Lifecycle Analysis of an Air Quality Sensor

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Abstract: Nowadays, it is becoming increasingly important to not only measure environmental impacts, in terms of energy efficiency, but also, in terms of the quality of life. We have developed an outdoor, low-cost environmental sensor that measures airborne dust concentrate and other air parameters. Our goal is to perform high-resolution measurements, based on hundreds of metering devices, to achieve full urban coverage. Using the data measured and collected by the sensors, our second goal is to establish the intelligent building management and settlement management systems and services. As the planned system will consist of hundreds of nodes, its environmental impact and durability cannot be neglected. Therefore, environmental planning is of paramount importance during the development. When developing sensors, it is advisable to focus on the most important factors of ecological design. During the life cycle analysis, the combined environmental impact of the nodes and the network itself, must be examined.

Keywords: Justify sensor network; green computing; air quality; LCA; eco design

1 Introduction

The high degree of industrialization, the spread of cars and poor-quality fuels have led to increased air pollution in major cities. For this reason, measuring the concentration of air pollution in cities, in particular PM10 and PM2.5, has become increasingly important. PM10 is the concentration of particles below 10 µm, and PM2.5 is the concentration of particles smaller than 2.5 µm. The competent environmental protection organization carries out such measurements in each country, which is the National Air Pollution Monitoring Network in Hungary [1] [2].

In the process of architecture, the designer has to think in a complex way, as it is not just a process of massing or spatialization, but a transdisciplinary work. It is a joint project in which innovation by the designers is just as important as the disciplined adherence to the design of the contractors during construction. Today, the emphasis is no longer on creating aesthetic forms and self-serving facade ornamentation, but on the extensive use of environmentally positive technical solutions. It is therefore essential, even for a small investment, to assess the energy efficiency, emissions and environmental impact of the building in a responsible manner, taking into account its entire life cycle. This includes all processes from the delivery of building materials to the site to the future demolition of the building. As explained in [3], one of the most important missions of contemporary architecture is to create a concept, whether it is a vacant site or a densely populated urban area, after a proper anamnesis has been carried out, including the installation of the tools to study the environmental impact. It is important for the designer to keep a constant eye on the use of "smart houses" and "smart devices", as not only the profession, but the clientele, are becoming increasingly aware of their everyday lives. The irresponsible, environmentally unaware approach of the Hungarian construction industry is responsible for about a fifth (20.1%), of the country's global emissions, with households accounting for a further 22.8%. Nearly three quarters of buildings are rated 'D' or worse. All of this gives us cause to rethink our activities in a major way. In the Solar Decathlon Europe 2021-22 competition, the designers of several buildings, including the Hungarian team's "Lungs of the city" house, have set and proposed important targets to users. For an existing building stock, the main goal is to achieve zero emissions, while for a completely new building, the aim is to achieve positive emissions. To achieve this, there is a need for continuous discussion and reflection on renewing the energy efficiency of the urban environment and maximizing emissions from households and transport systems. Architecture and automation cannot therefore be separated, either outside the home or inside.

Our ultimate goal is to develop and establish a model that can lead to implementation of a hardware/software system, that consists of up to, hundreds of sensors for the control, data collection, processing, monitoring and settlement system integration of technologies pre-embedded in sensor-integrated finished components. The procedure and the system model to be created, can offer more efficient, sustainable operation; they can even make decisions and interventions.

One of the key tasks of the project is to perform high-resolution measurements based on hundreds of self-designed air quality measuring devices to achieve full urban coverage and full coverage within public buildings.

These instruments measure air pollutants using sensors based on β- absorption and mass measurement, which undergo a rigorous calibration process every six months involving high costs, thus providing credible data. Unfortunately, there is an insufficient number of stations in Hungary to make an anomaly map from the data, as there are in most countries, as these organizations do not have enough resources to purchase large quantities of instruments capable of laboratory-quality measurements. However, many new low-cost sensors [4-8] based on the optical principle have appeared in recent years, suggesting a paradigm shift in this area with the emergence of new measurement methods.

Using the data measured and collected by the sensors, with different interpolation methods an anomaly map will be created (see Fig. 1), that represents the current measured values and will be freely available to everyone. The University of Miskolc, Faculty of Engineering, Department of Geography and Geoinformatics conducted a number of professional discussions and a new perspective on the processing of the parameters measured with the outdoor sensor unit. A data system that can be connected to a coordinate (in our case a sensor) can also be represented spectrally (like a heatmap). The procedure has already been successfully applied in the field of structural geology and morphology research [9] [10]. In our case, the essence of the method is to plot the time on the x and y axes at different scales, while the values (pm10 concentration, temperature, humidity) are displayed using color enhancement. This type of data representation can be key, as visual-based evaluation of spectra can provide us with additional information.

The measured data helps the Sustainable Development Goals SDG11 - sustainable cities and communities and SDG3 - good health and well-being goals. The high concentration of air pollution reduces the efficiency and lifetime of solar electricity generation, as described by Matusz-Kalász et al. (2021) [11], therefore the results of our research also contribute to the achievement of the Energy Efficiency Objectives.

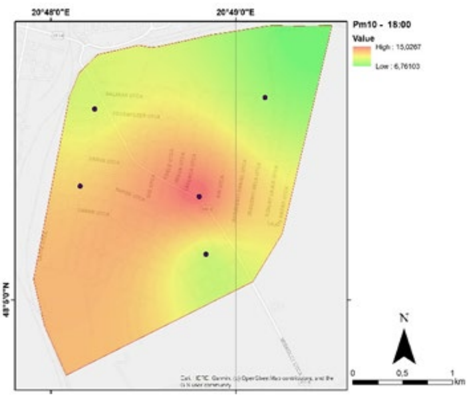

Figure 1

Modelling the distribution of atmospheric pollutants (own editing)

There are many studies with very good results in modelling nonlinear systems, including fuzzy and neural networks, and these contributions have provided a valuable insight into the problem [12-16].

Environmentally friendly design and implementation are of paramount importance in the design of measuring instruments and the development of the entire connected network. We have kept this approach in mind not only in terms of hardware, but also in software development, network design and deployment. We have focused on the most important factors in ecological design. However, the environmental assessment of ICT (Information and Communication Technology) infrastructures, still face methodological shortcomings. Bonvoisin et al. (2012) aims to identify current uncertainties in environmental assessment and suggest solutions to overcome them in the case of WSN (Wireless sensor network) [16]. To this end, in the first part of their study, they reviewed the existing literature on environmental assessment of ICT infrastructures and the related methodological problems and solutions.

Interesting studies can be found on the primary environmental impacts of each ICT infrastructure and service, using methods such as embodied energy and life cycle impact assessment (LCA). All of these studies analyzed environmental impacts in detail, which helped identify “hot spots” and provided useful information for eco-design. However, as Andrae and Andersen (2010) also observed, there is a problem with the distribution and unavailability of existing in-depth environmental data for environmental studies. The ICT sector does not have the necessary transparency [17]. Therefore, inconsistencies cannot be easily understood and cannot lead to a better scientific understanding of the environmental impacts of ICT. Reimann observed that the larger the perimeter of the system under study in LCA, the weaker its definition [5]. Some have tried to expand the range of methods available to allow environmental impact assessments for large systems such as ICT infrastructures. One such method is hybrid LCA, which successfully eliminates large data gaps and abstraction [18], but does not in itself contribute more to transparency. As the environmental assessment of ICT infrastructures has already shown interesting results, further research is needed on the system-wide description of infrastructures. The analyses still need to be improved in terms of clarity and transparency, and models are needed to improve formalization, which proved to be successful in modelling systems like [19]. This, in turn, would allow the results of environmental assessment to be used more effectively in planning. When calculating the environmental impact of a network, the life cycle of all components and synergistic effects must also be taken into account. During the life cycle analysis, the combined environmental impact of the nodes and the network itself must be examined. Preprocessing sensor data is also a crucial step as part of data preparation for further processing. The procedure helps to get clearer data with less noise, it is nevertheless important to consider embeddability of such devices so that production costs could be reduced.

The prototype measurement system, which is at TRL8 level, has now reached the point where we can perform LCA testing. This is to reduce the environmental impact of the finished product. After all, our aim is to help change society's attitude by monitoring air quality. We want to further minimize the environmental footprint of our prototype and final product by choosing our materials wisely. Our system can detect pollution hotspots, enabling rapid intervention and helping to stop illegal waste incineration. In addition, we plan to deploy hundreds of these systems, which will bring even greater benefits in monitoring and managing environmental impacts on a large scale.

2 Approaches

An important question in a research and development project is how can we balance environmentally friendly solutions between cost-effectiveness and longevity? Even in everyday life, we often find that environmentally friendly solutions are often more costly and can be used for a shorter lifetime, but there are also cases where cost-effective solutions are combined with very short lifespan and poor materials, making it difficult to find a balance between these three factors. The outdoor sensor prototype shown in Fig. 2, has been operating in Miskolc-Martinkertváros (Hungary) for more than 1 year. During the design and development, we paid special attention to certain aspects of the implementation, such as software development, network design, raw material use, maintenance, fault detection, etc.

Figure 2
Outdoor sensor prototype at Miskolc-Martinkertváros ([20])

2.1 Software and Network Design

During the prototype development, the software implementation was not only examined in terms of stable robust operation, but also the effect of the devices on energy consumption was taken into account. In a previous article, M. L. Kiss (2018) described the differences in energy consumption generated during the development by different software implementations of the metering system, so we tried to apply software solutions that provide low energy consumption, keeping in mind the green computing guidelines [20]. Of course, real-time data must be provided, as this is one of the basic conditions for integration into facility management systems.

Because green computing is the environmentally responsible and eco-friendly use of computers and their resources also main goal, therefore, we sought a solution where the sensors could connect to an existing built-in wireless network. Our choice fell on the LoRaWAN protocol specification based on LoRa technology developed by the LoRa Alliance. It uses non-licensed radio spectrum in the industrial, scientific and medical (ISM) bands to allow low-power, wide-ranging communication between endpoints and gateways connected to the network [21]. The block diagram of the sensor network on Fig. 3 illustrates the structure of the system. The sensors communicate with the LoRa Gateway via LoRa, which communicates via Ethernet with the LoRaWAN Network Server, which communicates with our proprietary University Application Server and where the data is saved and displayed.

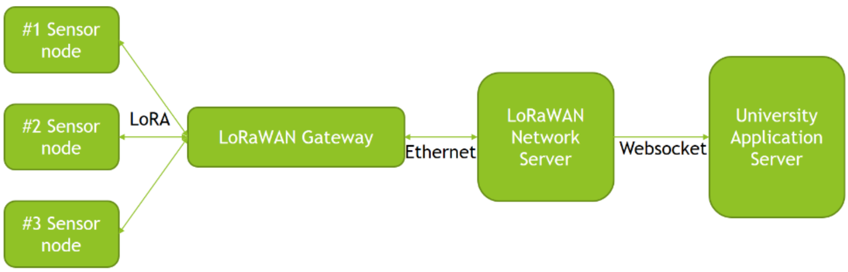

Figure 3
Block diagram of the sensor network (own editing)

These solutions not only promote low power consumption, but also efficient maintenance by minimizing on-site service, because during the development, based on our experience, we solved the detection of possible system faults and restarted the system remotely and also provided remote access. As the entire system will include not only outdoor but also indoor sensors and each sensor may have different constructions, a common universal database structure has been developed and the display will be implemented on the Node-Red platform. Node-RED provides a browser-based flow editor that makes it easy to wire together flows using the wide range of nodes. It provides a browser-based editor that makes it easy to wire together flows using the wide range of nodes in the palette that can be deployed to its runtime in a single-click. The advantage of the development environment is that it is modular, flexible and does not require more hardware resources [22].

2.2 Hardware Design

The developed sensor package consists of 3 main hardware units. 4 pieces of this device were installed in Miskolc – Martinkertváros. In terms of building the entire system, there is a Module 4, the data processing and display server itself as described here:

Sensor module:

This unit includes sensors for measuring various parameters, surrounded by an ABS-based housing made with self-designed 3D printed technology. When designing the cover, we had to take into account the weather conditions and ensure the permeability of the air inside the cover, otherwise false data would have been recorded. There are also two sensors in the house, a temperature and humidity meter and a sensor for measuring PM10 particulate matter. The box was manufactured locally on our own 3D printer, and the material was also obtained from a filament manufacturer in Miskolc. The sensor module is connected to the data processing and communication unit via a 7-wire cable, on which the supply voltage required for the sensors and the sensor interface cables run.

Data acquisition and transmission module:

The task of the data processing and communication module is for the sensors placed in the sensor module to read their data via the appropriate interface and to transmit it to the network server on the LoRaWAN network. The custom-designed PCB was in an IP67-protected mounting box placed with antenna to provide wireless communication. It was important to design our own PCB because it allowed us to integrate many functions into one, for which separate modules would have to be purchased from European distributors. In this way, we were able to manufacture the printed circuit board with a manufacturer operating within 100 km and we also bought its components from Hungarian suppliers. This unit is responsible for collecting and transmitting the data measured by the sensors and, in the event of an error, sending the corresponding error message.

Power supply:

The power supply is a 230V AC / 12V DC adapter that supplies power to the device. The power supply is needed to ensure continuous operation of the device. The use of the solar cell has also occurred, but the electrical power of the built-in sensors is too high to ensure continuous operation without installing a larger number of batteries.

3 Sensor Lifecycle Analysis

During the development, a sensor life cycle analysis (LCA) was performed. The analysis was performed according to ISO 14040, from assembly to end of life and it was performed manually, based on the characteristic factors of the components according to the CML 2001, focusing mainly on the greenhouse effect, but other important impact categories (ADP, AP, EP, HTTP) was also examined.

The life-cycle assessment, as an objective method, allows the quantification of the environmental impact of a product or service over its entire life cycle, from raw material extraction to the end of its life. However, this is only possible if the necessary input and output data are available at each stage of the life cycle. Often, in their absence, the life cycle under consideration is shortened in stages, for example, it may only include extraction, transport and manufacturing processes (A1-A3) according to EN 15804. This can range from procurement to the gate or even to the end of the use phase. However, it can also cover the full life cycle spectrum, including end-of-life waste management solutions.

Using the databases of GaBi and SimaPro software, the following impact categories can be examined to assess the environmental impact of the sensor using the CML 2001 and ReCiPe methods and the PEF/EF method adopted by the European Union in 2018. The characteristic factors are used from the database, which can be aggregated by correcting with the normalization and weighting factors according to the PEF/PE methodology and obtaining the results in environmental load points.

According to the ISO 14040 and ISO 14044 standards an LCA shall include the following phases:

- Goal and scope definition
- Inventory analysis, when resources consumptions and emissions of the life cycle are quantified
- Impact assessment, when potential environmental impacts due to resource consumptions and emissions are assessed
- Interpretation of results

The connection of these phases can be seen in the following figure of the ISO 14040 standard. [23]

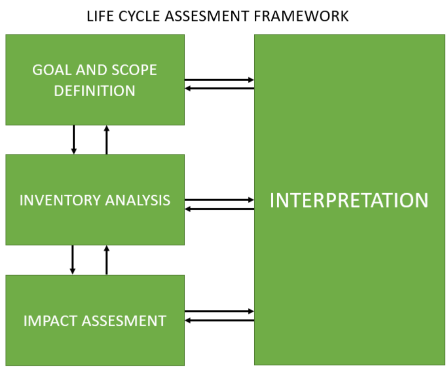

Figure 4
Methodological steps according to ISO 14040 (own editing)

The goal of the assessment is to determine the environmental load of one sensor, during a year. The Function unit: Environmental impact of 1 sensor under 1 year.

The system boundary covers the production, consumption and end-of-life phases, but the production phase includes the procurement related to the procurement and the previous environmental impact of the parts to be installed. The life of the sensor was determined at the following points, which form the backbone of the studies.

The next step was the inventory preparation, data collection and the inventory analysis. Measured data was used, allocation was not applied.

After meticulously measuring and identifying the materials used in the sensor components developed for the project's sensor measurement method, we compiled the inventory data categorized by material types, as displayed in Table 1. In order to assess the environmental impact of transportation, we calculated the transportation cost for each component in ton-kilometers (tkm). This calculation factored in the procurement location, transportation mode, and transportation distance. When it came to operating and monitoring the model, we determined the transportation cost in pizza kilometers (pkm). This measurement equated one round trip to the measurement point to the environmental impact of one pizza. The calculation considered the distance between the university and the measurement points, as well as the frequency of monitoring. We then recorded these results in the inventory data.

The results obtained only refer to the environmental performance of the sensor we have assembled. The environmental performance of a sensor depends on the environmental impact of the sensor components, its material and, in the use phase, the frequency of monitoring and the way it is travelled. The sensor performance can be assessed collectively depending on end-of-life scenarios and decarbonization solutions can vary depending on these scenarios.

The sensor components were measured one by one using decimal scales, as shown in Table 1. The table contains the measurement data for a single sensor, which means that if 10 sensors are installed, the quantities of material in the table are multiplied by 10.

Table 1

Sensor components (1 sensor) (own editing)

Components	**A1**	**A2**	**A3**	**B1**	**B2**	**B3**	**C1**	**C2**	**D1**	**D2**	**E1**	**E2**	**Total [g]**
Sn	1		0.8	2				4		Tools	Server	Web	**7.8**
Other metal	1.5		0.5	3				10					**15**
Epoxi resin	1		0.5	9				4					**14.5**
Cu	1.9	50		17	9		50	60					**187.9**
Steel	10	77		2		7			200				**296**
Fermit				2				10					**12**
ABS	6	15	0.9		2.4	174	10	11.5					**219.8**
Caoutchouc	2												**2**
Microchip	2.6		1	1									**4.6**
PLA		180											**180**
PVC		17					30		400				**447**

Hot-melt		80											**80**
Rubber									50				**50**
Total (g)	**26**	**419**	**3.7**	**36**	**11.4**	**181**	**90**	**99.5**	**650**	**-**	**-**	**-**	**1516.6**

1Acquisition distance: 6831 km; 231 g, Control distance: 10 km in 12 cases. Waste treatment: incineration, 881 g but 187.9 g Cooper recycled, and 447 g PVC reused in two times.

Our waste management strategy uses three main approaches: reuse, recycling and incineration. These approaches are in line with the principles of the circular economy, aiming to extend the life cycle of materials and conserve valuable resources.

Re-use is a process that seeks to recycle waste for re-use, reducing the need for new materials. By recycling, we convert waste into valuable products, so less waste ends up in landfills. Our incineration strategy focuses on energy recovery, reducing the use of fossil fuels.

By these approaches we leave a smaller ecological footprint and promote sustainable development.

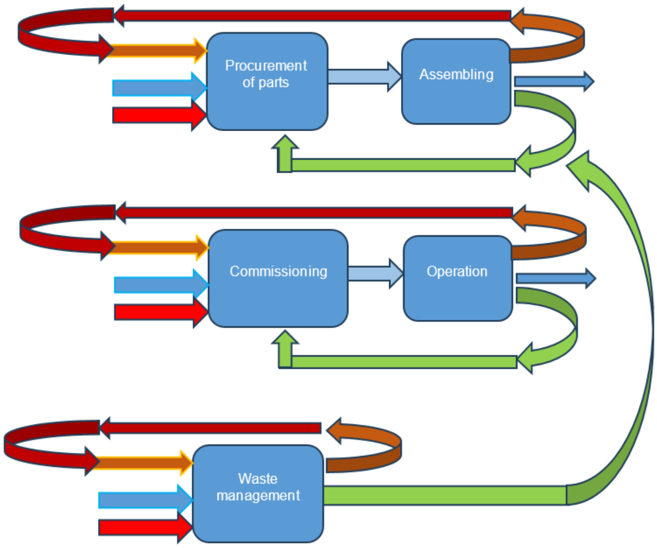

Figure 5

Stations of the sensor life cycle and their connections (own editing)

Fig. 5 shows the system boundary of the sensor system under study and the related processes: component procurement, assembly, maintenance and waste management. The analysis has taken into account the lifetime of the individual components of the sensor and the values for each impact category have been projected over one year. This was done as the lifetime of most of the components under consideration was approximately one year.

Their test results are presented as follows: Characteristic factors used to assessments

- Defining midpoint indicators:
  - for sensor components
  - for the sensor life cycle
  - for alternative scenarios
  - for different sensor boxes
  - different mode of transport
  - renewable energy

Investigation of the possibility of carbon neutralization by afforestation.

Table 2 contains the environmental pollution data of some components:

Table 2
Characteristic factors (CML 2001)

	GWP kg CO_2eq	**ADP kg Sbeq**	**AP kg SO_2eq**	**EP kg PO_4eq**	**HTP kg1,4- DBeq**
Sn	20.6	0.315	0.542	0.170647	36.31747
Other metal	3.18	0.0177	0.0199	0.002371	4.099038
Epoxy	8.05	0.0681	0.0214	0.003429	0.456291
Cooper	0.787	0.00488	0.00352	0.000359	0.033034
Steel	1.63	0.0113	0.00833	0.00156	0.033034
Fermit	3.41	0.0477	0.00832	0.000743	1.393727
ABS	3.74	0.0451	0.0124	0.001579	0.104363
kaucsuk	3.11	0.05	0.0471	0.001203	0.216929
microchip	0.269	0.00186	0.00196	2.494595	6.23E-06
PLA	3.11	0.0221	0.0116	0.011381	0.78657
PVC	2.83	0.0348	0.0198	0.001447	0.583863
Hot-melt	1.31	0.0372	0.037	0.000501	0.456291
Rubber	2.64	0.0383	0.0108	0.003664	0.940736
aircraft	0.062	0.000403	0.000257	0.000791	0.83031947
control	0.182	0.00124	0.000555	0.00014	0.066384
use kg/hour	5.20E-06	3.72E-07	3.44E-08	3.71E-08	6.23E-06

GWP: Global Warming Potential, unit: kg CO_2eq

ADP: Abiotic depletion Potential kg Sb eq

AP: Acidification Potential, kg SO_2eq

EP: Eutrophication Potential kg PO_4eq

HTP: Human toxicity Potential kg 1.4-DB eq

The manufacturing phase of the sensor, which involved the assembly of the components of each sensor module. The following were examined:

- The environmental impact of components performing the same function
- The impact of procurement distances
- The impact of procurement-related modes of transport
- Service life of parts
- Safety, service life and environmental impact of the sensor box material

Usage section covered the following:

- Energy consumption (if possible renewable energy, use of solar panels)
- maintenance
- Control (logistics planning, choice of means of transport)
- Data processing

The environmental impact of the end of life is affected by what happens to each component. After disassembly selection according to

- Can be reused in its material
- Suitable for energy purposes
- Can be disposed of by incineration
- Will be deposited

The research featured a model represented by the assembled sensor.

$$\mathbf{EI = M_i{*}EF_i/T_i} \tag{1}$$

where EI are the environmental impact category indicator values, $\mathbf{M_i}$ is the mass of each component, $\mathbf{EF_i}$ is the environmental factor for each material relating to the impact category, and $\mathbf{T_i}$: is the lifetime of the i^{th} component. The analysis was based on the input and output currents, as determined from the LCA datasheet. Specifically, this included the mass flows of the sensor's components, the ton-kilometer (tkm) value of transportations for procurement, the energy consumption during assembly, and the proportionate impact of the devices over their lifespan. On the output side, we considered the packaging waste of both the sensor and its components, along with the waste streams generated by each component at the end of their life cycle.

We examined:

- How the environmental impact per component develops
- How the environmental load of each life stage changes, which phase represents the greatest load
- How to reduce the environmental impact was examined

A new element of the sensor life cycle study is that we attempted to determine the possibilities for decarbonization and the compensation of the greenhouse effect associated with the life cycle of outdoor sensors.

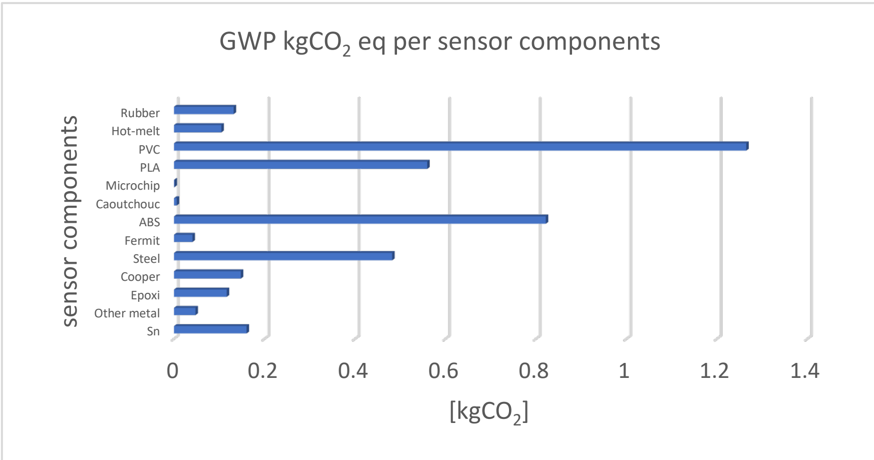

Figure 6

GWP per sensor component

Fig. 6 shows the GWP - Global warming potential values according to the material level composition of 1 sensor unit. The biggest greenhouse effects were PVC and ABS, followed by PLA and steel. These materials occur primarily in enclosures and protective insulation.

The situation is similar also in the other categories, the PVC and PLA have the biggest effect on the environment.

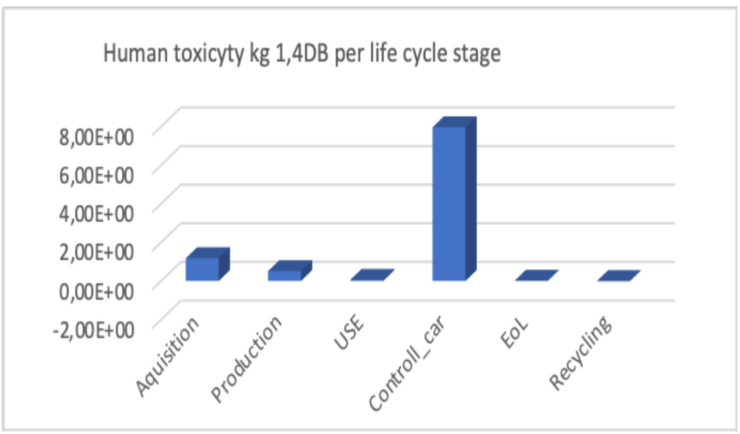

Figure 7

HT kg 1.4 DB per life cycle stage

By connecting several sensors (20) to the system, the environmental impact of this control is reduced as shown in Fig. 8. Depending on the level of use of the planned system (building or town level), it can have up to a 100 node.

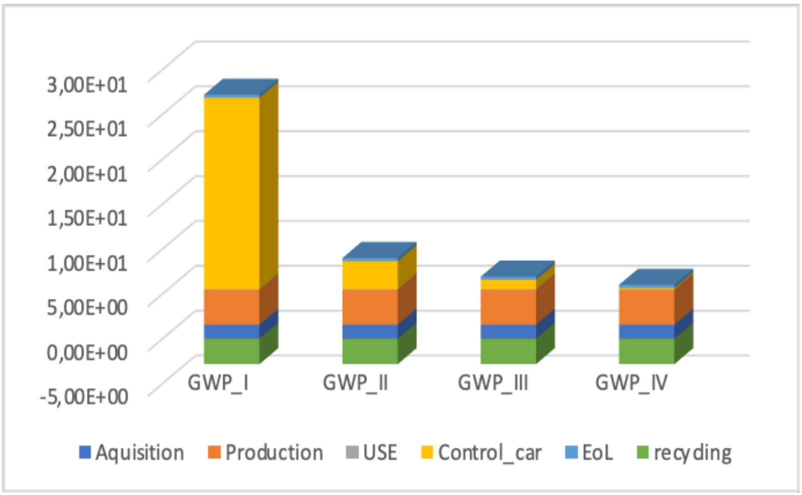

Figure 8
GWP kg CO2 of different scenarios

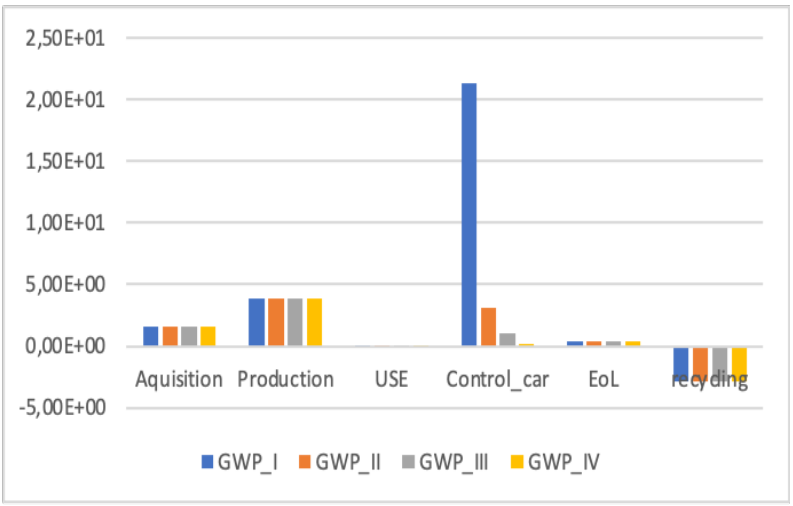

Figure 9
GWP in life cycle stage of scenarios

I: control by car, II: control by bicycle; III: 20 item, control by car; IV: 20 item control by bicycle

The weighted category values (it based on the EU environmental footprint factors [24]) show the relative contribution to the environmental loads.

It can be seen that 96% of the environmental load comes from greenhouse gases, and this is caused by inspections and repairs that occur in the use phase within the life cycle. So rightly, the question arises as to how to reduce it.

4 Results and Discussion

Based on the results of the life cycle analysis, there are three key points of the system to be built:

- Maintenance/depreciation
- The choice of cover and protective insulation material, which make up the bulk of the device, as it has to withstand a large temperature range on an annual basis due to climatic characteristics and ensure that the sensors can measure real value
- Recycling of components

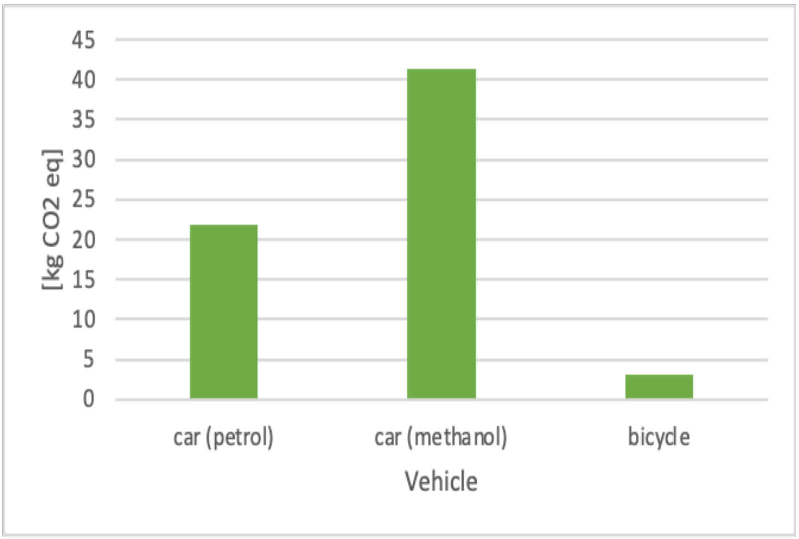

Figure 10
Control greenhouse effect

Regarding the issue of installation and maintenance tasks the choice of vehicle used for the inspection also has an impact on the environment [25]. Fig. 10 shows that in the case of bicycles, the environmental load was taken into account in pizza equivalent (the environmental impact of 12 cycling inspections is equal to 12 pizzas).

Due to the cladding and insulation, we examined several raw material alternatives, the comparison of which is shown in Fig. 11.

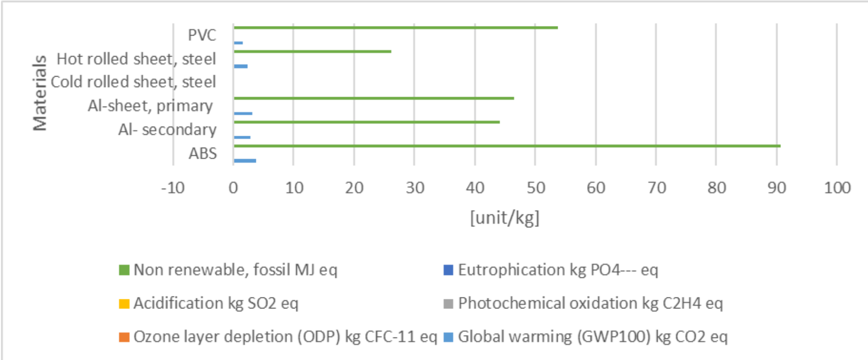

Figure 11
Potential box constituents' environmental impact

Based on the value of possible materials per unit mass, the load of ABS and PVC is outstandingly high. However, considering the quantities of actual material used for the box, the environmental impact of PVC is the lowest. Fig. 12 shows the GWP value of a box made of a given material.

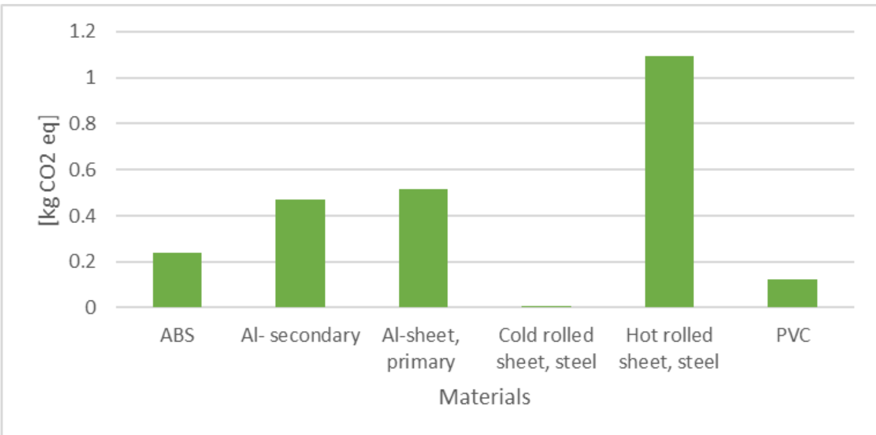

Figure 12
10 cm edge length 1 mm thick box GWP kg CO_2 eq

CO_2 offsetting through tree planting has arisen. In our case, the one-year operation of 1 sensor emits 24.4 kg of CO_2 and 6.1 kg when using a bicycle. If 1 cubic meter of leaf area is able to sequester 590 grams of CO_2 during a growing season, a minimum of 10 and a maximum of 41 mature trees would be required. The sensor units are currently powered by mains power, but we are also planning solar operation. In this case, we also need to examine the environmental impact of the design and how reliable it is to operate in this case, as this is an important criterion for facility management systems.

Conclusions

During the development of the prototype of the low-cost sensor, described herein, suitable for measuring air quality and other parameters, we sought to design and implement it, from an environmental point of view, in several respects. We wanted to strike a balance between environmentally friendly solutions and cost-effectiveness. The life cycle analyses performed, has shown that the three cornerstones of our planned system are maintenance, the choice of the coating material that makes up the bulk of the device and recycling potential. Based on the test results, the cover of the prototype is reworked both formally and in terms of material use.

We desired to reduce material consumption while maintaining the expected operating conditions. We developed a maintenance process that minimizes carbon emissions. In selecting new materials, we considered the potential for recycling and developed a methodology to determine which elements of the system are suitable for re-installation or calibration and which are no longer able to perform their function.

In the Business Model, we also looked at how and to what extent, we could reduce our ecological footprint and CO_2 emissions, for example, by planting trees. We also wanted to improve the system by identifying the pathways of pollutants. The dispersion is done using mathematical dispersion models and information is obtained by comparing the immission (the measured mass flux of the pollutant at the source) and emission.

These results and developments not only contribute to the practical development of a low-cost air pollution measurement sensor, but also emphasize the importance of sustainable practices in its' life-cycle. Our future plans also include the investigation of solar operation, the environmental impact and reliability of which, will be assessed as an important consideration for facility management systems. This broad approach, underlines our commitment to environmental responsibility, in the field of technological innovation.

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