Cyber Physical Systems and Environmental Issues: a Smart Home Case Study*

Mario Cortes-Cornax[1,*,†], Paula Lago[2,†] and Claudia Roncancio[1,†]

[1]Univ. Grenoble Alpes, CNRS, Inria, Grenoble INP, LIG, 38000 Grenoble, France
[2]Department of Electrical and Computer Engineering, Concordia University, Montreal, Canada

Abstract

Cyber Physical Systems (CPS) are becoming more ubiquitous, complex and powerful. Inherent benefit and comfort come with an environmental impact that is usually ignored when implementing these systems. This short paper intends to raise awareness of this impact due to the increasing number of connected devices and the data volume produced by their use. We rely on a specific smart home case study to illustrate the potential of considering life-cycle analysis of both the physical devices and data to set up a CPS. Our research in progress targets a design approach to converge into an equilibrium between utility, performance and minor environmental impact of smart systems.

Keywords

CPS, Environmental impact, Life-Cycle, Smart Home

1. Introduction and objectives

Cyber Physical Systems (CPS) are becoming part of critical infrastructures for a large variety of contexts including industry and our daily life (e.g., supply chain management, smart cities, cars, etc.). According to the 2020 Cisco Report [1], Machine-to-machine (M2M) connections will nearly attempt 15 billion devices in 2023. Among them, connected home applications will have nearly half of the M2M share, which corresponds to 1.8 M2M connections for each member of the global population. This complex infrastructures manage and exploit a huge quantity of data at the edge or at a cloud that should also be considered as part of its emissions [2]. Indeed, the inherent benefits and comfort offered by CPS are accompanied by an environmental impact (e.g., carbon footprint, abiotic resource depletion, water footprint, etc.) generated over the life-cycle of both the physical devices and the produced data, but often not considered [3].

Life-cyle assessment (LCA) is a systematic, standardized (ISO 14040 [4]) approach to quantify the potential environmental impacts of a product or service that occur from raw materials extraction to their end of life. LCA includes four phases devoted to the goal and scope definition, the inventory analysis, the impact assessment, and the interpretation. The scope, including system boundary and level of detail, depends on the subject and the intended use of the study

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*Corresponding author.
†These authors contributed equally.
mario.cortes-cornax@univ-grenoble-alpes.fr (M. Cortes-Cornax); paula.lago@concordia.ca (P. Lago); claudia.roncancio@univ-grenoble-alpes.fr (C. Roncancio)
0000-0003-2635-319X (M. Cortes-Cornax); 0000-0001-5290-6486 (P. Lago); 0000-0002-1118-6512 (C. Roncancio)

[4]. As CPS services rely on sensors, actuators, network infrastructure, and other devices, their LCA should include all of them and can be very complex. The analysis could go further by also considering the data life-cycle, as the data generated by these devices needs to be transferred, processed and stored, and may imply the use of Big data management systems.

Environmental concerns have been considered in several contexts. Regarding ICT in general, in [2] the authors show the necessity of working to keep greenhouse gas emissions low. In [3] the authors provide an extensive literature review on the environmental footprint of IoT and present a study (based on the LCA methodology) allowing a better understanding of the carbon footprint of the production of a wide range of IoT edge devices. In [5] the authors present an extensive work that quantifies the environmental performance of smart city solutions at an urban system level and evaluates their contribution to develop environmentally sustainable urban systems. The authors use the so-called urban metabolism-life cycle assessment (UM-LCA) approach.

The aim of this paper is to question the "more is better" approach for CPS, bringing the environmental impact assessment as a first-class citizen when designing them. Disclosing the infrastructure and information life-cycle may help designers analyze the trade-offs of CPS. We aim to go towards eco-friendly smart systems by design, to converge into an equilibrium between benefit and environmental impact.

To illustrate our purpose, we briefly discuss a smart home case: Amiqual4Home, A4H [6]. A4H is an experimental platform consisting of a smart apartment, a rapid prototyping platform and tools for observing human activity. In Section 2 we provide an overview of the infrastructure, some information related to the LCA and questions to push for an impact-benefit analysis that considers environmental criteria early in the design phase. Section 3 is devoted to a discussion in an eco-design perspective.

2. A Smart Home Case Study

Smart Homes include several connected devices to provide a wide range of services from smart management of water or electricity consumption to services for comfort like light or music management [7]. As mentioned before, the brutal expansion of connected devices enables many services but raise questions about the net benefit of CPS systems when we consider the environmental impact of their life-cycle. For instance, even if LED bulbs are known to consume less energy than traditional bulbs, 'smart' led bulbs that are always connected to the internet may counterbalance the minor consumption when the light is on by their continuous energy consumption when in standby. Questions also arise with other smart devices that are always connected and waiting for a "command". Although their individual manufacturing cost and consumption is generally low, when considering the whole system and the whole life-cycle of all devices, the impact is no longer insignificant and should be considered by designers and users. In fact, the analysis reported in [5] reveals that the introduction of smart solutions (like smart energy meters) to a city generally "has a negative influence on the environmental sustainability performance" of the city, calling for a need of optimizing the designs to fit the intentions.

In the following section, we introduce an example to raise awareness that even for apparently simple services, the required system support becomes non negligible when we consider their

Table 1
Installed Sensors in A4H

Type	Measures	Count
Environmental sensors	CO_2, Humidity, temperature, noise, brightness and presence in each room	23
Lamp sensors	Monitor state, light levels and color (hue)	22
Contact sensors	Monitor doors, windows and gabinets	21
Energy/water sensors	Monitor instant and total consumption at each point	20
Smart outlet	Monitor appliance state (most unused)	16
Interaction devices	Interrupters and remote controls. Monitor interactions with a controlled device	15
Shutter sensors	To control shutter opening level	8
Pressure sensor	Monitor presence in bed	1
Loud speaker	Registers songs played	1

use at a large scale (instances and time span[1]) and environmental criteria such as the greenhouse gas reduction requirements and, more generally, planet boundaries. In this perspective, we put forward some design questions.

2.1. Amiqual4Home - A4H

A4H is an experimental apartment[2] configured to unobtrusively monitor its consumption (e.g. electricity) and the inhabitant daily living activities such as cooking, sleeping or washing dishes. It is a two-story, one-bedroom, one-office and two-bathroom apartment equipped with 219 sensors and actuators (see Table 1). The ContextAct@A4H dataset [8] contains the data captured by these sensors in a three-week free-living experiment annotated with activity labels. The A4H smart home has been used for several studies including activity recognition [9], energy consumption analysis [10] and vocal commands [11].

To clarify the environmental impact of such a CPS, it is necessary to consider the life-cycle of the devices installed in the apartment, the produced data and the scenario of use. The life-cycle of a device includes its material extraction, manufacturing, transportation, use and end-of-life. In addition to sensing and communication devices (gateways, routers), user devices, like a smartphone or a tablet, are used to control and to monitor all devices, serving as a control panel for the house. Together, they compose the smart home's infrastructure.

The data life-cycle includes its production, transport, processing, storage and use. Data is transferred from the sensing devices to the processing center at a cloud or, as in A4H, at the edge. Sensors in A4H use different M2M communication protocols (e.g. KNX, MQQT), most of which use a hub or gateway to create a sensor network. As illustrated in Figure 1, a server (local in A4H) analyzes and stores sensor data and can communicate back with actuators when needed. Data can be stored in different formats, for extended periods of time.

[1] e.g. millions of smart buildings during many years
[2] A4H has an area of $87m^2$. The reader may refer to [6] for more information.

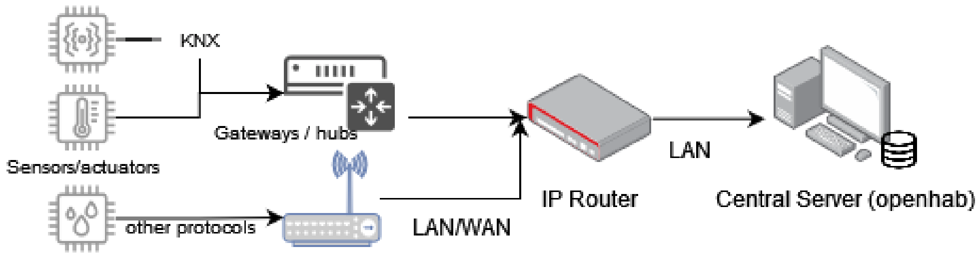

Figure 1: General architecture of the data collection system

2.2. Discussing environmental impacts

It is important to recognize that system design decisions have an impact in the environmental footprint of CPS. In this paper, we argue that these decisions should be considered as part of the *first design decisions* together with the functional analysis and expected benefits. Some choices of A4H, which is used for research purposes, are discussed here.

System configuration: deciding which and how many sensing devices should be installed in a smart home is a key decision. The number of devices can quickly grow, but the extra benefits can be minimal. In A4H redundant sensors were installed to make the system more robust and to create a versatile dataset that could be used by researchers in different areas, resulting in a large number of sensors installed. This configuration is related to functional requirements. In the ContextAct@A4H experiment, the considered functional service was a system to monitor elder activities at home, to support independence at home while still alerting a support network of unusual behaviours or events. The contact sensors installed at A4H, allowed monitoring the mobility, kitchen activity and bathroom use patterns. In contrast, if the main concern is the person going out and getting lost, one sensor at the entrance door and one at the door leading to the patio may be sufficient for initial alerts.

In final-user smart homes, it would be important to identify precise functional requirements and appropriate precision as well as the required fault-tolerance to limit the number of devices. The choice of the devices comes with different impacts depending on the manufacturer and on its complexity [3]. Unfortunately, today it is still hard to find the device's environmental impact information. Even if some manufacturers have agreed to disclose Product Environmental Profiles (PEP) for their devices, this information remains scarce and most consumer devices do not report their environmental impact following a life-cycle analysis.

To illustrate our purpose, we refer to the PEP (LCA according to the ISO standard [4]) published by Hager and Schneider for their contact sensors [12, 13] and KNX gateway [14, 15], a Fujitsu Computer [16] and the EcoDiag calculator[3] for various PC configurations. The mentioned manufacturers are referred hereafter as H, S and Fu. Considering the expected lifetime reported in the PEP documents, we show the energy consumption for the use phase and the total life-cycle of the devices in Figure 2 -left. The purpose of this paper is a general discussion and not to put forward one product or another. We focus on the mentioned devices as it was difficult to obtain information on the environmental impact of other devices installed at A4H. Although

[3]https://ecoinfo.cnrs.fr/ecodiag-calcul/

	Estimated lifetime	Energy use lifetime	Energy of life-cycle with 10-year use
Average PC	5 years	945	
Fu - PC max configuration	5 years	535	
Fu - PC standard configuration	5 years	165	
H -IP Gateway	10 years	755,56	794
H - Contact sensor	10 years	0,48	4,25
S -IP Gateway	10 years	177,5	183
S -Contact sensor	10 years	0*	14,25
*reported as 0 in the PEP as it represents less than <0.01% of total life-cycle energy			

	Monitoring	Configuration	10 year
1	Apartment doors and windows	Average PC, 21 H-contact sensors, 1 H gateway	2773,25kWh
2		Fu. PC max conf., 21 H-contact sensors, 1 H gateway	1900,15kWh
3		Fu. PC standard, 21 H-contact sensors, 1 S gateway	602,25kWh
4	*Entrance and back doors*	*Fu. PC standard, 2 H-contact sensors, 1 S gateway*	*521,5kWh*

Figure 2: Use of energy in kWh of devices (left) and various configurations (right). Energy estimates for 10 years of the PC's are left blank because their estimated lifetime is 5 years (two PC are required).

multi-criteria analysis is necessary (and available in the PEP), it will not be presented in the following. Our aim is to show the impact of some decisions in the total environmental impact and how it can grow exponentially. The energy consumption criterion allows us to discuss this in simple terms. A complete LCA is out of the scope of this paper.

In the table in Fig. 2-right, we show some configurations considering various combinations of sensors, gateway and PC and their estimated energy footprint. Configurations 1 to 3 monitor all the doors and windows of the apartment whereas configuration 4 targets exclusively the front and back doors. Let's notice that as the expected lifetime of a PC is 5 years, two of them are required for the 10 years period.

While we use the energy consumption in this paper, other criteria as resource depletion and the CO_2 footprint are important. It is worth noting, that the CO2 footprint of the electricity depends on the so-called energy mix. This evolves in time and differs from one country to another and even from one region to another in some countries. According to ElectricityMap [17], accessed on March 24, 2022 at 11am GMT, at that moment, the estimated equivalent CO_2 for a kwh (gCO2eqkwh) is 109 gCO2eqkwh in France, whereas it is only 27 gCO2eqkwh in Quebec. We note that in Australia there is a big difference between Flinders Island and Queensland, reporting 12 and 709 gCO2eqkwh respectively.

Multiple factors and trade-offs are involved in choosing a system configuration, including device complexity and additional services they might provide [3]. We argue that their expected lifetime and environmental impact are also important in the decision.

Sampling rate and data footprint Sampling rate greatly impacts the amount of data produced and transmitted. Sampling rate can be set in Hz (samples per second) or configured to send a new measure when an event is detected. Sampling rate also has an effect in the algorithms used to analyze the data, which need to adapt to the defined sampling approach, for example, by using different windows of analysis [18]. In this case study, we briefly discuss *data footprint* considering a 10-year lifetime. A sensor measure is a tuple $< timestamp, sensor\_id, value >$, 12 Bytes, considering integer values and ignoring any protocol overhead. Based on this, we estimate the volume of data produced by the 21 contact sensors of A4H during 10 years with four sampling approaches (Table 2). The *Event-based* sampling approach represents the scenario where the device sends data only when a state change occurs. Relying on the three-week experiment of A4H logged in the ContextAct@A4H dataset [8], we observe an average of seven events per day per device and a maximum of 128 events per day per device.

As mentioned, sensed data is transferred to and processed in a server. Architectures for data

Table 2
Estimated data produced by a contact sensor(ContextAct@A4H experience)

Sampling approach	10 yr Sensor Data	10 yr Apart. data
Event based, average, 7 measures/day	0.306 MB	0.006GB
Event based, max, 128 measures/day	5.6 MB	0.117GB
Sampling rate, 1 measure/minute	63.07 MB	1.32GB
Sampling rate, 2 measure/minute	126.14 MB	2.65GB
Sampling rate, 1 measure/second	3786.83 MB	79.52 GB

processing and learning models range from in device treatment, edge processing to hybrid or completely cloud-based systems. Each approach has its environmental footprint. In either cases, the sensor sampling approach entails a big difference in the total data produced, which is related to the resource consumption in the data life-cycle. The architecture choice depends on system and functional factors such as privacy requirements and whether or not patterns at the population level need to be analyzed (for instance, for improving public health policies).

We have described some of the CPS design decisions in A4H that affect the environmental impact of the system and we have shown how small changes can have significant impacts in its total energy consumption. This list is of course non-exhaustive but intends to raise awareness of how we can consider a life-cycle assessment of both the devices and the data in the analysis of CPS. Neither the analysis nor the decisions are easy, but the environmental factors should be one of the criteria considered along-side other requirements and restrictions like privacy, costs, and functional requirements.

3. Discussion and Conclusion

It is worth to state the undeniable benefits that cyber-physical systems (CPSs) have brought in both the industry and our daily life in different domains such as healthcare, supply change management, security or living places. Our position is that more than ever, considering the huge potential of CPS and the current environmental challenges, the choices for introducing "smart" functions should be analysed very carefully. We claim for a "fair trade" approach with a people-planet-system perspective that integrates an impact/benefit analysis including the whole life-cycle of the smart function. Performing a Life-Cycle Assessment for a complex cyber-physical system is challenging. Nevertheless, even if a complete LCA cannot be realized, conducting an approximate study will contribute to increase the environmental responsibility and sustainability during system development. As cyber-physical systems tend to be "invisible", there is a need for awareness of the underlying infrastructure and required resources, early in the design phases. Of course, this is not to say that functionality should be compromised. A form of systemic thinking that considers both the functional definition and the environmental impact when designing solutions would help. In this paper we discussed some choices that may influence the environmental footprint if they are scaled.

In future work, we'll focus on improving the approaches in design phases so as to introduce environment awareness together with the actual goal of the system (comfort, health, energy savings, etc.) and the induced benefits. Rebound effects should also be considered as the addition of a new service may enable other needs in terms of services, devices or data. The use of scenarios may also be useful to inquire about the various uses of the physical infrastructure. The context of the deployment is also important as the use of the system will differ from one country to another because of the origin of the electricity (nuclear, carbon, renewable, etc.). Indeed, the boundaries of the system has to be well defined as the LCA has to be feasible when looking for the required environmental information. We put forward a big challenge to motivate designers and developers to find the *good enough level* of services and not go to a *more is better* approach just because it is feasible from a technological and economical perspective.

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