Method and Tool to Assess the Environmental Impacts of Cyber-Physical Systems with a Life-Cycle Approach

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Abstract

The increasing environmental footprint of the information and communication technology sector calls for innovative strategies for assessing and improving its sustainability. Life Cycle Assessment (LCA) methods are suitable for estimating the negative environmental impacts of products or services. While some LCA methods start to be applied during the engineering of Cyber-Physical Systems (CPS), some challenges remain unresolved. For instance, the energy consumption, and therefore the greenhouse gas emissions, of CPS is influenced by the specific configuration of components in their architecture, as well as by the geographical location where the components are deployed. Also, the skills and efforts required by LCA projects, remain prohibitive to many CPS engineering projects. This paper presents an LCA-based method tailored for CPS that facilitates the analysis of the environmental impact and the comparison of architectural and location variants. Moreover, we have developed a supporting tool that guides the process and automates part of the data collection activity. Through an illustrative case and expert assessment, we have been able to assess the benefits and drawbacks of our proposal. With these contributions, we hope to lower the barrier to adopting LCA practices in CPS engineering projects, both in industry and academia.

Keywords

Cyber-physical systems, life cycle assessment, environmental sustainability, software for sustainability

1. Introduction

Cyber-Physical Systems (CPS) integrate computational and physical resources to offer systems that link physical devices with advanced computational capabilities [1, 2, 3]. Whereas CPS and the Internet of Things have brought about many benefits in varied domains like smart cities, telehealth, and smart homes [4], there is increasing concern about their negative environmental

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impacts. The low cost of technology is leading companies to bloat the CPS they design with components, machine-to-machine connections, and features that are not necessary or relevant to achieve the intended value proposition [5], worsening their environmental footprint. According to recent predictions [6], the worldwide production of interconnected devices could potentially result in a carbon footprint of over 1000 Mt of CO_2 equivalent emissions per year by 2027, in a worst-case scenario. The rapid growth in this field underscores the urgency of the matter.

To identify and estimate the impact of CPS on the environment, it is important to consider Life-Cycle Assessment (LCA) practices [7]. LCA entails assessing the environmental impacts of a product, process, or service throughout its entire or partial life-cycle [8, 9]. To apply LCA in the evaluation of CPS, some challenges remain unresolved. For instance, the energy consumption, and therefore the greenhouse gas emissions, of CPSs are influenced by the specific configuration of components in their architecture (due to an overall greater or lower energy demand), as well as by the geographical location where the components are deployed (due to the carbon intensity of the local electricity mix). Also, the skills and efforts required by LCA projects, remain prohibitive to many CPS engineering projects.

This paper builds on the insights proposed in [7] and addresses some of its current limitations. Section 2 describes the research method. Our main original contributions are the LCA4CPS method and a tool (see Section 4). Our proposed method assesses the environmental impact of CPS inspired by LCA- practices. Moreover, it facilitates the comparison of architectural and location variants considering the hardware components' life-cycle. It calculates environmental emissions due to data transfer and storage and includes indicators for (i) global warming impact, (ii) acidification of soil and water, (iii) water pollution, and (iv) freshwater usage. We chose those indicators because they represent the critical impacts CPS components have on the environment. We engineer a supporting tool that guides the environmental assessment process and automates part of the data collection and the calculation of indicators. We describe the validation of our proposal through expert assessment in Section 5. Finally, Section 6 concludes the paper and outlines future work.

2. Research method

The research questions are: **RQ1:** *"How can the environmental impacts of CPS be assessed cost-effectively?"* By cost-effectiveness, we refer to the fact that CPS engineers, users, and researchers should afford to apply the method. We aim to create an LCA-based method and a supporting tool. **RQ2:** *"What are the benefits and drawbacks of the proposed LCA-based method and tool?"* We aim to validate our proposals by eliciting the expert opinions of CPS engineers and researchers, to identify potential improvements.

Since this project aims at engineering artifacts (i.e. the LCA4CPS method and tool) while gathering knowledge about it (i.e. current limitations and the necessary features to overcome these, the benefits and drawbacks of our proposal), we follow a Design Science approach [10]. We also consider this to be a re-engineering project that takes an informal version of the LCA-based method in [7] and provides an improved and more formalized version as well as an implementation. Figure 2 shows the process we followed. During the **problem investigation**, (activity M1) we reviewed the literature on LCA (Section 3). Subsequently, (M2)

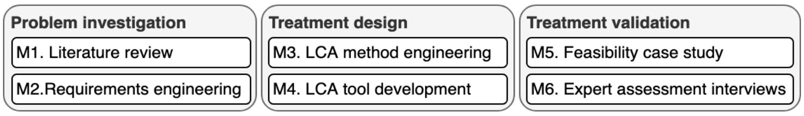

Figure 1: Overview of the research method

we expressed the pending challenges as requirements documented as user stories (Section 4). During the **treatment design**, (M3) we have applied situational method engineering to create the method (Section 4.1), documenting it with the Process-Deliverable Diagram technique [11]. This technique allows the specification of the process aspects of a method using UML Activity Diagrams and the intermediate and final products of the method using UML Class Diagrams, keeping both perspectives interrelated. We have then developed the supporting tool (M4) as shown in section 4.2, first defining a Feature Model that represents the tool functionalities and their dependencies [12]. During the **treatment validation** (Section 5), we have assessed the feasibility of our proposal by applying the method and tool to assess the impacts of a CPS (M5), which we use as an illustrative running example throughout the paper, and we have conducted eight expert assessment interviews (M6), in which nine experts in the field have provided feedback on the method and tool. We accompany this paper with a technical report where the reader can find details omitted due to space constraints [13].

3. Background knowledge

Life Cycle Assessment (LCA) is a methodology to assess the environmental impacts and resources used throughout (the entire or part of the) life cycle of products or services, i.e., from raw material acquisition, via production and use phase, to waste management [8], often to identify improvements that lead to reducing the negative impacts [14]. LCA methods are categorized as cradle-to-gate, including methods that focus on the manufacturing process, from raw material extraction (cradle) to the consumer (gate); and cradle-to-grave, which are methods that evaluate the impacts throughout the entire life cycle, up until disposal (grave) [8, 9, 15]. As there are several LCA methods available the International Organization for Standardization has established a set of standards known as the 14000 series, which includes widely recognized procedures for conducting LCAs. ISO 14040 provides the general principles and framework for conducting an LCA, and ISO 14044 provides more specific requirements for each step of an LCA. Both ISO standards employ generalized terminology, allowing for broad applicability across multiple industries [16, 17, 18]. ISO 14067 Carbon footprint standard, the latest one, offers principles, requirements, tools, and guidelines for quantifying and communicating the carbon footprint of products [19]. Nonetheless, these ISO standards leave some degrees of freedom to facilitate their adoption.

Product Environmental Profiles (PEPs) are verified reports that provide environmental declarations quantifying the environmental impacts of a product (process or service) over its entire life cycle. While mainly intended to support business-to-business interactions, they can also inform environmentally-conscious consumer choices. PEPs adhere to the ISO 14025 standard that regulates environmental labels and declarations [20]. This ensures that they can effectively compare similar products and are based on reliable quantified data obtained through LCA. In turn, information from a PEP of an electronic component type can be used in an LCA process of a CPS that includes one or several instances of such component type. The *PEP ecopassport* program allows companies to register their PEPs which, after independent verification, become available in an online database [21].

Carbon Intensity of Electricity Production refers to the amount of CO_2 emissions produced per unit of something. In the case of electricity production, it refers to the emissions produced per unit of energy generated. It is a crucial metric in understanding the environmental impact of a nation's electricity production. The carbon intensity is influenced by the electricity mix, which is the proportions of primary electricity sources a region utilizes, typically including fossil fuels, nuclear, and renewable sources [22].

4. The LCA4CPS framework

4.1. Method

As mentioned before, the main goal of our work is to help in the assessment of environmental impacts of CPS. We have produced a list of epics and user stories that address pending challenges in that domain[1], among them:

- As a user, I want to structure the analysis in a systematic and structured way; e.g. taking life-cycle stages into account.
- As a user, I want to specify and track different locations (i.e. regions) where the components of the CPS are located.
- As a user, I want to analyze environmental impact factors beyond CO_2 footprint; e.g. water usage and pollution, global warming impact, and acidification of soil and water.

The proposed method comprises five major activities. Its Process Deliverable Diagram is depicted in Figure 2. In the following, we briefly explain the process and major deliverables. Please refer to [13] for more detail.

Global CPS definition. A succinct definition of the CPS has to be provided by the user (activity A-TB.1 in Figure 2) including its name, a description, and its functional lifetime. This lifetime is the period during which the system can perform its intended functions effectively and efficiently. This is an important factor for the environmental assessment. This information is part of the deliverable `CYBER_PHYSICAL_SYSTEM (CPS)`.

Component definitions. The analyst needs to register the types of components that comprise the CPS (A-TB.2). A `COMPONENT_TYPE` refers to a class of components of the same kind, which technical and environmental specifications are available. This activity involves identifying the `ENVIRONMENTAL_DECLARATION` of each `COMPONENT_TYPE`. We assume the existence of an `ENVIRONMENTAL_DECLARATION_REPOSITORY` from which the declarations can be retrieved, such as the Product Environmental Profile (PEP Eco Passport) [21]. Additional specifications are recorded as `COMPONENT_TYPE_DETAILS`. In turn, `COMPONENT`s are concrete devices of a given `COMPONENT_TYPE`, that are later defined to be part of the CPS.

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[1] Refer to [13] for the full requirements specification

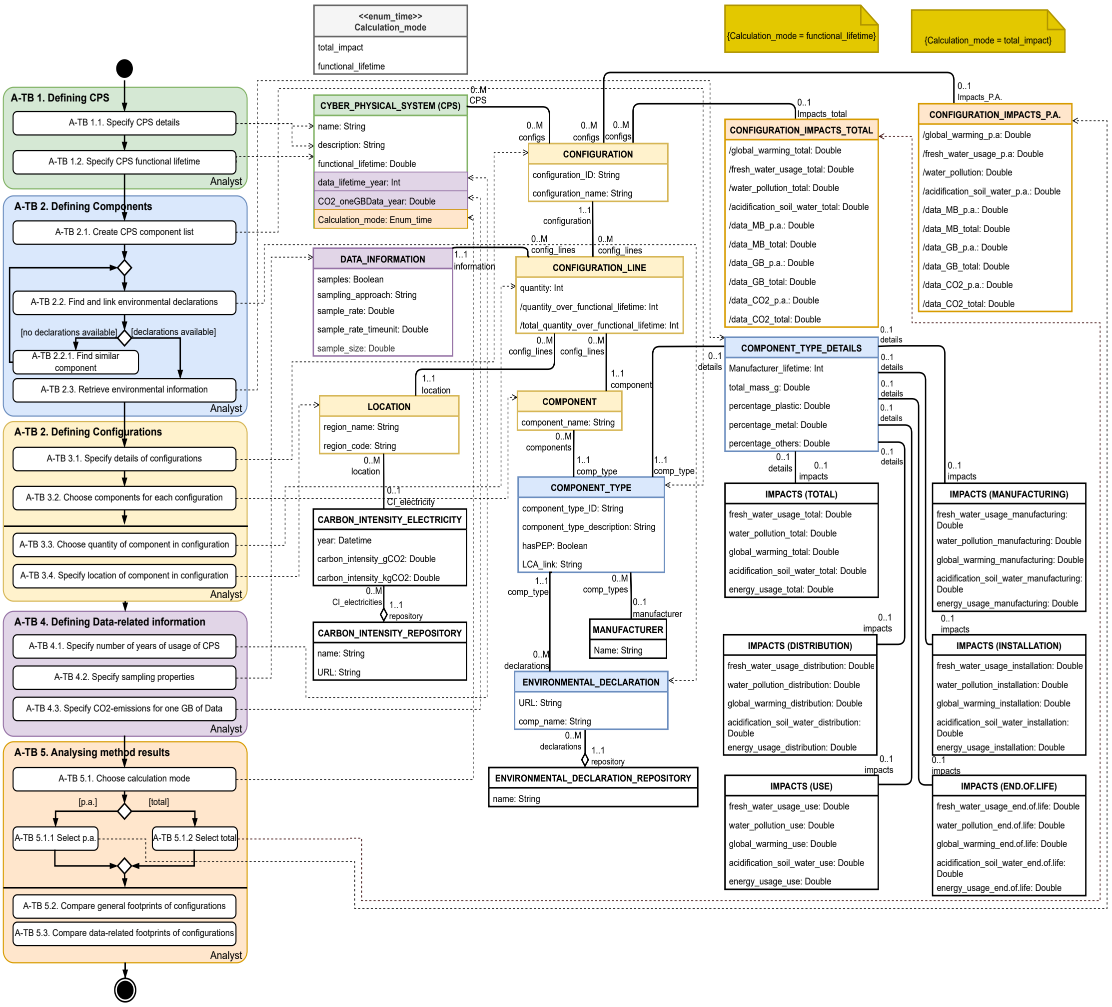

Figure 2: LCA4CPS method (process and product meta-model) expressed as a Process Deliverable Diagram [11]

CPS configurations. The analyst might consider one or several CPS configurations for assessment (A-TB.3). A CONFIGURATION refers to a combination of geographically situated components that constitute a CPS. They are typically architected by the CPS design team. Through CONFIGURATION_LINEs, the analyst reflects the quantity of COMPONENTs of each COMPONENT_TYPE. as well as their LOCATION. For example, the analyst may consider one configuration with a single *Schneider Door Sensor* while another may integrate two of them. Also, one CPS configuration could have its data center located in the Netherlands, and another configuration to have it in Spain. The environmental impact of the number and type of devices will include their production and their end-of-life (e.g. electronic waste). The location(s) of the CPS and functional lifetime will be determinants for the environmental impact of the use phases.

Data footprint. Our method includes the analysis of part of the data management. The analyst should provide data-related information (A-TB.4). This involves (i) determining the number of years over which the data-related footprint should be calculated, (ii) defining sampling properties for each component, including the sampling approach and frequency. To analyze the data-related environmental footprint, scientific literature will be used to estimate the CO_2 emissions for storing data (e.g. storing one gigabyte of data per year) in a particular data center. These aspects are recorded in `CYBER_PHYSICAL_SYSTEM (CPS)` and `DATA_INFORMATION`.

Environmental impacts. Based on the preceding information the impact estimations can be calculated and the results can be subject to interpretation (A-TB.5). While the calculations can be done manually, we recommend using the LCA4CPS tool to automate this process. The tool facilitates the study of several configurations and provides insights to help decision-making. Results can be presented annually (`CONFIGURATION_IMPACTS_TOTAL`) or as a total over the intended functional lifetime of the CPS (`CONFIGURATION_IMPACTS_P.A.`). The analyst can also delve into the impacts of specific `COMPONENT_TYPES`. Also, the focus can be placed in a general overview or on each of the life cycle stages (i.e. manufacturing, distribution, installation, use, end of life). The details are recorded in the six deliverables named `IMPACTS (<STAGE>)`. Moreover, when more than one configuration has been considered, the analyst can compare their general and data-related footprints.

4.2. LCA4CPS Tool

The structure of the tool and the guided interaction align with the method presented in the preceding section and expressed in Figure 2. The tool allows simple interactions to handle the CPS-related information, data repositories, and intermediate and global calculations.

Components Input. This sheet specifies component types, each having an identifier, a name, and a description. To calculate the environmental impacts of the CPS, the tool needs input related to the environmental declaration of its components. The analyst can choose to enter the necessary information manually or to provide the URL of the PEP Eco Passport. In the latter case, the tool extracts the environmental declaration data automatically and creates and stores a separate entry for the component type. For example, the manufacturer declares that the lifetime of the Schneider Door Sensor component type is 10 years and that the net use of fresh water during the manufacturing of one unit is 18.9 liters.

Configuration Input. The tool supports the analyst in defining the CPS configurations they intend to assess, following the method described above (see A-TB.2). The component quantity and geographical location are both essential. Specifying the locations increases the accuracy of the estimated impacts because the tool can take into account the carbon intensity of the electricity produced in the country where the component is located. The tool has a database detailing the average carbon intensity of electricity for various countries, allowing the calculation of the carbon intensity for one kWh and applying this to the energy consumption of the components[2]. The component type lifetime, declared by the manufacturer and sourced from the PEP, is used to calculate the quantity of components of each type that are needed over the expected lifetime of the CPS. For example, if the CPS is expected to last 20 years of service, then two Schneider Door Sensor components will be required (one after the other) as their lifetime is only 10 years.

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[2] In this version, variations of the electricity mix among time are not considered

Meta-data Input. The tool offers functionality to calculate the amount of data that each configuration generates. The analyst carries out the method activity A-TB.4; that is, inputting data-related attributes for each component, within each configuration [3]. The tool also needs the analyst to provide an estimated value of the CO_2 emissions factor for storing data. This value is specific to the data center, or storing solution, used in the CPS. In our example, we specify 0.0379 kgCO_2 per gigabyte of data per year, based on [23]. This information is later used to estimate the impacts of storing the cumulative data volumes.

Overview of Environmental Footprint. The tool provides a comprehensive view of the environmental footprint outcomes, presented either annually (P.A. stands for *per annum*) or as a cumulative total over the intended functional lifetime of the CPS (A-TB.5). For example, see Figure 3. The analyst can perform the comparative assessment of the environmental footprints of different CPS configurations (e.g. identifying those configurations with the greatest and smallest environmental impact). Also, each of the four impact indicators (CO_2 impact, use of fresh water, water pollution and acidification) has its charts to be able to perform a separate analysis of the effects produced by alternative configurations.

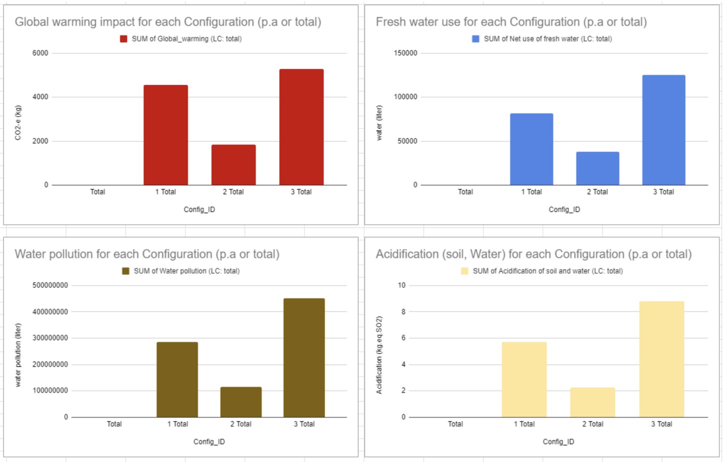

Figure 3: Screenshot of LCA for CPS tool overview environmental footprint including 4 indicators

Overview of Data Footprint. The tool calculates the data footprint of the CPS usage phase (related to A-TB.5). This helps users understand the environmental impact of data transmission and processing and can inform decision-making. The CPS architects can perform a trade-off analysis between CPS data-related features (or performance) and impact (e.g. lowering the sampling rate of a sensor will result in less frequent monitoring of the environment but also in a lower footprint).

About environmental indicators. As said before, four environmental indicators are estimated by the tool. The interviewees have stressed a special interest on the Global warming impact indicator. *GlobalWarming(use)* represents the impact of global warming of a configuration component estimated in kilograms of CO_2 equivalents (CO_2e) due to energy consumption over the life cycle use phase. It is estimated as follows:

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[3] The highlighted part in Figure 5 shows an example of this information

$$GlobalWarming(use) = \frac{energy\_consumption(use) \times carbon\_intensity}{manufacturer\_LT} \times functional\_LT \times quantity$$

The variable *energy_consumption (use)* denotes the energy consumption (in kWh) of a component type consumed during the life cycle use phase. *Carbon_intensity* represents the amount of CO_2 (Kg CO_2e) emitted per kWh of energy produced at the configuration component's location. *Manufacturer_LT* stands for the component lifetime which is the period given in years a component type can operate without failure, according to its manufacturer. The functional lifetime; i.e. the duration of time expressed in years the CPS is intended to operate, is denoted with *functional_LT*. Lastly, *quantity* is the number of components used simultaneously for a given CPS configuration.

Tool implementation. We have implemented the LCA4CPS prototype in Google Sheets, extending its functionality with Google Scripts (a version of JavaScript)[4]. The rationale is to lower the barrier for adoption by CPS researchers and practitioners, who can easily access the tool, make a copy, and run it after a simple configuration; also, it offers an interface that is familiar to many users. The manual is also available online[5].

5. Validation

We interviewed nine participants (**N=9**) to assess the tool's usefulness in general and by features. The majority of interviewees (5) work for a research institute, and the others work for a private company or a combination of private companies and research institutions. Moreover, most interviewees (8) have over 10 years of experience working with CPS. We asked them about the tool's strengths and weaknesses. A significant majority (8 out of 9) find the tool in general useful. One respondent expresses reservations, citing the perceived additional effort and work when using the tool, and does not feel the need to study the numbers that are calculated with the tool. However, the positive impressions of the tool outweigh what is also represented in the numbers. Respondents emphasize the tool's importance by highlighting the importance of the topic and the usefulness of the tool. For instance, respondent 9 stated, *"The tool is very effective and very useful and provides very good insights"*.

Evaluating each feature individually allows us to identify the most useful features (as indicated by the interviews). Feature 1, specifying configurations, was rated extremely useful (4.61 of 5). Feature 2 was deemed very useful (4.33) for comparing environmental impacts and aiding in sustainability-focused decisions. Feature 3, which allows for automatic data extraction from the PEP, received a high rating (4.44) because it reduces user effort. Feature 4 (F4) visually representing impacts, was rated very useful (4.22). Feature F5 which calculates the data volume generated by CPS, was deemed moderately useful (3.28), whereas Feature 6, which considers calculating the environmental impact of data was deemed very useful (4.17). Feature

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[4] The tool can be found here. Please make a copy, delete the data (intended for illustration purposes only), and you are ready to start your own LCA processes. https://drive.google.com/drive/folders/1Rw6YWDixBx586H3ZNyJMPiATHx2Ic0OL

[5] Tool manual can be found here. https://docs.google.com/document/d/1muqXv2GG6elV4TL-Uyc1I7NX00hNt-MM0aVtLP-2lF4

7, accounting for location-related carbon intensity of electricity, was deemed very useful (4) because it is crucial for cross-location comparison, acknowledging energy cost variations.

A minority of participants deemed the data-related features less useful, citing a general lack of interest in such analysis and arguing that the related costs of data are more meaningful than its environmental impact. 7 out of 9 interviewees identified "CO_2 footprint/global warming" as the most critical environmental indicator out of the four impact indicators used in the tool. Participants emphasize its widespread recognition both in the scientific community and the industrial sector. The participants highlight that the tool effectively raises awareness about the environmental implications of ICT as one of its strengths. Participants also commended it offers a very structured approach to accessing the environmental footprint of CPS. Furthermore, participants highlight that the tool is both important and necessary for enabling a clear understanding of the actual environmental impacts of CPS.

As for its weaknesses, interviewees find the tool time-consuming to use. Moreover, scalability presents an issue due to platform limitations, and the tool makes assumptions about the analyst's knowledge of CPS structure. Finally, the tool currently only considers direct life cycle impacts and does not take positive structural and enabling impacts into account.

6. Conclusions and future work

Measuring and understanding the environmental impact of IT from design phases, in general, and CPS in particular is a major issue. CPS are very appealing from business and practical points of view but tend to become harmful to the environment. This work is a contribution to encourage environmental assessment when developing CPS. We developed a prototype tool to help practitioners use the proposed environmental assessment method for CPS. The tool provides a simple way to describe a CPS, supports automatic integration of product environmental profiles, and estimates multiple environmental footprint indicators for various candidate configurations, including their hardware components description and data-related information. This tool aims to support decision-making in the design and development of CPS. The tool was validated with 9 practitioners who confirmed the importance of this work to raise awareness about the environmental impact of CPS. We are grateful for their time and expert opinion.

Several improvements are still needed, including enhancing the prototype and refining the analysis by presenting hypotheses, contextual information on component type environmental data, and characteristics of the CPS use phase. On a broader scale, it would be valuable to enable designers to assess the potential positive environmental impacts of utilizing CPS and state their overall net benefit.

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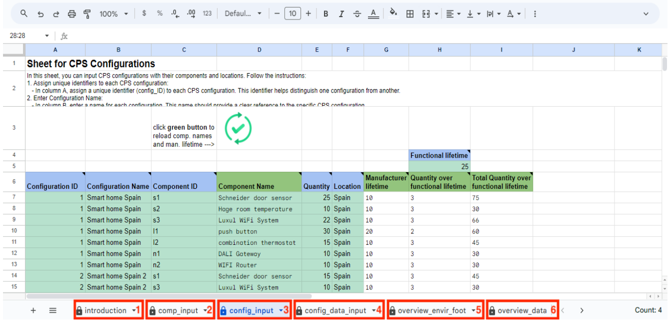
A. Appendix A – Tool screenshots



Sheet for CPS Configurations

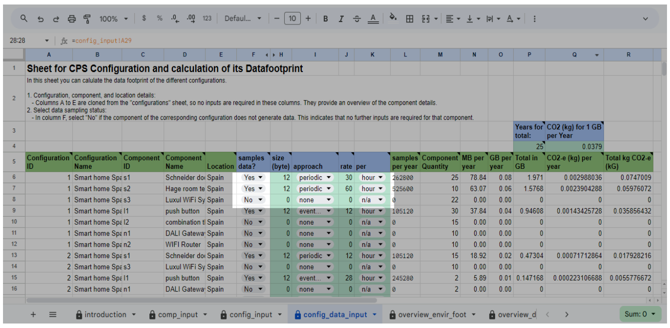
In this sheet, you can input CPS configurations with their components and locations. Follow the instructions:
1. Assign unique identifiers to each CPS configuration:
 - In column A, assign a unique identifier (config_ID) to each CPS configuration. This identifier helps distinguish one configuration from another.
2. Enter Configuration Name:
 - In column B, enter a name for each configuration. This name should provide a clear reference to the specific CPS configuration.

click **green button** to reload comp. names and man. lifetime --->

Functional lifetime: 25

Configuration ID	Configuration Name	Component ID	Component Name	Quantity	Location	Manufacturer lifetime	Quantity over functional lifetime	Total Quantity over functional lifetime
1	Smart home Spain	s1	Schneider door sensor	25	Spain	10	3	75
1	Smart home Spain	s2	Hage room temperature	10	Spain	10	3	30
1	Smart home Spain	s3	Luxul WiFi System	22	Spain	10	3	66
1	Smart home Spain	l1	push button	30	Spain	20	2	60
1	Smart home Spain	l2	combination thermostat	15	Spain	10	3	45
1	Smart home Spain	n1	DALI Gateway	10	Spain	10	3	30
1	Smart home Spain	n2	WIFI Router	10	Spain	10	3	30
2	Smart home Spain 2	s1	Schneider door sensor	15	Spain	10	3	45
2	Smart home Spain 2	s3	Luxul WiFi System	10	Spain	10	3	30

Figure 4: Screenshot of LCA for CPS tool configuration input sheet



=config_input!A29

Sheet for CPS Configuration and calculation of its Datafootprint

In this sheet you can calulate the data footprint of the different configurations.

1. Configuration, component, and location details:
 - Columns A to E are cloned from the "configurations" sheet, so no inputs are required in these columns. They provide an overview of the component details.
2. Select data sampling status:
 - In column F, select "No" if the component of the corresponding configuration does not generate data. This indicates that no further inputs are required for that component.

Years for total:	CO2 (kg) for 1 GB per Year
25	0.0379

Configuration ID	Configuration Name	Component ID	Component Name	Location	samples data?	size (byte)	approach	rate	per	samples per year	Component Quantity	MB per year	GB per year	Total in GB	CO2-e (kg) per year	Total kg CO2-e (kG)
1	Smart home Spa	s1	Schneider do	Spain	Yes	12	periodic	30	hour	262800	25	78.84	0.08	1.971	0.002988036	0.0747009
1	Smart home Spa	s2	Hage room te	Spain	Yes	12	periodic	60	hour	525600	10	63.07	0.06	1.5768	0.0023904288	0.05976072
1	Smart home Spa	s3	Luxul WiFi Sy	Spain	No	0	none	0	n/a	0	22	0.00	0.00	0	0	0
1	Smart home Spa	l1	push button	Spain	Yes	12	event...	12	hour	105120	30	37.84	0.04	0.94608	0.00143425728	0.035856432
1	Smart home Spa	l2	combination tl	Spain	No	0	none	0	n/a	0	15	0.00	0.00	0	0	0
1	Smart home Spa	n1	DALI Gatewa	Spain	No	0	none	0	n/a	0	10	0.00	0.00	0	0	0
1	Smart home Spa	n2	WIFI Router	Spain	No	0	none	0	n/a	0	10	0.00	0.00	0	0	0
2	Smart home Spa	s1	Schneider do	Spain	Yes	12	periodic	12	hour	105120	15	18.92	0.02	0.47304	0.00071712864	0.017928216
2	Smart home Spa	s3	Luxul WiFi Sy	Spain	No	0	none	0	n/a	0	10	0.00	0.00	0	0	0
2	Smart home Spa	l1	push button	Spain	Yes	12	event...	28	hour	245280	2	5.89	0.01	0.147168	0.000223106688	0.0055776672
2	Smart home Spa	n1	DALI Gatewa	Spain	No	0	none	0	n/a	0	2	0.00	0.00	0	0	0

Figure 5: Screenshot of LCA for CPS tool configuration data input sheet