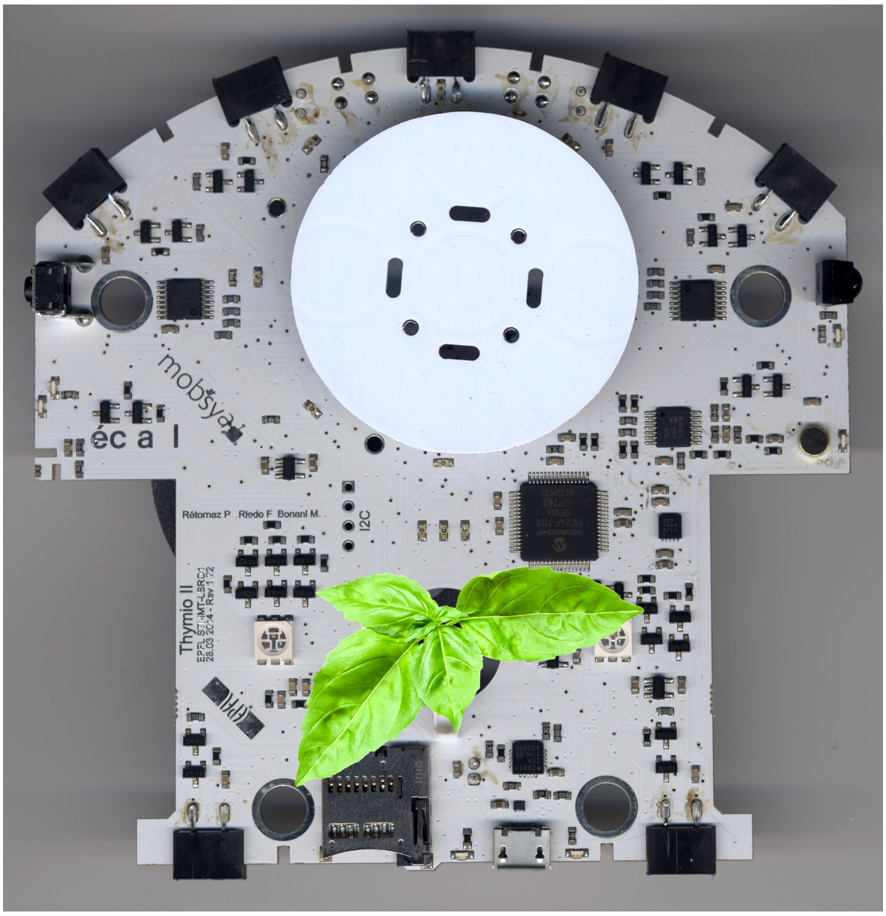

Open life cycle exploration

Spring semester project - Mobile Robotic Systems Group (MOBOTS)

EPFL

Alexandre de Terrasson de Montleau - 288111

Student picture: appendice E

Contents

0 Summary

The present project consists of conducting a life cycle assessment (LCA) of the Thymio and develop an educational activity centered around the LCA of the Thymio, targeting school students. The objective of this activity after discussion with experts is to teach students the following concepts: The use of resources and the environmental impacts of a technological object are multiple. Resources are limited and introduce the concept of a life cycle. The activity should also enable students to grasp the scale of various resources and impacts associated with everyday technological objects. The overall objective of the activity is to enhance student's understanding of current environmental challenges. Results of the LCA demonstrates that the environmental impacts of the robot are mainly attributed to the manufacturing phase and primarily due to integrated circuits and the printed circuit board. The realized educational activity consists of a multiplayer card game that uses the results of Thymio's LCA to teach the concepts defined above.

1 Introduction

With the rise of digital technologies and climate challenges, understanding the environmental impacts of technological products throughout their life cycle has become essential for both businesses and the general population. This knowledge is crucial for making sustainable choices during the manufacturing, transportation, use, and end-of-life stages of a product, as well as understanding today's environmental issues. The present project aims to make this knowledge accessible, similar to open-source initiatives such as open code, open hardware, open data, and open science. These movements share the common goal of promoting transparency by providing information about products or processes.

Through this project, we make the environmental impacts of the Thymio robot accessible throughout its life cycle, creating a kind of "Open life cycle". To achieve this, we collaborate with experts from various domains, conduct a life cycle assessment of the Thymio, and develop an educational activity based on its results.

2 Definition of the project

In this section, we explain the genesis of the project and the evolution of its definition.

2.1 Initial definition

According to the initial project description in appendix A, here is a short paragraph of the initial project:
This project aims to implement "open life cycles" by providing real-time access to comprehensive life cycle information and simulations for products. Inspired by the principles of open-source code and open data, the project seeks to enhance sustainability by enabling better understanding and decision-making based on transparent information. The concept involves a central repository where "open life cycle products" share

their impact data throughout their lifespan. Users can compare products, simulate the effects of choices such as repair versus replacement, and assess end-of-life options. The tools also support educational purposes, including teaching the concept of life cycles in schools. The project will conduct a thorough analysis of existing resources, define the platform's specifications, and prototype elements, potentially utilizing the Thymio robot [5] platform.

2.2 Refine the definition

2.2.1 First version

In order to realize this project, the platform must meet the following objectives:

- Educate people about the impact of their use of technology
- Helping consumers make the right choices about which technological device to buy, repair or throw away and how to best use their device to reduce its environmental impact.

More concretely, the first version idea of this platform is to make accessible the results of the life cycle assessment (LCA) of a technological object like the Thymio robot. We chose the LCA because this method covers the environmental impacts of all the phases of the life cycle of an object (manufacturing, transport, use and end of life). So the platform would give at the purchase, the environmental impacts of the manufacturing and transport phase with an empty part on use phase which would evolve as the digital object is used. This idea came after watching the "Lifecycle Performance of Product Systems" course given at EPFL by Damien Friot [1]. More precisely in this course, the slide of the figure 1 shows the results of a Coca Cola bottle LCA where we see that the majority of the impacts concern the user (46 %). Our idea took inspiration from this slide.

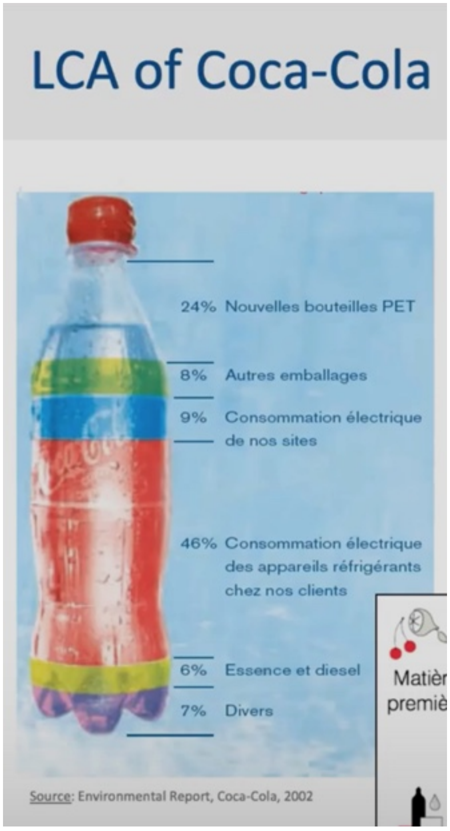

Figure 1: LCA results of a Coca-Cola Bottle [1]

Making visible the environmental impacts at different stages of the life cycle of a technological object allows to fulfill these objectives of education and comparison between products with the impacts at the manufacturing stage, or repair choices with the use stage of the life cycle. All of this allows to orient consumers towards a more responsible use of technological products. A prototype of this platform is possible by carrying out the LCA of the Thymio robot since we have the necessary information to make such an analysis thanks to Mobsya, the association which develops the Thymio [5].

2.2.2 Refine with Experts

We meet with various LCA experts to inquire about the feasibility of conducting an LCA for Thymio, discuss potential collaboration with them during the project, and confirm that the direction we are taking is relevant. We first meet with members of the company Resilio [3]: Gabriela Haenel (COO) and Amael Parreaux-Ey (CEO). Resilio is a startup supported by EPFL, providing training, consulting, and environmental impact analysis services in the field of responsible digital technology. Resilio operates internationally, supporting various types of organizations. Resilio offers comprehensive guidance to businesses and organizations for responsible digital practices. The team has developed Resilio Tech, a tool for measuring the environmental footprint of digital equipment and services.
After pitching our project to them, here is their feedback: they advise us to clearly define our target users because, at this stage, our audience is too broad. They are interested in our idea of making LCA accessible. According to them, the added value of our project lies in the educational aspect by sharing about the impacts of technologies like Thymio and transmitting a sense of scale regarding resources consumed and impacts. They believe that providing real-time information on the usage phase, with the intention of reducing people's environmental impact, is not useful because, for this type of product, the majority of impacts occur during the manufacturing phase.
Resilio confirms their expertise in assisting us with conducting the LCA of Thymio. They have already performed LCAs for companies, taking into account their technological equipment such as computers. Resilio offers their services to us. According to them, conducting the LCA of Thymio should take a few weeks as we can easily find the necessary information about Thymio, such as the bills of materials and transportation from the factory to Renens. Our organization will be as follows: They will transfer their knowledge to us and provide access to their Resiliotech platform. Additionally, a consultant from Resilio will act as a mentor and guide us at each step of the LCA through weekly meetings consisting of questions, answers, and progress updates. We will be responsible for conducting the LCA with the guidance of the Resilio consultant.
Afterwards, we meet with Damien Friot, founder of the LCA consulting company Quantis and teacher of the "Lifecycle Performance of Product Systems" course at EPFL [1]. Like Resilio members, he explains to us that for technological objects such as robots, smartphones, or computers, the majority of environmental impacts occur during the manufacturing phase. Therefore, educating people to reduce their impacts by providing real-time data on the use phase of the LCA, which changes based on their object usage, would have little to no influence on the overall impacts.
Mr. Friot finds the educational aspect of the project more interesting. For him, where our project is valuable is in the field of education by successfully transmitting two concepts: the notion of life cycle and the existence of multiple impact indicators. The main goal of the educational activity would be to prompt the audience

to ask the right questions regarding environmental impacts through the LCA of Thymio. The challenge for him in our project is not only to perform the LCA of Thymio but also to represent and use the results for educational purposes.

2.2.3 Final version of the project

After discussions with experts, we decide to focus on the educational aspect of the project. Therefore, we refine the definition and objectives of the project:
The project consists of conducting a life cycle assessment (LCA) of the Thymio, with the assistance of Resilio as described in section 2.2.2. Additionally, we aim to develop an educational activity centered around the LCA of the Thymio, targeting school students. We incorporate the concepts to transmit in section 2.2.2 by Mr. Friot and Resilio and define the objective of the activity. The objective of this activity is to teach students the following concepts: The use of resources and the environmental impacts of a technological object are multiple. Resources are limited and introduce the concept of a life cycle. The activity should also enable students to grasp the scale of various resources and impacts associated with everyday technological objects. The overall objective of the activity is to enhance student's understanding of current environmental challenges.

3 Life cycle assessment

This section presents the steps of the LCA. The LCA is the most successful method for assessing environmental impacts. Indeed, this method is the most quantitative and multi-criteria as shown in figure 2 which compares the different environmental impact assessment tools.

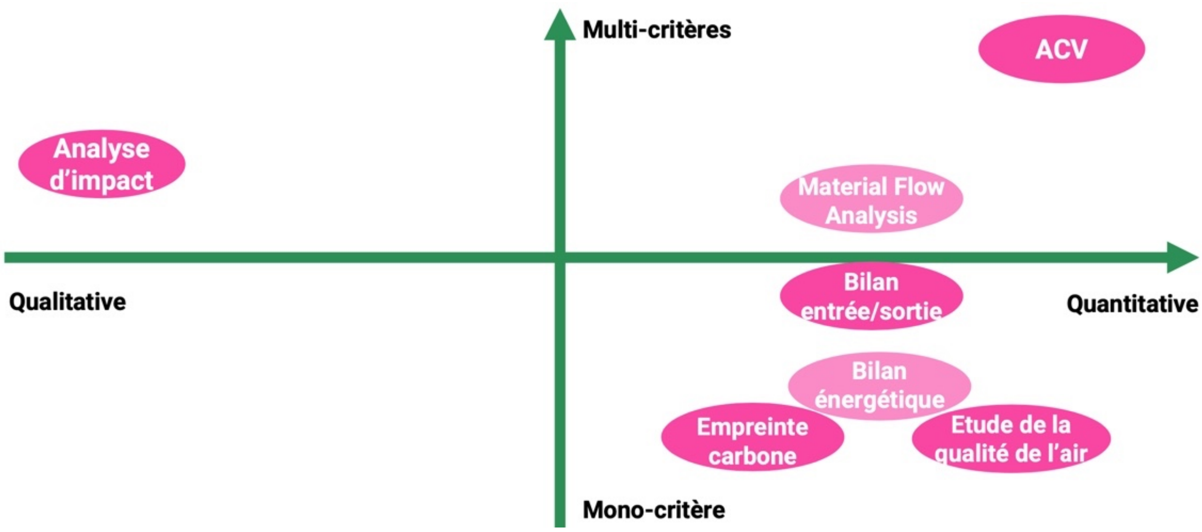

Figure 2: Environmental evaluation tools comparison [3]

3.1 Life Cycle Assessment definition

LCA allows to measure the quantifiable effects of products or services on the environment throughout its whole life cycle (manufacturing, transport, use and end of life). LCA allows to calculate the environmental footprint on a multitude of environmental indicators required by the PEF methodology (European standard) [2]. All indicators are gathered in the figure 4. A description of each indicators is available in appendix B. LCA consists of three steps: "goal and scope definition", "inventory analysis" and "impact assessment". These three steps are detailed in the following parts and represented in figure 3.

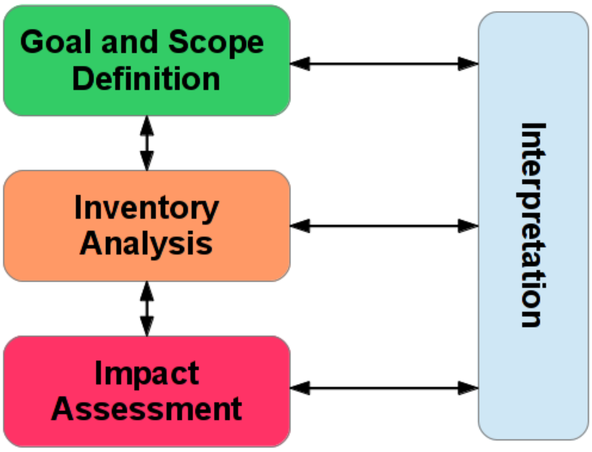

Figure 3: Main ACV steps [3]

- ADPe - Resource use, minerals and metals (kg Sb eq.)
- ADPf - Resource use, fossils (MJ)
- AP - Acidification (mol H+ eq.)
- CTUe - Ecotoxicity, freshwater (CTUe)
- CTUh-c - Human toxicity, cancer (CTUh)
- CTUh-nc - Human toxicity, non-cancer (CTUh)
- Epf - Eutrophication, freshwater (kg P eq.)
- Epm - Eutrophication, marine (kg N eq.)
- Ept - Eutrophication, terrestrial (mol N eq.)
- GWP - Climate change (kg CO2 eq.)
- GWPb - Climate change - Biogenic (kg CO2 eq.)
- GWPf - Climate change - Fossil (kg CO2 eq.)
- GWPlu - Climate change - Land use and land use change (kg CO2 eq.)
- IR - Ionising radiation, human health (kg U235 eq.)
- LU - Land use (dimensionless)
- ODP - Ozone depletion (kg CFC-11 eq.)
- PM - Particulate matter (disease occurrences)
- POCP - Photochemical ozone formation (kg NMVOC eq.)
- WU - Water use (m3 eq.)
- MIPS - Material Input per Service-Unit (kg of excavated materials)
- TPE - Total Primary Energy (MJ)
- WEEE - Mass of Electric and Electronic Wastes (kg of WEEE)

Figure 4: All ACV Indicators [3]

3.2 Goal and scope definition

In this step, we define the objectives of the LCA and the scope of the study through a following series of definitions. The present study was carried out following the requirements of the ISO 14 044 [3] standard in order to allow comparison with other LCAs.

- Objectives

  As defined above, the objective of this study is to exploit the results of the LCA to develop an educational activity for schoolchildren.

- Functional unit

  The object of study is defined with the functional unit. In our study, it is defined as: "Use over one year of a Thymio in a school classroom".

- System studied

  The studied system is the educational robot Thymio 2. Thymio was chosen for this project because it is a technological object that students and teachers are already familiar with. Indeed, Thymio is widely present at primary, secondary and university level (about 70 000 units). Furthermore, through Mobsya, we have access to all the necessary information about the robot for conducting its LCA.

- Usage scenario

  The usage scenario is determined based on intern measurements made by Mobots of pre-programmed Thymio usage recorded in 93 cycle 1 classes over a period of one year, encompassing both the pilot and deployment phases of the Thymio robot. Analysis of this data reveals that, on average, a teacher utilized Thymio for a total of 4 hours and 22 minutes over the course of one year as shown on figure 5.

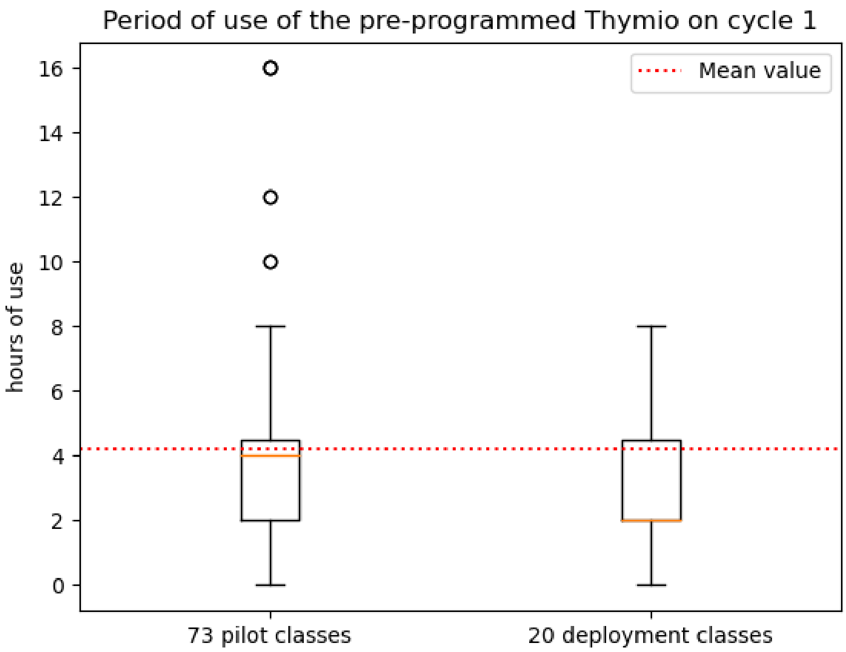

Figure 5: Period of use of the pre-programmed Thymio in cycle 1 schools for one year

- Life Cycle Phase and Boundary

  The evaluated life cycle stages encompass manufacturing, transportation, and use. However, as all Thymio robots introduced in schools a decade ago are still in active service, there is a lack of data regarding the end-of-life phase. Consequently, the study excludes the end-of-life stage.

- Study perimeter and cuts:

  The study perimeter includes the Thymio robot and all the elements that compose it. The box, the cables and the USB key are excluded from the study.

3.3 Life cycle inventory

The life cycle inventory step constitutes the stage of collection of useful data in each phase of the Thymio's life cycle.

Our study is based primarily on data provided by Mobysa, the association that manufactures and sells the Thymio robot. Additionally, we gather public data from manufacturers and suppliers of Thymio robot components. We also use the Ecoinvent database [6]. It is a repository covering a wide range of sectors on global and regional level. It contains more than 18'000 activities, otherwise referred to as 'datasets', modeling environmental impacts of human activities or processes. Furthermore, we make assumptions regarding certain missing data. All data sources and assumptions are documented alongside the life cycle inventory.

3.3.1 Manufacturing phase

Manufacturing phase includes all the processes involved in creating the component, starting from raw material extraction and continuing through processing, assembly, and energy consumption for the part's production. In this phase, we want to extract all the environmental impacts (listed in figure 3) in the manufacturing of each component of the robot using Ecoinvent database, Mobysa data and public data from component manufacturers and retailers.

The Ecoinvent database provides environmental impacts per kilogram of the specific component. In order to determine the mass of each component of the Thymio, we consult the supplier's website for the mass information. If the information is not available, we refer to the mass of a similar component on another website. Additionally, for components such as the motor, PCB plate, shell, and screws, we directly measure their mass using a scale. By summing up the individual masses of all the components, we arrive at a total of 262 grams, while the overall mass of the Thymio is 263 grams. This confirms the accuracy of the extracted component masses.

Subsequently, we employ the following method: for each component of the robot, we identify its equivalent counterpart in the Ecoinvent database and extract the corresponding environmental impacts provided per kilogram. An illustrative example of this method is presented in figure 6. These impact values are then multiplied by the mass in kilograms of the respective component. It is during this stage that approximations are made for certain components due to the limitations of Ecoinvent, which does not offer an exact match for the specific component with the one in the database. For example the accelerometer is not available on Ecoinvent so we approximate this component by the element integrated circuit logic type available on the Ecoinvent platform. The approximation of each element is available in the bills of materials in appendix C. Each approximation is chosen by discussing with Thymio's creators and reading Ecoinvent reports [7] and [8] that describe datasets in the electronic sectors.

After extracting the respective environmental impacts for each component, we categorize them into main blocks, encompassing "Basic electronic components", "Power supply" (or battery), "Light emitting diode", "Motor", "Microcontroller", "Sensors", "Shell", and "Peripheral Connectors". The environmental impacts of each block are then aggregated to derive the overall environmental impacts. A description of all the blocks is provided in figures 7, 8, and 9.

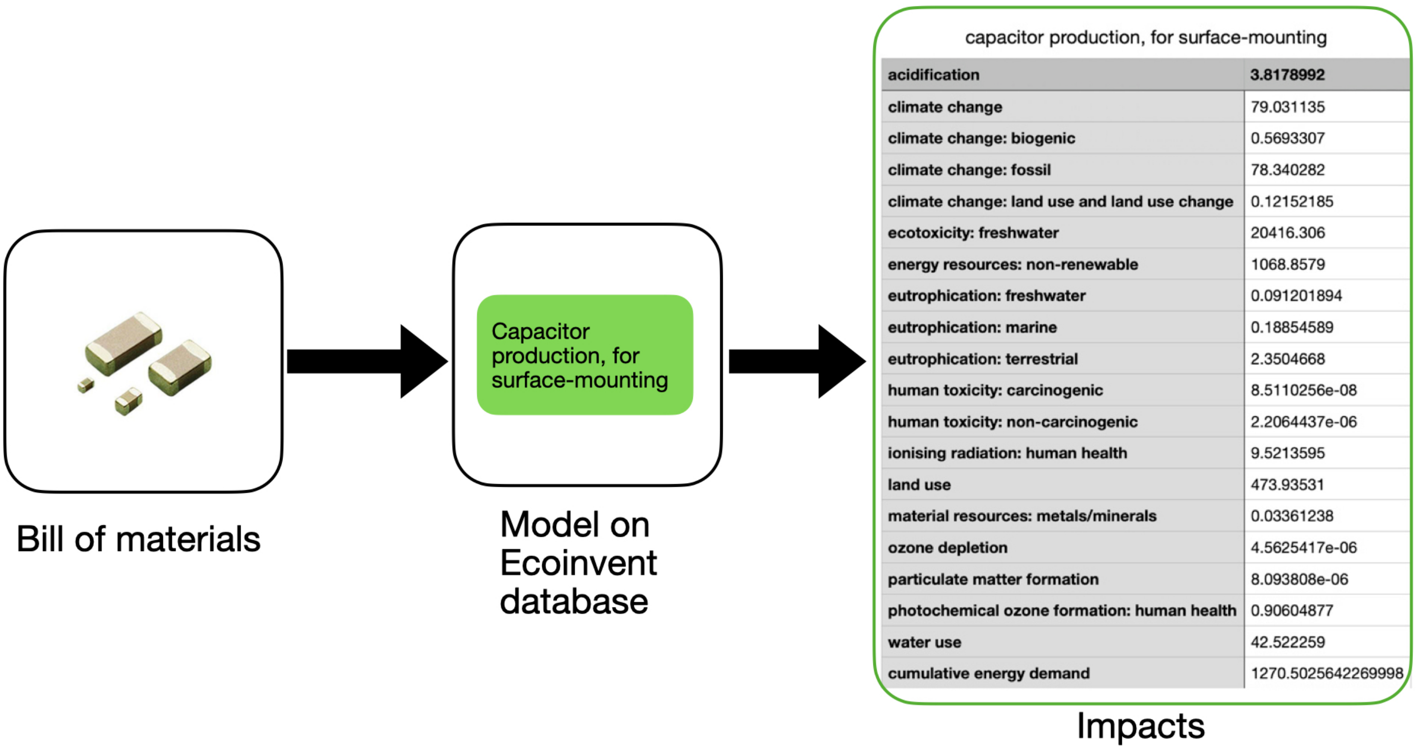

Figure 6: Example of environmental impacts extractions of capacitors of the robot using Ecoinvent database

	Block	Equipment type
0	Basic electronic	['Resistances 4,7K Ohm', 'Resistances 33 Ohm', 'Resistances 2,7K Ohm', 'Resistances 22K Ohm', 'Resistances 2,2K Ohm', 'Resistances 1,5K Ohm', 'Resistances 1K Ohm', 'Resistances 10K Ohm', 'Resistances 6,2 Ohm', 'Resistances 56 Ohm', 'Resistances 39 Ohm', 'Resistances 200 Ohm', 'Resistances 82 Ohm', 'Resistances 100 Ohm', 'Resistances 180 Ohm', 'Resistances 5,6K Ohm', 'Resistances 100K Ohm', 'Resistances 680K Ohm', 'Resistances 6,8K Ohm', 'Resistances 820 Ohm', 'Resistances 47K Ohm', 'Resistances 270K Ohm', 'Resistances 0 Ohm', 'Capacitor 100nf', 'Capacitor 10 uF', 'Capacitor 51 pF', 'Capacitor 4,7 nF', 'Capacitor 4,7 uF', 'Capacitor 10 uF X5R \n', 'Capacitor 18 pF', 'Capacitor 1 nF', 'Capacitor 1uF', 'Capacitor 1,5 nF', 'Capacitor 47 nF', 'SMD ferrite bead for EMI suppression ', 'General purpose transistor', 'Transistor MOSFET', 'Transistor MOSFET type 2 ', 'Operational Amplifier', '8-bit Shift Register with 3-state output registers', 'CMOS process low dropout linear regulator ', 'ULDO REGULATOR', 'Audio power amplifier', '1 x 6 pins connector', 'Surface Mount Quartz Crystal 8Mh\xa0', 'PCB']
1	Battery	['Multicell Battery 3,7V, 1500 mAh', 'Battery Charge Management Controller']
2	Light emitting diode	['LED red 56', 'LED RGB\xa0', 'LED red mounted on Thymio's side', 'LED blue mounted on Thymio's side', 'LED Standard', 'LED red 57', 'Diode Schottky Barrier Double Diode ']
3	MOTOR	['Motor, General Kind']
4	Microcontroller	['General Purpose USB Microcontroller']
5	Peripheral Connectors	['Micro SD connector', 'USB/Charger and over voltage detection device', 'WR-COM Micro USB']
6	Sensors	['Loudspeaker', 'Omnidirectional Back Electret Condenser', 'Thermistors\xa0', 'Switch\xa0', 'Accelerometer', 'Opto Interrupter \npart 1/2 ', 'Opto Interrupter \npart 2/2 ', 'Opto Interrupter type 2 Part 1/2', 'Opto Interrupter type 2 Part 2/2', 'IR receiver part 1/2', 'IR receiver part 2/2', 'ON/OFF BUTTON']
7	Shell	['Casing - ABS', 'Casing - Polycarbonate', 'Screw']

Figure 7: Blocks content

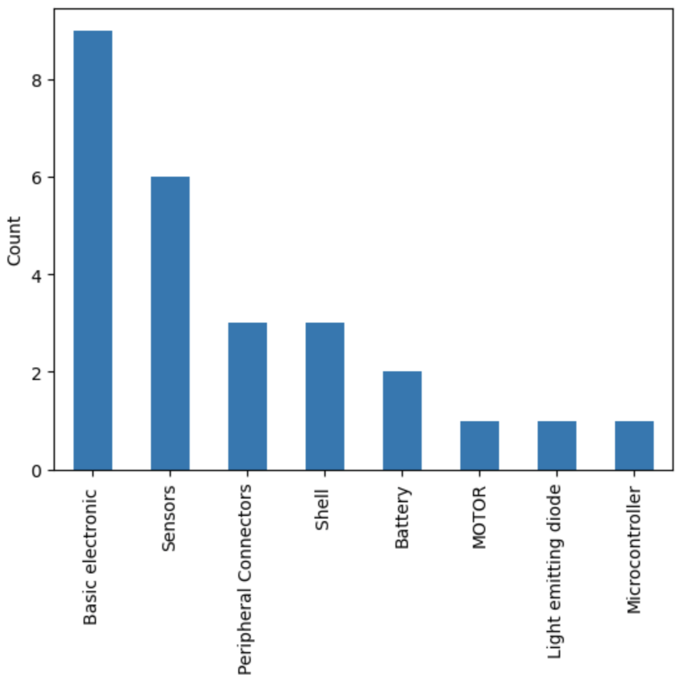

Figure 8: Number of different elements from the bills in each block

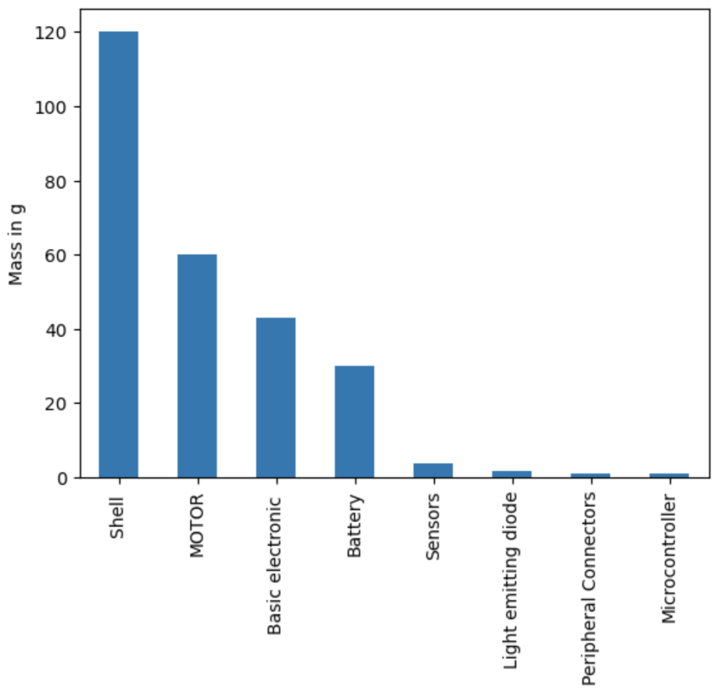

Figure 9: Total mass in each block

3.3.2 Transport phase

The life cycle's transport phase comprises the transportation that the equipment undergoes from the manufacturer to the consumer.
In this phase, we only consider transportation from the assembly factory in Shenzhen China, to the final delivery destination at Mobsya headquarters in Renens. We concentrate on these specific travels as we possess information exclusively for this route. However, despite not encompassing the entire transportation process (delivery to consumer or delivery of raw materials), this particular journey represents a significant portion of the overall travel distance, making it a reliable approximation of the whole travel distance. A travel from Shenzhen China to Mobsya headquarters in Renens represents 21734 km by boat and 780 km by truck as we can see on figure 10.

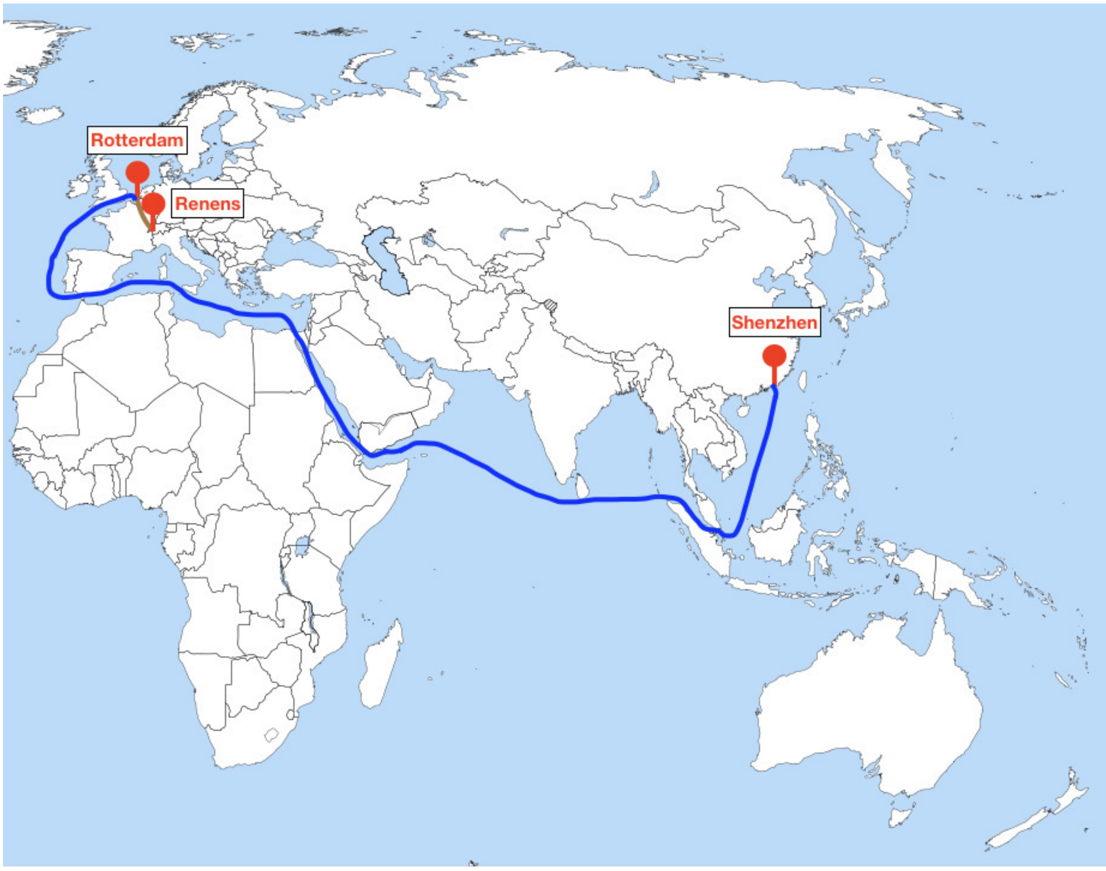

Figure 10: Thymio travel from Shenzhen China factory to Renens Switzerland

3.3.3 Use phase

This phase is limited to the actual use of the equipment, considering its actual environmental impact until the day it is disposed of.
To assess the impact during the use phase, it is necessary to determine the Thymio's electrical consumption within its designated school class scenario. Based on the defined parameters of the usage scenario, which

indicate an annual usage time of 4 hours and 22 minutes, and the recorded electric consumption of 5.55 Wh for a 2-hour Thymio usage, we calculate an annual consumption of 12.21 Wh.

3.4 Life cycle assessment results

In this section, we analyze the data generated from the LCA to interpret the results. Figure 11 provides a compilation of all the impact values calculated from the LCA. Each impact indicator defined in figure 4 is accompanied by its corresponding calculated value. To interpret the results, we follow a three-step process. First, we evaluate the significance of the impacts to determine the most important ones. Next, we examine the blocks that contribute to these impacts. Finally, we delve into the specific components that are responsible for generating for the blocks impact values.

indicator	unit	value	Detail
CTUe	CTUe	2.325165e+03	Ecotoxicity. freshwater (CTUe)
TPE	MJ	2.912730e+02	Total Primary Energy (MJ)
ADPf	MJ	2.491409e+02	Resource use. fossils (MJ)
LU	sans dimensions	8.950800e+01	Land use (dimensionless)
GWP	kg CO2 eq.	1.950440e+01	Climate change (kg CO2 eq.)
GWPf	kg CO2 eq.	1.928338e+01	Climate change - Fossil (kg CO2 eq.)
WU	m3 eq.	7.109953e+00	Water use (m3 eq.)
IR	kBq U235 eq.	2.344374e+00	Ionising radiation. human health (kg U235 eq.)
Ept	mol N eq.	2.950739e-01	Eutrophication. terrestrial (mol N eq.)
GWPb	kg CO2 eq.	1.915871e-01	Climate change - Biogenic (kg CO2 eq.)
AP	mol H+ eq.	1.425274e-01	Acidification (mol H+ eq.)
POCP	kg NMVOC eq.	7.696151e-02	Photochemical ozone formation (kg NMVOC eq.)
GWPlu	kg CO2 eq.	3.231070e-02	Climate change - Land use and land use change ...
Epm	kg N eq.	2.760584e-02	Eutrophication. marine (kg N eq.)
Epf	kg P eq.	2.691432e-02	Eutrophication. freshwater (kg P eq.)
ADPe	kg Sb eq.	7.636741e-03	Resource use. minerals and metals
ODP	kg CFC-11 eq.	1.698000e-06	Ozone depletion (kg CFC-11 eq.)
PM	occurrences de maladies	1.031100e-06	Particulate matter (disease occurrences)
CTUh-nc	CTUh	8.519000e-07	Human toxicity. non-cancer (CTUh)
CTUh-c	CTUh	1.850000e-08	Human toxicity. cancer (CTUh)

Figure 11: Total impacts

3.4.1 Identify the most significant environmental impacts

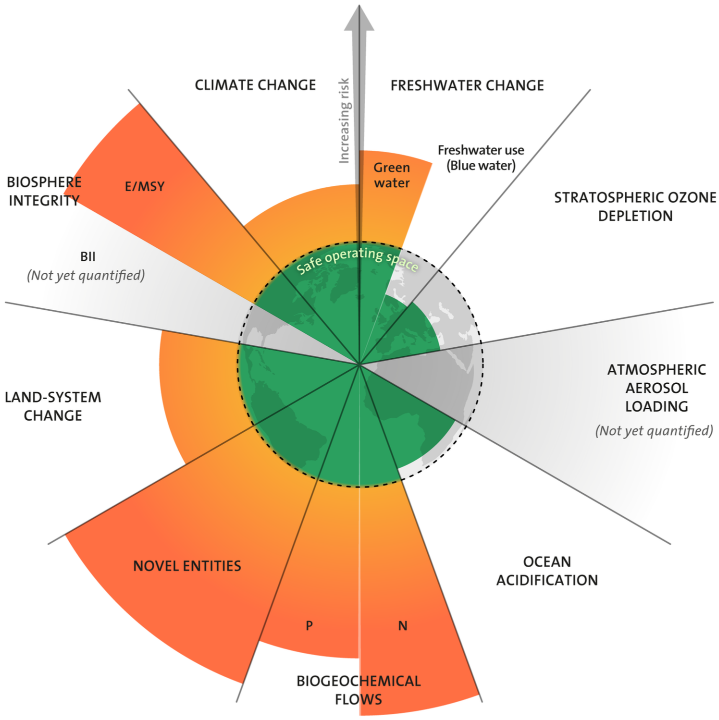

Figure 12: Planetary boundaries diagram [9]

Impact category	Abbreviation	Unit	PB	PB per capita*	Sources
Climate change	CC	kg CO_2 eq	6.81E+12	9.85E+02	Bjørn & Hauschild (2015)
Ozone depletion	ODP	kg CFC-11 eq	5.39E+08	7.80E-02	Bjørn & Hauschild (2015)
Eutrophication, marine	MEU	kg N eq	2.01E+11	2.90E+01	Bjørn & Hauschild (2015)
Eutrophication, freshwater	FEU	kg P eq	5.81E+09	8.40E-01	Bjørn & Hauschild (2015)
Eutrophication, terrestrial	TEU	molc N eq	6.13E+12	8.87E+02	recalculated by Bjørn (personal communication)
Acidification	AC	molc H^+ eq	1.00E+12	1.45E+02	recalculated by Bjørn (personal communication)
Land use	LU	kg soil loss	1.27E+13	1.84E+03	Bjørn & Hauschild (2015)
Water use	WU	m^3 world eq	1.82E+14	2.63E+04	based on recalculation by Bjørn (personal communication)
Particulate matter	PM	Disease incidence	5.16E+05	7.47E-05	based on Vargas-Gonzalez et al. (2019)
Photochemical ozone formation, human health	POF	kg NMVOC eq	4.07E+11	5.88E+01	recalculated by Bjørn (personal communication)
Human toxicity, cancer	HTOX_c	CTUh	9.62E+05	1.39E-04	based on Vargas-Gonzalez et al. (2019)
Human toxicity, non-cancer	HTOX_nc	CTUh	4.10E+06	5.93E-04	based on Vargas-Gonzalez et al. (2019)
Ecotoxicity, freshwater	ECOTOX	CTUe	1.31E+14	1.90E+04	Bjørn & Hauschild (2015)
Ionising radiation, human health	IR	kBq U^{235} eq	5.27E+14	7.62E+04	based on Vargas-Gonzalez et al. (2019)
Resource use, fossils	FRD	MJ	2.24E+14	3.24E+04	JRC calculation based on factor 2 concept (Bringezu, 2015; Buczko et al., 2016)
Resource use, mineral and metals	MRD	kg Sb eq	2.19E+08	3.18E-02	JRC calculation based on factor 2 concept (Bringezu, 2015; Buczko et al., 2016)

*Global population in 2010: 6,916,183,482, as from Bjørn & Hauschild (2015). Planetary Boundaries order

Figure 13: Planetary Boundaries values [10]

Life cycle assessment allows to calculate the environmental footprint on a multitude of environmental indicators, However, for the sake of conciseness and communication, it is easier to provide the footprint in relation to a global environmental score, taking into account all indicators. This allows use to sort environmental impacts and find the most important ones. In order to aggregate the environmental impacts from different indicators into a single unit score, the results are normalized using the planetary boundaries methodology. Planetary boundaries are a concept that reflects the finite nature of our world. Each environmental indicator has a planetary limit, which corresponds to the annual budget that the Earth can sustain in the face of the pressure exerted by human activities on the environment. The values used (in Planetary Boundaries per Capita metric) correspond to the one determined by the Joint Research Center (JRC), science and knowledge service of the European Union EU, in its report "Consumption and consumer footprint: methodology and results" [10].

To compare each environmental impact indicators between them, we normalized them into a score of the same unit by dividing their impact values with their corresponding PBC (Planetary Boundaries per capita) value (figure 13). In this way, Impact closer to boundaries will have a bigger PBCI score (Planetary Boundaries per Capita per Indicator). This comparison is presented through a chart in Figure 14 displaying the contribution (in percentage) of each environmental indicator to the footprint, and a value table in Figure 15 that provides the PBCI score for each indicator. Based on the findings from Figure 14, we can conclude that the five indicators with the greatest impact are, in order: ADPe, CTUe, LU, Epf and GWP.

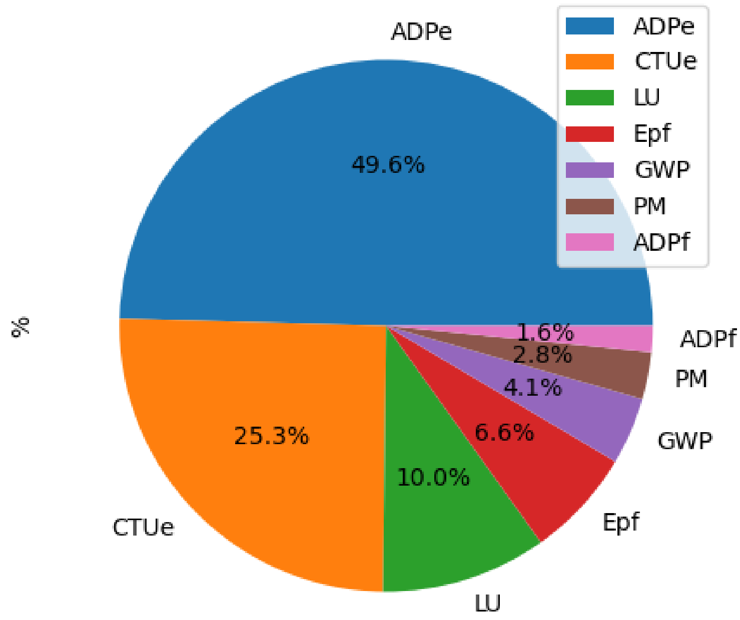

Figure 14: Contribution of indicators to the total footprint

indicator	unit	value	%
ADPe	PBCI	0.240149	49.039444
CTUe	PBCI	0.122377	24.989910
LU	PBCI	0.048646	9.933644
Epf	PBCI	0.032041	6.542876
GWP	PBCI	0.019801	4.043533
PM	PBCI	0.013804	2.818761
ADPf	PBCI	0.007690	1.570235
CTUh-nc	PBCI	0.001437	0.293374
POCP	PBCI	0.001309	0.267277
AP	PBCI	0.000983	0.200722
Epm	PBCI	0.000952	0.194387
Ept	PBCI	0.000333	0.067932
CTUh-c	PBCI	0.000133	0.027178
IR	PBCI	0.000031	0.006283
ODP	PBCI	0.000022	0.004445

Figure 15: PBCI indicators values

3.4.2 Blocks responsible for the most important indicator values

According to figure 16 which presents the contributions of each block to the environmental indicators values, the "Basic electronic components" are the most responsible for the different impacts values including the main impacts identified in figure 14. Indeed, "Basic electronic components" contribute to at least 60 percent of all environmental indicators values, followed by "Sensors" and the "Microcontroller".
The figure 17 also shows the contribution of the life cycle stage to the indicator values. It can be seen that manufacturing overwhelmingly dominates distribution (which corresponds to the transportation defined in the scope of the study) and the use phase. Therefore, the impacts on resources and waste produced occur mainly during the manufacturing phase.

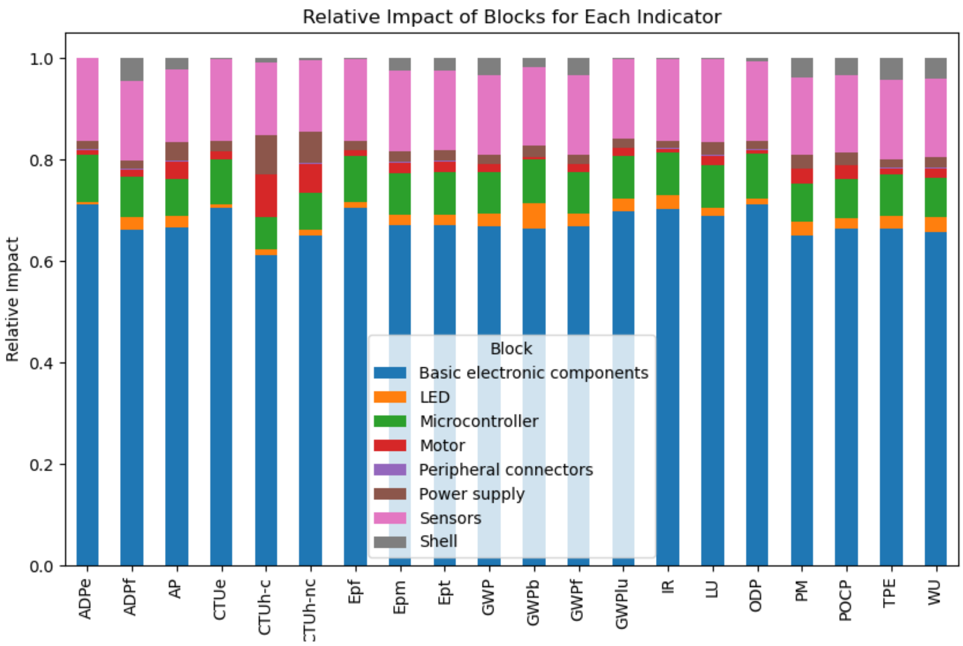

Figure 16: Total impacts per blocks contribution

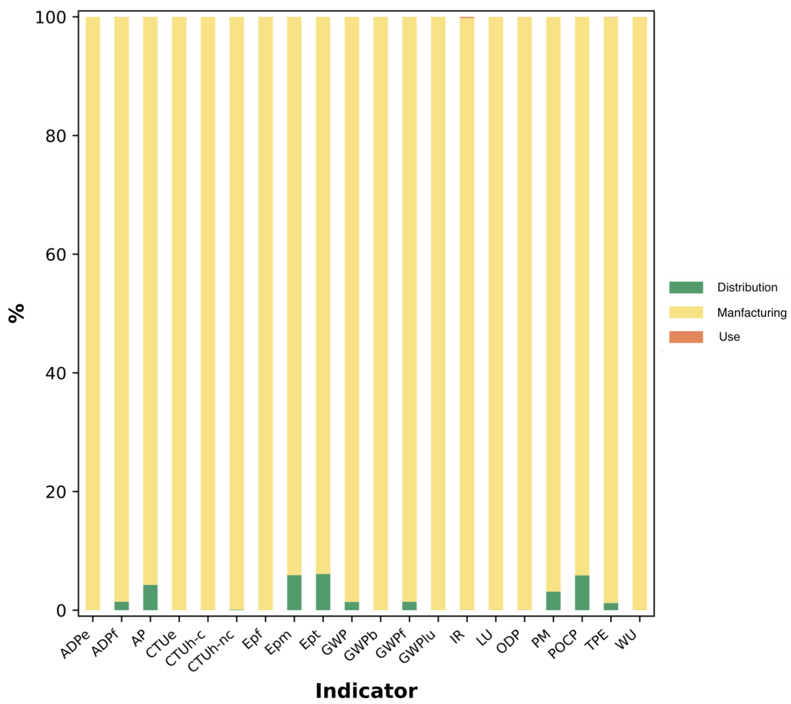

Figure 17: Total impacts per life cycle stage

3.4.3 Components in blocks responsible for the most important indicator values

In this section, we explore which components inside "Basic electronic components", "Microcontroller" and "Sensors" are responsible for the ADPe, CTUe and LU values.

According to figure 18, which illustrates the contribution of the three most influential components to the overall environmental impact value of the "Basic electronic components" block, the printing wiring board bears the greatest responsibility for the ADPe and CTUe values. In terms of the LU value, the surface-mounted transistors take on the highest level of responsibility.

In the case of the "Sensors" block, as depicted in Figure 19, the integrated circuits bear the greatest responsibility for the ADPe, CTUe, and LU values of the block.

In the "Microcontroller" block, which only contains integrated circuits, they account for 100 % of the ADPe, CTUe, and LU values for this particular block.

3.4.4 Results interpretation

As a reminder, a printed circuit board (PCB) consits of several electric current, conducting and non conducting layers which are sandwiched together.

The reason Thymio's printed circuit board (PCB) is so dominant in ecotoxicity is because according to paper "Life cycle assessment of a printed circuit board manufacturing plant in Turkey" [11], manufacturing of PCBs plays a significant role in contributing to freshwater aquatic ecotoxicity potential (FAETP). Specifically, 89 % of FAETP is attributed to PCB manufacturing. Almost all of this contribution can be attributed to the disposal of copper containing wastewater treatment sludge from etching operations (removal of excess copper during the creation of circuit patterns on the PCB boards) to incineration. Among the various stages of PCB manufacturing, etching operations are particularly influential in all impact categories except eutrophication potential (EP). Also Thymio's PCB is dominant in resource use because the PCB industry makes use of a large number of chemicals and resources such as copper throughout the various stages in the process. Lastly, Thymio's PCB is one of the heaviest electrical component as it represents 7 % of the total Thymio mass. It is for this reason that is contributes more than integrated circuits to ecotoxicity and resource use. For Land use, Transistor is dominant compared to PCB because it requires advance technology and infrastructures to produce such a component. In the block "Sensors" where PCB is not present, the integrated circuits are the most dominant. This is explained due to the advanced technology employed, significant energy consumption, and the use of specialized materials for the production stages of integrated circuits.

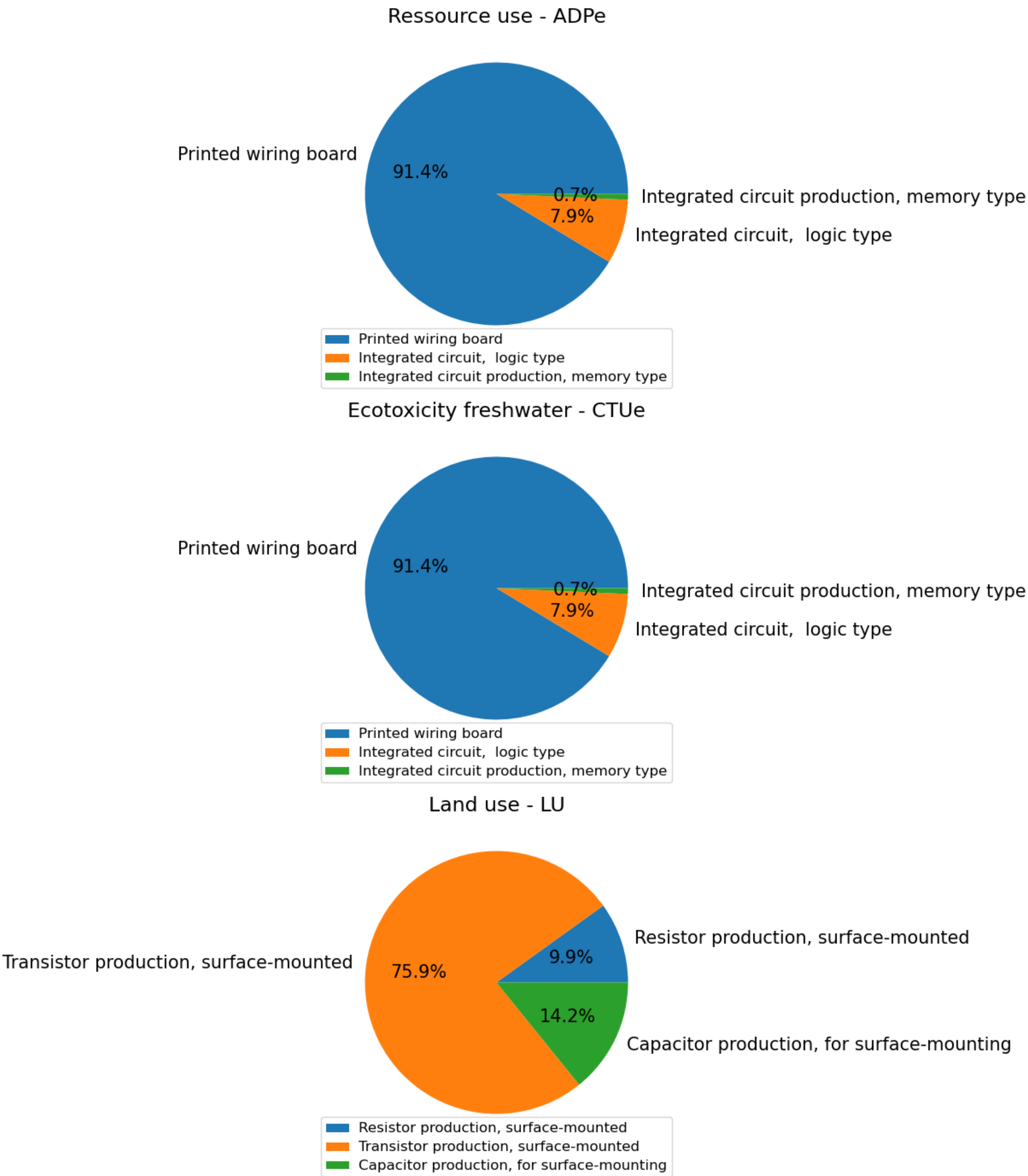

Figure 18: Contribution of elements inside block: Basic electronic components

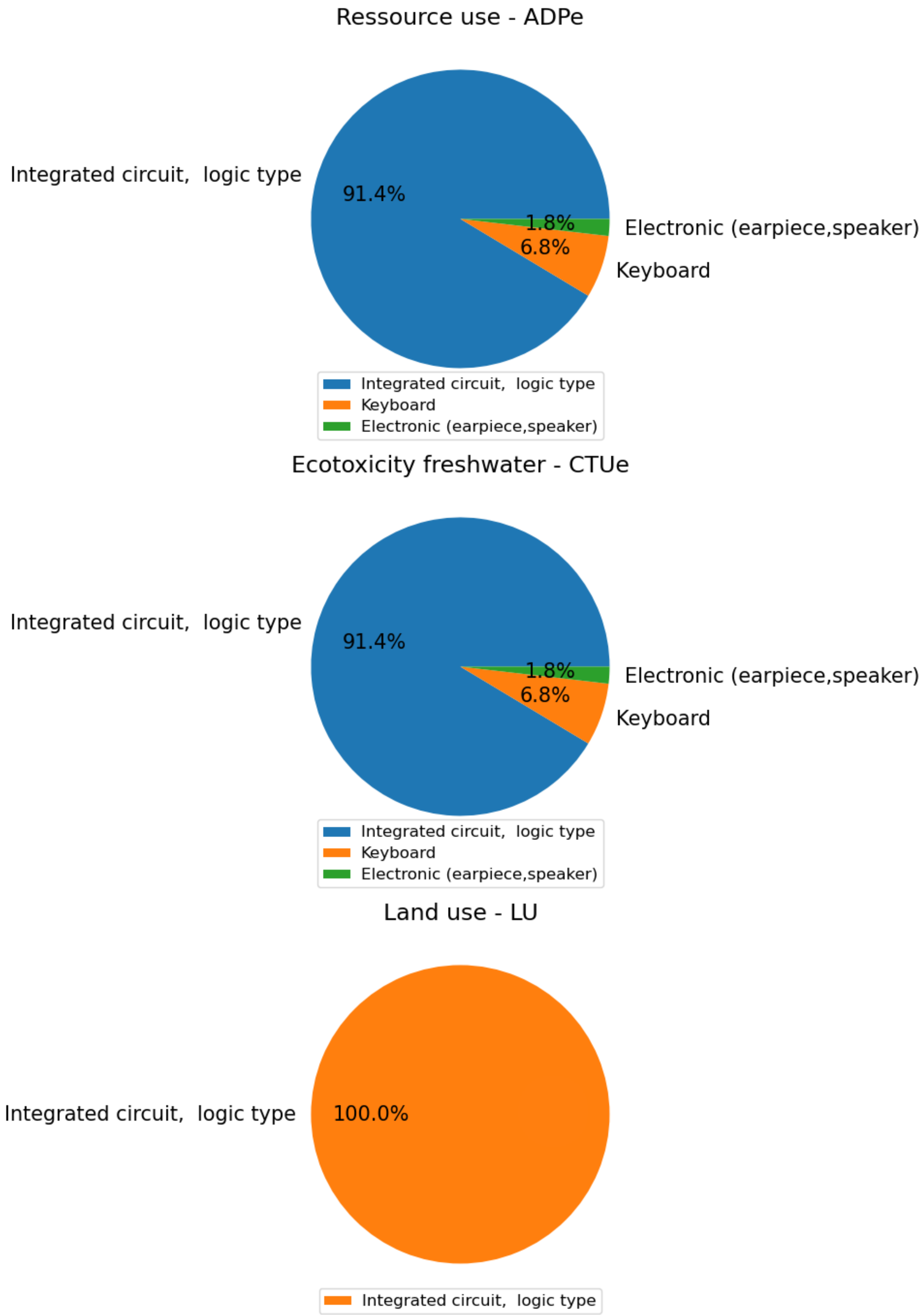

Figure 19: Contribution of elements inside block: Sensors

4 Pedagogical activity

In this section we extract important information from the LCA results to build a pedagogical activity. This activity is intended to be implemented in schools. The activity was developed under the guidance of educational activity experts Sonia Agrebi and Alizé de La Harpe, project managers at the Center for Learning Sciences at EPFL and [12].

4.1 Objectives and target public

The objective of the activity corresponds to that of the LCA defined in part 3.2. The objective of this activity is to teach students the following concepts: The use of resources and the environmental impacts of a technological object are diverse. Resources are limited and introduce the concept of a life cycle. The activity should also enable students to grasp the scale of various resources and impacts associated with everyday technological objects. The overall objective of the activity is to enhance student's understanding of current environmental challenges.

The target audience determines the level of detail we will reach in the activity. According to the Romand study plan on digital education for cycles 3 (EN32 [14]), the concepts of environmental impacts of technology are addressed in the 9th, 10th, and 11th year of the third cycle of study. Within the framework of the computer science course in the Romand study plan [14], the section on computer science and society aims to "raise awareness of the constant evolution of digital technology by identifying social, economic, and environmental impacts." The fundamental expectations for this course are to "distinguish the main issues of digital technology at the social, economic, and environmental levels." Therefore, our activity aligns perfectly with this course and is intended for children aged between 12 and 15 years old.

4.2 Form of the activity

After discussing with the experts, it has been determined that the best format for the activity is a game, as it helps to maintain the student's attention and encourage active participation.

Initially, the activity was intended to be in the form of a video game, given the extensive possibilities offered by this type of platform. However, the experts suggested prioritizing an "unplugged" version of the game, meaning without the use of screens. According to them, having an offline version is more popular among teachers as it requires less organization to use computers in the classroom.

4.3 Game scenario

After several iterations, brainstorming sessions with the experts regarding game play, coherence of the scenario, and its alignment with the learning objectives defined earlier, we have arrived at the following game scenario in the form of a card game. The following items corresponds to what the player will read before playing the game.

- Synopsis:

  In a region, there are 3 cities: A, B, and C. In each city, there is a school. Each player is the principal of school A, B, or C.

  Your school is new, and you need to create courses by equipping yourself with tablets or Thymio robots for the upcoming school year. A tablet allows for 3 lessons, while a Thymio robot allows for 1 lesson.

  Due to environmental concerns, the manufacturer of Thymio robots and tablets asks you to provide the missing resources to build these objects. They request water and a precious mineral (antimony) that can be found underground in your city.

  You have made an agreement with your city, which provides a portion of its groundwater, representing 100,000 liters of water, and the vacant lands of the city that will allow you to dig and find the mineral. The city guarantees that there are 50,000 tons of soil beneath these lands.

  The mayor of the city asks you not to exceed the limits of 100,000 liters of water and 50,000 tons of excavated soil.

- Purpose of the game:

  The objective of the game is to have the highest number of lessons for your school by constructing tablets or Thymio robots (1 tablet allows for 3 lessons, 1 Thymio allows for 1 lesson) without exceeding the resource limits set by the mayor (100,000 liters of water and 50,000 tons of excavated soil). If you surpass these limits, you will deplete the resources that are vital for the population of your city, putting it in an emergency situation. As a result, you will have no more resources available, and you will be unable to continue playing.

  The winner is determined by either the player with the most lessons or the player who has used the fewest resources. This choice is made randomly or through a show of hands vote by the players. At the end of the game, the player who drew the last card gets to decide how the game concludes (random choice or hands vote).

- Rules of the game:

  The game operates in turns, clockwise. At the beginning of the game, each city provides 10,000 liters of water and 50,000 tons of soil. The player who starts is the principal of the school in City A. At each turn, the player draws a card from the top of the single deck. Once the card is read, it is placed in the discard pile.

  If a Thymio or tablet card is drawn, the player can choose whether or not to construct the object. If they choose to do so, they must provide the necessary resources. If a different type of card is drawn, such as a natural disaster, the player who drew the card immediately loses the number of resources indicated on the card.

  At the end of each turn, the player records their remaining resources, the number of constructed Thymio robots or tablets, and the number of lessons obtained.

If a player exceeds any of the resource limits set by the mayor, they will be unable to continue playing until the end of the game.

The game ends when the deck of cards is depleted.

4.4 Game features

In this section, we explore the features of the game.

4.4.1 Game version

This game version is the simplest version possible in order to be quickly tested and improved. It is simple in the sense that the resources affected by the events are currently only water. Therefore, water is the only resource that can decrease rapidly and the only parameter to monitor during the game. In a future version, we can integrate minerals resources by adding cards that impact this resource.

4.4.2 Cards

The cards that can be drawn fall into two categories:

1. Object to build:

   In this category, there are two types of cards: tablet cards (Figure 20b) and Thymio cards (Figure 20a). Each card contains the additional necessary resources to provide to the manufacturer to build the object, measured in liters of water and tons of excavated soil. There are also two wastes produced in terms of CO2 and CTUe. The resources used and waste values for Thymio are based on the results of the LCA conducted in Part 3. For the tablet, the values are based on LCAs from a smartphone and a screen computer 20b. By reading the cards, players understand that building a tablet requires much more resources than building a Thymio. However, according to the game instructions, one Thymio allows for one lesson, while the tablet allows for three lessons.

2. Events

   The events cards gather unexpected events that can happen to the player. These events either grant the player water resources (Figure: 20e) or cause them to lose resources (Figures: 20c, 20f, and 20d).

(a) Thymio (b) Tablet (c) Ecotoxicity

(d) Water loss (e) Groundwater (f) Natural disaster

Figure 20: Event cards

4.4.3 Expectations

As the game progresses, the student will realize the enormous resources required to build technological objects such as a tablet or a Thymio, as demonstrated by the water resources and tons of soil examples. They will also come to understand that the resources they use are not sufficient as they are finite and used in multiple sectors, as illustrated by the population needs on the card in Figure 20d. Furthermore, we aim to convey to students that these resources are subject to climate disruption through examples of natural disasters (Figure 20f) and water pollution (Figure 20c). The end of the game also reflects reality in the sense that players can decide whether to prioritize the environment or not because they choose how the game ends: whether the winner is determined by the most lessons or the most resources.

4.4.4 Choices

In this section, we explain our choices of environmental indicators for the game.
For the sake of simplicity, we have chosen to use two resources and two waste types. Before making the game more complex, we want to ensure that it works in its simplest version.
For resources, we have chosen minerals and metals (ADPe) because its value has the highest impact on the environment according to Part 3.4.1. To make the value more relatable, we use the following equivalence: 1 kg of Sb (antimony) equals 5,000 tons of excavated soil. Therefore, we multiply the ADPe indicator value of Thymio (0.0076 kg Sb eq) by 5,000 to obtain its equivalence in excavated soil, which is rounded up to 35 tons. Additionally, we have chosen the resource water use (WU), even though its impact on the environment is lower for Thymio compared to other indicators. We selected it because it is a resource that everyone is familiar with, easy to visualize, and can be easily compared to other LCAs. To simplify the calculation of remaining resources during the game, we round the WU indicator value to 10,000 liters of water.
Regarding waste production, we have chosen ecotoxicity freshwater (CTUe) as it is the waste indicator with the highest impact according to Part 3.4.1. We also choose the Global Warming Potential (GWP) indicator because it is widely known and easily comparable to other LCAs.

4.5 Game testing with the experts and future improvements

The game was tested twice with the experts, who played the role of players. An example of such sessions can be seen in appendix D. Each session followed the following format: The experts gathered around a table with a sheet containing exactly the content in section 4.3. They read the scenario together, and their feedback was noted. Then, the game started. At the end of the game, their feedback was collected. Here are their comments: The game rules are clear. The game is fun and engaging. The foundation of the game is good. As for areas of improvement, it is suggested to add a collaborative dimension to encourage players to share their resources when they acquire them. They also suggest increasing the complexity of the game by introducing more resources into play. The concepts defined in section 4.1, which need to be understood by the students, are well-presented and understood, except for the concept of the life cycle. In the game, only the manufacturing phase of the Thymio's life cycle is explored. In a future version, the concept of the life cycle could be mentioned in the scenario or incorporated into the game play.

5 Conclusion

This project was distinguished by the variety of people with whom we collaborated to carry it out (Thymio robot creators, LCA experts, and pedagogical activity experts). The life cycle analysis of Thymio helped us better understand the environmental impacts of this type of technology, which are mainly attributed to the manufacturing phase and primarily due to integrated circuits and the printed circuit board. This project also allowed us to comprehend the enormous resources required to build such an object. Additionally, the developed pedagogical activity serves as a solid foundation for understanding the concepts we wish to teach the younger generations, such as the diversity and orders of magnitude of resources and impacts of technologies, resources are limited, and introducing the concept of the life cycle. However, further tests and modifications will need to be made to refine the game before introducing it to schools.

A Original Semester project definition

FACULTE SCIENCES ET TECHNIQUES DE L'INGENIEUR

GROUPE MOBOTS

CH - 1015 LAUSANNE

EPFL

PROJET DE SEMESTRE – PRINTEMPS 2022-2023

Titre:	Open Life Cycle exploration		
Candidat(s):	Alexandre de Montleau	**Section:**	MT
Professeur:	Francesco Mondada		
Assistant 1:	Francesco Mondada	**Assistant 2:**	Daniel Badoux

Donnée & travail demandé :

Open-source code, open hardware, open data, open science, all are movements that share the effort to make transparent the information behind products or processes, allowing a better sharing of the resources, a better understanding, and possibly to better choose and act on those open information and processes. Sustainability could take advantage from this transparency which could translates into better understanding of what's happening, take sustainable choices, use and repair / recycle, reduce impact of the life cycle.

The core concept here is this last one, the "life cycle". Understanding this concept is a fundamental step toward understanding the role of various aspects of our relationship with products, and making choices toward sustainability.

The goal of this project is to prototype an implementation of "open life cycles", where the information of the life cycle is available not only partially and statically, as done now, but in real time and with simulations of future options, allowing to understand and act on the impact of the products. The idea is that an "open life cycle product" shares all its impact data on a central repository that can be accessed in real time during the life of the product. The data on the production are stored at the end of production and delivery, then the products inform in a regular way the repository on consumption, and each partner making a repair updates the repository as well. Tools are provided to make comparisons among products and prediction/simulations of impact in case of choices the user can do, typically for repair VS replacement (with tracking of replacement part production) and for end-of-life options, the situations of the life cycles that have most impact. One should be able to simulate choices of use, for instance in comparing various electricity providers, and see the related impact. The tools should also be able to show the waste of resources of a product that is not used, or to balance the use of a large fleet of products (laptops in schools, for instance) and optimize the impact. The same tools can be used for education about the concept of life cycle in compulsory schools.

The goal of the project is to do a state of the art in this area (existing resources close to the goal of the global project), draft the definition of the platform (data available, update, simulations) and prototype some elements of it, for instance using the Thymio robot platform. The definition of the paths to follow will be made during the project based on the results achieved. In particular two critical moments of decisions will be when during the working plan, and for the intermediate defense in the middle of the semester.

Remarques :

Un plan de travail sera établi et présenté aux assistants avant le vendredi 3 mars 2023.

Une présentation intermédiaire (environ 10 minutes de présentation et 10 minutes de discussion) de votre travail aura lieu dans le courant du mois d'avril 2023. Elle a pour objectifs de donner un rapide résumé du travail déjà effectué, de proposer un plan précis pour la suite du projet et d'en discuter les options principales.

Un rapport, comprenant en son début un titre avec les données générales et une photo portrait de l'étudiant, suivi par l'énoncé du travail (présent document), puis d'un résumé d'une page (selon canevas), sera remis le lundi 5 juin 2023 avant 12 heures en format électronique à l'assistant responsable. L'accent sera mis sur les expériences et les résultats obtenus. Le public cible est de type ingénieur EPF sans connaissance pointue du domaine. Une version préliminaire du rapport sera remise à l'assistant le 19 mai 2023. Tous les documents en version informatique, y compris le rapport (aussi en version source), le document de la présentation orale, ainsi que les sources des différents programmes doivent rendu selon les consignes qui seront donnée avant la terminaison du projet.

B Environmental indicators definition

Impact category / Indicator	Unit	Description
Climate change – total, fossil, biogenic and land use	kg CO_2-eq	Indicator of potential global warming due to emissions of greenhouse gases to the air. Divided into 3 subcategories based on the emission source: (1) fossil resources, (2) bio-based resources and (3) land use change.
Ozone depletion	kg CFC-11-eq	Indicator of emissions to air that causes the destruction of the stratospheric ozone layer
Acidification	kg mol H+	Indicator of the potential acidification of soils and water due to the release of gases such as nitrogen oxides and sulphur oxides
Eutrophication – freshwater	kg PO_4-eq	indicator of the enrichment of the freshwater ecosystem with nutritional elements, due to the emission of nitrogen or phosphor-containing compounds

Eutrophication – marine	Kg N-eq	Indicator of the enrichment of the marine ecosystem with nutritional elements, due to the emission of nitrogen-containing compounds.
Eutrophication – terrestrial	mol N-eq	Indicator of the enrichment of the terrestrial ecosystem with nutritional elements, due to the emission of nitrogen-containing compounds.
Photochemical ozone formation	kg NMVOC-eq	Indicators of emissions of gases that affect the creation of photochemical ozone in the lower atmosphere (smog) catalysed by sunlight.
Depletion of abiotic resources – minerals and metals	kg Sb-eq	Indicator of the depletion of natural non-fossil resources.
Depletion of abiotic resources – fossil fuels	MJ, net calorific value	Indicator of the depletion of natural fossil fuel resources.
Human toxicity – cancer, non-cancer	CTUh	Impact on humans of toxic substances emitted to the environment. Divided into non-cancer and cancer-related toxic substances.

Human toxicity – cancer, non-cancer	CTUh	Impact on humans of toxic substances emitted to the environment. Divided into non-cancer and cancer-related toxic substances.
Eco-toxicity (freshwater)	CTUe	Impact on freshwater organisms of toxic substances emitted to the environment.
Water use	m3 world eq. deprived	Indicator of the relative amount of water used, based on regionalized water scarcity factors.
Land use	Dimensionless	Measure of the changes in soil quality (Biotic production, Erosion resistance, Mechanical filtration).
Ionising radiation, human health	kBq U-235	Damage to human health and ecosystems linked to the emissions of radionuclides.
Particulate matter emissions	Disease incidence	Indicator of the potential incidence of disease due to particulate matter emissions

Source: https://ecochain.com/knowledge/impact-categories-lca/#:~:text=A%20Life%20Cycle%20Assessment
20(short,the%20raw%20material%20production%2C%20etc.

C Bills of materials

Equipement type	Description	Quantity	Mass (g)	Equivalent type on Ecoinvent	BLOCKS
Resistances 4,7K Ohm	Surface mount pads, Chip Resistor	18,00	0,001	resistor production, surface-mounted	Basic electronic
Resistances 33 Ohm	Surface mount pads, Chip Resistor	2,00	0,001	resistor production, surface-mounted	Basic electronic
Resistances 2,7K Ohm	Surface mount pads, Chip Resistor	2,00	0,001	resistor production, surface-mounted	Basic electronic
Resistances 22K Ohm	Surface mount pads, Chip Resistor	10,00	0,001	resistor production, surface-mounted	Basic electronic
Resistances 2,2K Ohm	Surface mount pads, Chip Resistor	17,00	0,001	resistor production, surface-mounted	Basic electronic
Resistances 1,5K Ohm	Surface mount pads, Chip Resistor	7,00	0,001	resistor production, surface-mounted	Basic electronic
Resistances 1K Ohm	Surface mount pads, Chip Resistor	10,00	0,001	resistor production, surface-mounted	Basic electronic
Resistances 10K Ohm	Surface mount pads, Chip Resistor	16,00	0,001	resistor production, surface-mounted	Basic electronic
Resistances 6,2 Ohm	Surface mount pads, Chip Resistor	7,00	0,001	resistor production, surface-mounted	Basic electronic
Resistances 56 Ohm	Surface mount pads, Chip Resistor	18,00	0,001	resistor production, surface-mounted	Basic electronic
Resistances 39 Ohm	Surface mount pads, Chip Resistor	14,00	0,001	resistor production, surface-mounted	Basic electronic
Resistances 200 Ohm	Surface mount pads, Chip Resistor	4,00	0,001	resistor production, surface-mounted	Basic electronic
Resistances 82 Ohm	Surface mount pads, Chip Resistor	4,00	0,001	resistor production, surface-mounted	Basic electronic
Resistances 100 Ohm	Surface mount pads, Chip Resistor	4,00	0,001	resistor production, surface-mounted	Basic electronic
Resistances 180 Ohm	Surface mount pads, Chip Resistor	2,00	0,001	resistor production, surface-mounted	Basic electronic
Resistances 5,6K Ohm	Surface mount pads, Chip Resistor	2,00	0,001	resistor production, surface-mounted	Basic electronic
Resistances 100K Ohm	Surface mount pads, Chip Resistor	15,00	0,001	resistor production, surface-mounted	Basic electronic
Resistances 680K Ohm	Surface mount pads, Chip Resistor	1,00	0,001	resistor production, surface-mounted	Basic electronic
Resistances 6,8K Ohm	Surface mount pads, Chip Resistor	1,00	0,001	resistor production, surface-mounted	Basic electronic
Resistances 820 Ohm	Surface mount pads, Chip Resistor	5,00	0,001	resistor production, surface-mounted	Basic electronic
Resistances 47K Ohm	Surface mount pads, Chip Resistor	1,00	0,001	resistor production, surface-mounted	Basic electronic
Resistances 270K Ohm	Surface mount pads, Chip Resistor	1,00	0,001	resistor production, surface-mounted	Basic electronic
Resistances 0 Ohm	Surface mount pads, Chip Resistor	6,00	0,001	resistor production, surface-mounted	Basic electronic
Capacitor 100nf	Surface Mount pads, Chip capacitor	38,00	0,001	capacitor production, for surface-mounting	Basic electronic
Capacitor 10 uF	Surface Mount pads, Chip capacitor	8,00	0,001	capacitor production, for surface-mounting	Basic electronic
Capacitor 51 pF	Surface Mount pads, Chip capacitor	2,00	0,001	capacitor production, for surface-mounting	Basic electronic

Capacitor 4,7 nF	Surface Mount pads, Chip capacitor	7,00	0,001	capacitor production, for surface-mounting	Basic electronic
Capacitor 4,7 uF	Surface Mount pads, Chip capacitor	9,00	0,001	capacitor production, for surface-mounting	Basic electronic
Capacitor 10 uF X5R	Surface Mount pads, Chip capacitor	8,00	0,001	capacitor production, for surface-mounting	Basic electronic
Capacitor 18 pF	Surface Mount pads, Chip capacitor	2,00	0,001	capacitor production, for surface-mounting	Basic electronic
Capacitor 1 nF	Surface Mount pads, Chip capacitor	2,00	0,001	capacitor production, for surface-mounting	Basic electronic
Capacitor 1uF	Surface Mount pads, Chip capacitor	3,00	0,001	capacitor production, for surface-mounting	Basic electronic
Capacitor 1,5 nF	Surface Mount pads, Chip capacitor	1,00	0,001	capacitor production, for surface-mounting	Basic electronic
Capacitor 47 nF	Surface Mount pads, Chip capacitor	3,00	0,001	capacitor production, for surface-mounting	Basic electronic
Motor, General Kind	DC plastic gear motor	2,00	30,000	electronic motor, vehicle	MOTOR
Multicell Battery 3,7V, 1500 mAh	Li-Po, 3,7V, 1'500 mAh, rechargeable via USB,	1,00	30,000	battery production, Li-ion, rechargeable, prismatic	Battery
LED red 56	Red led with Light intensity: 56 mcd	4,00	0,050	diode production, glass-, for surface-mounting	Light emitting diode
LED RGB	Light LED with 3 colors available	4,00	0,050	diode production, glass-, for surface-mounting	Light emitting diode
LED red mounted on Thymio's side	Red led on side of thymio	12,00	0,050	diode production, glass-, for surface-mounting	Light emitting diode
LED blue mounted on Thymio's side	Blue led on side of thymio	3,00	0,050	diode production, glass-, for surface-mounting	Light emitting diode
LED Standard	Light LED with 3 colors available	11,00	0,050	diode production, glass-, for surface-mounting	Light emitting diode
LED red 57	Red led with Light intensity = 57 mcd	2,00	0,050	diode production, glass-, for surface-mounting	Light emitting diode
Diode Schottky Barrier Double Diode	Diode Schottky	2,00	0,050	diode production, glass-, for surface-mounting	Light emitting diode
SMD ferrite bead for EMI suppression	Ferrite bead to suppress electromagnetic field interference due to	5,00	1,000	ceramic tile	Basic electronic
Loudspeaker		1,00	1,000	Micro Speaker	Sensors
Omnidirectional Back Electret Condenser	Small microphones for general use, Back electret type designed for high resistance to vibrations,	1,00	0,200	Micro Speaker	Sensors
General purpose transistor	General purpose : current amplification	36,00	0,010	transistor production, surface-mounted	Basic electronic
Thermistors	temperature Sensors -> Approximate by resistor 10 kOhm at 25°C	1,00	0,010	resistor production, surface-mounted	Sensors
Micro SD connector	Micro SD connector	1,00	0,430	Connector, computer Peripheral type	Peripheral Connectors

Switch	Reset pushbutton switch	1,00	1,000	keyboard production, GLO	Sensors
Transistor MOSFET	Transistor MOSFET surface mounted	4,00	0,000	transistor production, surface-mounted	Basic electronic
Transistor MOSFET type 2	Transistor MOSFET surface mounted	4,00	0,000	transistor production, surface-mounted	Basic electronic
Accelerometer	three-axis linear accelerometer belonging to the “femto” family with digital I2C/SPI serial	1,00	1,000	IC LOGIC	Sensors
Opto Interrupter part 1/2	infrared emitting diode and an NPN silicon phototransistor, encased side-by-side on converging optical axis in	2,00	0,005	transistor production, surface-mounted (10% of tot mass)	Sensors
Opto Interrupter part 2/2	infrared emitting diode and an NPN silicon phototransistor, encased side-by-side on converging optical axis in	2,00	0,045	diode production (90% tot mass), glass-, for through hole mounting	Sensors
Operational Amplifier	operational amplifier is an integrated circuit that can amplify weak electronic	2,00	0,200	IC LOGIC	Basic electronic
Opto Interrupter type 2 Part 1/2	infrared emitting diode and an NPN silicon phototransistor, encased side-by-side on converging optical axis in	7,00	0,005	transistor production, surface-mounted (10% of tot mass)	Sensors
Opto Interrupter type 2 Part 2/2	infrared emitting diode and an NPN silicon phototransistor, encased side-by-side on converging optical axis in	7,00	0,045	diode production (90% tot mass), glass-, for through hole mounting	Sensors
8-bit Shift Register with 3-state output registers	8-bit Shift Register with 3-state output registers	5,00	0,104	IC MEMORY	Basic electronic
CMOS process low dropout linear regulator	CMOS process low dropout linear regulator with enable function, the	2,00	0,001	IC LOGIC	Basic electronic
General Purpose USB Microcontroller	Microcontroller 128 KB program memory , 16-bit flash memory, CPU	1,00	1,000	IC LOGIC	Microcontroller
IR receiver part 1/2	miniature type infrared receiver 38kHz, with wire	1,00	0,040	IC LOGIC (10% tot mass)	Sensors
IR receiver part 2/2	miniature type infrared receiver 38kHz, with wire	1,00	0,360	diode production (90% tot mass), glass-, for through hole mounting	Sensors
Battery Charge Management Controller	Stand-Alone System Load Sharing and Li-Ion/Li-	1,00	0,040	IC LOGIC	Battery
ULDO REGULATOR	The AP2210 is a 300mA ULDO regulator which provides very low noise,	3,00	0,015	IC LOGIC	Basic electronic

USB/Charger and over voltage detection device	The FAN3988 is a USB-connection-monitoring device used top	1,00	0,014	IC LOGIC	Peripheral Connectors
Audio power amplifier	350mWAudioPower Amplifier	1,00	0,143	IC LOGIC	Basic electronic
1 x 6 pins connector	Pins connector	1,00	0,048	brass production	Basic electronic
WR-COM Micro USB	WR-Communication Connector	1,00	0,700	Connector, computer Peripheral type	Peripheral Connectors
Surface Mount Quartz Crystal 8Mh	Play the role of clock	1,00	0,040	silica sand production	Basic electronic
Casing - ABS	Robot's shell	1,00	107,000	Acrylonitrile-butadiene-styrene copolymer	Shell
Casing - Polycarbonate	Robot's tyre	2,00	4,000	Polycarbonate production	Shell
ON/OFF BUTTON	Button to start/stop robot	1,00	0,500	IC LOGIC	Sensors
Screw	Screw	8,00	0,625	Steel	Shell
PCB	Printed wiring boards	1,00	36,570	Printed wiring board, surface mounted	Basic electronic

D Test with experts

E Student picture

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