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► **To cite this version:**

Ernesto Quisbert-Trujillo, Thomas Ernst, Karine Evrard Samuel, Emmanuelle Cor, Elise Monnier. Lifecycle modeling for the eco design of the Internet of Things. *Procedia CIRP*, 2020, 90, pp.97 - 101. 10.1016/j.procir.2020.02.120 . hal-03491587

**HAL Id: hal-03491587**

**<https://hal.science/hal-03491587v1>**

Submitted on 22 Aug 2022

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Procedia CIRP 00 (2020) 000–000



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27th CIRP Life Cycle Engineering (LCE) Conference

## Lifecycle modeling for the eco design of the Internet of Things

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### Abstract

The number of smart things in our societies is booming. This trend challenges the eco design of the Internet of Things (IoT) because decisions depend on material availability for manufacturing devices, and energy for powering supporting infrastructures. So far, research has oriented much effort on local devices and instruments allowing environmental assessment like lifecycle modeling fall short against the complexity of the full IoT infrastructure. This article examines such complexity and proposes an adapted lifecycle modeling approach to sharpen the environmental evaluation and eco design of IoT systems, putting emphasis on the IoT hardware and the energy consumption of mutualized infrastructure.

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Peer-review under responsibility of the scientific committee of the 27th CIRP Life Cycle Engineering (LCE) Conference.

**Keywords:** Internet of Things; IoT Infrastructure; Lifecycle Modeling; Lifecycle Thinking; Multiple Lifecycle Models; Component Lifecycle models; Eco design; Raw Materials; Energy Consumption.

### 1. Introduction

Recent studies report the accelerated growth of connected things in last years and present concerning predictions in the short- and long-term. For example, a statistical study reported 6.4 billion of connected objects by 2016 [1] and one year later estimated that that number will increase to 25 billion by 2021 [2]. This increasing number of smart objects implies environmental loads not only in terms of the required energy to manufacture and use these devices but also in terms of the required energy to power supporting infrastructures, and imposes new difficulties for impact estimations [3]. A reasonable approach to tackle this issue could be considering the lifecycle of mutualized infrastructure in addition to that one of edge devices. Such holistic approach would permit a multi-layered design including the representation of every resource [4] and constituting a complex IoT system of

multiple lifecycle models. This complex system would also merit the analysis of connections among lifecycle models and common processes in where they may overlap [5].

This article investigates these aspects and presents a multilayered lifecycle modeling approach for IoT systems. Such systems are composed of electronic devices with different capacities that are connected to the internet [6]. These capacities, at the same time, are limited by different components' functionalities and they all together contribute not only to the delivery of a particular IoT service but also to the environmental impacts of the whole system.

Our approach includes a complementary abstraction of the data flow that describes the electronic components' interactions and acts as the common denominator between the local and shared infrastructure representation. In this manner, we tackle the complexity of the IoT infrastructure and facilitate its holistic lifecycle modeling. The proposed

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doi:10.1016/j.procir.2020.xx.xxx

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approach will be also required to enable the accurate environmental assessment and eco design of IoT solutions by considering the cloud and local computing load distribution and electronic component arrangements.

The rest of the paper is organized as follows: section 2 presents the available literature related to lifecycle modeling of IoT systems, pervasive systems, sensor systems, etc.; and presents the current trends of IoT infrastructure design and management. Section 3 paves the way for our holistic, IoT lifecycle modeling approach that is instantiated in section 4. Section 5 discusses our contributions to the environmental assessment and eco design of IoT solutions and section 6 presents conclusions and future research perspectives.

## 2. Literature review

Lifecycle modeling is intensively used for environmental assessment and eco design. A comprehensive literature review including this tool in the IoT context reveals two groups: one group showing lifecycle modeling as the means to conduct environmental assessment using IoT for data collection and the other showing lifecycle modeling as the research focus or as the instrument to conduct environmental studies of IoT systems. This section presents the latter group in a structural way and summarizes the research focus of concerned studies in table 1 to understand their limitations.

Table 1. Research that includes lifecycle modeling (LM) as the research focus or the means to conduct environmental studies of IoT.

Structural layer	LM as the research focus	LM as an instrument for environmental Studies
Sensing layer	- Soós et al. [7] (BoL, MoL, and EoL of terminal devices).	- Van der Velden et al. [10] (knitted textile sensors, Printed Circuit Boards (PCB), DC vibration motors, and a batteries).
Edge layer	- Canedo [8] (IoT device management) - Bonvoisin et al. [12] (device lifecycle modeling and network lifecycle modeling of WSN)	- Van Dam et al. [9] (Multifunctional HEMS, energy management devices, and energy monitors (composed of sensors, transmitting units, and displays)). - Köhler et al. [11] (proximity sensors, adapters, a transceivers, and conductive textiles).

Authors address IoT systems by layers. At the sensing layer, Soós et al. [7] introduce a generic IoT lifecycle model based on Business Process Model Notation (BPMN) flows and Velden et al. [10] conduct a cradle-to-grave environmental study of electronic textiles for health-care applications.

At the edge layer, while Canedo [8] analyzes industrial IoT lifecycle through a management lifecycle-based mechanism called Digital Twins, the rest of authors pays particular attention to lifecycle environmental assessment of sensor systems. For example, Van Dam et al. [9] conduct an energy cost-saving analysis of Home Energy Management Systems (HEMS) using a cradle-to-grave lifecycle analysis and Köhler et al. [11] carry out a Lifecycle Assessment (LCA) of a

sensing floor system to support environmentally conscious decision-making in the course of product development.

Bonvoisin et al. [12] provide a system-level, lifecycle modeling approach to estimate the first order environmental impacts of a municipal Wireless Sensor Network (WSN) of smart glass-waste containers. Specifically, they combine a device lifecycle model (a cradle-to-grave representation of sensors, repeaters, and gateways) with a network lifecycle model, which is a logical representation of essential functions of the physical infrastructure (deployment, operation & maintenance, use, and dismantling). Interestingly, the authors of this study also suggest the future inclusion of servers and telecom infrastructure to their model to get a sharp understanding of its environmental impact.

This reveals not only the need to model mutualized infrastructures and assess their impacts but also —as noted by Mashhadi and Behdad [13]— the ambiguity of physical system boundaries when defining the functional unit of smart solutions. Indeed, how the inclusion of shared infrastructure in the system boundary of a smart application affects its global environmental impact is not yet fully understood.

A possible explanation for not including the network and cloud infrastructure in the environmental estimation of a sensor system may be due to an unclear idea of their role. For example, WSNs may operate with or without internet connection while IoT solutions necessarily require internet-based communication [14]. This aspect could be also interpreted in words of van Dam et al. [15] who claim that conventional HEMS (intermediary devices intended to give users direct insight of their energy consumption) enable smart metering systems (automatic energy management systems interacting with energy suppliers).

Thus, two important insights emerge from the studies discussed so far:

- From the scarce literature dedicated to lifecycle modeling or environmental assessment of IoT systems, no studies encompass the full infrastructure.
- An important reason for disregarding shared infrastructure lies on the vague definition of IoT system boundaries.

To deal with these issues and pave the way for a holistic lifecycle representation, the following section reviews the current approaches for designing and managing full IoT infrastructures.

### 2.1. Design and management of IoT Infrastructure

Most researchers investigating the design and management of IoT infrastructure propose three-layered structures composed of a sensing, edge, and cloud layers [16], [17-19]. Such structures mainly include sensing devices (terminal nodes, sensor networks, pervasive systems, etc.); middle devices (intermediate computing nodes, network cores, fog servers, etc.); and cloud devices (internet devices, data centers, cloud information centers, cloud servers, etc.). While the sensing layer includes constrained devices, the edge layer

may also include powerful local servers and local networks. The cloud layer generally includes powerful data centers and large communication networks.

On the other hand, an IoT device is constituted by components with different capacities such as clock frequency for microprocessors or storage capacity for memories. These components execute different functions such as analog-to-digital conversation, data storage, data processing, data transmission, etc. In this sense, studies such as that conducted by Mekki et al. [20] usually propose hardware improvement according to components' functionalities and other studies such as that conducted by Souza et al. [21] usually propose service allocation methods to manage and reduce energy consumption and latency based on resource availability. The problem of the first kind of studies is that the full IoT infrastructure is not considered. The problem of the second kind of studies is that service allocation methods aim to manage available resources in deployed IoT infrastructures to satisfy in-run-time application requests, ignoring infrastructures features such as application component distribution in early design stages [16].

Alternatively, and with the aim of supporting design decisions based on performance properties, Ashouri et al. [16] attributes the sensing, receiving and actuation responsibilities to the thing layer; the manipulation, analysis and dispatching data responsibilities to the edge layer; and the massive computation, storage, and communication responsibilities to the cloud layer. In this sense, they propose three basic guidelines to distribute functionalities along the IoT infrastructure: (1) distributing the sensing and actuating functions in the thing layer, (2) distributing the processing functions in the edge layer when local resources are sufficient and terminal nodes do not need to interact with the cloud layer, or when edge devices act as data proxies between terminal nodes and cloud servers; and (3) distributing the processing functions in the cloud layer when massive and elastic processing and storage are needed or when data collection from various distributed locations is required.

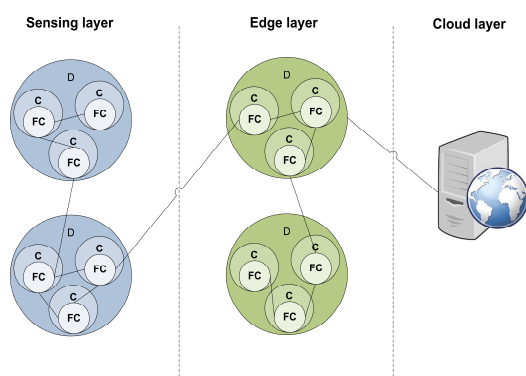


Fig. 1. IoT Infrastructure design and management approaches.

Fig. 1 represents the current design and management approaches for IoT infrastructure and concludes this section as follows: authors describe a three-layered IoT infrastructure composed of a sensing, an edge, and a cloud layer. Each of these layers includes devices (D) constituted by components

(C) that interact with each other by means of functionalities linked to capacities (FC). Such function-capacity association allows the design and resource management of IoT infrastructure. The next section synthesizes all these findings in the context of the lifecycle modeling of IoT systems.

### 3. Towards a holistic lifecycle modeling of IoT infrastructure

From the previous section, one realizes the connection between functionalities and capacities of devices and components; each of them contributes —through specific functions and within its capacities— to the delivery of a service and to the environmental impact of the whole system. This insight is increasingly noticed and adopted for hardware and product design in the IoT or electronic industry. For example, Adegbiya et al. [22] proposed the identification of primitive functions (i.e.: sensing, communication, Image processing, etc.) to determine computational kernels for IoT microprocessor design when Gehin et al. [23] had already suggested the use of a functional model to support a decisional framework oriented to components selection in the early eco design stage of assembled products. The latter research presents an adapted lifecycle model in which components are separated from the assembled-product. In this way, this model would facilitate the eco design of compound products with levers identification for environmental impact reduction of essential functions (i.e.: by changing the technology), by reducing the environmental impact of a component (i.e.: by changing its material), or by reorganizing the product's structure according to partial environmental scores of every lifecycle phases of components.

On the other hand, Wellsandt et al. [5] suggest that the increasing complexity of products and services —such as IoT services based on multiple devices— requires future research covering multiple lifecycle models, their relations, and their common processes where they may overlap. From their compiled literature related to these aspects [24 - 28], the approach presented by Peças et al. [25] seems to be suitable for an adaptation towards lifecycle modeling of IoT. Certainly, although the lifecycle models of the sensing, edge, and cloud devices may not run in such concurrent way (see Fig. 2), they inevitably converge in interdependent processes from which energy consumption of data flow is the common denominator.

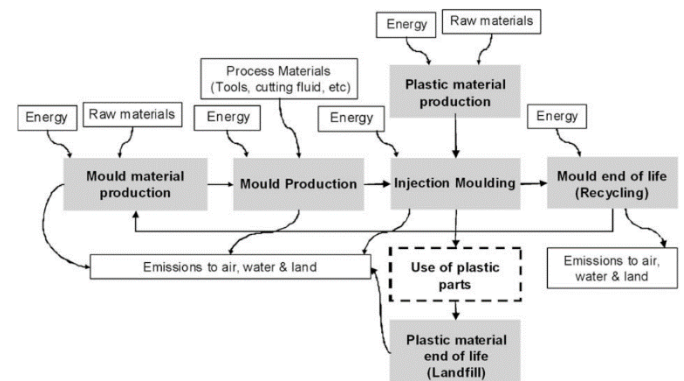


Fig. 2. Cross-typed lifecycle model of a mould and plastic product [25].

Thus, based on this insight and inspired by the previous component analysis, we believe that an appropriate and complete lifecycle model of an IoT system should include a cross-typed lifecycle modeling of the sensing, edge, and cloud devices together with a representation of hardware components. To support this posture, the cross-typed-component lifecycle model of a case study is presented in next section.

**4. Case Study: Lifecycle modeling of smart metering**

The case study presents a commercial IoT application of smart metering for irrigation systems. The work realized on this system to model its lifecycle includes two main tasks. The first task consists on deploying the full system according to the fabricant indications [29, 30] to understand the data flow through the system. The second task consists on dismantling every device to identify each electronic component and their functions in the system. Also, technical data about electronic components’ capacities and material composition was collected for further research described in section 5.

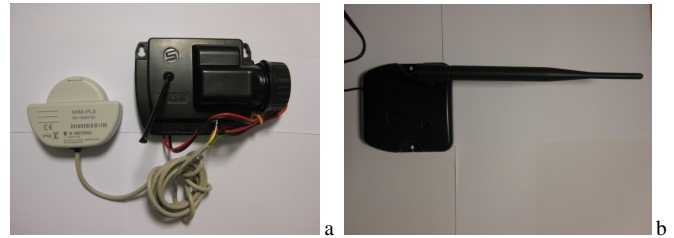


Fig. 3. (a) Flow controller with a pulse emitter; (b) WiFi/LoRa relay.

The IoT System is composed of two devices: for the sensing layer, a 9V battery, Bluetooth/LoRa flow controller (Fig. 3.a) compatible with a pulse emitter and, for the edge layer, a 230 VAC powered, WiFi/LoRa/Bluetooth relay (Fig. 3.b). The system operates as follows: The pulse emitter attached to a conventional flow meter sends electrical signals to the flow controller. Then, the flow controller transmits volume consumption data to the cloud layer by means of the WiFi/LoRa relay and a conventional internet access point (internet box). Simultaneously, the cloud layer may send alert notifications to a smartphone when water consumption thresholds, previously established by the final-user, are crossed.

Fig. 4 shows the cross-typed-component lifecycle model for our case study with the principal processes that electronic components (bold text) of every devices/infrastructure (Capital bold text) in each layer perform to accomplish the functional unit of the IoT System (i.e.: monitoring the water consumption of a particular terrain during a period of time). Black arrows represent material flow between processes and Red arrows represent data flow between electronic components. For simplicity, only the sensor, microcontrollers, and communication components of IoT devices are showed. Light-blue processes show the life cycle model of the pulse emitter (Fig. 3.a) and the flow meter controller (Fig. 3.a) —the sensing devices, light-green processes show the lifecycle model of the relay (Fig. 3.b) —the edge device, and gray processes represent the mutualized infrastructure (Internet and Data center infrastructure). In this simplified model, the end of life of all devices is excluded and material flow of cloud infrastructure is not considered (physical facilities).

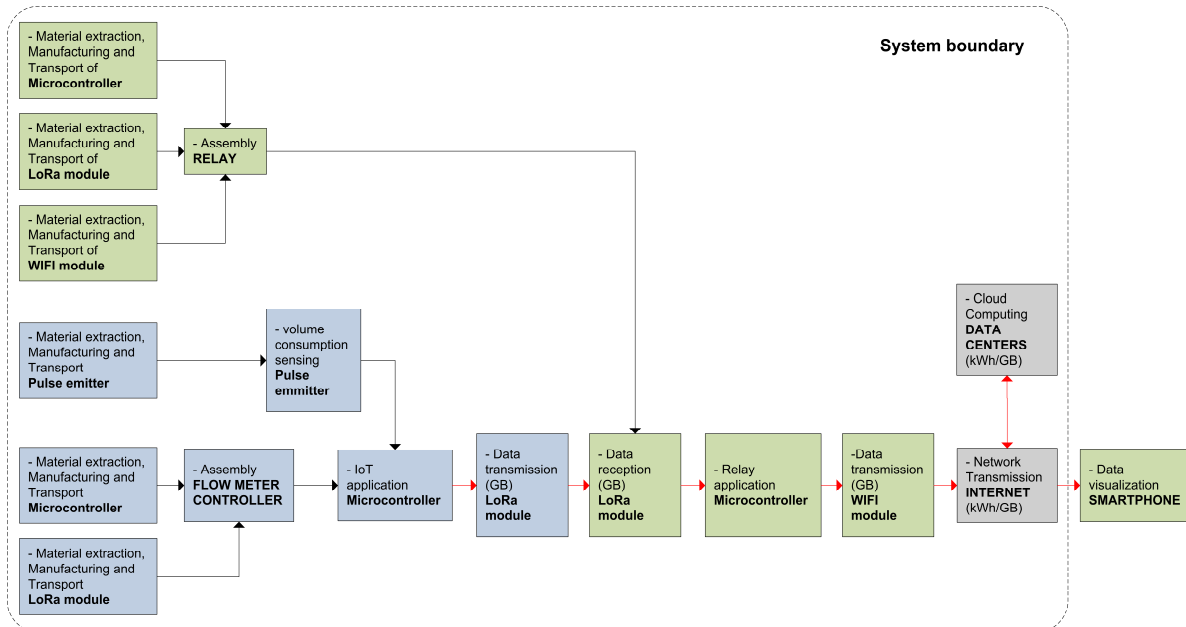


Fig. 4. Cross-typed-component lifecycle model for the smart metering case study. It is assumed that the flow controller and the relay are assembled in the same facilities. Transportation of finished devices to end-user is not taken into account and environmental impacts of the smartphone (edge device) are excluded from the system boundary for simplicity.

The Cloud layer can be represented by two macro processes: network transmission on internet and cloud

computing in data centers. Recent studies modeling internet infrastructure [31-35] have been carried out to estimate its

electricity intensity whereas limited literature with the same focus is found for data center infrastructure [36–38]. By inspecting these works, it can be observed that the common energy consumption (kWh) to transmitted data (Gigabytes) ratio is consistent with the data flow approach presented in our model. Thus, we include the process “Network Transmission” for the internet infrastructure and the process “Cloud Computing” for the data center infrastructure in our model assuming a kWh/GB parameter.

## 5. Discussion

The cross-typed life cycle model of this paper includes the sensing, edge, and cloud layers of an IoT application in a systematic way. It represents (1) the mass flow of every sensing and edge device and (2) the data flow between all their hardware components. The latter approach would facilitate a more accurate estimation of the energy consumption of the cloud infrastructure because every device generates—at a constant or variable rate—data that reduce or increase the computing loads on the network and server side.

For illustration, the reader should consider the simulation study conducted by Bonvoisin et al. [12] in which the environmental impacts of a monitoring system for municipal glass waste containers are extensively analyzed by a system-level perspective, but how data transmission through telecom infrastructures and data processing in application servers affects the environmental performance of this system remains unknown.

Here, for example, if one assume 288 acoustic rangefinder sensors sending glass-level data at a rate of 100Kbps (approximate estimation for acoustic applications according to Samie et al. [40]) during one second every hour along 10 years, the whole system would generate 315.36 GB. Such volume data would need approximately 45 KWh to be transmitted through the internet infrastructure (according to the electricity intensity rate of 0.14 kWh/GB of the IP core and access network infrastructure reported by Aslan et al. [39]) and other 45 KWh to be treated by data center facilities (at an electricity intensity rate of 0.14 kWh/GB according to Andrae and Edler [42]). Using an appropriate conversion ratio for electricity energy such as that provided by the Environmental Protection Agency [43], both calculations would account an additional environmental load of 63.6 kg CO<sub>2</sub>-eq to the operation phase of the IoT system.

On the other hand, considering data flow between electronic components in a cross-typed-component life cycle model would also facilitate an appropriate design of IoT systems because hardware of sensing and edge devices could be selected according to their functionalities and capacities.

By way of illustration, an experimental study based on the Atmel Atmega328 microcontroller conducted by Samie et al. [40] identified the necessary processing capacities of IoT microprocessors to perform basic operations on raw sensing data by considering the typical data generation rate of different sensor applications. Results from this work suggest, for example, that data-intensive generation rates of smart city applications (approximately between 100Kbps and 1Mbps) require a processing capacity (clock frequency) from 100MHz

to 1GHz to handle sensing data, or a processing capacity from 1MHz to 100MHz to only encrypt and transmit sensing data to gateways. Such technical features may complement the eco-design process of the internet of things.

In the context of the smart metering case study of this paper, we identified the electronic components of every device in a cross-typed-component life cycle model that reveals interactions between the sensing, edge, and cloud layers according to the manufacturer design (base case). In future research, we will use this model to (1) estimate the full environmental impact of this base case (including the mutualized infrastructure), (2) identify environmental impact hotspots based on the mass flow and the data-intensive profile of electronic components, and (3) propose eco-design alternatives based on the technical features and constraints of optional components.

## 6. Conclusions and future research perspectives

After reviewing the available literature of the lifecycle modeling and environmental impact assessment of IoT, this article firstly presents the reasons that account for an adaptation of lifecycle modeling towards IoT applications. Then, it reviews the current approaches of IoT infrastructure design and management to build a cross-typed-component lifecycle modeling approach that covers local and shared resources. Such approach would facilitate more precise environmental impact estimations of IoT solutions and eco design alternatives for IoT systems by a more informed components selection. Further research will apply our modeling approach to conduct environmental impact assessment of the base case presented in this paper together with other case studies. With the results of this research, we will also propose eco design alternatives based on local-shared infrastructure computing load trade-offs and components selection in real eco design fieldwork of commercial IoT products.

## Acknowledgements

This work is supported by the French National Research Agency in the framework of the “Investissements d’avenir” program (ANR-15-IDEX-02).

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