The Dark Side of Cloud and Edge Computing: An Exploratory Study

Klervie Toczé
klervie.tocze@liu.se
Linköping University
Linköping, Sweden

Maël Madon
mael.madon@irit.fr
Université de Toulouse
Toulouse, France

Muriel Garcia
garcia_muriel@gmx.de
Independent researcher
Germany

Patricia Lago
p.lago@vu.nl
Vrije Universiteit
Amsterdam
The Netherlands

ABSTRACT

Information and communication technologies are increasingly pervasive in our everyday lives. Their use has greatly evolved from an ancillary service to a component of all our activities, anytime, anywhere. To this aim, we rely heavily on cloud computing and, more recently, on edge computing. Hence, their contribution (or obstruction) to the sustainability of our society at large is pivotal.

Unfortunately, cloud/edge provisioning has a dark side: it too often prioritizes economic gain over the cost of long-lasting sustainability. Also, sustainability is often absent from the discussions in the cloud/edge research community.

To start the discussion and highlight a number of sustainability shortcomings of the cloud and edge computing paradigms, we carry out an exploratory study involving experts-in-the-field, capture their inputs in the form of so-called *unsustainable patterns*, and complement them with examples of possible countermeasures. The results of our study include: (i) the definition of a Pattern Model, (ii) a catalog of unsustainable patterns for the cloud and edge computing paradigms, and (iii) the identification of preliminary countermeasures and takeaways in order to make these two paradigms more sustainable.

KEYWORDS

Unsustainable pattern, cloud computing, edge computing, exploratory research, focus group, energy footprint, sustainability.

ACM Reference Format:
Klervie Toczé, Maël Madon, Muriel Garcia, and Patricia Lago. 2022. The Dark Side of Cloud and Edge Computing: An Exploratory Study. In *LIMITS '22: Workshop on Computing within Limits, June 21–22, 2022.*

1 INTRODUCTION

Information and communication technologies (ICT) are taking more space in our lives day after day. We use them for communication, information, work, entertainment, etc. every day. Traditionally, a user would use the computing power of her device (*e.g.,* a personal computer) eventually connected to the Internet to carry out some task like writing a document, uploading photos or finding information. However, during the past decade, the usages of ICT have greatly evolved and the computing part has progressively shifted to big centralized infrastructures connected to high-speed networks: the data centers.

Now, all the usages previously listed can be done in the *cloud*, offering countless advantages such as accessing the same document through several devices, sharing it with others, saving the battery of mobile devices or renting large computing resources. Recently, other applications' requirements are pushing for moving part of the resources closer to the end user, to the *edge* of the network. This offers other advantages such as lower response times, reduced data traffic to the central cloud and local context awareness, paving the way to innovations like autonomous vehicles. In a recent work [59], researchers have drawn up a "technology landscape" of solutions for energy-efficient digital infrastructures. They identified four trends (so-called "scenarios") to address this challenge, that they order temporally from the one that is currently taking place to the one that may only happen in a long time horizon. The first two scenarios correspond to the trends we just touched upon: "Scenario 1: cloud centralization" is the migration from on-premise resources to a centralized remote cloud and "Scenario 2: flexible geolocation" is characterized by the exploitation of resources available at the edge of the network.

In parallel, our society has overshot many of the planetary boundaries [48] and urgently needs to adapt to become more sustainable. In this work we use the words "sustainable" and "unsustainable" in the broad sense. We include environmental, social and economic concerns and refer to popular frameworks like the triple bottom line [18] or the UN Sustainable Development Goals [58].

Sustainability is often absent from the discussions in the cloud/edge research community. It may be because one assumes that technology is "neutral": only the way it is *used* can harm or do good. Another reason may be the belief in the many promises of these two paradigms for a "greener society": economies of scale, energy efficiency, hardware sharing, user device longevity, better use of renewable energies, enabling the development of "smart" technologies, etc. Earlier editions of LIMITS have shown some skepticism about the neutrality of technology in practice and the very possibility of a way out of the environmental crisis, only through technological solutions and without ever questioning our needs. We can ask ourselves: to what extent will the cloud and edge promises be fulfilled? Isn't there a risk that they will be counterbalanced by negative effects of adopting these paradigms? In short, what is the "dark side" of cloud/edge?

In this exploratory paper, we start to challenge the widespread "tech for good" discourse and highlight a number of sustainability shortcomings of the cloud and edge computing paradigms. Our hope for this work is to act as a trigger to inspire researchers to react.

We do so by capturing them in the form of so-called *unsustainable patterns*.

The contributions of this paper are the following:

- The definition of a Pattern Model.
- A catalog of unsustainable patterns for the cloud and edge computing paradigms.
- Examples of preliminary countermeasures and takeaways in order to make these two paradigms more sustainable.

This paper is structured as follows: we describe the study design and execution in Section 2. In Section 3, we provide a definition of unsustainable patterns. Then, we present the unsustainable patterns identified for the cloud in Section 4 and for the edge in Section 5. After that, we discuss main takeaways and limitations of the study in Section 6. Finally, we present related works in Section 7 and conclude in Section 8.

2 STUDY DESIGN AND EXECUTION

To uncover the catalog of unsustainable patterns, we design and conduct a qualitative mixed-method empirical study that is illustrated in Figure 1.

With the scenarios from the technology landscape in mind [59], we carry out two focus groups to extract expert knowledge about the remote cloud and edge computing, respectively. The first focus group took place digitally at a workshop during the 2021 edition of the ICT4S summer school. Remote collaboration happened through Miro[1]. The second focus group, however, took place at a separate dedicated occasion and was video-recorded and transcribed afterwards, with the permission of the participants.

Focus Group (cloud). At first, the participants of the workshop brainstorm about the sustainability of the cloud-migration scenario (*i.e.,* where digital assets are migrated from on-premise to a centralized cloud provider, cf. Section 4) in order to identify the *components* (*e.g.,* stakeholders, incentives, interests, etc.) that are involved. These components are collected as "digital sticky notes" through Miro. Then the same group arranges the components in clusters to highlight the benefits and drawbacks for each stakeholder and the possible related patterns of consumption and provisioning. Throughout the five days of the summer school, we gather inputs from the same group of participants composed of three PhD students, one senior researcher and three industry practitioners, all in the field of cloud computing and related research. The four authors of this paper are included in the participants.

Focus Group (edge). Based on the data that emerged from the first focus group and with the help of the literature, we define a generic Pattern Model (see Section 3). We use it to design the session for a second focus group of edge-computing experts, with the aim to collect data similar to the first focus group but this time related to edge computing. We carry out a dry-run with knowledgeable colleagues to gather feedback on the session design. Finally, we carry out the focus group session, where we gather inputs from three senior researchers in the field of edge computing and related research.

Data Extraction and Analysis. Following these two focus groups, we use the related Miro- and video-recordings to extract the data about the elicited unsustainable patterns; and we use the components of the Pattern Model as labels guiding the data extraction.

[1]Miro is a whiteboard platform for online collaboration https://miro.com.

All four authors participate in the data extraction and analysis, first independently and then in collaboration until consensus is reached. In particular, from the data output of each focus group we extract a list of specific unsustainable patterns. To this aim, we take all the data entities and look for links between them that would result in unsustainable patterns, *i.e.,* (i) we analyze the positive/neutral entities to uncover possible sources of unsustainability (or otherwise we remove them); (ii) we analyze the negative entities and described them in terms of the elements of the Pattern Model; and (iii) we remove the duplicates and the entities that were just comments and could not be translated into patterns.

After having obtained the final list of specific unsustainable patterns, we label them in categories based on their intent; and cluster them based on category similarity. Finally, for each cluster we create a generic unsustainable pattern (*e.g.,* cloud patterns C1 through C10 in Table 1) and assign a logical name illustrating the unsustainable nature of the pattern (*e.g.,* Over-consumption for cloud pattern C7).

Literature Study. For each of the identified unsustainable patterns, we perform a quick literature review to collect evidence on such pattern and possible measures to counteract them. The final list of unsustainable patterns is presented in Sections 4 and 5, where each pattern is described and accompanied by example countermeasures.

Study replication. For the sake of transparency, we provide a replication package on Zenodo [55] containing material used for this study. The following is included:

- Images of the notes from the Miro board.
- The slide set used for the edge focus group.
- The Excel sheets used as a support for the analysis of the data gathered during both focus groups.

For privacy reasons, the video recording and transcripts are not included and the data is anonymized.

3 UNSUSTAINABLE PATTERNS

In this section, we introduce the notion of unsustainable patterns which is used for describing in a structured way the relationship between the cloud and edge paradigms and sustainability. This concept is influenced by the concept of *dark patterns*, which we explain after giving some background about the pattern approach.

3.1 On the notion of patterns

The pattern concept and approach originate from a book written by Christopher Alexander [2] about the built environment. In their work, they introduced the basic pattern idea, presenting 253 patterns (all following the same format) for building beautiful and convivial structures. Since then, the pattern approach has been adopted in a large range of other fields.

One of these fields is software design, in which a pattern is described as "at the core of [...] patterns is a solution to a problem in a context" [22]. Our work is close to this general description with a focus on problem (the unsustainable patterns) and solution (the countermeasures), as a starting point. However, the Pattern Model presented in Section 3.3 can capture both problematic and

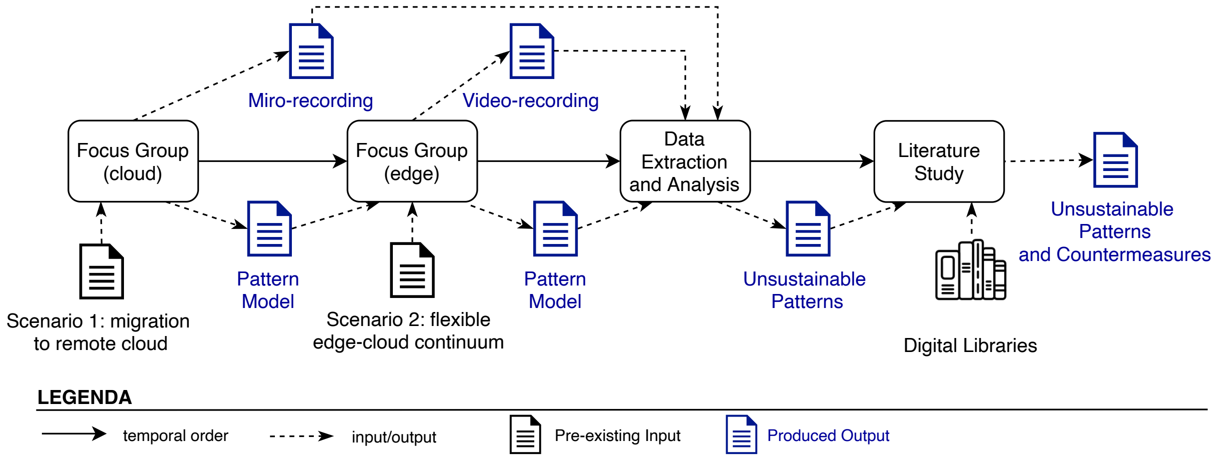

Figure 1: Study Overview

non-problematic aspects of the cloud/edge paradigm (as discussed in Section 6).

3.2 UX dark patterns

In the last decade, the user experience (UX) field also came up with its own concept of *dark patterns*, which has been drawing increasing attention and has greatly inspired our work. Harry Brignull first coined the term [8] and describes it as "tricks used in websites and apps that make you do things that you didn't mean to, like buying or signing up for something" [7]. They are "anti-patterns" according to the book by Alexander [2], where patterns represent goals to strive for. Examples of common dark patterns are: when it is very easy to subscribe to a service but very hard to unsubscribe, or when the user feels guilty of declining a proposition due to how the different options are presented. Since then, dark patterns have been analyzed more in depth, in both industry and research [15, 25, 38].

In this work, we look into the different definitions of dark patterns in order to identify the key related components and analyze how such a concept could be adapted to sustainability. One of the main insights of this analysis is that dark patterns in UX put a strong emphasis on the fact that the identified patterns are implemented *deliberately*, with a malign purpose. In the case of sustainability shortcomings, the pernicious intention is less obvious. Moreover, since sustainability is a complex and broad concept impacting different domains in multiple dimensions (*e.g.*, social, environmental and economic), we find that classifying a given pattern as "dark" is not straightforward. Therefore, we do not provide a text definition but rather construct a Pattern Model, *i.e.,* a conceptual model for identifying sustainability-related patterns.

3.3 Sustainability-related patterns

In order to facilitate and structure the identification of sustainability shortcomings in the different computing paradigms under study, we design and use the Pattern Model presented in Figure 2. This model emerged from the analysis of the data collected in the first focus group, versus the components of both the UX dark patterns and the scenarios used for quality considerations in software architecture [4].

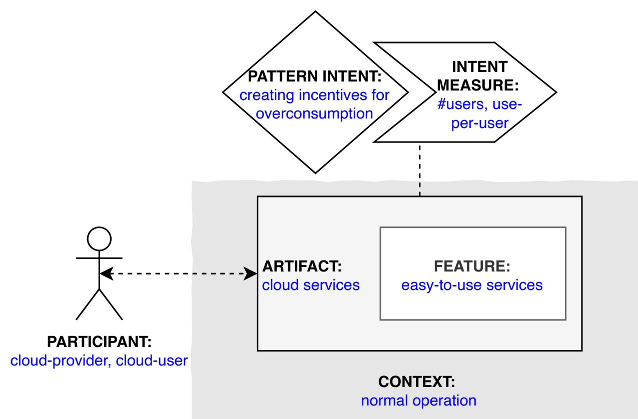

Figure 2: The Pattern Model (with a pattern example in blue text)

The Pattern Model is made of six components. Each pattern embodies a sustainability shortcoming that is described by the **pattern intent** using an *-ing* formulation. In order to assess to what extent this goal is achieved, the pattern intent is accompanied by an **intent measure**. The **participants** are the actors that are involved in or affected by the pattern. The pattern happens through the use of a specific **artifact** and the **feature** is the attribute of this artifact that leads to the sustainability shortcoming, when used in a certain **context**.

Overall, a pattern may be qualified as *unsustainable* due to several reasons. Each reason, in turn, may be located in one or several of the pattern's components. It is part of the analysis to determine why a pattern is unsustainable, and where the unsustainability originates. In this paper, we focus on the presentation of unsustainable patterns.

Of course a scenario may exhibit sustainable patterns, too, but these are not the focus of this work.

4 CLOUD COMPUTING SCENARIO

In this Section, we present the identified unsustainable patterns for the cloud computing scenario and their analysis.

4.1 Scenario: Migration to remote cloud

We use as a reference for the first focus group the first scenario from the technology landscape [59] in which cloud users migrate their digital assets (*e.g.,* software applications, data management, computing resources) to a centralized cloud provider. Such migration may entail, for instance, truly migrating existing on-premise software to cloud hosting (*e.g.,* for business customers), or the use of pay-per-use cloud-native applications (*e.g.,* for end users).

4.2 Identified patterns and countermeasures

The list of unsustainable patterns resulting from the Data Extraction and Analysis of the cloud focus group is provided in Table 1. Each column of the table corresponds to an element of the Pattern Model (Figure 2). For each pattern, we provide below a quick analysis and present countermeasures.

Dependency (C1). In some situations, the cloud user may become dependent on the cloud provider, and he risks being compromised would the cloud provider not provide services with high enough quality. For example, if the customer support does not handle issues in a good way (*e.g.,* by taking a long time to solve issues) and the cloud user is completely dependent on the customer support to solve any problem, then this creates unsustainability. Relying heavily on cloud providers and therefore lacking planning and preparation to deal with unexpected issues with the cloud service has been identified as one of the major risks when adopting cloud computing [16]. As a countermeasure, it is advised that cloud users assess early on (*e.g.,* in the cloud provider selection process) the quality of the customer support [51].

Lock-in (C2). Closely related to the previous pattern, vendor lock-in is economically unsustainable for cloud users because the difficulty to change cloud provider diminish their bargaining power, prevent them from reacting if the provider fails to provide the agreed service or even threaten their business assets in case of data breach or cyberattack on the cloud provider side [41]. As countermeasures, the literature mentions standardization of cloud APIs and proposes solutions that increase portability and interoperability [53].

Environmental blindness (C3). Real-time information about energy consumption can help to save energy [35]. When migrating to the cloud, the user adds an additional intermediary between her and her impacts, thus becoming less aware of them. Because of the Jevons paradox[2], the problem of reducing the high energy consumption cannot be solved solely by increasing efficiency. If the energy consumption is hidden from the end user by the cloud provider, this creates unsustainability. Better information to the user seems to be a countermeasure. For example, the literature investigates different approaches and instruments to trigger behavior change at the cloud user and end user side [57].

[2]https://en.wikipedia.org/wiki/Jevons_paradox

Environmental control giveaway (C4). Similarly, by migrating their digital assets to a remote cloud provider, cloud users effectively give away the control over the definition of their energy consumption strategies. Cloud providers have hence the responsibility to demonstrate to their customers, how they enable which strategies; and the extent to which their assets contribute by providing *significant* SLAs and metrics/indicators that cloud users can use *e.g.,* for decision making. At the same time, cloud providers acquire the power to decide to invest in such strategies, or not. Unfortunately, by feeding myths about the energy optimizations *automatically* coming with economies of scale [45, 49], energy control results to be regularly misused. Countermeasures include introducing laws and regulations of the data center industry, *e.g.,* awarding tax reductions against quantified energy optimizations [27]; or following systematic cloud migration models and frameworks [17] that help users analyze *e.g.,* how detailed the SLAs are wrt. energy consumption.

False promises (C5). Due to the high level of market competition, cloud providers promise applications benefits that do not always materialize [52]. As an example, many cloud providers present their offer as free of charge. At first glance, this seems to be correct, as no money is involved in the first subscription. In the long term however, the cloud users end up paying either directly for optional (but almost unavoidable) features or once the trial period is passed, or indirectly (*e.g.,* with their data). This is often not in the interest of the user and is therefore not sustainable. One countermeasure could be to introduce audit organisations that check the promises made by companies and, in the case of false promises, make them transparent to the public.

Patterns C6, C7 and C8 are *direct rebound effects* of cloud migration. By providing cheaper, less energy-intensive and easier-to-use technologies, the cloud computing paradigm tends to foster **growth in data traffic (C6)** and **consumption (C7)** and to enable the **emergence of superfluous usages (C8)** that were not possible before (*e.g.,* using a navigation system on the phone although your car has one already built-in). This negates (at least partially) the promised energy savings. Cisco [11] reveals evidences of such a traffic growth. The average traffic per capita per month was expected to grow from 12.9GB in 2016 to 35.5GB in 2021, while the number of Internet users would grow from 44% of the global population to 58% in the same period. This growth may not be caused solely by the shift to cloud computing but it remains an indicator of a potential rebound effect. Unfortunately, rebound and transformational effects are insufficiently discussed in the field [1] and their multifaceted nature makes them hard to measure. Walnum & Andrae [60] and Adelmeyer *et al.* [1] provide nonetheless definitions of rebound effects in cloud computing and frameworks to categorize them, paving the way to more precise assessment. Counteracting the rebound effect of a technology means to question ourselves on the basic need that this technology is fulfilling. Lange & Santarius [30] introduce *digital sufficiency* as a principle for sustainable digitalization, which they define as "as much digitalization as necessary and as little as possible". The idea is to shift towards designing longer-lasting and reparable hardware and software, only collecting necessary data and placing the user back at the center of the concerns.

Privacy violation (C9). The characteristics of cloud computing (*e.g.,* remote data storage, platform sharing, service dynamic

ID	Name	Pattern Intent	Intent Measure	Participant	Artifact	Feature	Context
C1	Dependency	Making the cloud user dependent on the cloud provider	Degree of dependency	cloud-user, cloud-provider	Cloud infrastructure and associated services	Provided service	Normal operation
C2	Lock-in	Locking the cloud user in a specific technology, hence hindering the change for a different cloud provider	Cloud-provider changeability	cloud-user, cloud-provider	Cloud technology used	Termination of the service	Choice of technology
C3	Environmental blindness	Making the negative environmental impact generated by the cloud user less visible to the cloud user	Environmental cost of service use, monetary counterpart	end-user, cloud-user	Subscribed services	Absence of environmental indicator	Normal operation
C4	Environmental control giveaway	Giving away the control (owned by the cloud user) over the definition of environmental / energy consumption strategies and metrics	Service Level Agreements	cloud-user, cloud-provider	Data center	Energy consumption / Environmental strategies and metrics	Energy optimization, strategy making
C5	False promises	Promising benefits (*e.g.,* better or free services) that do not materialize	Extent of the validity of the promise	cloud-user, cloud-provider	Cloud technology/service	Marketing of cloud services	Choice of adopting cloud services
C6	Data traffic growth promotion	Fostering more data traffic	Amount of data traffic in the network	cloud-user, cloud-provider	Data produced on end-devices	Easy and cheap access to resources (*e.g.,* storage, processing)	Innovation with the creation of new products (hardware/software)
C7	Over-consumption	Creating incentives for over-consumption	#users, use per user	end-user, cloud-user	Cloud services	Easy-to-use services	Normal operation
C8	Superfluous usages	Enabling the emergence of new and superfluous usages	#services available	cloud-user	Cloud technology	Easy and cheap access to resources (*e.g.,* storage, processing)	Innovation with the creation of new products (hardware/software)
C9	Privacy violation	Violating user privacy (*e.g.,* for marketing purposes, unauthorized monitoring)	Private-data-leak frequency and degree of seriousness	end-user, cloud-user, cloud-provider	Cloud services	Data storage and utilization metadata	Normal operation
C10	Security threat	Granting unsupervised access to own device (by cloud user)	Security breaches	cloud-user, cloud-provider	Cloud utility services (automatic updates)	Data protection	Normal operation

Table 1: Identified unsustainable patterns for the cloud computing scenario (according to Figure 2)

change, just to mention a few) make privacy protection particularly challenging. Privacy violation, however, regularly occurs purposely, when cloud providers *e.g.,* do not comply with enterprise policies or legislation, or force/persuade users to give personal information against their will [42]. Due to the many recent scandals in various ICT industries[3], countermeasures are fast emerging, *e.g.,* legislation[4]. Another example would be to give back to users the power to decide what to share.

Security threat (C10). There are multiple security concerns in cloud computing. One of them, mentioned in the focus group, is when the cloud user grants unsupervised access to her own device. This may lead to sensitive information leak if either the cloud provider misuses his access rights or does not provide enough security to prevent third-party attacks. These two issues are related to two of the top threats to cloud computing [6]. Countermeasures can be found in the important body of work about cloud security issues and solutions (read for example this review [12]).

4.3 Insights

An analysis of the unsustainable patterns found for the cloud reveals different insights that can be used as a starting point for a better incorporation of sustainability thinking into the paradigm.

First of all, the 10 identified patterns show that the cloud computing paradigm may not be as virtuous as it seems. It has a number of dark sides that may prove to be serious threats to users' integrity or environmental sustainability, by fostering the use of personal data, energy and resources.

Then, we notice that only 3 out of the 10 identified patterns include the end user as a participant. This suggests that the end user is powerless in many aspects and the change needs to come from other directions than trying to change their behavior. If changes need to have a significant effect (that could be quantified as diminishing the occurrence of several unsustainable patterns), it will be more efficient to "put pressure" on the cloud user or the cloud provider. For example by encouraging a higher transparency on what using the cloud *actually* costs (to the environment or the society). Too often, the cloud is marketed as an immaterial (and almost magical) solution to all problems. But there is no free lunch: fast and easy access to cloud services is only possible because the earth is crisscrossed with networks and data centers. Far from being immaterial, they make up about two third of ICT footprint, itself estimated to 2.1%–3.9% of global greenhouse gas emissions [21].

Finally, with 5 patterns out of 10 being in the context of normal operation (meaning almost always happening), it is necessary to take action there. This can start by questioning our behaviors: do I really need to use the cloud for this task? Do I need to send this data or host this service in the cloud? Do I really need to have all my blurred pictures backed up in the cloud? Everyday, every ICT user generates data to be stored in the cloud. Most of it will never be used but still takes up resources. How can this be prevented or detected? How can it be made easier to clean up our digital lives? What amount of digitalization is really necessary in our lives (digital

[3]An example being the Facebook–Cambridge Analytica data scandal https://en.wikipedia.org/wiki/Facebook-Cambridge_Analytica_data_scandal.
[4]https://digital-strategy.ec.europa.eu/en/policies/digital-privacy

sufficiency)? These are examples of questions that are crucial to answer in order to move towards a sustainable future.

5 EDGE COMPUTING SCENARIO

In this section, we move on to the results of our study for the second focus group *i.e.,* the edge computing scenario.

5.1 Scenario: Flexible edge-cloud continuum

For the second focus group, we considered the scenario in which the remote cloud is complemented by the use of resources at the edge of the network, *i.e.,* edge computing [50]. In this paradigm, existing cloud users and new edge users choose to use resources closer to the end user to host their digital assets. Reasons for doing so may be the need to decrease end-to-end latency, perform data pre-processing, and address privacy concerns or difficulties in connecting to the remote cloud.

5.2 Identified patterns and countermeasures

The list of unsustainable patterns resulting from the Data Extraction and Analysis of the edge focus group is provided in Table 2. Here also, each column of the table corresponds to an element of the Pattern Model (Figure 2 and for each pattern, we provide below a quick analysis and present countermeasures.

Fragmentation (E1). Edge computing infrastructures are distributed across multiple actors and include a variety of devices. Moreover, the edge applications are also very diverse and do not require the same type of service from the edge provider. This creates fragmentation and silo thinking of different natures. Bhardwaj *et al.* [5] identify four types of such silos: application-specific, software-stack-specific, data source-specific, and provider-specific. As a countermeasure, they introduce the concept of *Edge Exchange*, as a way to enable cross-actor cooperation and resource sharing, while still providing control and accountability.

Hardware multiplication (E2). The distributed nature of edge computing leads to a lot of hardware being produced. This has an impact on resource utilization that has to be investigated both for producing them but also for running them, *i.e.* to perform life-cycle assessments. As part of this effort, Pirson & Bol [46] provide a carbon footprint assessment of IoT edge devices (focusing on the production and transport phases) that shows the consequent impact these devices have. A countermeasure mentioned during the focus group is to use already existing devices as edge devices (for example embedded systems) instead of building dedicated edge devices.

Unprofitable optimization (E3). Since the energy consumption of an edge computing centre is usually not very high (because of its small size and the type of devices used), there is currently no incentive for the provider to optimize resource utilization in order to save energy. A countermeasure to this is the shift to another business model where the users are charged only for the actual time they use resources and not, as before, for reserving resources even if they are not using it. This is called serverless computing [9] and it pushes the incentive on the provider to optimize so that they decrease the amount of idle resources, for which they will not get paid anymore.

Always on (E4). Edge devices are by default considered as being always on even when they do nothing. This causes energy waste, but enables real-time services (like in-hospital patient monitoring or cloud gaming) anytime, or at least when needed. Cloud computing faced a similar problem in the past [47]; countermeasures for the edge can build upon those created for the cloud.

Unauthorized surveillance (E5). Because the edge is closer to the edge users and end users, access to applications running at the edge generate more and richer metadata, like the user geolocation (and movements) by monitoring the location of the edge device, or the presence and use of collocated applications *e.g.,* for smart-home or IoT appliances. This enables exploiting metadata against privacy [40], sometimes authorized (*e.g.,* in smart surveillance for safety reasons), but often unauthorized with malicious intents (*e.g.,* facial spoofing, people tracking) or for commercial reasons (*e.g.,* monitoring of customers behavior). Countermeasures are fast appearing, *e.g.,* to detect unauthorized accesses and raise alarms [40].

One-sided infrastructure control (E6). If the owner of the edge infrastructure has malicious intentions, it is easy for him to cut access to the technology or control the people using it (*e.g.,* in a dictatorship). This represents a social sustainability threat to anyone using the technology while not in full control of the equipment and applications in the infrastructure. In fact, security and privacy issues are mentioned as more prominent in edge than in cloud [36]. To counteract these risks, it is necessary to establish trust between the devices, for which there exist an important body of work (see for example [31, 36, 39]). Of course these trust evaluation mechanisms come with an overhead, as discussed in pattern E12.

Concealed impact (E7). To date, end users lack visibility on their impact, *e.g.,* the energy footprint of their use of digital services. By being unaware of their negative impact, they have no incentives to change their behavior towards a more sustainable consumption. The power of awareness creation is well known, *e.g.,* by creating indicators-as-a-service and green labels [59]. Hindering it, however, can be a (malicious) instrument for *e.g.,* edge providers (and service providers in general) to bring additional revenues based on impact invisibility. Tactics for an energy-aware edge computing provide additional countermeasures [28].

Uninformed use (E8). Nowadays, there are a lot of applications that are very easy to use but act to some extent as a black box for the user who has no idea about what data the application gathers about herself and/or what technology it uses. This has consequences on social sustainability: first the user may not be aware of what information is available about her or what consequences her actions may have, but also she does not feel the need to know more as it is just so easy to use. As the edge computing paradigm develops and new applications emerge, it is going to become more complicated to know what data is gathered and where it is stored. Educating the users to such questions becomes crucial in order to avoid *e.g.,* integrity issues, and policies should evolve to better protect the end users' interests. At the same time as edge computing applications are released, it would be interesting to assess the level of technology literacy [13] of edge users and design appropriate education.

Digital exclusion (E9). Digital exclusion happens when new technology that requires advanced or new infrastructure or devices is not going to be available for all, thus preventing a part of the

ID	Name	Pattern Intent	Intent Measure	Participant	Artifact	Feature	Context
E1	Fragmentation	Making it hard to optimize and share resources, hindering communication outside of your edge (silo thinking)	Level of fragmentation (how many actors in a given area)	end-user, society	Infrastructure	Ownership is split among many actors	Normal operation
E2	Hardware multiplication	Spreading hardware devices that need to be produced	Amount of hardware needed, Life cycle assessment of the hardware considered	hardware-producer, edge-provider	Infrastructure	Distributed nature of edge	Deployment and normal operation
E3	Unprofitable optimization	Making it not profitable to perform resource consumption optimization on the provider side	Level of incentives?	edge-provider, edge-user	Infrastructure	Cost or business model, switching on/off techniques	Normal operation
E4	Always on	Consuming energy to enable real-time services all the time	Uptime of a service (availability) and energy use.	edge-provider	infrastructure	Switching off devices	Normal operation
E5	Unauthorized surveillance	Exploiting metadata against privacy	How much private information leaks	end-user, edge-user	Application running at the edge	Metadata creation/collection	Surveillance
E6	One-sided infrastructure control	Giving great privileges to whoever owns the infrastructure	Extent of (un)lawful interception	edge-provider, end-user, edge-user	Infrastructure	Infrastructure owner privileges	Normal operation
E7	Concealed impact	Hindering the awareness of the end user's negative impact	Level of awareness of the end user	end-user, edge-user, edge-provider, government	Application/service	Visibility of usage and cost of resource consumption	Normal operation
E8	Uninformed use	Making it hard for the end user to understand what it is she is using, which may lead to unwanted usage	Level of awareness of the end user	end-user, edge-user, policy makers	Technology	Service used	Using a new service / technology
E9	Digital exclusion	Excluding part of end users because of difficulties to access/use services	Nr. of people excluded from services (different metrics depending on category)	edge-provider, government	Technology or specific services requiring specific HW/SW - depending on the type of exclusion	Service users are excluded from	Deployment and normal operation
E10	Security overhead	Adding a computational and communication overhead to increase security	Size of overhead	end-user, edge-user	Application running at the edge	Crypt/decrypt data in the edge before sending it to the cloud	Handling of privacy-sensitive data
E11	Redundancy overhead	Provisioning extra resources to guarantee continuity of service	Size of overhead	edge-provider	Infrastructure	Redundancy	Failure mitigation
E12	Trust overhead	Using resources on an external devices that may not be trustworthy	Size of overhead	edge-user, edge-provider	Infrastructure	Resource sharing and associated trust enforcement mechanism	Normal operation
E13	Efficiency trap	Using more a technology, even a more energy-efficient one, which leads to an increase in total energy consumption	How much a service is used - Growth in usage	end-user, edge-user, edge-provider	Technology	A specific service	Normal operation
E14	Bloating	Enabling more data-intensive usage.	Amount of data traffic - Growth of data traffic	end-user, edge-user, edge-provider, 5G-network-provider	End-user application	Video resolution (or other resource hungry feature)	Normal operation following application innovation
E15	Planned rebound effect	Pretending to ignore what could be a consequence of launching a new service	Extent of rebound effect analysis	edge-user	application/service	Prediction of use	Normal operation
E16	Technical debt	Requiring the user to adapt its application	Adequacy between resource needs and use, technical debt when no adaptation	edge-user	Application/service	Functions composing the application	New business model
E17	Green-washing	Using a small fraction of "green" applications as an excuse to develop the technology which will mainly be used for other purposes	Share of the applications being directly aimed at sustainability	edge-provider, edge-user, innovation-driver	Technology	Motivation behind the development of the technology	Innovation

Table 2: Identified unsustainable patterns for the edge computing scenario (according to Figure 2)

target end users (either in different countries or inside the same country) to get access to services. The complexity of computing at the edge makes it increasingly difficult for edge providers to plan for and provision resources to meet the ongoing dramatic growth in demand [54]. A strategy often adopted by edge providers is to focus only on a part of the potential users, typically those bringing highest revenues, hence widening the digital divide and contributing to a society that is socially unsustainable. Countermeasures should make trade-offs between the benefits of edge computing like reducing latency and energy consumption, and the investments needed to avoid digital exclusion. For example, in healthcare personalized home-care (hence at the edge) is meant to learn the profile of the patient and adapt for usability [26].

Security, redundancy and trust overheads (E10-E12). Edge computing creates new unforeseen security and privacy issues [3]. Literature on these topics comes up with edge-specific mechanisms to counteract them, as already touched upon in patterns E5 and

E6. However, these mechanisms almost always require extra computation to be performed *e.g.,* for encryption and decryption in case of security, or for establishing trust between devices. The overhead is also present in the network as additional metadata become needed in the payloads. At the same time, in order to offer uninterrupted provisioning of edge computing applications, redundant resources must be set up, which increases the environmental impact. Certainly, smarter mechanisms can still be developed to increase security, guarantee continuity of service or establish trust at lower cost. One could also ask if these overheads are significant enough to matter. In any case, a first step would be to generalize the evaluation of the extra environmental cost (or at least the extra computation and communication required) of any such mechanisms and compare it with the concurrent approaches.

Efficiency trap (E13) and bloating (E14). Similarly to cloud computing (patterns C6-C8), the adoption of edge presents a risk of rebound effect. New technologies part of the edge paradigm are often presented as being more energy-efficient than their predecessors and hence more sustainable. However, as energy-efficient a technology may become, if the rebound in usage is substantial then the overall energy consumption may increase. This increased use may come from the services using the technology, *e.g.,* transmitting 4K video on a device with a small screen just because it is possible, but with no (or negligible) increase in quality of service. It can also come from the technology itself. This is for example the case in 5G, where although a base station is four times more energy-efficient than its 4G counterpart, its total power consumption is still four times higher than a 4G base station (*e.g.,* due to extra antennas required), in addition to the fact that more 5G base stations are needed compared to a 4G network [10]. To counter these two patterns at the service level, the concept of digital sufficiency should be envisioned to reflect upon the quantity of data that is relevant for a certain service/device combination. As a countermeasure regarding the technology itself, the telco providers are already investigating new antennas technologies, network architectures and roll-out strategies and improved base station implementations with energy-saving features for the 5G technology [10, 19].

Planned rebound effect (E15). Majchrzak *et al.* describe that an ICT system can always have positive and negative consequences which are either intended or unintended [37]. Edge computing is no exception. The edge providers thus have the option of supposedly ignoring known negative consequences for society or the environment when launching their products on the market so that they can increase their profits. As a countermeasure, similar to the false promises in cloud computing, an audit organisation could create awareness about this problem in society.

Technical debt (E16). When new technologies or business models are developed[5] their adoption by the users is not automatic and require some efforts. Some users end up remaining in previous and outdated versions'/models' ways of working that are less optimized, resulting in an extra resource consumption for the same use. The user either pays for the extra consumption and has an increased technical debt (unsustainable way) or makes the effort to adapt (sustainable way). There is work going on to describe the technical debt issues related to serverless computing, which shows clearly the drawbacks of choosing the unsustainable way [32]. In addition to spreading such studies to increase awareness about the drawbacks of technical debt, a countermeasure to this is for the provider to provide training in the new technology so that the users completely adopt it, and not seemingly adopt it.

Greenwashing (E17). During the focus group, edge-enabled applications with a positive impact on sustainability were cited by the participants, for example in the area of environmental monitoring or renewable energy management. Added to the common promises of the edge paradigm (more energy-efficient, more decentralized), there is a potential for greenwashing from ICT companies or lobbies, *i.e.,* "the act of misleading consumers regarding the environmental practices of a company or the environmental benefits of a product or service" [14]. An example is the report published by the cooperation of ICT firms Global e-Sustainability Initiative predicting a saving of 20% of the world's CO2 emissions thanks to ICT technologies from 2015 to 2030 [23]. This report has been relayed by many companies and in numerous press articles to highlight the reduction potential even though its methodology has been highly criticized [20, 21]. Countermeasures to greenwashing are to raise awareness about it, increase regulation or improve transparency of environmental reporting [14].

5.3 Insights

Through the analysis of the unsustainable patterns presented above, different insights are gained about the edge computing paradigm sustainability aspects, especially in comparison to the cloud computing ones.

First of all, like for cloud computing, the 17 identified patterns show that edge computing has several dark sides, too. These may also prove to be serious threats, although not necessarily the same as for the cloud computing scenario.

For example, Table 2 shows that 8 patterns out of 17 (47%) include the end user as a participant. This is a higher share than for cloud computing (30%). Keeping in mind that the patterns presented are not exhaustive, this is however an indication that the end user is more involved in edge than in cloud. Considering that the edge paradigm is about bringing the resources closer to the end user, this finding is not surprising but emphasizes the importance of the end user for making the edge sustainable, both as a potential source of unsustainability but also as an actor to push for more sustainability.

The fact that we identify so many unsustainable patterns for a technology that is still under development should give us food for thought. Is this something that we really want to happen? Will the advertised benefits of this new paradigm be greater than the sustainability drawbacks? Could it be that sustainability was and still is not taken into consideration when investigating this technology?

6 DISCUSSION

We now discuss some results and related takeaways, and how we mitigated main threats to the study validity.

6.1 Takeaways

The Pattern Model is meant to be generic and reusable. The Pattern Model presented in Section 3.3 and used for analyzing the

[5]such as the pay-per-use model discussed in pattern E3 which moves the optimization burden to the provider

two scenarios and identifying unsustainable patterns is generic in different ways. First, even if we focus only on *unsustainable* aspects of the paradigms in this paper, the Pattern Model can be used to identify sustainable patterns. This has been tested during the second focus group, where experts were asked to use it for identifying both sustainable and unsustainable dimensions of edge computing. Second, the Pattern Model is not tied to either cloud or edge computing and can therefore be used for identifying (un)sustainable patterns in any other area.

Future research is needed to explore the pattern intentionality. We want to attract attention on the fact that in the UX definition of dark patterns, the intention behind the pattern (the malign purpose described in Section 3.2) is a cornerstone of the concept. In this work, we adapt the idea of dark patterns to sustainability and focus on the intent. However, the intentionality of an unsustainable pattern is a sustainability problem and studying this requires a lot more research.

The impact of using cloud/edge has to become more transparent. Our study highlights the importance of making the impact of the use of cloud/edge computing more transparent to the user (especially with regards to environmental impact but not only). Currently it is hard for a user to know his impact (patterns C3 and E7). As mentioned in the analysis of E7, creating awareness is a powerful tool for behavior change. Therefore, it is of high importance that all actors involved within the cloud/edge paradigms (providers, users, but also researchers and governments) start to take into account the negative side effects of these technologies. This is even more important for the edge which is still to some extent in the design phase, giving the opportunity to make it more sustainable from the start.

Research on systemic effects of cloud/edge is missing. This study also makes us question whether the research efforts are targeting the relevant problems for achieving sustainability. We see a large body of work addressing technical challenges such as privacy, security, trustworthiness or even energy efficiency. We are however missing sound research on systemic effects such as rebound effects, awareness or digital exclusion.

Research on systemic effects of cloud/edge needs interdisciplinarity. As the participants mention in the second focus group, there is sometimes a misunderstanding between people of different backgrounds, leading to a discrepancy in the objectives. They gave the example of latency: while in edge research the optimization is in the range of milliseconds, the bottleneck in a system if often somewhere else. Practitioners may think that they need edge for low-latency in their application while a response time of one hour would be more than enough. Insightful and multidisciplinary research is needed to more efficiently tackle the unsustainable patterns.

Future research should tackle all sustainability dimensions. The cloud and edge computing are both powerful and disruptive paradigms. As any innovation, they come with a number of advantages but also increased risks. For example, this study showed that both cloud and edge computing exhibit unsustainable patterns related to privacy and security (C9, C10, E5, E6, E8, E10, E12). Considering the consequent impact these patterns have on social sustainability, the efforts ongoing in these areas need to be continued and extended, so that not all efforts are concentrated on environmental sustainability.

Issues and countermeasures should always be tailored for cloud and/or edge. There are sometimes an apparent similarity between unsustainable patterns found in the cloud and in the edge studies. For example, C7 and E14 both mention the fact of overusing the service, *i.e.* consuming resources that are in fact not really needed. However, this does not mean that the issues are identical and/or that a similar countermeasure can be applied. This is due for example to the differences in the architectures, the cloud being heavily centralized while the edge is distributed. Therefore, specific efforts in researching and tackling the unsustainable patterns have to be conducted for both cloud and edge, in order to avoid missing issues that only appear in one paradigm and for designing efficient countermeasures.

The identified patterns lead to overshooting real-world limits. More than half of the unsustainable patterns we identified relate to direct or indirect environmental impact of cloud/edge. They make explicit how these paradigms might contribute to pollution and resource consumption beyond the ability of planet Earth to recover. Other patterns relate to human-rights limits by showing how pervasive technologies are a threat to our integrity (unauthorized surveillance (E5), privacy violation (C9)) or lead to the exclusion of parts of the population (digital exclusion (E9)). Finally, seemingly technical patterns like dependency (C1), lock-in (C2) or technical debt (E16) come as an addition to the others to highlight the underlying logic of "profit by all means", deep-rooted in a capitalist economic system. However infinite growth is not possible in a finite world.

Degrowth as a solution. We observe that a number of unsustainable patterns point toward the need for *degrowth*, which advocates a transformation of economies so that they produce and consume less, differently and better [29]. For the cloud, these patterns are data traffic growth promotion (C6), overconsumption (C7) and superfluous usages (C8). For the edge, the concerned patterns are hardware multiplication (E2), redundancy overhead (E11), efficiency trap (E13) and bloating (E14).

6.2 Threats to Validity

In this section we discuss some main threats to validity of our study, categorized according to Wholin *et al.* [62].

Internal Validity. As any qualitative research investigation, the subjective influence of researchers on the data collection, analysis, and synthesis may have influenced our results. In order to mitigate this threat, the focus groups are conducted and reviewed by at least two researchers; the data extraction is first split among all involved researchers and then scrutinized jointly by at least two researchers; and the analysis is conducted jointly by all researchers who adopt measures to minimize subjectivity, including crosschecking notes and applying iteratively the emerged Pattern Model for guidance.

Construct Validity. An inherent threat to construct validity of our study may be caused by the setup for the two focus groups being different (see Section 2). The cloud focus group was more exploratory: it lasted longer, had more participants (7) including the authors and was not video-recorded. The insights from its discussions also helped to define the Pattern Model. In comparison, the edge focus group was directly oriented towards collecting the unsustainable patterns, had a smaller number of active participants (3) and was video-recorded. We partially mitigate this threat by ensuring that the number of *external* participants was the same for both focus groups.

Another potential threat is the moderator's bias on data collection. To mitigate this threat, we determine the edge focus group's structure with all researchers' agreement prior to the session, make use of the same Pattern Model for guidance; and again, we had at least two authors present to make sure that moderation would overcome the subjectivity.

External Validity. External validity regards the generalization extent of the study. Given its exploratory nature and the relative limited number of participants, we cannot claim that the identified catalog of patterns can be generalized to the whole field, nor that they are exhaustive. Rather, we consider them as an initial list; more patterns can surely be found through further studies. In the same vein, the performed literature study is not to be taken as a comprehensive survey, but as an inspiration towards further investigations.

Conclusion Validity. Finally, given the exploratory and qualitative nature of our study, and as discussed by Lund [34], statistical conclusion validity is less relevant. A related threat, however, may regard the face validity of focus group [61], *i.e.,* its fit for purpose. To mitigate this threat and ensure that the context and questions were sufficiently clear to the participants, and no important aspect was missing, we first dry-run it with knowledgeable colleagues; and closed it with the open-ended question ("*Anything to add?*"), where participants could add clarifications to their answers, doubts, and remarks.

7 RELATED WORKS

To the best of our knowledge, there is no work similar to this one. We identify further related works regarding dark patterns, identification of similar concepts in other contexts, and sustainability for the cloud/edge.

As explained in Section 3.2, the concept of unsustainable patterns presented in this paper is inspired from Brignull's *dark patterns* in UX. In this field, some works are looking at ethical concerns behind the dark patterns expressed by practitioners [25], while others study actual software artifacts. For example, Mathur *et al.* [38] analyze around 11000 shopping websites, searching for such dark patterns, expose deceptive practices and propose recommendations on how to study, mitigate and minimize the use of such patterns. Similarly, Di Geronimo *et al.* [15] analyze dark patterns contained into popular mobile applications.

Our work is the first one identifying unsustainable patterns, *i.e.* sustainability shortcomings, in cloud and edge computing. However, it is interesting to note that some identified patterns have already been mentioned in the literature, when studying the cloud paradigm with a widely different angle. For example, dependency, lock-in, privacy and security concerns (related to patterns C1, C2, C9 and C10) have often been identified as "barriers to adoption" of cloud computing in companies [41, 56] when looking at it more from a business perspective and without a focus on sustainability.

Although not included in the majority of the cloud and edge computing papers, there is some work ongoing about sustainability and cloud/edge. Gill & Buyya [24] present in their survey a taxonomy of research about sustainability in cloud. This research is organized into nine categories ranging from application design to waste heat utilization. However, these nine categories only cover work dealing with environmental sustainability and not other dimensions of sustainability. Moreover, they only include technical leverages and do not take into account the bigger picture and in particular rebound effects. Similarly, research within edge computing mainly focuses on energy-efficiency aspects [33, 44]. Only few works mention security and privacy as important components for sustainability [43].

8 CONCLUSION

In this paper, we present an exploratory study of the cloud and edge paradigm with regards to sustainability. Inspired by dark patterns in UX, we introduce the concept of *unsustainable patterns* that we formalize into a Pattern Model. Then, we present and analyze a set of 27 unsustainable patterns resulting from the analysis of two focus groups. We also identify countermeasures and discuss takeaways in order to pave the way for further studies in this area. For different reasons, we think that more research is needed in cloud and edge. In the cloud case because it is more mature and research needs to be rethought of to include sustainability; the edge is more recent, which gives the opportunity to embrace sustainability early on.

We are aware that we raise more questions than provide answers. This is however one of the aims of this work, namely to get the key actors of these paradigms (*e.g.,* users, practitioners, researchers, governments, etc.) to reflect upon them and place sustainability back in the center of the discussions.

Interesting directions for future works include further studies on the identified unsustainable patterns, the identification of additional unsustainable patterns, as well as the definition of sustainable patterns and ways to transform unsustainable patterns into sustainable ones. Moreover, we plan to create a digital version of the pattern catalog for others to use and expand it.

ACKNOWLEDGMENTS

Klervie Toczé is supported by the Swedish national graduate school in computer science (CUGS). The authors would like to thank the participants to the two focus groups: Jorge Larraco, Flavia Paganelli, and Julia Trzcińska for the cloud one and Ivona Brandić, Panos Patros, and Guillaume Pierre for the edge one. The authors would also like to thank the reviewers for their insightful comments.

REFERENCES

[1] Michael Adelmeyer, Marc Walterbusch, Peter Biermanski, Kai Seifert, and Frank Teuteberg. 2017. Rebound Effects in Cloud Computing: Towards a Conceptual Framework. (2017), 15.

[2] Christopher Alexander. 1977. *A pattern language: towns, buildings, construction.* Oxford university press.

[3] Abdulmalik Alwarafy, Khaled A. Al-Thelaya, Mohamed Abdallah, Jens Schneider, and Mounir Hamdi. 2021. A Survey on Security and Privacy Issues in Edge-Computing-Assisted Internet of Things. *IEEE Internet of Things Journal* 8, 6 (2021), 4004–4022. https://doi.org/10.1109/JIOT.2020.3015432

[4] Len Bass, Paul Clements, and Rick Kazman. 2021. *Software Architecture in Practice* (4th ed.). Addison-Wesley Professional.

[5] Ketan Bhardwaj, Ada Gavrilovska, Vlad Kolesnikov, Matt Saunders, Hobin Yoon, Mugdha Bondre, Meghana Babu, and Jacob Walsh. 2019. Addressing the Fragmentation Problem in Distributed and Decentralized Edge Computing: A Vision. In *2019 IEEE International Conference on Cloud Engineering (IC2E)*. 156–167. https://doi.org/10.1109/IC2E.2019.00030

[6] Anthony Bisong and Syed Rahman. 2011. An Overview Of The Security Concerns In Enterprise Cloud Computing. *International Journal of Network Security & Its Applications* 3 (2011). https://doi.org/10.5121/ijnsa.2011.3103

[7] Harry Brignull. [n.d.]. *Dark Patterns*. Retrieved Nov 23, 2021 from https://www.darkpatterns.org/

[8] Harry Brignull. 2010. *Dark Patterns: dirty tricks designers use to make people do stuff*. Retrieved Nov 23, 2021 from https://90percentofeverything.com/2010/07/08/dark-patterns-dirty-tricks-designers-use-to-make-people-do-stuff/

[9] Paul Castro, Vatche Ishakian, Vinod Muthusamy, and Aleksander Slominski. 2019. The Rise of Serverless Computing. *Commun. ACM* 62, 12 (2019), 44–54. https://doi.org/10.1145/3368454

[10] I Chih-Lin, Shuangfeng Han, and Sen Bian. 2020. Energy-efficient 5G for a greener future. *Nature Electronics* 3, 4 (2020), 182–184.

[11] Cisco. 2016. *VNI Complete Forecast Highlights*. Technical Report. 6 pages.

[12] Luigi Coppolino, Salvatore D'Antonio, Giovanni Mazzeo, and Luigi Romano. 2017. Cloud security: Emerging threats and current solutions. *Computers & Electrical Engineering* 59 (2017), 126–140. https://doi.org/10.1016/j.compeleceng.2016.03.004

[13] Randall S Davies. 2011. Understanding technology literacy: A framework for evaluating educational technology integration. *TechTrends* 55, 5 (2011), 45–52.

[14] Magali A. Delmas and Vanessa Cuerel Burbano. 2011. The Drivers of Greenwashing. *California Management Review* 54, 1 (2011), 64–87. https://doi.org/10.1525/cmr.2011.54.1.64

[15] Linda Di Geronimo, Larissa Braz, Enrico Fregnan, Fabio Palomba, and Alberto Bacchelli. 2020. UI Dark Patterns and Where to Find Them: A Study on Mobile Applications and User Perception. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA). 1–14.

[16] Amab Dutta, Guo Chao Alex Peng, and Alok Choudhary. 2013. Risks in Enterprise Cloud Computing: The Perspective of it Experts. *Journal of Computer Information Systems* 53, 4 (2013), 39–48.

[17] Anastasija Efremovska and Patricia Lago. 2017. From Legacy to Cloud: Risks and Benefits in Software Cloud Migration. In *Software Architecture for Big Data and the Cloud*. 147–165.

[18] John Elkington. 2004. Enter the Triple Bottom Line. In *The Triple Bottom Line*. Routledge.

[19] Ericsson. 2020. *Breaking the Energy Curve*. https://www.ericsson.com/495d5c/assets/local/about-ericsson/sustainability-and-corporate-responsibility/documents/2020/breaking-the-energy-curve-report.pdf

[20] Fabrice Flipo. 2021. L'impératif de la sobriété numérique. *Cahiers Droit, Sciences & Technologies* 13 (2021), 29–47. https://doi.org/10.4000/cdst.4182

[21] Charlotte Freitag, Mike Berners-Lee, Kelly Widdicks, Bran Knowles, Gordon S. Blair, and Adrian Friday. 2021. The Real Climate and Transformative Impact of ICT: A Critique of Estimates, Trends, and Regulations. *Patterns* 2, 9 (2021). https://doi.org/10.1016/j.patter.2021.100340

[22] Erich Gamma, Richard Helm, Ralph Johnson, and John Vlissides. 1995. *Design Patterns. Elements of Reusable Object-Oriented Software*. Addison-Wesley Publishing Company.

[23] GeSI. 2015. *SMARTer2030. ICT Solutions for 21st Century Challenges*. Technical Report.

[24] Sukhpal Singh Gill and Rajkumar Buyya. 2018. A Taxonomy and Future Directions for Sustainable Cloud Computing: 360 Degree View. *Comput. Surveys* 51, 5 (2018), 104:1–104:33. https://doi.org/10.1145/3241038

[25] Colin M. Gray, Yubo Kou, Bryan Battles, Joseph Hoggatt, and Austin L. Toombs. 2018. The Dark (Patterns) Side of UX Design. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. 1–14.

[26] Eoin Martino Grua, Martina De Sanctis, Ivano Malavolta, Mark Hoogendoorn, and Patricia Lago. 2021. Social Sustainability in the e-Health Domain via Personalized and Self-Adaptive Mobile Apps. In *Software Sustainability*. 301–328.

[27] Qing Gu, Patricia Lago, Henry Muccini, and Simone Potenza. 2013. A Categorization of Green Practices used by Dutch Data Centers. *Procedia computer science* 19 (2013), 770–776.

[28] Congfeng Jiang, Tiantian Fan, Honghao Gao, Weisong Shi, Liangkai Liu, Christophe Cérin, and Jian Wan. 2020. Energy aware edge computing: A survey. *Computer communications* 151 (2020), 556–580.

[29] Giorgos Kallis. 2018. *Degrowth*. Agenda Publishing. 313 pages.

[30] Steffen Lange and Tilman Santarius. 2020. *Smart Green World?: Making Digitalization Work for Sustainability*.

[31] Rabia Latif, Malik Uzair Ahmed, Shahzaib Tahir, Seemab Latif, Waseem Iqbal, and Awais Ahmad. 2021. A Novel Trust Management Model for Edge Computing. *Complex & Intelligent Systems* (2021). https://doi.org/10.1007/s40747-021-00518-3

[32] Valentina Lenarduzzi, Jeremy Daly, Antonio Martini, Sebastiano Panichella, and Damian Andrew Tamburri. 2021. Toward a Technical Debt Conceptualization for Serverless Computing. *IEEE Software* 38, 1 (2021), 40–47. https://doi.org/10.1109/MS.2020.3030786

[33] Wei Li, Ting Yang, Flavia C. Delicato, Paulo F. Pires, Zahir Tari, Samee U. Khan, and Albert Y. Zomaya. 2018. On Enabling Sustainable Edge Computing with Renewable Energy Resources. *IEEE Communications Magazine* 56, 5 (2018), 94–101. https://doi.org/10.1109/MCOM.2018.1700888

[34] Thorleif Lund. 2005. The Qualitative–Quantitative Distinction: Some comments. *Scandinavian Journal of Educational Research* 49, 2 (April 2005), 115–132.

[35] John Lynham, Kohei Nitta, Tatsuyoshi Saijo, and Nori Tarui. 2016. Why Does Real-Time Information Reduce Energy Consumption? *Energy Economics* 54 (2016), 173–181. https://doi.org/10.1016/j.eneco.2015.11.007

[36] Xinyu Ma and Xiaoyong Li. 2018. Trust Evaluation Model in Edge Computing Based on Integrated Trust. In *Proceedings of the 2018 International Conference on Algorithms, Computing and Artificial Intelligence*. 1–6. https://doi.org/10.1145/3302425.3302491

[37] Ann Majchrzak, M. Lynne Markus, and Jonathan Wareham. 2016. Designing for Digital Transformation: Lessons for Information Systems Research from the Study of ICT and Societal Challenges. *MIS Quarterly* 40, 2 (2016), 267–277. https://doi.org/10.25300/MISQ/2016/40:2.03

[38] Arunesh Mathur, Gunes Acar, Michael J. Friedman, Elena Lucherini, Jonathan Mayer, Marshini Chetty, and Arvind Narayanan. 2019. Dark Patterns at Scale: Findings from a Crawl of 11K Shopping Websites. *Proc. ACM Hum.-Comput. Interact.* 3, 11, Article 81 (2019), 32 pages.

[39] Wen Mo, Tian Wang, Shaobo Zhang, and Jinhuan Zhang. 2020. An Active and Verifiable Trust Evaluation Approach for Edge Computing. *Journal of Cloud Computing* 9, 1 (2020). https://doi.org/10.1186/s13677-020-00202-w

[40] Deeraj Nagothu, Ronghua Xu, Seyed Yahya Nikouei, and Yu Chen. 2020. Smart Surveillance for Public Safety Enabled by Edge Computing. In *Edge Computing: Models, technologies and applications*. 1–24.

[41] Justice Opara-Martins, Reza Sahandi, and Feng Tian. 2016. Critical analysis of vendor lock-in and its impact on cloud computing migration: a business perspective. *Journal of Cloud Computing* 5, 1 (2016), 4. https://doi.org/10.1186/s13677-016-0054-z

[42] Siani Pearson. 2009. Taking account of privacy when designing cloud computing services. In *ICSE Workshop on Software Engineering Challenges of Cloud Computing*. ACM/IEEE, 44–52.

[43] Charith Perera, Yongrui Qin, Julio C. Estrella, Stephan Reiff-Marganiec, and Athanasios V. Vasilakos. 2017. Fog Computing for Sustainable Smart Cities: A Survey. *Comput. Surveys* 50, 3, Article 32 (2017), 43 pages. https://doi.org/10.1145/3057266

[44] Giovanni Perin, Michele Berno, Tomaso Erseghe, and Michele Rossi. 2021. Towards Sustainable Edge Computing through Renewable Energy Resources and Online, Distributed and Predictive Scheduling. *IEEE Transactions on Network and Service Management* (2021). https://doi.org/10.1109/TNSM.2021.3112796

[45] Mark Pesce. 2021. *Cloud Computing's Dark Cloud*. https://spectrum.ieee.org/cloud-computings-coming-energy-crisis

[46] Thibault Pirson and David Bol. 2021. Assessing the embodied carbon footprint of IoT edge devices with a bottom-up life-cycle approach. *Journal of Cleaner Production* 322 (2021). https://doi.org/10.1016/j.jclepro.2021.128966

[47] G Procaccianti, P Lago, and G A Lewis. 2014. A Catalogue of Green Architectural Tactics for the Cloud. In *International Symposium on the Maintenance and Evolution of Service-Oriented and Cloud-Based Systems*. IEEE, 29–36.

[48] Johan Rockström, Will Steffen, Kevin Noone, Åsa Persson, F. Stuart Chapin, Eric Lambin, Timothy M. Lenton, Marten Scheffer, Carl Folke, Hans Joachim Schellnhuber, Björn Nykvist, Cynthia A. de Wit, Terry Hughes, Sander van der Leeuw, Henning Rodhe, Sverker Sörlin, Peter K. Snyder, Robert Costanza, Uno Svedin, Malin Falkenmark, Louise Karlberg, Robert W. Corell, Victoria J. Fabry, James Hansen, Brian Walker, Diana Liverman, Katherine Richardson, Paul Crutzen, and Jonathan Foley. 2009. Planetary Boundaries: Exploring the Safe Operating Space for Humanity. *Ecology and Society* 14, 2 (2009).

[49] Thoran Rodrigues. 2012. *The five big myths of cloud computing*. https://www.techrepublic.com/blog/the-enterprise-cloud/the-five-big-myths-of-cloud-computing/

[50] Mahadev Satyanarayanan. 2017. The Emergence of Edge Computing. *Computer* 50, 1 (2017), 30–39. https://doi.org/10.1109/MC.2017.9

[51] Stephan Schneider and Ali Sunyaev. 2015. CloudLive: a life cycle framework for cloud services. *Electronic Markets* 25, 4 (2015), 299–311.

[52] Shadab Siddiqui, Manuj Darbari, and Diwakar Yagyasen. 2019. A Comprehensive Study of Challenges and Issues in Cloud Computing. In *Soft Computing and Signal Processing (Advances in Intelligent Systems and Computing)*. 325–344. https://doi.org/10.1007/978-981-13-3600-3_31

[53] Gabriel Costa Silva, Louis M. Rose, and Radu Calinescu. 2013. A Systematic Review of Cloud Lock-in Solutions. In *Fifth International Conference on Cloud Computing Technology and Science (cloudcom), Vol 2* (New York). IEEE, 363–368.

[54] Sergej Svorobej, Patricia Takako Endo, Malika Bendechache, Christos Filelis-Papadopoulos, Konstantinos M Giannoutakis, George A Gravvanis, Dimitrios Tzovaras, James Byrne, and Theo Lynn. 2019. Simulating Fog and Edge Computing Scenarios: An Overview and Research Challenges. *Future Internet* 11, 3

(2019).
[55] Klervie Toczé, Maël Madon, Muriel Garcia, and Patricia Lago. 2022. The Dark Side of Cloud and Edge Computing: Replication package. https://doi.org/10.5281/zenodo.6390610
[56] Sara Trigueros-Preciado, Daniel Pérez-González, and Pedro Solana-González. 2013. Cloud Computing in Industrial SMEs: Identification of the Barriers to Its Adoption and Effects of Its Application. *Electronic Markets* 23, 2 (2013), 105–114. https://doi.org/10.1007/s12525-012-0120-4
[57] Kazutoshi Tsuda, Michinori Uwasu, Keishiro Hara, and Yukari Fuchigami. 2016. Approaches to Induce Behavioral Changes with Respect to Electricity Consumption. *Journal of Environmental Studies and Sciences* 7 (2016). https://doi.org/10.1007/s13412-016-0396-3
[58] United Nations. [n.d.]. THE 17 GOALS | Sustainable Development. https://sdgs.un.org/goals.
[59] R. Verdecchia, P. Lago, and C. de Vries. 2021. *The LEAP Technology Roadmap: Lower Energy Acceleration Program (LEAP) Solutions, Adoption Factors, Impediments, Open Problems, and Scenarios.* Technical Report. Vrije Universiteit Amsterdam.
[60] Hans Jakob Walnum and Anders S.G. Andrae. 2016. The Internet: Explaining ICT Service Demand in Light of Cloud Computing Technologies. In *Rethinking Climate and Energy Policies: New Perspectives on the Rebound Phenomenon.* 227–241. https://doi.org/10.1007/978-3-319-38807-6_13
[61] Irving B Weiner and W Edward Craighead. 2010. *The Corsini Encyclopedia of Psychology, Volume 4.* Vol. 2. John Wiley & Sons, 637–638.
[62] Claes Wohlin, Per Runeson, Martin Höst, Magnus C Ohlsson, Björn Regnell, and Anders Wesslén. 2012. *Experimentation in software engineering.* Springer Science & Business Media.