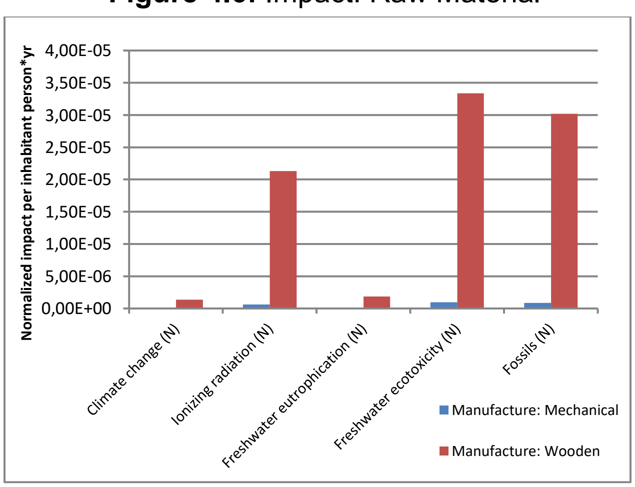


Figure 4.8: Impact: Distribution

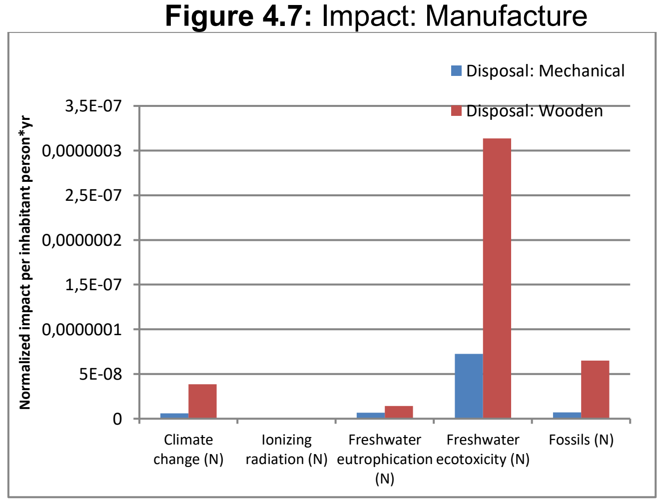


Figure 4.9: Impact: Disposal

4.1 Climate Change

In this section, climate change impact based on the characterized values for the mechanical and wooden pencils is shown in Figure 4.10. The highest climate change effect is observed for the wooden pencil with a value of 0.1169 kg CO2 level. The mechanical pencil has the lowest contribution with a total amount of around 0.0788 kg CO2. It can be generalized from the graph that the impact of the mechanical pencil is about 38% less than the wooden pencil in the climate change impact category. This is mainly due to raw material processing. In order to see the effect of the other phase's raw material stage was removed from the analysis, and Figure 4.11 shows the influence of other phases, the manufacturing cycle primarily emerging as a main contributor.

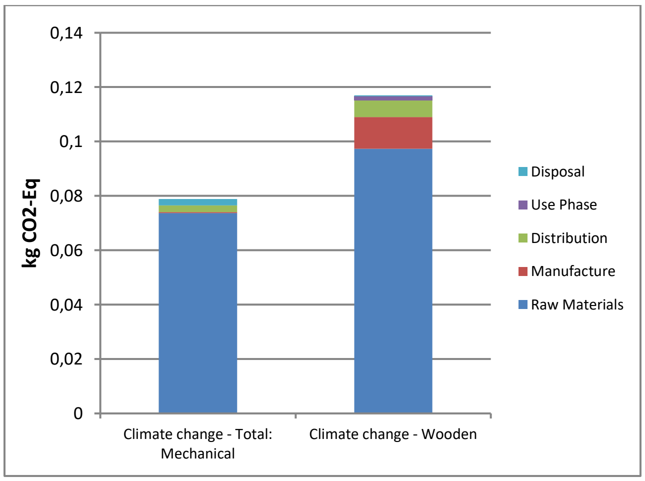


Figure 4.10: Climate change impact category

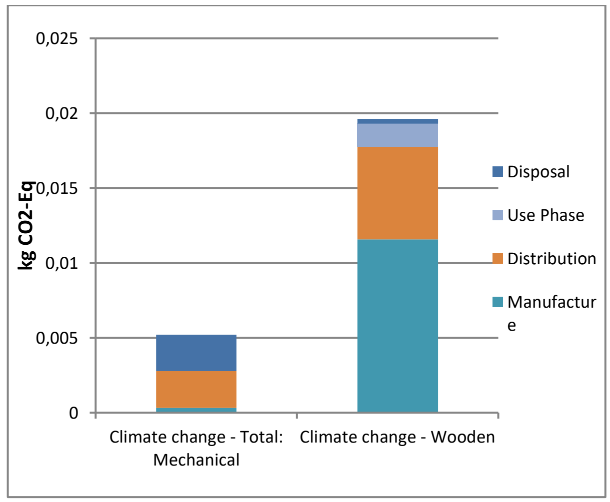


Figure 4.11: Climate Change impact without raw materials phase

For climate change, in order to indicate which processes contribute to this impact category, based on the results from Umberto 11, a graph was plotted in Figure 4.12. The graphs show that for mechanical pencil graphite clay processing and plastic molding had the highest climate-change emissions in comparison with other processes. For wooden pencils, graphite clay mixing and ferrule & eraser molding are the leading procedures. The main reason for this higher value in contribution is that the processing of these materials is energy intensive. Especially the clay-and-graphite mixing process requires high energy input that will lead to increased greenhouse gas emissions.

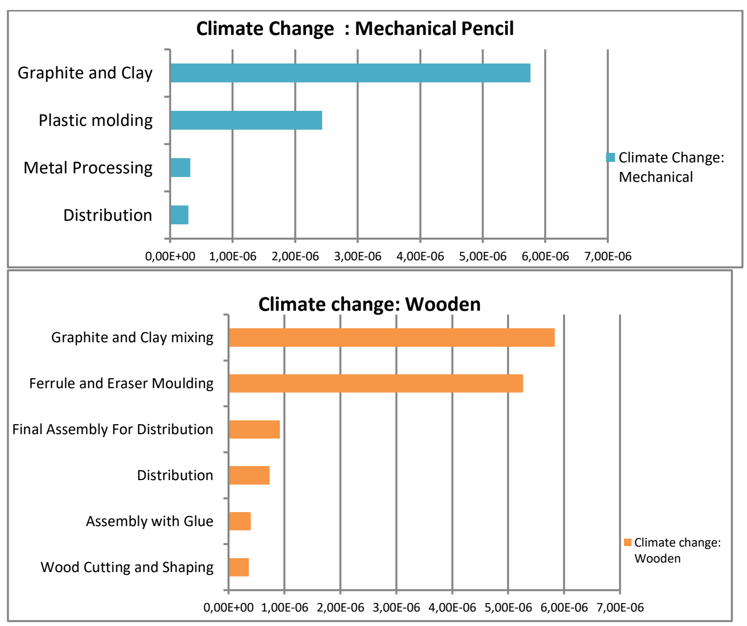


Figure 4.12: Impact by process for Mechanical and wooden pencil: Climate Change

4.2 Ionizing Radiation

Ionization radiation impact is linked mainly to the usage of nuclear power for production process. For pencil production, the wooden pencil impact is about 20% higher than that of mechanical pencil. As it can be seen from Figure 4.13 the ionization radiation value for both pencil options in raw material processing impact is almost similar. When we exclude the effect of raw material from our assessment as indicated in Figure 4.14, we can see that the wooden pencil manufacturing process is the leading phase which created the difference in impact amount. The main reason could be because the number of pencils used in one academic year is higher for wooden pencils as the mechanical pencil can be reused throughout the year.

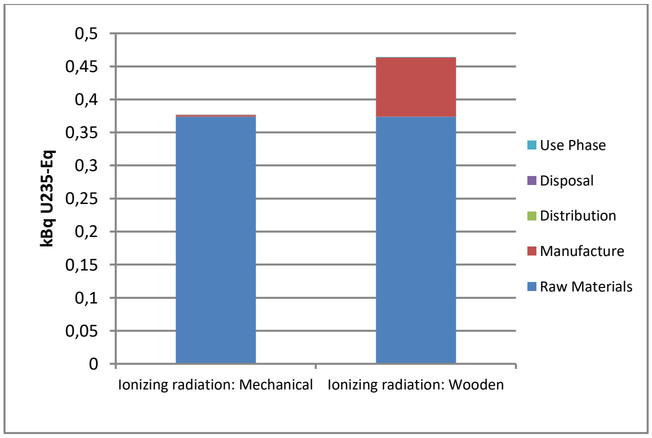


Figure 4.13: Ionization radiation impact category

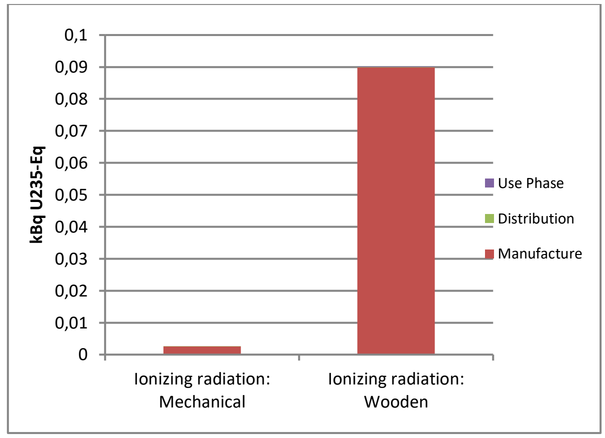


Figure 4.14: Ionization radiation impact category without raw material phase

As indicated in Figure 4.15 for pencil production, in the mechanical option graphite & clay processing is the only process that contributes to ionizing radiation whereas, for wooden pencil graphite & clay mixing, ferrule & eraser molding, and assembly with glue were found to be the contributing processes. Previously it was determined that for ionization radiation impact, raw material processing was the major contributor. The reason is mainly due to the fact that the French electricity mix, where the factory is situated is dominated by nuclear power as a means of electricity generation (Le-Boulch et al., 2024).

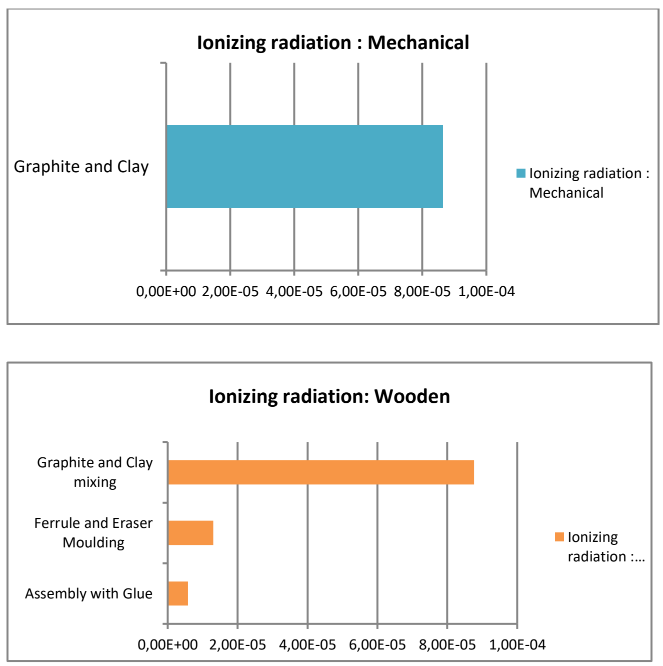


Figure 4.15: Impact by process for Mechanical and wooden pencil: Ionizing Radiation

4.3 Freshwater Eutrophication

The results of freshwater eutrophication in Figure 4.16 show that the wooden pencil impact is almost three times higher than that of the mechanical pencil with values of 2.435E-05 Kg P-Eq and 7.998E-06 Kg P-Eq respectively. This is resulted mainly from the contribution of raw materials. When we remove the effect of raw materials in Figure 4.17, for other phases the impact of the wooden pencil is still higher than that of the mechanical pencil and the difference is more than ten times. In this impact category, the effect of use phase which is shown in purple color can be seen for the wooden pencil.

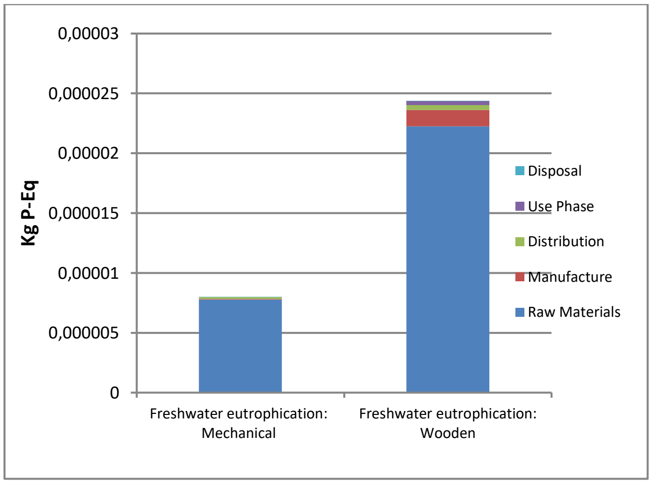


Figure 4.16:Freshwater eutrophication impact category

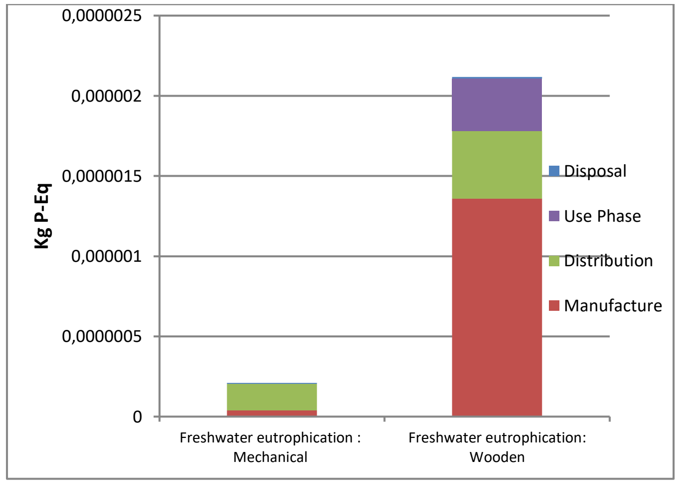
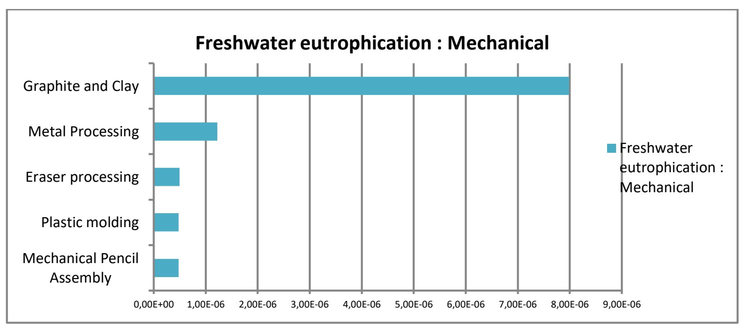


Figure 4.17: Freshwater eutrophication impact category without raw materials

Freshwater eutrophication occurs mainly due to graphite & clay processing for both mechanical and wooden pencils. Additionally, ferrule & erase molding, plastic molding and assembly process contribute most to the impact as shown in Figure 4.18. In general, freshwater eutrophication occurs because of high concentrations of phosphate and nitrates that result in the growth of algae and weeds in water bodies. Therefore, for this project phosphate emission into to water can be linked to, the French electricity mix which can create phosphorous emission into the water (Le-Boulch et al., 2024).



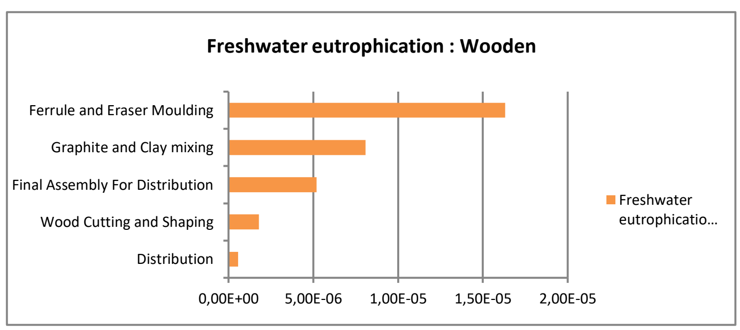


Figure 4.18: Impact by process for Mechanical and wooden pencil: Freshwater Eutrophication

4.4 Freshwater Ecotoxicity

Freshwater ecotoxicity impact category is level III based on a recommendation level of EF impact assessment due to inventory robustness (III) and inventory coverage completeness (III) (Sala et al., 2017). Therefore, the analysis and result of this impact assessment should be considered with caution due to the uncertainties with the model. For this report, it can be noticed from Figure 4.19 that for the wooden pencil the impact has a total value of 3.3464 CTUe and for mechanical pencil it is 1.9725 CTUe. The percentage difference between the impact values is around 51%, where the wooden pencil exhibits a higher impact. It can also be seen in Figure 4.20 that the impact of other phases besides raw material is also significant for wooden pencils than mechanical counterparts.

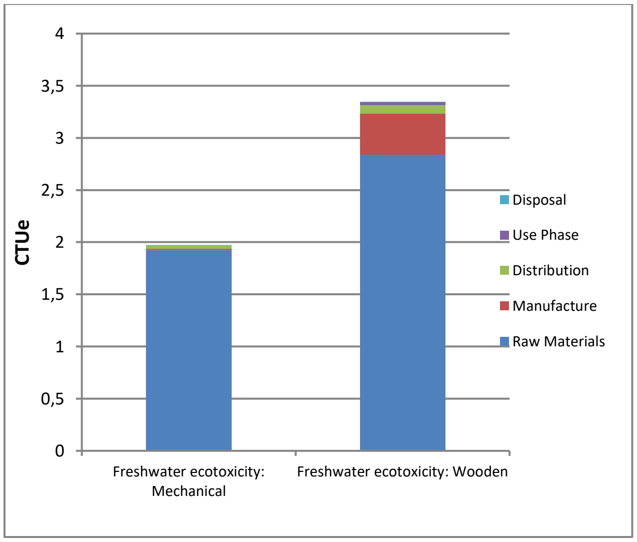


Figure 4.19: Freshwater Ecotoxicity impact category

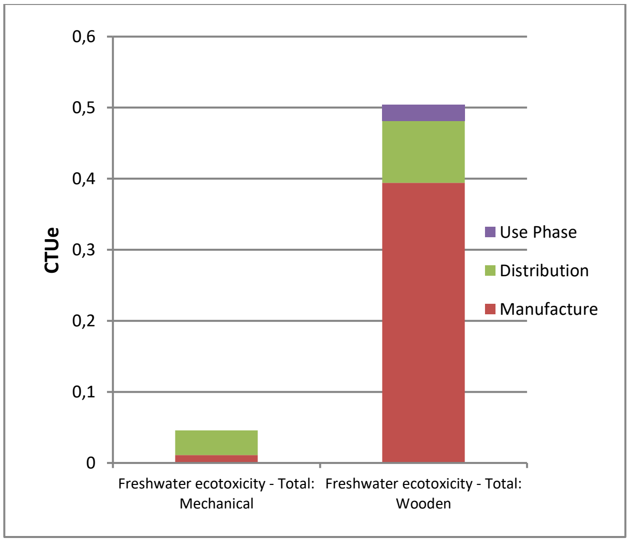
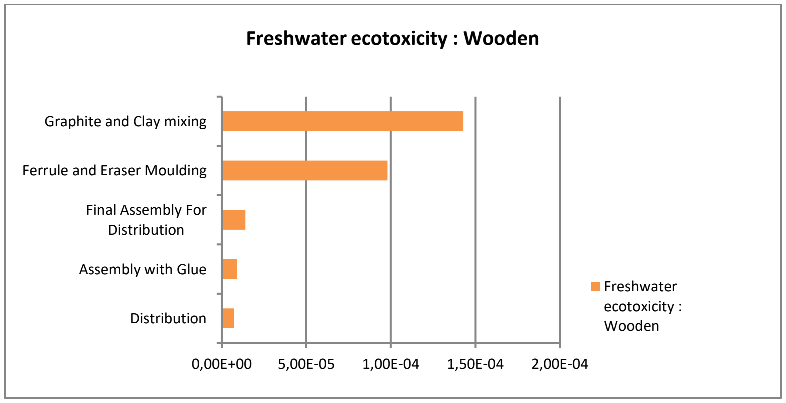


Figure 4.20: Freshwater Ecotoxicity impact category without raw materials

For mechanical and wooden pencils, the major processes that contribute to this impact category are shown in Figure 4.21. The processes include procedures that are undertaken in an industry that involves the combustion of fuel including transportation processes in distribution.



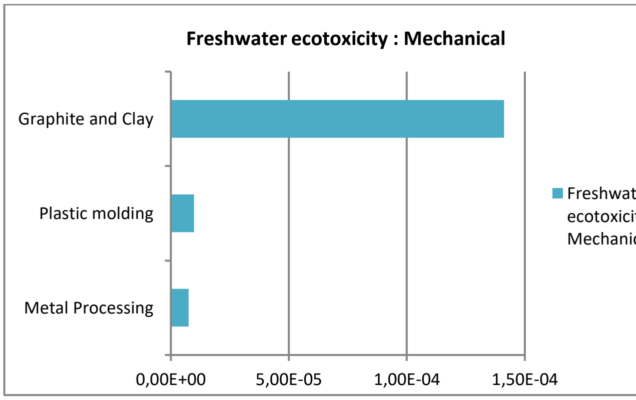


Figure 4.21: Impact by process for Mechanical and wooden pencil: Fresh water ecotoxicity

4.5 Fossils

In general, the analysis indicates that wooden pencils have approximately 20% higher fossil depletion impact when compared to mechanical pencils as shown in Figure 4.22. The figure shows that for the two pencil options the raw material impact is about the same. However, for wooden pencils the impact will be high for the subsequent phases from manufacturing to disposal phases. As pointed out in Figure 4.23 the impact of wooden pencils is around 180% higher than mechanical pencils for phases excluding the raw material processing which is mainly due to the manufacturing stage.

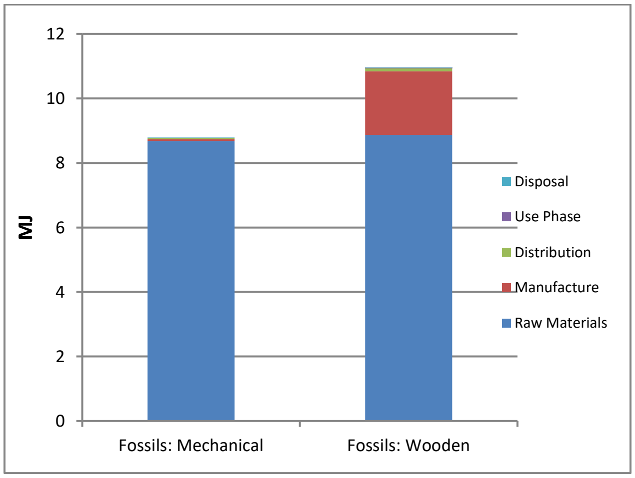


Figure 4.22: Fossils Impact Category

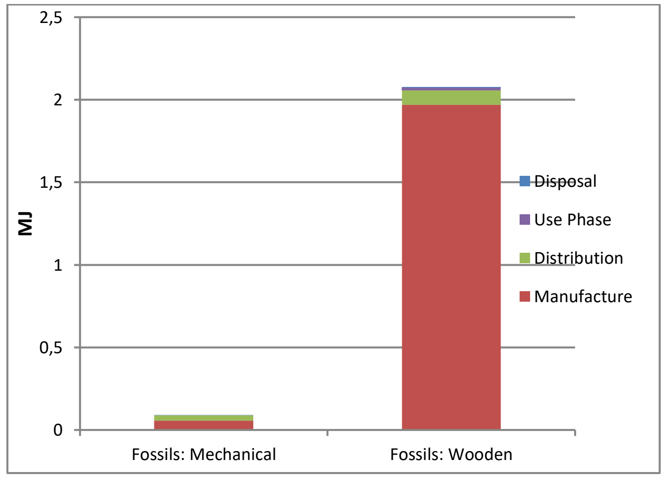
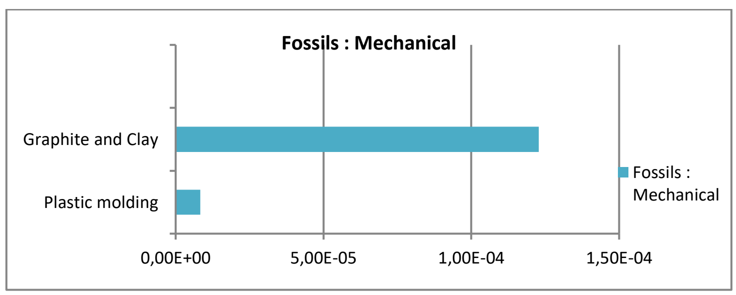


Figure 4.23: Fossils Impact Category without raw materials

In pencil production, the main processes that contribute to fossil depletion are graphite & clay processing, plastic, ferrule, and eraser molding. The major reason is that these processes can be linked to the use of fossil resources in the material extraction and manufacturing stage in the combustion process. As can be noted from Figure 4.24, the processes specified are the major material resources required for producing pencils.



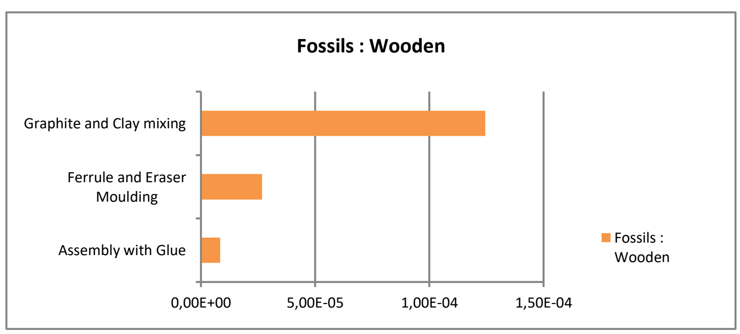


Figure 4.24: Impact by process for Mechanical and wooden pencil: Fossils Impact Category

5 Sensitivity analysis

Several parameters used to model the systems in LCA analysis have a certain degree of uncertainty, especially considering the assumptions. For this study, three sensitivity analyses which are discussed below were carried out.

5.1 Plastic Used for Mechanical Pencil Case

The type of plastic used in the mechanical pencil is an important factor since it affects the environmental impact raw materials have, which is the largest contributor in all lifecycle stages. In the baseline scenario, high impact polystyrene (HIPS) was used for modeling. In real life, polystyrene is also a popular raw material for the mechanical pencil case (The Ohio State University, n.d.).

Table 5.1. Results of sensitivity analysis of HIPS and polystyrene

	Base Scenario	Polystyrene	Percentage of Variation
Fossils(MJ)	8,776152024	8,773603148	-0,029%
Freshwater ecotoxicity (CTUe)	1,972569179	1,970371836	-0,111%
Climate Change (kg CO2-Eq)	0,076501846	0,076304445	-0,258%
Ionizing Radiation (kBq U235-Eq)	0,376389347	0,376379402	-0,003%
Freshwater Eutrophication (Kg P-Eq)	7,99814E-06	7,96092E-06	-0,465%

From Table 5.1 we can see that HIPS has a slightly higher environmental impact in all impact categories than polystyrene does. This suggests that polystyrene could be a better alternative for producing mechanical pencils, as they do not require high resistance to breakage.

5.2 Hardness of Graphite Core

The graphite-clay ratio of the core pencil affects the darkness, smoothness and application of the pencil. In the baseline scenario, HB wooden pencil was modeled. Then 4B wooden pencil was considered in the sensitivity analysis, with a graphite-clay ratio of 79:15 by mass. The results as shown in Table 5.2 indicate that 4B pencils have less than 1% higher impacts in all considered impact categories than HB pencils. The reason for such results is that the production of graphite has a larger environmental impact than clay does. But generally speaking, we can conclude that 4B pencils and HB pencils have similar environmental impacts.

Table 5.2 LCA results of the 4B pencils in the characterization phase.

	Base Scenario	4B	Percentage of Variation
Fossils(MJ)	10,94973936	10,95056441	0,008%

Freshwater ecotoxicity (CTUe)	3,346461494	3,349846334	0,101%
Climate Change (kg CO2-Eq)	0,116990307	0,11705401	0,054%
Ionizing Radiation (kBq U235-Eq)	0,463624721	0,463629575	0,001%
Freshwater Eutrophication (Kg P-Eq)	2,43794E-05	2,43946E-05	0,062%

5.3 Distribution Method

Distribution of the mechanical pencil has the second highest impact among all the lifecycle phases. The sensitivity analysis of distribution comparing lorry transport and railway transport highlights differences in their environmental impacts, as shown in Table 5.3. Trains have 2.6% less climate change than lorries do, but it also introduces an increase of 2.5% in ionizing radiation.

In conclusion, with both processes, train distribution is generally better for reducing climate change impacts, but it does have drawbacks in areas like freshwater eutrophication and ionizing radiation. Choosing between lorry and train distribution depends on which environmental impacts are the priority, as each process has its advantages and disadvantages. Considering the higher fuel efficiency and the larger capacity railway transport has, it could be a better transportation method.

Table 5.3. Results of sensitivity analysis of Lorry Transport and Train Transport

	Base Scenario	Train	Percentage of Variation
Fossils(MJ)	8,776152024	8,748951827	-0,310%
Freshwater ecotoxicity (CTUe)	1,972569179	1,946158657	-1,339%
Climate Change (kg CO2-Eq)	0,076501846	0,074466016	-2,661%
Ionizing Radiation (kBq U235-Eq)	0,0376389347	0,038593045	2,535%
Freshwater Eutrophication (Kg P-Eq)	7,99814E-06	8,06635E-06	0,853%

6 Conclusion

The present study compared the environmental impacts of two pencil alternatives: wooden pencils and mechanical pencils. In the assessment, using Environmental Footprint (EF) 3.0 methodology and Umberto 11 software, special focus was given to five impact categories which are; climate change, ionizing radiation, freshwater eutrophication, freshwater eco-toxicity, and fossils. The analysis reveals that the mechanical pencil is more environmentally friendly than the wooden pencil. Among the five impact categories studied, the wooden pencil has a higher impact in all those categories. For instance, in the climate change category, it has a 38% higher impact than the mechanical pencil. For mechanical pencils, the major contributor to the reduction in impact is its high reusability which creates a lower impact during the production process. Therefore, we can generalize that the mechanical pencil will be sustainable if it is refilled and used multiple times as it was assumed in this analysis.

It is worth noting that the study evaluated the use of pencil per student per one academic year while over 15 billion pencils are manufactured worldwide each year (Hone-young, 2022). Consequently, we can extrapolate that worldwide the cumulative effect on the environment is substantial.

The findings also reveal that the raw material stage has the highest impact for both pencil types. For wooden pencils, deforestation can be a major concern as it can have an amplifying effect on climate change. Furthermore, the energy intensive method of wood processing will have an added effect on the environment. In contrast, for mechanical pencils, because of the plastic cover, there is a concern about plastic waste which will contribute to pollution. Additionally, the use of plastic as a cover material makes it energy intensive in the manufacturing process. To mitigate this, we recommend that the cover used for mechanical pencils should be replaced with recycled materials so that it can have a reduction in the environmental impact. Furthermore, for wooden pencils to reduce the impact of wood processing on the environment, it is recommended to use alternative means of casing for graphite, such as recycled paper which can help in preserving trees.

Additionally, some critical inputs to the study were further investigated in sensitivity analysis. The sensitivity analysis undertaken in this study compares the impacts of wooden pencils with different hardness, mechanical pencils made of different types of plastic and mechanical pencils using different distribution methods. It can be seen that the overall environmental impact is barelyinfluenced by the hardness of the pencil cores and the material used for making mechanical pencils. While the use of trains instead of lorries as the distribution method represents a decrease of 2.6% in climate change, it also brings an increase in ionizing radiation of 2.5%.

7 Reference

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Annex 1: Results from Umberto: Characterized, Normalized and Weighted

Mechanical pencil

Row Labels	Raw Materials	Manufacture	Distribution	End-of-Life
Climate change - Total	0.073676871	0.000330592	0.002445177	4.92062E-05
Carcinogenic effects - Total	4.11296E-11	1.36465E-13	1.08408E-12	2.98392E-14
Non-carcinogenic effects - Total	6.46858E-10	3.23048E-12	3.19002E-11	5.5682E-13
Respiratory effects, inorganics	4.2293E-09	2.03279E-11	1.89386E-10	4.05317E-12
Ozone layer depletion	2.34513E-09	1.26694E-11	5.17623E-11	5.77462E-13
Photochemical ozone creation	0.000240052	1.09405E-06	1.15911E-05	2.90809E-07
Ionizing radiation	0.373775484	0.002567065	4.51383E-05	1.66053E-06
Freshwater ecotoxicity - Total	1.92608451	0.011267035	0.034358468	0.000859165
Freshwater eutrophication	7.78784E-06	3.88218E-08	1.66501E-07	4.98436E-09
Marine eutrophication	8.42638E-05	4.39191E-07	2.66812E-06	8.24571E-08
Terrestrial eutrophication	0.000662781	3.09644E-06	2.81828E-05	7.80353E-07
Freshwater and terrestrial acidification	0.000298073	1.30415E-06	7.75912E-06	1.92817E-07
Fossils	8.685433911	0.056269579	0.03398892	0.000459614
Minerals and metals	2.04272E-07	8.08653E-10	7.81887E-09	1.69426E-10
Land use	0.265668092	0.001453232	0.020083104	0.000162673
Water scarcity	0.104813142	0.000629197	0.000166643	3.91377E-06
Climate change (N)	8.77491E-06	3.93735E-08	2.91221E-07	5.86046E-09
Human toxicity, cancer (N)	1.06626E-06	3.53777E-09	2.81041E-08	7.73562E-10
Human toxicity, non-cancer (N)	1.36412E-06	6.81255E-09	6.72722E-08	1.17424E-09
Respiratory effects, inorganics (N)	5.89188E-06	2.8319E-08	2.63835E-07	5.6465E-09
Ozone layer depletion (N)	1.00446E-07	5.4265E-10	2.21706E-09	2.47336E-11
Photochemical ozone creation (N)	5.91205E-06	2.69444E-08	2.85468E-07	7.16211E-09
Ionizing radiation (N)	8.85744E-05	6.08323E-07	1.06965E-08	3.93499E-10
Freshwater ecotoxicity (N)	0.00016297	9.53328E-07	2.90714E-06	7.26958E-08
Freshwater eutrophication (N)	1.06135E-05	5.29073E-08	2.26912E-07	6.79281E-09
Marine eutrophication (N)	2.97986E-06	1.55314E-08	9.43542E-08	2.91597E-09
Terrestrial eutrophication (N)	3.74628E-06	1.75022E-08	1.59299E-07	4.41084E-09
Freshwater and terrestrial acidification (N)	5.36678E-06	2.34811E-08	1.39702E-07	3.47166E-09
Fossils (N)	0.000133097	8.62286E-07	5.20853E-07	7.04321E-09
Minerals and metals (N)	3.20874E-06	1.27025E-08	1.2282E-07	2.66137E-09
Land use (N)	1.90043E-07	1.03956E-09	1.43663E-08	1.16367E-10
Water scarcity (N)	9.13754E-06	5.4853E-08	1.45278E-08	3.412E-10
Climate change (W)	0.000113196	5.07918E-07	3.75675E-06	7.55999E-08
Ozone layer depletion (W)	5.60487E-07	3.02798E-09	1.23712E-08	1.38014E-10
Human toxicity, cancer (W)	7.25057E-06	2.40568E-08	1.91108E-07	5.26022E-09
Human toxicity, non-cancer (W)	8.02101E-06	4.00578E-08	3.95561E-07	6.90454E-09

Respiratory effects, inorganics (W)	3.23464E-05	1.55471E-07	1.44846E-06	3.09993E-08
Ionizing radiation (W)	0.000504874	3.46744E-06	6.09701E-08	2.24295E-09
Photochemical ozone creation (W)	2.81414E-05	1.28256E-07	1.35883E-06	3.40916E-08
Freshwater and terrestrial acidification (W)	2.65119E-05	1.15997E-07	6.9013E-07	1.715E-08
Freshwater eutrophication (W)	3.38569E-05	1.68774E-07	7.23848E-07	2.16691E-08
Marine eutrophication (W)	8.7608E-06	4.56622E-08	2.77401E-07	8.57296E-09
Terrestrial eutrophication (W)	1.10515E-05	5.16315E-08	4.69933E-07	1.3012E-08
Freshwater ecotoxicity (W)	0.000997377	5.83437E-06	1.77917E-05	4.44898E-07
Land use (W)	1.71799E-06	9.39759E-09	1.29871E-07	1.05196E-09
Water scarcity (W)	8.85428E-05	5.31526E-07	1.40775E-07	3.30623E-09
Fossils (W)	0.000980927	6.35505E-06	3.83869E-06	5.19085E-08
Minerals and metals (W)	2.14344E-05	8.48525E-08	8.20439E-07	1.7778E-08

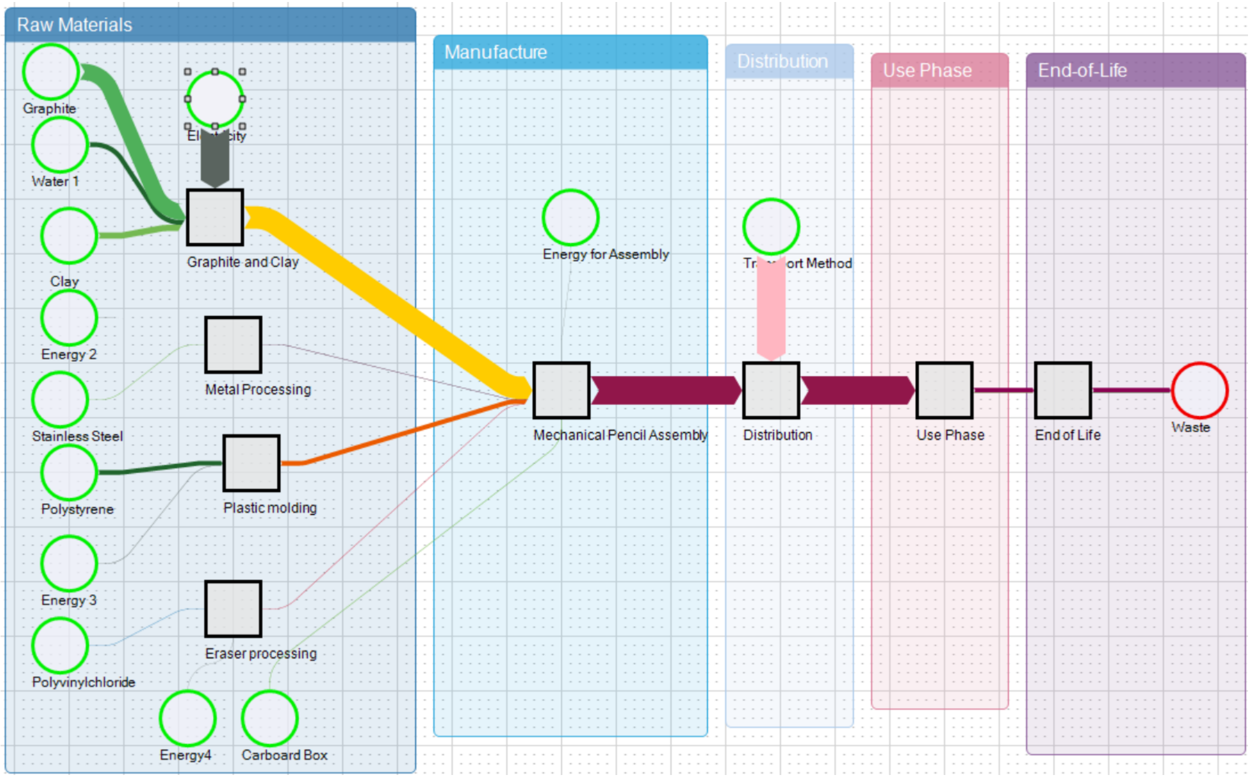
Wooden pencil

Row Labels	Raw Materials	Manufacture	Distribution	End-of-Life	Use Phase
Climate change - Total	0,097376043	0,011570707	0,006196982	0,001521867	0,000324708
Carcinogenic effects - Total	7,38262E-11	4,77627E-12	2,74746E-12	2,17396E-12	7,58323E-14
Non-carcinogenic effects - Total	1,4328E-09	1,13067E-10	8,08468E-11	9,53856E-11	2,53717E-12
Respiratory effects, inorganics	7,05396E-09	7,11478E-10	4,79974E-10	1,50899E-10	3,89661E-11
Ozone layer depletion	9,57537E-09	4,43428E-10	1,31185E-10	2,84488E-11	5,39634E-12
Photochemical ozone creation	0,000353587	3,82917E-05	2,93761E-05	1,40076E-05	2,98321E-06
Ionizing radiation	0,373637581	0,089847263	0,000114397	2,26217E-05	2,85805E-06
Freshwater ecotoxicity - Total	2,838641831	0,39434624	0,087077034	0,022689861	0,003706528
Freshwater eutrophication	2,2262E-05	1,35876E-06	4,21975E-07	3,26276E-07	1,04073E-08
Marine eutrophication	0,000126873	1,53717E-05	6,76201E-06	7,22528E-07	5,14777E-06
Terrestrial eutrophication	0,001034384	0,000108375	7,14255E-05	4,88554E-05	7,80077E-06
Freshwater and terrestrial acidification	0,000440006	4,56453E-05	1,96645E-05	1,0206E-05	1,6912E-06
Fossils	8,8726863	1,96943527	0,086140464	0,017234042	0,004243286
Minerals and metals	5,33843E-07	2,83029E-08	1,98159E-08	3,84268E-09	3,83154E-10
Land use	5,089358387	0,050863126	0,050897995	0,010690577	0,001117153
Water scarcity	0,110249127	0,022021901	0,000422335	0,002673707	1,09109E-05
Climate change (N)	1,15975E-05	1,37807E-06	7,3806E-07	1,81254E-07	3,86727E-08
Human toxicity, cancer (N)	1,9139E-06	1,23822E-07	7,12262E-08	5,63587E-08	1,96591E-09
Human toxicity, non-cancer (N)	3,02154E-06	2,38439E-07	1,70493E-07	2,01152E-07	5,35046E-09
Respiratory effects, inorganics (N)	9,82694E-06	9,91166E-07	6,68656E-07	2,10218E-07	5,4284E-08
Ozone layer depletion (N)	4,10128E-07	1,89927E-08	5,61885E-09	1,21851E-09	2,31134E-10

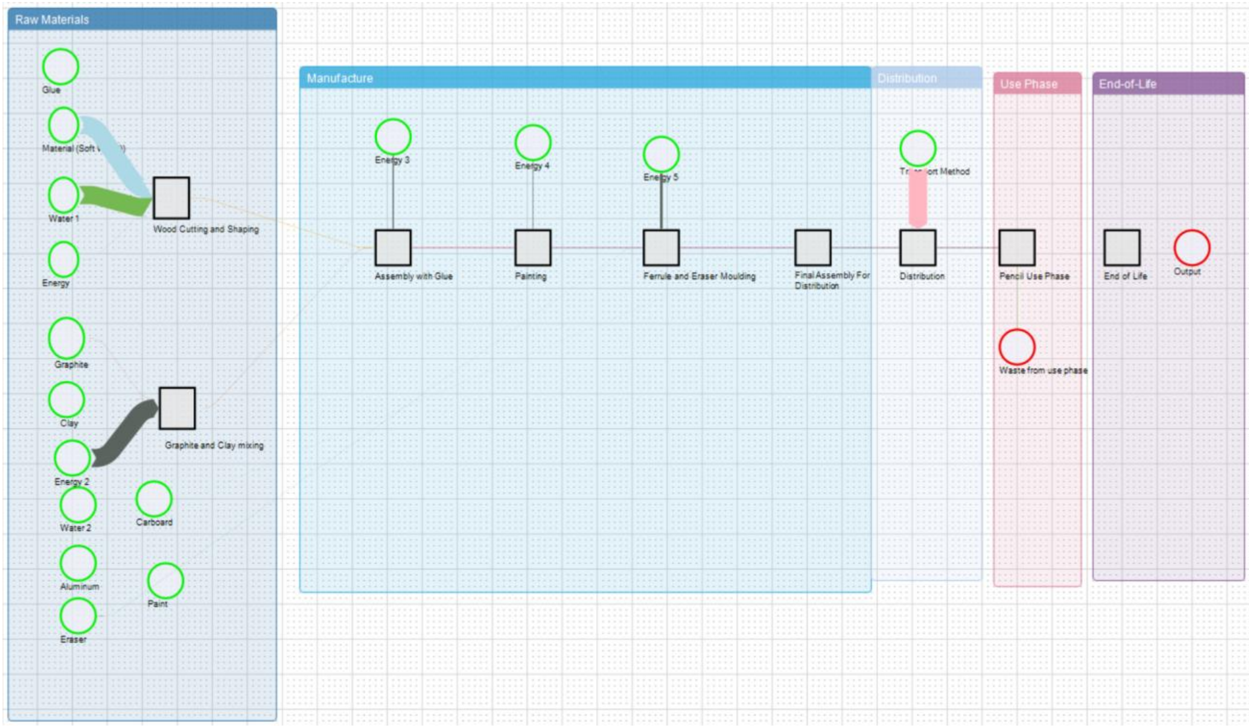
Photochemical ozone creation (N)	8,7082E-06	9,43055E-07	7,2348E-07	3,44981E-07	7,34711E-08
Ionizing radiation (N)	8,85417E-05	2,12913E-05	2,71089E-08	5,36071E-09	6,77278E-10
Freshwater ecotoxicity (N)	0,000240184	3,33665E-05	7,36777E-06	1,91984E-06	3,13617E-07
Freshwater eutrophication (N)	3,03392E-05	1,85175E-06	5,75078E-07	4,44657E-07	1,41833E-08
Marine eutrophication (N)	4,48666E-06	5,43598E-07	2,39128E-07	1,82043E-07	2,55511E-08
Terrestrial eutrophication (N)	5,84672E-06	6,12577E-07	4,03723E-07	2,76149E-07	4,40928E-08
Freshwater and terrestrial acidification (N)	7,92228E-06	8,2184E-07	3,54058E-07	1,83757E-07	3,045E-08
Fossils (N)	0,000135967	3,018E-05	1,32003E-06	2,64098E-07	6,5025E-08
Minerals and metals (N)	8,3857E-06	4,44586E-07	3,11272E-07	6,03615E-08	6,01865E-09
Land use (N)	3,64063E-06	3,63845E-08	3,64094E-08	7,64741E-09	7,99145E-10
Water scarcity (N)	9,61145E-06	1,91986E-06	3,68189E-08	2,33092E-07	9,51208E-10
Climate change (W)	0,000149608	1,77771E-05	9,52098E-06	2,33818E-06	4,98878E-07
Human toxicity, cancer (W)	1,30145E-05	8,41988E-07	4,84338E-07	3,83239E-07	1,33682E-08
Human toxicity, non-cancer (W)	1,77666E-05	1,40202E-06	1,0025E-06	1,18278E-06	3,14607E-08
Respiratory effects, inorganics (W)	5,39499E-05	5,4415E-06	3,67092E-06	1,1541E-06	2,98019E-07
	2,28852E-06	1,05979E-07	3,13532E-08	6,79928E-09	1,28973E-09
Photochemical ozone creation (W)	4,1451E-05	4,48894E-06	3,44377E-06	1,64211E-06	3,49722E-07
Ionizing radiation (W)	0,000504688	0,00012136	1,54521E-07	3,0556E-08	3,86048E-09
Freshwater ecotoxicity (W)	0,001469923	0,000204203	4,50908E-05	1,17494E-05	1,91934E-06
Freshwater eutrophication (W)	9,67819E-05	5,9071E-06	1,8345E-06	1,41846E-06	4,52449E-08
Marine eutrophication (W)	1,31908E-05	1,59818E-06	7,03038E-07	5,35207E-07	7,51203E-08
Terrestrial eutrophication (W)	1,72478E-05	1,8071E-06	1,19098E-06	8,14639E-07	1,30074E-07
Freshwater and terrestrial acidification (W)	3,91361E-05	4,05989E-06	1,74904E-06	9,07762E-07	1,50423E-07
Fossils (W)	0,001002075	0,000222427	9,72865E-06	1,9464E-06	4,79234E-07
Minerals and metals (W)	5,60165E-05	2,96984E-06	2,0793E-06	4,03215E-07	4,02046E-08
Land use (W)	3,29113E-05	3,28916E-07	3,29141E-07	6,91326E-08	7,22427E-09
Water scarcity (W)	9,3135E-05	1,86034E-05	3,56775E-07	2,25866E-06	9,21721E-09

Annex 2: Print screen of Umberto model

Mechanical pencil



Wooden pencil



Annex 3: Used inputs from Ecoinvent database

Mechanical pencil

Material	Inputs from Ecoinvent
electricity, high voltage	FR, electricity, high voltage, production mix
tap water	Europe without Switzerland, market for tap water
steel, chromium steel 18/8, hot rolled	GLO, market for steel, chromium steel 18/8, hot rolled
graphite	GLO, market for graphite
clay	RoW, market for clay
polystyrene, high impact	GLO, market for polystyrene, high impact
polyvinylchloride, emulsion polymerised	GLO, market for polyvinylchloride, emulsion polymerised
corrugated board box	RER, market for corrugated board box
transport, freight, lorry 16-32 metric ton, EURO5	RER, market for transport, freight, lorry 16-32 metric ton, EURO5

Wooden pencil

Material	Inputs from Ecoinvent
electricity, high voltage	FR, electricity, high voltage, production mix
tap water	Europe without Switzerland, market for tap water
sawlog and veneer log, softwood, debarked, measured as solid wood	RER, market for sawlog and veneer log, softwood, debarked, measured as solid wood

graphite	GLO, market for graphite
clay	RoW, market for clay
ethylene	RER, market for ethylene
acrylic binder, with water, in 54% solution state	RER, market for acrylic binder, with water, in 54% solution state
polyvinylchloride, emulsion polymerised	GLO, market for polyvinylchloride, emulsion polymerised
aluminium alloy, AlMg3	GLO, market for aluminium alloy, AlMg3
corrugated board box	RER, market for corrugated board box
transport, freight, lorry 16-32 metric ton, EURO5	RER, market for transport, freight, lorry 16-32 metric ton, EURO5