Usage Control Specification, Enforcement, and Robustness: 
A Survey

INES AKAICHI and SABRINA KIRRANE, Institute for Information Systems & New Media, Vienna University of Economics and Business, Austria

The management of data and digital assets poses various challenges, including the need to adhere to legal requirements with respect to personal data protection and copyright. Usage control technologies could be used by software platform providers to manage data and digital assets responsibly and to provide more control to data and digital asset owners. In order to better understand the potential of various usage control proposals, we collate and categorize usage control requirements, compare the predominant usage control frameworks based on said requirements, and identify existing challenges and opportunities that could be used to guide future research directions.

CCS Concepts: • Security and privacy → Information accountability and usage control; • Social and professional topics → Computing / technology policy; Intellectual property; Privacy policies.

Additional Key Words and Phrases: Usage Control, Policy Languages, Enforcement Frameworks, Robustness

1 Introduction

Modern decentralized systems, such as the Internet of Things (IoT) and virtual data spaces, face a variety of challenges from a data and digital asset management perspective. According to Zrenner et al. [113], data owners are reluctant to share their data with decentralized systems, as often they have no control over how their data are used. Since the General Data Protection Regulation (GDPR) [18] entered into force, in 2018, the need to provide more control and transparency to data subjects with respect to how personal data are collected, stored, and processed is mandated in Europe, and also outside of the European Union if the data relates to European citizens. More broadly, the importance of digital asset management is underlined by the new copyright legislation [19], which came into effect in 2021, with the aim to protect creativity in the digital age.

When it comes to digital asset management, Pretschner [88] and Park and Sandhu [86] highlight that the sharing of data in decentralized environments goes beyond traditional access control, as existing solutions do not provide control over data usage once access to the data has been granted. Technologies that aim to address this challenge, which are usually classified as usage control [89], aim to ensure that data consumers handle data according to usage rules stipulated by data owners. More broadly, usage control is an umbrella term for data management software that caters for data protection, copyright, and/or various legislative and institutional policies [88].

The term usage control was first introduced by Park and Sandhu [86] whose research focuses on supporting the continuous monitoring of digital asset usage in dynamic distributed environments. Over the years, researchers have proposed various usage control conceptual models (cf., [13, 78, 86]) and policy languages (cf., [17, 37, 53]). Other works focus on enforcing the respective policies, via proactive mechanisms that aim to prevent policy violations (cf., [44, 56, 64]) and reactive mechanisms that detect security breaches and policy violations (cf., [7, 27, 92]). Additionally, there are a handful of surveys that aim to better understand the state of the art with respect to usage control. For instance, Pretschner et al. [90] survey existing usage control mechanisms with a specific focus on digital rights management (DRM) technologies. Another survey conducted by Lazouski

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Authors’ address: Ines Akaichi, ines.akaichi@wu.ac.at; Sabrina Kirrane, sabrina.kirrane@wu.ac.at, Institute for Information Systems & New Media, Vienna University of Economics and Business, Vienna, Austria.
et al. [63] focuses specifically on the usage control (UCON) model proposed by Park and Sandhu [86], with the authors reviewing the various implementations and extensions. In turn, Nyre [81] analyzes the strengths and weaknesses of existing usage control solutions, with a particular focus on enforcement mechanisms.

Considering the potential of usage control as a tool for ensuring compliance with respect to data protection, copyright, as well as institutional policies, there is need for a more holistic overview of existing works and their support for a broad set of usage control requirements. Towards this end, in this paper, we perform a comprehensive analysis of existing usage control frameworks based on a variety of usage control requirements gleaned from the literature. Our primary contributions are summarized as follows: (i) we present and align various usage control concept definitions found in the literature; (ii) we propose a comprehensive taxonomy of usage control requirements that are commonly used to guide the development of usage control solutions; (iii) we conduct a qualitative comparison of the predominant usage control proposals found in the literature based on the aforementioned taxonomy; and (iv) we draw on the comparison in order to outline various challenges and opportunities for the usage control domain in general and decentralized systems in particular.

The remainder of this paper is structured as follows: In Section 2, we present our motivating use case scenario and introduce several important usage control concepts. In Section 3, we discuss the methodology underpinning our literature review and requirements taxonomy generation process. In Section 4, we describe the proposed taxonomy of usage control requirements. In Section 5, we compare and contrast the predominant usage control frameworks found in the literature. In Section 6, we discuss open challenges and opportunities for the usage control domain. Finally, we conclude by summarizing the paper in Section 7.

2 Motivational Scenario

We start by describing a practical usage control scenario that can be used to guide our analysis. Following on from this, we provide the necessary background in terms of usage control concept definitions.

2.1 Use Case

Our usage control scenario is inspired from the internet of things (IoT) domain. Figure 1 illustrates a smart city scenario, where residents make use of multiple smart objects, such as smart homes, cars, parking lots, watches, etc. Smart objects contribute, among other things, to simplifying every day activities. These objects produce different types of data that are captured by sensors or actuators. In such a scenario, data can relate to the smart objects, such as power consumption, battery status, etc., or the users themselves, such as Global Positioning System (GPS) location or any other type of private information that relates specifically to the user. Different stakeholders, such as institutions that manage the supply of water or energy, are interested in the data produced by these smart objects in order to derive insights on consumption that can be used to optimize their service offerings. Such information could also be used by marketing companies in order to devise new or adjust existing marketing strategies. Thus, the manufacturers of these objects may host or use data sharing platforms whereby data resulting from the use of smart objects are shared with both their customers and various third parties. Such platforms could offer the following sharing possibilities to subscribers: (i) an option to download data relating to smart objects or their users; (ii) the ability to access ad-hoc analysis and statistics about specific smart objects; and (iii) the possibility to perform on-the-fly analysis based on statistical or machine learning models. The decentralized nature of this data sharing scenario and the nature of the data imply usage concerns that involve personal
data (e.g., control the usage of location information) and regulations (e.g., delete all personal data after a certain time, as mandated by the GDPR), among others.

2.2 Usage Control: What and How?

The goal of this section is to establish a common understanding in terms of the various concepts that are collectively used to specify usage control policies (what?) and to describe how usage control policies can be enforced (how?).

2.2.1 What? Pretschner et al. [89] refer to an entity that provides a resource (e.g., data) together with a policy that describes its access and usage restrictions as a data provider. Whereas, an entity that receives a copy of a resource and the respective policy is called a data consumer. Park and Sandhu [86] refer to both the data consumer and the data provider as subjects. The resources that are governed by the policy are referred to as data by Pretschner et al. [89] and objects by Park and Sandhu [86]. Usage control policies express restrictions in the form of rules that govern the use of resources, in particular the actions or operations on the data that can be performed by data consumers (e.g., accessing, processing, downloading). Park and Sandhu [86] refer to such actions as rights.

Furthermore, Bettini et al. [8] and Pretschner et al. [89] define usage control rules in terms of two basic classes: provisions and obligations. Provisions refer to specific activities that need to be performed before an access decision is taken (i.e., before access to data is provided), while obligations refer to activities that need to be performed in the future (i.e., after access to data has been granted). The problem with this definition is that it does not capture the generality of usage rules in terms of what should or should not (i.e., positive and negative obligations) and what can or can not (i.e., permissions and prohibitions) be done with the data [16]. This definition focuses only on the specific activities that must be performed by users before and after access to the data is provided. Park and Sandhu [86], in turn, define usage control policies in terms of decision factors that determine the final decision made by a system, also known as the usage decision. Decision factors denote: authorizations, obligations, and conditions. Authorizations refer to constraints on subject or object attributes that are used to enforce usage decisions. Attributes denote the properties or the capabilities of subjects or objects. For instance, based on our use case scenario, we could specify an attribute called role that could take the following values: admin for platform operators, owner for smart device owners, and external for third parties. Additionally, we could define a subscription attribute that indicates whether a stakeholder has a subscription to a data sharing platform or not. Another important aspect with respect to attributes is the level
of sensitivity attached to the data, which may be different depending on the type of data, e.g., energy consumption, location, medical, etc. An example of such a rule could be that full access to personal data that is classified as sensitive should only be given to the data subject themselves. While, obligations refer to activities that an entity must carry out in order to be permitted to perform particular actions. For example, in our motivating scenario, we assume that a stakeholder, namely, the marketing company, is interested in performing data analysis with respect to electricity consumption, however if the marketing company wishes to download user data (with the users consent) the company must delete the data within 10 days. Conditions, in turn, refer to environmental or system requirements that have to be satisfied in order to perform certain actions on data objects. For example, a condition can refer to the purpose for which the data may be used, for instance the marketing company may only use data for scientific purposes. Conditions are also used to refer to contextual information, such as the time and location of environmental conditions.

Moreover, Park and Sandhu [86] present an important aspect of usage control, which is the continuity of enforcement. This feature implies that usage decisions are enforced not only when data providers or data consumers generate access requests, but also during the ongoing usage of the data. Continuity of enforcement also implies that a usage control system must continuously evaluate conditions and obligations. This means, that the conditions have to be satisfied before (i.e., pre-condition) or during (i.e., ongoing-condition) a usage process. In addition, the usage control system must ensure the fulfillment of obligations before (i.e., pre-obligation), during (i.e., ongoing-obligation), and after (i.e., post-obligation) data are accessed. Once the conditions no longer hold or the obligations are not met by data consumers, the system can deny or revoke access to the data. In this paper, we define usage control policies in terms of deontic concepts, both due to their generality [82] but also because they provide support for what should or should not as well as what can or cannot be done with data [8, 82]. This definition is close to the definition of Park and Sandhu [86], but includes more specific decision factors (i.e., permissions, prohibitions, obligations, and dispensations) that are needed in order to represent legislative requirements. Bearing these different definitions in mind, usage control policies can be defined in terms of the continuity of enforcement and the following decisions factors: permissions, prohibitions, obligations, dispensations, conditions, each of which support a variety of attributes. Given that obligations, conditions, and attributes have already been defined by Park and Sandhu [86], we build upon the definitions and examples presented above by providing definitions and examples for the remaining concepts. Permissions represent positive authorizations that allow entities to perform actions. For instance, the marketing company is permitted to download data about the energy consumption of a specific neighborhood. Prohibitions refer to negative authorizations, implying that an entity is not allowed to perform the specified actions. For example, the marketing company is prohibited from downloading personal information. Dispensations refer to actions that an entity is no longer required to perform, thus, they act as waivers for existing obligations. For example, a user is exempt from deleting their data after usage because they are the owner.

Figure 2 depicts a usage control model that encapsulates the various decision factors that are necessary in order to create a usage control policy based on the given definition. In the proposed model, a policy is made up of a set of rules that encode permissions, prohibitions, obligations, or dispensations. Each rule is associated with an action that is performed by a subject on a target object. A rule can also be constrained by one or more conditions. The various entities in the model can have specific attributes (e.g. policy attributes and condition attributes). In addition, the model supports nested rules that can express nested requirements, which are needed to encode regulatory requirements, such as those set forth by the GDPR. The modeling of the nested rules is inspired by the open digital rights language (ODRL) regulatory profile proposed by Vos et al. [104].
Figure 3 shows an instantiation of the model using a permission, a prohibition, and an obligation with a nested dispensation that are inspired by our motivating use case scenario.

2.2.2 How? According to Pretschner et al. [90], usage control policies immediately raise the question of enforcement. Indeed, policies depend on the actual implementation and deployment of a usage control solution, which is limited to the ability of the solution to continuously validate and enforce the usage control decisions [86, 89]. In this paper, we refer to a usage control framework, as a complete framework that allows for the specification, the enforcement, and the administration of usage policies. According to Zhang et al. [112], a usage control framework addresses both the “how” and “what” aspects of policy enforcement. Generally speaking, usage control frameworks are comprised of the following components: (i) a formal machine-readable policy language that is used to express usage control policies; (ii) an enforcement mechanism that can monitor compliance with said policies; and (iii) an administration interface that can be used to manage and monitor usage control policies. Although there are several frameworks in the literature, a detailed analysis is needed in order to better understand how well the various usage control proposals support various usage case requirements, which is the aim of this paper.

3 Methodology

Our survey was guided by the integrative literature review methodology proposed by Torraco [102]. While, the requirements taxonomy generation process followed the development methodology suggested by Nickerson et al. [80]. Finally, the requirements taxonomy was used to perform a targeted analysis of the predominant usage control frameworks found in the literature.

3.1 Literature Identification

The literature review involved the identification of concrete research questions (RQs) and the corresponding review strategy [102]. Considering that our overarching goal was to assess the status quo in terms of usage control solutions found in the literature, and to identify open challenges and opportunities, our research was guided by the following research questions: RQ1. What requirements are used to guide the development of usage control solutions?
RQ2. Which specific requirements are supported by the predominant usage control frameworks found in the literature?

RQ3. What are the open challenges and opportunities for the usage control domain?

The papers subject to the review were found using the Google Scholar search interface using keywords consisting of a combination of "usage control", "requirements", and "framework" and the following inclusion and exclusion criteria: (i) include papers that mention usage control requirements; (ii) include papers that propose usage control frameworks and/or extensions; and (iii) exclude papers that focus on non-implemented frameworks.

First, we collected all papers that were returned using our Google Scholar keyword search. Following on from this, the title, abstract, introduction, and conclusion of all articles that matched our keyword search were examined for relevancy based on our inclusion and exclusion criteria. Then, a full read through of the remaining articles was performed in order to identify and extract usage control requirements (RQ1) and to compare and contrast existing frameworks (RQ2) as well as derive open challenges and opportunities (RQ3). For every paper, an iterative backward (i.e., searching the citations of the identified articles) and forward (i.e., locating the papers that cite the identified articles) search was performed in order to improve the coverage of related work.

3.2 Taxonomy Generation

The method for taxonomy development proposed by Nickerson et al. [80] was subsequently used to build a usage control requirements taxonomy. We started by determining the meta-characteristic of our taxonomy (essentially the goal behind its development). In our case, the desire to identify requirements that are used to guide the development of usage control solutions. Following on from this, we identified the condition that would be used to end the taxonomy construction process. In our case, when no new requirements are introduced.

The iterative taxonomy generation method identifies common characteristics that are logical consequences of a meta-characteristic. In our case, the (usage control) specification requirement encapsulates other fine-grained requirements related to usage control specification, such as the expressiveness of the usage control policy language. Consequently, individual requirements were
Table 1. Usage Control Requirements and Sources

| Authors                     | Specification | Enforcement | Robustness |
|-----------------------------|---------------|-------------|------------|
|                            | Expressiveness| Flexibility & Extensibility | Usability |
|                            | Formalization | Preventive | Detective | Continuity of Enforcement | Conflict Detection & Resolution | Administration | Interoperability & Compatibility | Performance & Scalability | Usability | Reliability |
| Katt et al. [49]            | X             |             |           |               |                        |                  |                           |                           |         |            |
| Hilty et al. [38]           | X             |             |           |               |                        |                  |                           |                           |         |            |
| Kumari [55]                 |               |             |           |               |                        |                  |                           |                           |         |            |
| Pretschner et al. [90]      |               |             |           |               |                        |                  |                           |                           |         |            |
| Pretschner et al. [89]      |               |             |           |               |                        |                  |                           |                           |         |            |
| Branco-Amaral et al. [77]   |               |             |           |               |                        |                  |                           |                           |         |            |
| Clemente et al. [40]        |               |             |           |               |                        |                  |                           |                           |         |            |
| Hoys and Cheng [76]         |               |             |           |               |                        |                  |                           |                           |         |            |
| Moreau [77]                 |               |             |           |               |                        |                  |                           |                           |         |            |
| Sung et al. [47]            |               |             |           |               |                        |                  |                           |                           |         |            |
| Foth and Pretschner [39]    |               |             |           |               |                        |                  |                           |                           |         |            |
| Cai et al. [39]             |               |             |           |               |                        |                  |                           |                           |         |            |
| Schäfer and Brest [98]      |               |             |           |               |                        |                  |                           |                           |         |            |
| Teixeira et al. [100]       |               |             |           |               |                        |                  |                           |                           |         |            |
| Cui et al. [51]             |               |             |           |               |                        |                  |                           |                           |         |            |
| Back et al. [100]           |               |             |           |               |                        |                  |                           |                           |         |            |
| Roth and Colin [95]         |               |             |           |               |                        |                  |                           |                           |         |            |
| Zomer et al. [113]          |               |             |           |               |                        |                  |                           |                           |         |            |
| Cel et al. [11]             |               |             |           |               |                        |                  |                           |                           |         |            |
| Karamysh and Surdich [101]  |               |             |           |               |                        |                  |                           |                           |         |            |
| Kall et al. [60]            |               |             |           |               |                        |                  |                           |                           |         |            |
| Ilahi et al. [60]           |               |             |           |               |                        |                  |                           |                           |         |            |
| Kaneni et al. [11]          |               |             |           |               |                        |                  |                           |                           |         |            |
| Khaled and Alshehri [101]   |               |             |           |               |                        |                  |                           |                           |         |            |
| Sha [86]                    |               |             |           |               |                        |                  |                           |                           |         |            |
| Lammers et al. [61]         |               |             |           |               |                        |                  |                           |                           |         |            |
| Park and Sandhu [66]        |               |             |           |               |                        |                  |                           |                           |         |            |
| Kegal et al. [66]           |               |             |           |               |                        |                  |                           |                           |         |            |

grouped according to more general requirements, for example, placing expressiveness under specification. The taxonomy building process ended once the final condition was triggered, i.e., when no further requirements were introduced.

3.3 Comparison and Synthesis

The resulting taxonomy was subsequently used to compare the various usage control frameworks that have been proposed to date. The analysis, which was initially performed using Excel spreadsheets, was later synthesized using high level comparative tables and supporting textual descriptions. Finally, building upon the insights gained from our detailed analysis, we derived opportunities and challenges for the usage control domain in general and decentralized systems in particular.

4 A Taxonomy of Usage Control Requirements

In the following, we describe our taxonomy of usage control requirements. Table 1 displays a matrix of requirements and the corresponding sources from which they are taken. The respective requirements are illustrated in Figure 4, which depicts our final taxonomy. The taxonomy is divided into three high level usage control dimensions: (i) the policy language; (ii) the enforcement mechanism; and (iii) the robustness of the overall solution.

4.1 Specification

The specification dimension includes four sub-dimensions that represent requirements relating to policy specification and policy representation.
4.1.1 Expressiveness [5, 13, 15, 28, 38, 45, 49, 55, 67, 73, 89, 90, 101, 112]. According to Pretschner et al. [89], policy based usage control systems rely on the ability of the policy language to formally express usage control policies by translating high-level policies defined by data providers into machine-readable usage policies. Mont [73] argue that the language used to encode usage control policies must be expressive enough such that requests for access to objects can be permitted or prohibited. According to Zhang et al. [112], various usage control decision components (i.e., obligations, attributes, and conditions) must be encoded using an appropriate language. Moreover, Colombo et al. [17] introduced a mutability decision property, which they argue is an important usage control requirement, as attributes often need to be changed as a side effect of the subject’s use of an object. Cao et al. [13], Kumari [55], Pretschner et al. [90], and Zhang et al. [112] describe different types of conditions, which relate to time, cardinality, purpose of use, and technical or governance constraints, which may need to be included in usage control policies, in order to accommodate different application contexts (e.g., privacy, copyright protection, regulations) and different fields (e.g., IoT and information and communications technology (ICT)). Moreover, several studies [5, 28, 38, 45, 67] highlight the need for policies that can specify rules with respect to contextual information, such as GPS information in the context of mobile and ubiquitous applications.

4.1.2 Flexibility & Extensibility [16, 75, 101]. Usage control can be applied in different application contexts (e.g., digital rights management (DRM) and data privacy) or different fields (e.g., ICT and IoT). This, as highlighted by Munoz-Arcentales et al. [75], gives rise to the need for flexible usage control solutions that can be adapted to cater for various use case scenarios. Besides, Clemente et al. [16] and Teigão et al. [101] highlight the need for an extensible usage control solution that allows for new types of policies to be supported at a later point in time.
4.1.3 **Unambiguous** [16, 73, 76, 101]. In order to automatically enforce usage control policies, said policies need to be translated from high-level goals to formal rules, such that they can be deployed and enforced by the usage control system. This is only possible if the usage control policy language is able to unambiguously specify the meaning of such policies via a well-defined syntax and semantics [16, 73]. According to Myers and Chong [76] and Teigão et al. [101], expressive, formal, and well-defined information policies can ensure the correct enforcement of high level goals.

4.1.4 **Formal Semantics** [13, 28, 44, 96]. Formal semantics refers to approaches that are used to specify the precise meaning for the various concepts and rules encoded in usage control policies. According to Lazouski et al. [63] and Schütte and Brost [96], the formalization of usage control policies helps to facilitate system governance by verifying compliance against higher level goals. Moreover, Feth and Pretschner [28], Jung et al. [44] and Cao et al. [13] state that formal policies can help with automated analysis (i.e., automatizing the decision of the system and checking for policy conflicts).

4.2 Enforcement

Enforcement refers to the mechanisms used to enforce and manage usage policies throughout the usage process, which consists of three phases: before usage, ongoing usage, and after usage [15]. According to Pretschner et al. [89], in order for usage control policies to work as intended, the policy enforcement must be applied continuously.

4.2.1 **Preventive** [9, 56, 86, 90]. According to Bexheti and Langheinrich [9], Kumari et al. [56], Pretschner et al. [90], and Park and Sandhu [86], the dynamic and proactive enforcement of data usage policies implies the ability of the usage control solution, in particular, the preventive mechanism to at least: (i) allow or prohibit requests for data usage; (ii) revoke access in the event of policy violations; (iii) delay an attempted usage request until the corresponding obligations are fulfilled; (iv) update user or object attributes as a result of usage decisions; and (v) execute actions such as sending notifications to data owners.

4.2.2 **Detective** [89]. According to Pretschner et al. [89], detective mechanisms are very important, particularly if the usage control framework is not able to dynamically enforce the policy restrictions or prevent policy violations from happening. For instance, it is difficult to see if data are actually deleted, but there may be technical means to show that the respective command has been executed by using different detective mechanisms, such as auditing, logging, or simply notifying a user when the command is executed.

4.2.3 **Continuity of Enforcement** [63, 86, 89]. According to Lazouski et al. [63], Park and Sandhu [86], and Pretschner et al. [89], a usage control framework should be capable of handling the continuous enforcement of policies. This implies the management of attributes, conditions, and the fulfillment of obligation actions that reflect the validity of the continuous usage of data objects.

4.2.4 **Conflict Detection & Resolution** [13, 16, 46, 96]. Another aspect of enforcement is the management of conflicting rules, which is particularly difficult in decentralized or distributed systems, as data may be governed by a variety of policies [16, 46]. According to Schütte and Brost [96] and Cao et al. [13], an enforcement engine should be able to detect and resolve conflicting or incomplete rules.

4.2.5 **Administration** [73, 93]. According to Mont [73], a complete usage control solution must include an administration tool, which provides an interface to manage (i.e., create, edit, and delete) usage control policies. Rath and Colin [93] highlight the importance of administration interfaces, especially for users that use healthcare information systems, as such a feature allows them to customize their usage policies without the help of system administrators.
4.3 Robustness

Robustness is an all encompassing term used to refer to requirements that relate to the overall effectiveness of the usage control system.

4.3.1 Performance & Scalability \[16, 31, 52, 75, 93, 113\]. Several works \[16, 31, 75, 93, 113\] highlight that a usage control infrastructure should be performant enough to cater for the parallel processing of a large number of requests by data requestors and for a short loading time of the requested data. Furthermore, Keromytis and Smith \[52\] and Zrenner et al. \[113\] highlight the fact that policy management systems need to be realized using scalable architectures that can handle an increasing number of users.

4.3.2 Interoperability & Compatibility \[16, 75, 90, 93, 113\]. Zrenner et al. \[113\] state that usage control needs to work even if data providers and data consumers have different infrastructures. While, Munoz-Arcentales et al. \[75\], Rath and Colin \[93\], and Clemente et al. \[16\] highlight the importance of establishing interoperable mechanisms as without them the system can only be utilized on particular devices, which according to Pretschner et al. \[90\] will limit the uptake of usage control technologies. Besides, Jamkhedkar et al. \[42\] attest that it is necessary to have mechanisms that allow for the specification of usage policies that can be interpreted and enforced across multiple different computing environments. This can be fulfilled by: (i) applying standards; and (ii) separating the usage control system components for policy expression, policy interpretation, and policy enforcement. Such separation allows policies to express the restrictions with minimal apriori knowledge of the IT environments in which the policies will be interpreted.

4.3.3 Usability \[9, 38, 55, 93\]. According to Rath and Colin \[93\] and Hilty et al. \[38\], the usability of administration tools is an important requirement that should be supported via user-friendly interfaces or easy-to-use languages. Hilty et al. \[38\] state that administration tools may be used by end users (as opposed to system administrators) in order to enter their preferences and manage the use of their data. Usability is especially important when it comes to mobile and/or web applications \[9, 55, 93\] where users need to manage how their data are used.

4.3.4 Reliability \[9, 10, 13, 31, 35, 36, 39, 55, 56, 73, 75, 89, 90, 113\]. Reliability refers to the ability of a usage control mechanism to be compliant with usage control policies and transparent with respect to the way data are used \[89\].

System Reliability \[31, 35, 36, 73, 90\]. Mont \[73\], Pretschner et al. \[90\], and Gil et al. \[31\] highlight the importance of system reliability when dealing with distributed usage control systems, as sometimes the infrastructure of the provider is hosted by a third party, leaving the owner with little or no control over how their data are used. System reliability depends on the level of compliance with respect to usage control policies that can be ensured by two factors: controllability and observability, notions initially introduced by Hilty et al. \[35\]. On one hand, controllable restrictions are policies by which the data provider can ensure that the data consumer complies with everything that has been mentioned in the policy. On the other hand, observable restrictions are policies that the data provider cannot control. In this context, the data provider can only observe violations and take compensatory actions, such as lowering the trust or credibility rating of the data consumer or taking some form of legal action.

Transparency \[9, 10, 13, 15, 39, 55, 56, 75, 89, 113\]. The usage control process should be transparent to and comprehensible by data providers and data consumers alike \[9, 56, 113\]. Pretschner et al. \[89\] mention data auditing as a means to observe the fulfillment or the violation of non-observable restrictions. Moreover, Hosseinzadeh et al. \[39\] state that the logging of data usage information can ensure both transparency and reliability, as logs provide visibility with respect to the inner
workings of a software system. Bier [10] and Munoz-Arcentales et al. [75] indicate that data provenance tracking is complementary to distributed data usage monitoring. Cao et al. [13] and Kumari [55] state that providing explanations, with respect to actions performed by the system, is part of ensuring transparency as explanations provide a basis for decision-making. While, Munoz-Arcentales et al. [75], Cao et al. [13], and Cirillo et al. [15] highlight the importance of a trusted infrastructure, especially when it comes to guaranteeing secure data sharing and adherence to usage policies.

5 Frameworks

The goal of this section is to provide a detailed analysis of existing usage control frameworks with a particular focus on the domain of usage, as well as their support for the various policy specification, enforcement, and robustness requirements.

5.1 Domain of Usage

In Table 2 we provide a high level overview of the domain of usage of the various usage control frameworks. The specification, enforcement, and robustness columns of the table, which serve to provide a single snapshot of existing usage control proposals, are discussed in detail in the subsequent sub-sections. Due to the variety of usage control domains, we group together the usage control framework proposals according to three application domains, namely, mobile, cloud, IoT, and industry 4.0; networking, operating systems and collaborative software; and domain-agnostic.

5.1.1 Mobile, Cloud, IoT, and Industry 4.0. A prominent framework found in the literature is the usage control systems framework proposed by Lazouski et al. [62] and Carniani et al. [14], which can be used to control data usage in modern decentralized and distributed environments, for instance, IoT, cloud computing, mobile computing, and data sharing platforms. The same framework was later refined and used in various industry 4.0 use cases [20, 32, 60, 61]. Additionally, an adaptation of the proposed framework is used by Martinelli et al. [67] in a mobile computing context. The intent-oriented data usage control for federated data analytics or IntentKeeper framework proposed by Cirillo et al. [15], which protects data during federated data analytics, is applied in an automotive setting. The trusted usage framework proposed by Baldini et al. [6], Neisse et al. [78] is intended to address the challenges of heterogeneity in IoT technologies. The trustworthy data sharing platform framework proposed by Cao et al. [13] is designed with a smart city use case in mind. Another framework that deals with data sharing in smart cities is proposed by Munoz-Arcentales et al. [74] was later implemented by the same authors [75]. In turn, the integrated distributed data usage control enforcement (IND²UCE) [44] framework is designed to support usage control in cloud environments. IND²UCE is originally proposed by Steinebach et al. [99] in order to manage data usage in industry 4.0 environments. A technical implementation of IND²UCE, under the name MYDATA technologies, is described in [24]. The framework is also mentioned as a solution for business ecosystems in [113]. The framework proposed by Wüchner et al. [108] is designed to preserve regulatory compliance in federated cloud storage. The context-aware usage control (ConUCE) framework [5] is designed for mobile computing and uses contextual information in order to enhance data protection. While, the framework proposed by Feth and Pretschner [28] aims to enhance Android security by allowing users to manage fine-grained security policies.

5.1.2 Networking, Operating Systems and Collaborative Software. The usage control systems framework proposed by Lazouski et al. [62] and Carniani et al. [14] is further refined and used to enhance network security [58, 59, 69]. The xDUCON framework, proposed by Russello and Dulay [94] is intended to regulate how data are managed and shared among distributed environments and organizations. While, LUCON [96] is a message-based system that guarantees the secrecy of messages.
Table 2. High Level Overview of Existing Usage Control Frameworks

| Framework                                      | Name         | Domain                                      | Specification                                                                 | Enforcement                                      | Robustness                                      |
|------------------------------------------------|--------------|---------------------------------------------|-------------------------------------------------------------------------------|-------------------------------------------------|-------------------------------------------------|
| Bai et al. [5]                                 | ConUCON      | mobile, cloud, IoT, and industry 4.0        | obligations, conditions, mutable attributes, context                         | continuity, preventive, administrative           | implementation, performance evaluation          |
| Baldini et al. [6], Neisse et al. [78]          | trusted usage framework | mobile, cloud, IoT, and industry 4.0 | logic-based obligations, conditions, attributes, context | continuity, preventive, detection, conflict resolution, administrative | implementation, performance evaluation, use case validation |
| Cao et al. [13]                                 | trustworthy data sharing platform | mobile, cloud, IoT, and industry 4.0 | logic-based obligations, conditions, attributes, context | continuity, preventive, administrative conflicts resolution, administration | implementation, performance evaluation          |
| Carniani et al. [14], Lazouski et al. [62]      | usage control systems - proposal | mobile, cloud, IoT, and industry 4.0 | obligations, conditions, mutable attributes, context | continuity, preventive, administrative conflicts resolution, administration | implementation, performance evaluation          |
| Costantino et al. [20]                         | usage control systems - extension | mobile, cloud, IoT, and industry 4.0 | obligations, conditions, mutable attributes, context | continuity, preventive, administrative conflicts resolution, administration | implementation, performance evaluation          |
| Cirillo et al. [15]                            | IntentKeeper  | mobile, cloud, IoT, and industry 4.0        | obligations, conditions, mutable attributes, context | continuity, preventive, administrative conflicts resolution, administration | implementation, performance evaluation          |
| Feth and Pretschner [28]                       |              | mobile, cloud, IoT, and industry 4.0        | logic-based obligations, conditions, context | continuity, preventive, administrative conflicts resolution, administration | implementation, performance evaluation          |
| Giorgi et al. [32]                             | usage control systems - extension | mobile, cloud, IoT, and industry 4.0 | obligations, conditions, mutable attributes, context | continuity, preventive, administrative conflicts resolution, administration | implementation, performance evaluation          |
| Jung et al. [44]                               | IND4UCE      | mobile, cloud, IoT, and industry 4.0        | logic-based obligations, conditions, attributes, context | continuity, preventive, administrative conflicts resolution, administration | implementation, performance evaluation          |
| Kateb et al. [48]                              | OB-XACML     | domain-agnostic                             | obligations, attributes, context                                              | continuity, preventive, administrative conflicts resolution, administration | implementation, performance evaluation          |
| Lazouski et al. [64]                           | U-XACML      | mobile, cloud, IoT, and industry 4.0        | obligations, conditions, mutable attributes, context                         | continuity, preventive, administrative conflicts resolution, administration | implementation, performance evaluation          |
| La Marra et al. [58], Martini et al. [69]       | usage control systems - extension | mobile, cloud, IoT, and industry 4.0 | obligations, conditions, mutable attributes, context                         | continuity, preventive, administrative conflicts resolution, administration | implementation, performance evaluation          |
| La Marra et al. [60]                           | usage control systems - extension | mobile, cloud, IoT, and industry 4.0 | obligations, conditions, mutable attributes, context                         | continuity, preventive, administrative conflicts resolution, administration | implementation, performance evaluation          |
| La Marra et al. [61]                           | usage control systems - extension | mobile, cloud, IoT, and industry 4.0 | obligations, conditions, mutable attributes, context                         | continuity, preventive, administrative conflicts resolution, administration | implementation, performance evaluation          |
| La Marra et al. [59]                           | usage control systems - extension | mobile, cloud, IoT, and industry 4.0 | obligations, conditions, mutable attributes, context                         | continuity, preventive, administrative conflicts resolution, administration | implementation, performance evaluation          |
| Martinelli et al. [68]                         | usage control systems - extension | mobile, cloud, IoT, and industry 4.0 | obligations, conditions, mutable attributes, context                         | continuity, preventive, administrative conflicts resolution, administration | implementation, performance evaluation          |
| Martinelli et al. [67]                         | usage control systems - extension | mobile, cloud, IoT, and industry 4.0 | obligations, conditions, mutable attributes, context                         | continuity, preventive, administrative conflicts resolution, administration | implementation, performance evaluation          |
| Munoz-Arcentales et al. [74, 75]               |              | mobile, cloud, IoT, and industry 4.0        | obligations, conditions, mutable attributes, context                         | continuity, preventive, administrative conflicts resolution, administration | implementation, performance evaluation          |
| Neisse et al. [77]                             |              | domain-agnostic                             | obligations, conditions                                                       | continuity, preventive, administrative conflicts resolution, administration | implementation, performance evaluation          |
| Russello and Dalay [94]                        | xDUCON       | networking, operating systems and collaborative software | obligations, conditions, mutable attributes, context | continuity, preventive, administrative conflicts resolution, administration | implementation, performance evaluation          |
| Schütte and Brost [96]                         | LUCON        | networking, operating Systems and collaborative Software | logic-based obligations                                                     | continuity, preventive, administrative conflicts resolution, administration | implementation, performance evaluation          |
| Teigao et al. [101]                            |              | networking, operating systems and collaborative software | obligations, conditions, mutable attributes, context | continuity, preventive, administrative conflicts resolution, administration | implementation, performance evaluation          |
routed between services. LUCON also appears in the context of MYDATA technologies for controlling data flows between endpoints. In turn, the framework presented in [109] aims to monitor the use of confidential data at the operating system level. The frameworks proposed by Teigão et al. [101] and Xu et al. [110] cater for the management of operating systems resources (e.g., files, network connections, memory areas, and system applications). While, the framework proposed by Weber and Silva [105] is evaluated in an operating system context. Finally, the framework proposed by Zhang et al. [112] is applied in a collaborative systems context. An architectural instantiation of the same framework with some improvements can be found in [49].

5.1.3 Domain-agnostic. The framework presented in [64] is designed for modern distributed computing systems, without a specific use case in mind. Although the IND²UCE framework [44] is applied in a cloud computing context, the framework was originally proposed for controlling data usage in modern distributed environments, in general. Other usage control frameworks proposed by Weber and Silva [105] and Wüchner and Pretschner [109] that are meant to be domain agnostic are evaluated using operating system use cases. While, Martinelli et al. [68] demonstrate the effectiveness of the usage control systems framework proposed by Lazouski et al. [62] and Carniani et al. [14] as a general purpose architecture. The domain-agnostic OB-XACML framework, proposed by Kateb et al. [48], deals with enhancing XACML in order to cater for usage control obligations and continuity of enforcement. In turn, the framework proposed by Neisse et al. [77] can be used to specify and enforce general purpose usage control policies.

5.2 Specification

According to Bier [10], when it comes to policy specification, one has to differentiate between the policy language, the representation format, and the model underpinning the usage control system. In Table 3, we present a comparison of the various approaches used for policy specification.

5.2.1 Expressiveness. The expressiveness of a policy language is reflected by the different decision factors used to express high-level usage control policies. Decision factors depend on the specification of policy rules, conditions, subject and object attributes, as well as contextual information.
Table 3. Usage Control Policy Specification

| Framework | Expressiveness | Conditions | Attributes | Context | Flexibility & Extensibility | Unambiguous | Formal Semantics |
|-----------|----------------|------------|------------|---------|-----------------------------|-------------|-----------------|
| Bai et al. [5] | A, O | environmental system-oriented | mutability | model based | XML | UCON | – |
| Baldini et al. [6], Neisse et al. [78] | E, C, A | cardinal temporal event-defined | model based | XML | – | – | OSL |
| Cao et al. [13] | P, Pr, O | actor spatial temporal purpose monetization | model based | XML | DUPO | – | defeasible logic |
| Carniani et al. [14], Lazouski et al. [62] | A, O | environmental system-oriented | mutability | system based | XML | XACML | – |
| Costantino et al. [20] | A, O | environmental system-oriented | mutability | system based | XML | XACML | – |
| Cirillo et al. [15] | P, Pr, O | purpose temporal spatial event-defined | – | XML | ODRL | – | – |
| Feth and Pretschner [28] | E, C, Ac | environmental system-oriented | – | XML | – | – | OSL |
| Giorgi et al. [32] | A, O | environmental system-oriented | mutability | system based | XML | XACML | – |
| Jung et al. [44] | E, C, Ac | environmental system-oriented | system-based | system based | XML | – | – | OSL |
| Kateb et al. [48] | A, O | environmental system-oriented | mutability | system based | XML | XACML | – |
| Lazouski et al. [64] | A, O | environmental system-oriented | system-based | system based | XML | XACML | – |
| La Marra et al. [58], Martini et al. [69] | A, O | environmental system-oriented | system-based | system based | XML | XACML | – |
| La Marra et al. [60] | A, O | environmental system-oriented | mutability | system based | XML | XACML | – |
| La Marra et al. [61] | A, O | environmental system-oriented | mutability | system based | XML | XACML | – |
| La Marra et al. [59] | A, O | environmental system-oriented | mutability | system based | XML | XACML | – |
| Martinelli et al. [67] | A, O | environmental system-oriented | mutability | system based | XML | XACML | – |
| Martinelli et al. [68] | A, O | environmental system-oriented | mutability | system based | XML | XACML | – |
| Munoz-Arcentales et al. [74, 75] | P, Pr, O | amount-based cardinal spatial | – | XML | ODRL | – | – |
| Neisse et al. [77] | E, C, Ac | environmental system-oriented | mutability | – | XML | – | – | OSL |
| Russello and Dalay [94] | S, T, Ac | spatial temporal | mutability | model based | – | – | – | – |
| Schütte and Brust [96] | Al, D, O | – | – | Java | DSL | – | first order logic |
| Teigão et al. [101] | A, O | environmental system-oriented | mutability | – | LALR | UCON | – | – |
| Weber and Silva [105] | E, C, Ac | temporal spatial cardinal | – | XML | – | – | OSL |
| Wüchner et al. [108] | E, C, Ac | temporal spatial | – | XML | – | – | OSL |
| Wüchner and Pretschner [109] | E, C, Ac | temporal spatial | – | XML | – | – | OSL |
| Xu et al. [110] | E, P, Ac | – | mutability | – | XML | UCON | – |
| Zhang et al. [112] | A, O | environmental system-oriented | mutability | model based | XML | UCON | PEI | – |

1P= permission; Pr= prohibition; O= obligation; D= dispensation; A= authorizations; E= event; C= conditions; P= predicate; Ac= actions, Al= allow; D= drop; S= Subject; T= Target; For attributes, if ‘mutability’ then the policy supports mutable
Operators/ Rules. The policy languages presented in \[5, 101, 110, 112\] support the core UCON [86] model components, namely, authorizations and obligations. UCON\textsubscript{K}, a policy language proposed by Xu et al. [110], which only supports authorizations, is an event-based UCON model that uses the Event-Predicate-Action (EPA) language that originated from Event-Condition-Action (ECA) [3] rules. An event is an activity carried out by a subject; the action part consists of preventive and detective mechanisms; and the predicate part defines UCON authorizations.

The frameworks presented in \[14, 20, 32, 58–62, 64, 67–69\] use the U-XACML policy language and model, which was originally proposed by Colombo et al. [17]. U-XACML is an extension of XACML that introduces attribute updates and continuous policy evaluation. It mainly supports UCON authorizations and XACML obligations. In the UCON model, obligations are actions that have to be performed by subjects. Whereas, in XACML obligations have different semantics and are considered as duties that are performed by the enforcement mechanism in order to enforce access decisions [63]. Later Martinelli et al. [68] extended U-XACML in order to provide support for UCON obligations. A similar policy language to U-XACML is OB-XACML, which is proposed by Kateb et al. [48]. However, OB-XACML is able to formalize post-obligations and contextual information via the OB-XACML model.

Cao et al. [13] propose a data usage control model, entitled DUPO, that can be used to cater for diverse usage control policies. The policy language is based on defeasible logic and enriched with deontic operators. Another policy language that uses deontic operators to express usage control policies is the open digital rights language (ODRL) [106], which is used by both Munoz-Arcentales et al. [74, 75] and Cirillo et al. [15]. ODRL is a World Wide Web Consortium (W3C)\textsuperscript{2} standard that provides an information model, vocabulary, and encoding mechanisms that can be used to represent statements about content and services usage\textsuperscript{3}.

The policy language adopted by \[6, 28, 44, 77, 78, 105, 108, 109\] uses ECA rules to express policies. Conditions, which are mainly used to impose temporal and cardinal constraints on data usage, are expressed using the obligation specification language (OSL) [37]. The formal model of OSL is logic based and specified in the \textit{Z} language [1]. The action part consists of preventive and detective mechanisms. Unlike the original UCON model, OSL is able to formalize, alongside pre-obligations and ongoing-obligations, post-obligations [63].

The policy language proposed by Schütte and Brost [96], which is represented in a domain specific language (DSL), named LUCON DSL, is specified in Java and compiled into first order logic. The DSL grammar is used to express the rules that determine whether the sending of a message is allowed or prohibited. This grammar also allows a decision to be linked to an obligation, in particular a pre-obligation. The policy language underpinning the xDUCON framework proposed by Russello and Dulay [94] is represented in xDSpace, an implementation of the \textit{shared data space} [30] programming system. xDSpace allows rules to be expressed as tuples that include subjects, targets (or objects), and actions to be performed on the object by the subject.

Conditions. UCON-based policy languages \[5, 14, 20, 32, 48, 58–62, 64, 67–69, 101, 110, 112\] allow different environmental and system-based conditions to be expressed. However, the policy language proposed by Teigão et al. [101] only caters for four predefined conditions, namely, the current time, the amount of CPU in use, and the amount of free memory and disk space. ODRL [15, 74, 75] allows various conditions to be expressed, such as, temporal, spatial, amount-based, purpose, and event-defined. The DUPO policy language presented in [13] also allows event-defined

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\textsuperscript{2}W3C, https://www.w3.org/

\textsuperscript{3}ODRL, https://www.w3.org/community/odrl/
conditions to be expressed. DUPO allows five pre-defined conditions to be expressed, namely, actor, spatial, temporal, purpose and monetization. The OSL-based policy languages presented in [6, 28, 44, 77, 78, 105, 108, 109] are mainly used to express temporal and cardinal conditions on the data using OSL. Moreover, the policy language used in the framework proposed by Feth and Pretschner [28] allows additional attributes defined as XML spatial conditions to be captured. Whereas, the policy language proposed by Jung et al. [44] makes use of the condition part to refer to additional attributes such as contextual information relating to the policy. The xDUCON policy language [94] allows for the expression of two predefined conditions that represent the contextual information captured by the framework, namely, temporal and spatial conditions.

Attributes. Most of the UCON-based policy languages presented in [5, 14, 20, 32, 58–62, 64, 67–69, 101, 110, 112] support attribute mutability by allowing attribute updates. The authors of the framework presented in [5] detailed the policy attributes responsible for controlling ongoing obligations and attributes using the XML policy attribute obligationTime and an update policy, respectively, which indicates the attribute to be updated and the update time. In addition, the U-XACML policy language presented in [14, 20, 32, 58–62, 64, 67–69] supports attribute mutability by introducing AttrUpdate in the policy specification. The framework proposed by Neisse et al. [77] allows attributes to be updated by exploiting the attributeMatch element in XML, which is bound to temporal operators. The attributes supported by the various policy languages depend significantly on the scope of the usage control solution.

Context. Several authors [5, 6, 13, 44, 48, 78, 94, 112] introduced contextual information in their policy specification. For instance, the policy languages adopted by Zhang et al. [112] and Jung et al. [44] use conditions to support context-based authorizations. Another framework, the one proposed by Bai et al. [5] presents the ConUCON policy language based on the ConUCON policy model, which is an extension of UCON with a new component that caters for contextual information. The new context component allows ongoing environmental (e.g., spatial and temporal) and system (e.g., CPU and battery) information to be captured. The remaining frameworks presented in [14, 20, 32, 58–62, 64, 67–69] are context based-systems, as they directly make use of the contextual information collected via their system components.

5.2.2 Flexibility & Extensibility. Some policies owe their flexibility and extensibility to the conceptual model that expresses the policy in an abstract way and/or to the language used to encode policies.

Representation Format. Most of the policy languages are represented in XML. The remaining ones are represented either in DSL specified in Java [96] or the look-ahead-left-to-right (LALR) grammar [101]. Zhang et al. [112] state that the XML language is extensible enough to meet the expressiveness and flexibility of the UCON model, but also its extensions. Besides, Feth and Pretschner [28] agree that XML allows new policy rules to be added in order to express and extend different models, which is confirmed by Colombo et al. [17] who successfully incorporated UCON components in the XACML policy language. For the remaining representation languages, Teigão et al. [101] and Schütte and Brost [96] assert that their proposed languages, which use the LALR grammar and Java, respectively, are sufficiently extensible and flexible to meet new conditions and usage rules.

Conceptual Model. The UCON model has demonstrated great flexibility as it has been used in different application contexts, such as industry 4.0, operating systems, and mobile computing. For example, Bai et al. [5] claim that the ConUCON policy model can be implemented not only for Android but also for other mobile platforms due to the policy flexibility and extensibility. Moreover, Katt et al. [49] incorporated post-obligations in the context of an Industry 4.0 application and
Bai et al. [5] extended the original UCON model with context components in order to develop context-aware ubiquitous systems. As for ODRL, according to Munoz-Arcentales et al. [74] and Cirillo et al. [15], the policy language presents a flexible policy model, which allows various usage scenarios to be expressed, but also a fully extensible model, which provides mechanisms to extend and/or deprecate the original model. Regarding XACML, although the model was originally used for access control specification, it has shown a high level of flexibility and extensibility to support UCON components, as indicated by Colombo et al. [17]. Besides, the framework proposed by Lazouski et al. [64] and the framework proposed by Lazouski et al. [62] and Carniani et al. [14] and its various extensions presented in [20, 32, 58–61, 67–69] have underlined the degree of extensibility of XACML as it has undergone various extensions over time in order to cater for different types of attributes (e.g., attributes that account for different sensors in an IoT scenario or describe the features of subjects, resources, and environment change) and conditions (e.g., location, time, occurrence, and event-based).

5.2.3 Unambiguous. Zhang et al. [112] describe the highest level of policy (i.e., the high level objectives of normative policies) as being informal and fuzzy, which makes it difficult to enforce them effectively. In their work, the authors developed their framework using the layered policy-enforcement-implementation (PEI) [95] methodology. PEI seeks to bridge the gap between informal or high-level policies and the actual enforcement mechanism, thereby undermining the ambiguity of informal usage control policies. PEI is composed of five layers: security and system goals, policy models, enforcement models, implementation models, and actual implementations. The first layer is necessarily informal, while the second layer aims to take high-level informal goals and provide concrete details using formal or quasi-formal notation. For the authors, the UCON model presents the formal layer of their policy language, while enforcement and implementation models are associated with the actual code that implements the solution. The designers of the remaining frameworks do not mention any methodology or formal ways of dealing with the unambiguity requirement.

5.2.4 Formal Semantics. Logic-based approaches that formalize the proposed policy languages were employed by [6, 28, 44, 77, 78, 105, 108, 109], which use OSL, and the ones presented in [13, 96], which use defeasible logic and first order logic, respectively. While the remaining policy languages such as U-XACML and ODRL do not provide any formal foundations, some works such as [66, 100] propose ways to formalize these languages.

5.3 Enforcement

In Table 4, we outline the various components employed in each framework, while in Table 5, we present a comparative overview of the predominant usage control frameworks found in the literature. Most of the frameworks depicted in Table 4 are XACML [98] reference architectures, and thus include some or all of the following components: a policy decision point (PDP) [5, 6, 14, 20, 28, 32, 44, 48, 58–62, 64, 67–69, 74, 75, 77, 78, 94, 108–110, 112], a policy enforcement point (PEP) [5, 6, 14, 15, 20, 28, 32, 44, 48, 58–62, 64, 67–69, 77, 78, 94, 108, 109, 112], a policy information point (PIP) [5, 14, 20, 32, 44, 48, 58–62, 64, 67–69, 108, 109], a policy execution point (PXP) [44, 74, 75], a policy administration point (PAP) [5, 14, 20, 32, 44, 58–62, 64, 67–69], a policy retrieval point (PRP) [44], a policy management point (PMP) [44], and/or a policy translation point (PTP) [74, 75]. Although the vast majority of frameworks introduce usage control extensions for XACML, some frameworks [13, 96, 101, 105] also introduce novel enforcement mechanisms.

Various extensions of XACML include components for the continuous evaluation and the enforcement of usage control policies. Existing proposals include a variety of new components that are responsible for managing and evaluating policy attributes, namely an attribute manager
| Framework                          | Type   | Components                                                                 |
|-----------------------------------|--------|-----------------------------------------------------------------------------|
| Bai et al. [5]                    | XACML  | PEP, PDP, PIP, PAP, evaluation engines                                       |
| Baldini et al. [6], Neisse et al. [78] | XACML  | PEP, PDP, role manager, policy management, graphical user interface, policy repository, policy server |
| Cao et al. [13]                   | custom | identification, policy management, policy composition, data usage transparency, data usage traceability, jDUPO |
| Carniani et al. [14], Lazouski et al. [62] | XACML  | PEP, PIP, PDP, PAP, context handler, attribute manager, session manager      |
| Cirillo et al. [15]               | XACML  | policy management, PEP, graphical user interface, infrastructure services    |
| Costantino et al. [20]            | XACML  | PEP, PIP, PDP, PAP, context handler, user monitor                           |
| Feth and Pretschner [28]          | XACML  | PEP, PDP, PEP, PIP, PDP, PAP, context handler, attribute manager, session manager |
| Giorgi et al. [32]                | XACML  | PEP, PIP, PDP, PAP, context handler, attribute manager, session manager      |
| Jung et al. [44]                  | XACML  | PXP, PEP, PRP, PDP, PIP, PAP, PAP                                          |
| Kateb et al. [48]                 | XACML  | PIP, PDP, obligation manager                                                |
| Lazouski et al. [64]              | XACML  | PEP, PIP, PDP, PAP, context handler, user monitor                           |
| La Marra et al. [58], Martini et al. [69] | XACML  | PEP, PIP, PDP, PAP, context handler, user monitor                           |
| La Marra et al. [60]              | XACML  | PEP, PIP, PDP, PAP, context handler, user monitor                           |
| La Marra et al. [61]              | XACML  | PEP, PIP, PDP, PAP, context handler, user monitor                           |
| La Marra et al. [59]              | XACML  | PEP, PIP, PDP, PAP, context handler, user monitor                           |
| Martinelli et al. [68]            | XACML  | PEP, attribute manager, PIP, PDP, PAP, session manager, context handler, OEP, OOP, POP, ODP |
| Martinelli et al. [67]            | XACML  | PEP, PIP, PDP, PAP, context handler, user monitor                           |
| Munoz-Arcentales et al. [74, 75] | XACML  | PDP, PXP, PTP                                                                |
| Neisse et al. [77]                | XACML  | policy manager, policy repository, PDP, attribute resolver, action resolver, PEP |
| Russello and Dulay [94]           | XACML  | PEP, PDP, xDSpace                                                            |
| Schütte and Brost [96]            | custom | Prolog engine                                                                |
| Teigão et al. [101]               | custom | reference monitor, usage mediator, rule parser                               |
| Weber and Silva [105]             | custom | policy editor, notification manager, policy monitor, control monitor, event signaler |
| Wüchner et al. [108]              | XACML  | PEP, PIP, PDP                                                                |
| Wüchner and Pretschner [109]      | XACML  | PEP, PIP, PDP                                                                |
| Xu et al. [110]                   | XACML  | enforcer, attribute repository, PDP                                          |
| Zhang et al. [112]                | XACML  | PDP, PEP, policy enforcement, attribute repository                            |

[14, 32, 62, 68], a session manager [14, 32, 62, 68], a usage monitor [20, 58–61, 64, 67, 69, 112], an attribute repository [110, 112], a role manager [6, 78], and an evaluation engine [5]. Additionally, there are various proposals for managing and evaluating policy obligations via an obligation manager [48], an evaluation engine [5], a session manager [14, 32, 62, 68], an action resolver [77], an obligation enforcement point (OEP) [68], an obligation observation point (OOP) [68], and a policy obligation
Table 5. Usage Control Enforcement Mechanisms

| Framework                        | Preventive                  | Detective            | Continuity of Enforcement | Conflict & Detection | Administration                      |
|----------------------------------|-----------------------------|-----------------------|---------------------------|----------------------|-------------------------------------|
| Bai et al. [5]                   | permission, inhibition, revoke, delay, update | –                     | monitor attribute and context updates, monitor obligation fulfillment | –                    | FAP interface                       |
| Baldini et al. [6, Neisse et al. [78]] | permission, inhibition, revoke, delay, modification | –                     | monitor condition updates and obligations fulfillment combining algorithms | –                    | graphical user interface            |
| Carniani et al. [14, Lazouski et al. [62]] | permission, inhibition, revoke, update | –                     | monitor attribute, context, and condition updates | –                    | FAP interface                       |
| Cao et al. [53]                  | permission, inhibition, revoke, delay | –                     | monitor condition and context updates, monitor obligation fulfillment logic-based | –                    | jDUPO                               |
| Costantino et al. [20]           | permission, inhibition, revoke, update | –                     | monitor attribute, context, and condition updates | –                    | PAF interface                       |
| Cirillo et al. [13]              | permission, inhibition, execution | execution actions     | –                         | –                    | graphical user interface            |
| Feth and Pretschner [28]         | permission, inhibition, execution | execution actions     | monitor condition updates and obligations fulfillment | –                    | Android interface                   |
| Giorgi et al. [32]               | permission, inhibition, revoke, update | –                     | monitor attribute, context, and condition updates | –                    | PAF interface                       |
| Jung et al. [44]                 | permission, inhibition, execution, modification, execution, revoke | –                     | monitor condition updates and obligations fulfillment | –                    | PAF interface                       |
| Kateb et al. [48]                | permission, inhibition, revoke, delay | –                     | monitor obligation fulfillment | –                    | –                                   |
| La Marra et al. [58, Martini et al. [69]] | permission, inhibition, revoke, update | –                     | monitor attribute, context, and condition updates | –                    | PAF interface                       |
| Lazouski et al. [64]             | permission, inhibition, revoke, update | –                     | monitor attribute, context, and condition updates | –                    | PAF interface                       |
| La Marra et al. [60]             | permission, inhibition, revoke, update | –                     | monitor attribute, context, and condition updates | –                    | PAF interface                       |
| La Marra et al. [61]             | permission, inhibition, revoke, update | –                     | monitor attribute, context, and condition updates | –                    | PAF interface                       |
| La Marra et al. [59]             | permission, inhibition, revoke, update | –                     | monitor attribute, context, and condition updates | –                    | PAF interface                       |
| Martinelli et al. [87]           | permission, inhibition, suspend, resume, update | –                     | monitor attribute, context, and condition updates | –                    | PAF interface                       |
| Martinelli et al. [68]           | permission, inhibition, revoke, delay, update | –                     | monitor attribute, context, condition and updates, monitor obligation fulfillment | –                    | PAF interface                       |
| Munoz-Arcentales et al. [74, 75] | permission, inhibition, revoke, delay, modification | –                     | monitor condition and obligation fulfillment | –                    | PAF interface                       |
| Neisse et al. [77]               | permission, inhibition, revoke, delay, modification, execution, update | execution actions     | monitor condition and attributes updates, monitor obligations fulfillment | –                    | –                                   |
| Russello and Dulay [94]          | permission, inhibition, revoke, delay, update | –                     | monitor condition and context updates, monitor obligation fulfillment | –                    | –                                   |
| Schütte and Brost [96]           | permission, inhibition, modification | auditing              | monitor data flow logic-based integrated development environment | –                    | –                                   |
| Teigão et al. [101]              | permission, inhibition, revoke, update | –                     | monitor attribute updates | –                    | –                                   |
| Weber and Silva [105]            | permission, inhibition, revoke, delay, modification, execution | execution actions     | monitor condition updates and obligations fulfillment | –                    | policy editor                        |
| Wüchner and Pretschner [109]     | permission, inhibition, revoke, delay, modification, execution | execution actions     | monitor condition updates and obligations fulfillment | –                    | –                                   |
| Wüchner et al. [108]             | permission, inhibition, revoke, delay, modification, execution | execution actions | monitor condition updates and obligations fulfillment | –                    | –                                   |
| Xu et al. [110]                  | permission, inhibition, revoke, update | –                     | monitor attribute updates | –                    | LINUX command line                  |
| Zhang et al. [112]               | permission, inhibition, revoke, update, delay | –                     | monitor attribute updates and obligation fulfillment | –                    | –                                   |

point (POP) [68]. When it comes to managing contextual information, extensions include a context handler [14, 20, 32, 58–62, 64, 67–69], a context manager [6, 78], a session manager [14, 32, 62, 68],
and an evaluation engine [5]. Whereas, policy management [6, 13, 15, 78], policy manager [77], and policy repository [6, 77, 78] components have been proposed in order to support the management of usage control policies. Finally, there are a number of suggestions for managing the communication between various components, including an infrastructure service [15] that can be used as a means to develop trust and a shared data space (xDSpace) [94] that can be used as a tool for coordinating the execution of distributed applications.

When it comes to the novel frameworks, various architectural designs are motivated by different aims and requirements. For instance, the trustworthy data sharing platform [13] includes five predominant features: identification, policy management (visualization tool), policy composition, data usage transparency, and data usage traceability. The framework proposed by Schütte and Brost [96] uses a Prolog engine as a PEP and an interceptor for events as a PDP. The enforcement architecture proposed by Teigão et al. [101] is based on three main components: a reference monitor that acts as a PDP, a usage mediator that acts as a PEP, and a LALR rule parser that translates the rules expressed by the LALR grammar into an internal representation, which is used by the reference monitor. The framework proposed by Weber and Silva [105] includes a control monitor and a policy monitor that together act as a PDP, an event signaler that acts as a PEP, and a notification manager that sends notifications to the control monitor in the case of violations.

5.3.1 Preventive. The preventive mechanisms of a variety of frameworks are provided by the enforcement points. With the exception of the frameworks described in [67], [15] and [96], each of the frameworks can enforce: permissions, prohibitions, and revocations. These classes of enforcement are responsible for enforcing usage decisions by allowing, denying access to or usage of a resource, and revoking access in the case of policy violations. While, the suspend and resume framework proposed by Martinelli et al. [67] allows access to be resumed after suspension by the system as a result of an ongoing-evaluation. The frameworks proposed in [15] and [96] do not allow access to data to be revoked. Another class of enforcement is modification. The frameworks presented in [6, 28, 44, 74, 75, 77, 78, 96, 105, 108, 109] modify certain data values after access is granted in order to allow the user to use the data while ensuring privacy protection and policy compliance. Only a few frameworks [15, 28, 44, 77, 105, 108, 109] cater for the execution of actions or non-usage actions that trigger required actions to be performed (e.g., sending a notification, triggering a payment, or writing in logs). Cirillo et al. [15] state that their framework enforces three main types of actions, namely, anonymization of the data before use by the data consumer; making sure that the data never leave the providers domain; and deleting traces of data usage (e.g., search results) in the data consumers domain-memory. The frameworks proposed in [5, 14, 20, 32, 58–62, 64, 67, 69, 96, 110] provide mechanisms that allow for the enforcement of obligation fulfillment, which is usually referred to as a delay class of enforcement, as the framework delays the access to or the usage of a resource until users perform certain obligations, which in turn trigger the re-evaluation of the relevant policies. The framework proposed by Zhang et al. [112] only enforces pre-obligations, whereas the rest can enforce pre-obligations, on-obligations, and post-obligations. The frameworks presented in [5, 14, 20, 32, 58–62, 64, 67, 69, 96, 110] only consider XACML-type obligations that are handled internally. While, the framework presented in [101] considers obligations as external to the decision system and thus said obligations are managed by external routines. The various frameworks that are based on the UCON model [5, 14, 20, 32, 58–62, 64, 67–69, 101, 110, 112] and the frameworks proposed by Russello and Dulay [94] and Neisse et al. [77] consider attribute updates as a mechanism to trigger the re-evaluation of policies. Zhang et al. [112] support dynamic resource attributes (e.g., virtual machine storage and network bandwidth) that can affect the usage of data in the context of collaborative computing systems.
5.3.2 Detective. In addition to providing preventive mechanisms, the frameworks presented in [15, 28, 44, 77, 96, 105, 108, 109] also include detective mechanisms. The detective mechanisms proposed by Jung et al. [44], Neisse et al. [77], Wüchner and Pretschner [109], Wüchner et al. [108], Weber and Silva [105], and Feth and Pretschner [28] allow for the enforcement of actions performed by the PXP, the PEP, or the event signaler. According to Pretschner et al. [89], execution actions are actions that typically involve internal interactions between system components. Feth and Pretschner [28] group execution actions into four main types: logging; notifying a user; starting an activity; and faking information (e.g., a location). In turn, Cirillo et al. [15] enforce actions such as anonymizing data and deleting traces of data. While, Schütte and Brost [96] define detective enforcement as a statistic type of enforcement that acts as a formal audit support system, which provides evidence in the event of a policy violation or is used to manage policy conflicts.

5.3.3 Continuity of Enforcement. Continuity of enforcement involves re-evaluating a policy in order to test if the subject still complies with the policy rules and checking the validity of the continuous usage of an object, for instance checking for updates to attributes, context, or conditions and/or the fulfillment of obligations. Most of the usage control frameworks address one or more of the following factors: (i) monitoring attribute updates; (ii) evaluating the fulfillment of obligations; and (iii) evaluating changes to environmental conditions, system conditions and/or contextual information. Depending on the specific framework, continuity of enforcement triggers the re-evaluation of a policy by: a PDP, a Prolog engine, an evaluation engine, a reference monitor, a control monitor, or a data usage transparency component. In cases where the framework supports the mutability of attributes, some components are used to observe and store attribute updates during an ongoing usage process. For instance, the frameworks presented in [5, 14, 20, 32, 58–62, 64, 67–69] employ a usage monitor or a session manager, the framework proposed by Zhang et al. [112] uses an attribute repository, whereas the framework proposed by Bai et al. [5] utilises an evaluation engine. The remaining frameworks use a dedicated continuity of enforcement component in order to monitor updates to policy conditions and contextual information, as well as the fulfillment of obligations. While, the framework proposed by Schütte and Brost [96] continuously monitors data flow by observing and controlling security breaches using a Prolog engine and data flow tracking tools (DFT). The framework proposed by Cirillo et al. [15] performs policy matching of data consumer requests against data provider policies before allowing users to access the data. Although this framework does not apply continuous monitoring of data usage after access is granted, it does provide preventive execution actions performed via infrastructure services, such as anonymizing data or orchestrating services that prevent users from performing certain actions on the data.

5.3.4 Conflict Detection & Resolution. A handful of papers [6, 13, 78, 96] specifically mention conflict detection and resolution. The data usage transparency component proposed by Cao et al. [13] employs a defeasible reasoning engine that can detect and resolve conflicts that arise from usage control policies. However, the authors do not elaborate on the specific conflict resolution strategies that they employ. In the case of the LUCON framework [96], policies are compiled into Prolog programs. The authors highlight the importance of the employed logic based formalism as it allows for reasoning over policies in order to detect conflicting or incomplete rules. However, here again, the authors do not specify any conflict resolution strategies. In turn, the frameworks proposed by Baldini et al. [6] and Neisse et al. [78] uses XACML combining algorithms [41], such as permit-overrides, deny-overrides, or first-applicable algorithms, in order to reach a decision when multiple rules return conflicting responses.
Table 6. Robustness of Usage Control Mechanisms

| Framework | Performance & Scalability | Interoperability & Compatibility | Usability | Transparency | Reliability | System Reliability |
|-----------|---------------------------|---------------------------------|-----------|--------------|-------------|-------------------|
| Bai et al. [5] | performance metrics comparison | XML | – | – | – | – |
| Baldini et al. [6], Neisse et al. [7] | performance metrics | XML | use of templates | trust | support for trust management | – |
| Can et al. [13] | performance metrics | XML, REST APIs | technical expertise required | explanations provenance | – | – |
| Carniani et al. [14], La-zouski et al. [62] | performance metrics | XML | – | – | – | – |
| Costantino et al. [20] | performance metrics | XML | – | – | – | – |
| Cirillo et al. [15] | performance metrics | XML | – | audit provenance | decentralized policy enforcement | – |
| Feth and Pretschner [28] | performance metrics | XML | – | trust | – | – |
| Giorgi et al. [32] | performance metrics | XML | – | – | – | – |
| Jung et al. [44] | performance metrics | XML | technical expertise required | audit | – | – |
| Kalb et al. [48] | performance metrics | XML | – | – | – | – |
| Lazouski et al. [44] | performance metrics | XML | – | – | – | – |
| La Marra et al. [58], Martin et al. [69] | performance metrics | XML | – | – | – | – |
| La Marra et al. [60] | performance metrics | XML | – | – | – | – |
| La Marra et al. [63] | performance metrics | XML | – | – | – | – |
| La Marra et al. [59] | performance metrics | XML | – | – | – | – |
| Martellini et al. [57] | performance metrics | XML | – | – | – | – |
| Martellini et al. [68] | performance metrics | XML | – | – | – | – |
| Munoz-Arcentales et al. [74, 75] | performance metrics | XML | – | trust | trusted technology | stack |
| Neisse et al. [27] | performance metrics | XML | – | – | – | – |
| Russello and Dulay [94] | performance metrics | XML | technical expertise required | audit | – | – |
| Schütte and Brost [96] | performance metrics | Java | technical expertise required | audit | – | – |
| Teijão et al. [101] | performance metrics | – | – | – | – | – |
| Wüchner and Pretschner [109] | performance metrics | – | – | – | – | – |
| Wüchner et al. [108] | performance metrics | XML | trust | reduced system complexity | – | – |
| Weber and Silva [105] | performance metrics | XML | – | audit | – | – |
| Xu et al. [110] | performance metrics | XML | – | trust | – | – |
| Zhang et al. [112] | performance metrics | XML | – | – | – | – |

5.3.5 Administration. Interfaces that allow users to create and manage their usage control policies, modelled on XACML policy administration points, are proposed by [5, 14, 20, 32, 44, 58–62, 64, 67–69, 74, 75]. Other frameworks propose graphical user interfaces (GUI) [6, 13, 15, 78], simple policy editors [105], relying on operating system command line interfaces [28, 110], or leverage editors that are built into development environments [96].

5.4 Robustness

Usage control robustness is an all-encompassing term used to refer to performance, scalability, interoperability, compatibility, usability, transparency, and reliability. In the following, we elaborate on the various robustness mechanisms employed by the usage control frameworks that are summarized in Table 6.

5.4.1 Performance & Scalability. The framework adopted by Lazouski et al. [62] and Carniani et al. [14] was originally employed in a cloud computing setting. In order to validate the original proposal, different extended versions of the same framework are evaluated in various use cases, such as, enforcing parental control using Smart TVs [32]; enhancing the security of Fifth Generation (5G) network systems [58, 69]; enforcing data protecting in industrial IoT settings, namely, collaborative smart services [20], smart homes [60], general-purpose IoT architectures [61], and securing communications between IoT devices [59]. Moreover, another extension is mentioned in [68] without any details on the physical implementation or performance. Finally, the framework
was used in a mobile computing context [67], however, the authors do not provide any evaluation
details. The frameworks presented in [5, 6, 13, 15, 28, 64, 74, 75, 77, 78, 96, 101, 105, 108, 109, 112]
are evaluated using various performance metrics, such as the time needed to evaluate a policy
decision request; memory usage; or the time needed to enforce a policy decision. While, the frame-
works presented in [6, 13, 15, 74, 75, 78] are validated using different uses cases in the context of
industry 4.0, particularly, for easing and ensuring secure data sharing in ecosystems, such as smart
cities. Only the framework proposed by Bai et al. [5] is evaluated in comparison to other usage
control proposals. The authors compared the execution time of ConUCON to an existing security
mechanism based on common actions that a user would perform on their phone. In addition to
using performance metrics to evaluate their approaches, the frameworks proposed by Feth and
Pretschner [28], Wüchner and Pretschner [109], and Wüchner et al. [108] employ others measures
that are relevant from a security perspective (e.g., analyzing attacker models and evaluating security
countermeasures).

5.4.2 Interoperability & Compatibility. Most frameworks encode their policies using XML due to
its strong interoperability capability. Additionally, Cao et al. [13] have designed their framework
components as an Application Programming Interface (API) in order to support the interoperability
of shared services between data consumers and data providers that do not belong to the same
domain. Although, the authors highlight the fact that semantic technologies could be used to
facilitate exchange between users, they do not leverage semantic technologies in their framework.
In turn, Schütte and Brost [96] adopt the Java programming language, which supports different
protocol adapters that are particularly suitable for IoT scenarios where data from different sources
must be unified. Hence, the authors implemented their PEP using Apache Camel, which supports
more than 240 protocols (e.g., Hypertext Transfer Protocol (HTTP), MQ Telemetry Transport
(MQTT), etc.).

5.4.3 Usability. The frameworks presented in [5, 15, 20, 32, 60, 61, 64, 67, 68, 74, 75] do not discuss
the usability of either their policy languages or their user interfaces. Whereas, Feth and Pretschner
[28] mention that the usability of a policy language is always a concern. On the one hand, the
expressiveness of a language can reflect the real use cases of usage control policies. On the other
hand, the correct and adequate use of complex policies is hard for non-expert users. The authors of
the framework proposed by Teigão et al. [101] claim that their policy language is an easy-to-use and
well-defined language, but they do not provide any evaluation of the usability of their prototype.
Cao et al. [13] provide an interface whereby users need to have basic knowledge with respect to
defeasible logic in order to manage policies. The GUI proposed by [6, 78] simplifies personal data
management by providing a variety of policy templates that can be employed by users. Additionally,
although the authors of the LUCON framework [96] claim that their language is easy to understand,
users need to be familiar with the UCON DSL grammar in order to write policies. The interface
proposed by Jung et al. [44] can only be used by experts that know the various events and system
actions that can be used within the policy description. However, the authors mentioned that they
are researching approaches on how to build user-friendly specification interfaces that allow even
unskilled users to specify their security demands. They also indicated that the use of different
usability patterns that include different user groups with varying skill levels and expertise will be
further studied.

5.4.4 Reliability. The reliability of the usage control framework is highly dependent on different
mechanisms employed in order to ensure the transparency and reliability of the system.

Transparency. As depicted in Figure 4, transparency can be established through four dimensions.
The first dimension for ensuring transparency is the use of auditing tools. Several authors [15, 28,
44, 77, 94, 96, 105, 108, 109] have emphasized the importance of using auditing mechanisms by including logging tools in their frameworks in order to provide evidence that users are using the data according to agreed policies, but also to track violations that usage control solutions are not able to detect (i.e., uncontrollable policies). The second dimension relates to data provenance. Cao et al. [13] designed the data usage traceability component based on defeasible logic for the purpose of tracing data usage history, whereas Cirillo et al. [15] made use of blockchain technologies in order to ensure traceability of data usage. The third dimension concerns explanations. Only two frameworks [13, 96] provide proofs to justify the decisions of the system using inference engines based on defeasible and first order logics, respectively. Providing explanations of how the decision of either granting, denying, or revoking access was reached can help users to trust the decisions of the framework, but also support policy authors in fixing issues. The last dimension concerns trust. According to Cao et al. [13], one important aspect of building trust is for the data owner to be able to exercise control over the usage of the data by other actors. Munoz-Arcentales et al. [74, 75] highlight the importance of using reliable and transparent usage control mechanisms in order for trust to be fully ensured. The frameworks presented in [28, 77, 105, 108, 109] employ trusted computing technologies, which enhance usage control mechanisms through the inclusion of hardware-based trust components. Whereas, the reference architecture presented in [74, 75] relies on international data space (IDS) [83] connectors, which ensure that all the connectors or mechanisms involved in a data exchange run on top of a certified software stack. This is done through the IDS certification body that provides certifications for the connectors in order to establish trust among all participants. The framework presented in [6, 78] includes trust management by modelling trust relationships and recommendations using the Seckit policy language.

System Reliability. The level of reliability depends on the ability of usage control solutions to guarantee that usage control policies are enforced correctly. Baldini et al. [6] and Neisse et al. [78] relate the reliability of their usage control framework to the support for trust management that can ensure reliable and trusted relationships between architectural components and users. Cirillo et al. [15] mention that their choice of decentralized enforcement of policies improves the reliability of their framework by ensuring a good orchestration and synchronization between the system components. The framework proposed by Munoz-Arcentales et al. [74, 75] relies on IDS trusted connectors, which guarantee a reliable environment that enables usage control. Wüchner and Pretschner [109] claim that the reduction in complexity of their system compared to other usage control systems increases the reliability of their usage control framework. In turn, Russello and Dulay [94] highlight the importance of adopting robust and reliable usage control frameworks. Although the authors do not consider or assess the reliability of their proposed framework, they do stress the importance of employing mechanisms that can protect usage control policies from unauthorized access, especially in distributed environments.

6 Discussion

In this section, we use the insights gained from our detailed usage control framework analysis in order to highlight open challenges and opportunities for the usage control domain in general and decentralized systems in particular.

6.1 Gaps Analysis

In the following, we identify open challenges and opportunities for the usage control domain, which we categorize under the headings: generality of policies; automated formal analysis, usability, verification and validation; and benchmarking.
6.1.1 Generality of Policies. The majority of frameworks rely on specific policy languages that were developed according to domain-specific requirements in relation to Mobile, Cloud, IoT, and Industry 4.0. (e.g., DUPO [13] and U-XACML [17]) and networking, operating systems, and collaborative software (e.g., LUCON [96] and UCONK [110]). While, the policy languages that are meant to be domain-agnostics are either not validated using use cases (e.g., OB-XACML [48]) or are only evaluated in a specific domain (e.g., INDUCE [44] and [105]). Hence, it is unclear if the existing proposals could be used for usage control in the general sense, where a single system may need to support privacy preferences, regulatory requirements, licenses, etc. Given that usage control policies require both domain and application specific information, semantic technologies could potentially be used to develop a common policy model that provides support for different types of usage control policies. Semantic technologies are particularly suitable for the specification of policies, as ontologies and vocabularies can be used to formalize both policy concepts and rules in an extensible manner. In their privacy and data protection survey, Esteves and Rodriguez-Doncel [26] examine various policy languages that leverage semantic technologies, such as ODRL [106], the data privacy vocabularies (DPV) [11], GDPRtExt [84], and the SPECIAL policy language (SPL). In another survey, Pellegrini et al. [87] discuss how semantic technology based policy languages can be used to express DRM restrictions. Among the most prominent vocabularies are MPEG-21, ODRL, the creative commons rights expression language (ccREL), and XACML, to name but a few. However, here also, it is unclear if the existing proposals are suitable for a system that needs to consider a variety of different usage control policies.

6.1.2 Automated Formal Analysis. The majority of existing usage control frameworks do not include a reasoning engine that could be used to automatically enforce usage control policies. This is usually due to the fact that their policy languages lack underlying formal semantics. According to Han and Lei [34], formal approaches for describing policy languages facilitate automated analysis, policy verification, and explanations that can help manage the behavior of a system. For instance, automatic formal analysis could help to continuously verify compliance using usage policies, audit trails, and shared data. While, policy verification could be used to manage conflicting policies and to ensure policy consistency. Growing dynamic environments, such as the web or IoT-based data sharing systems, where new users continuously join, pose new challenges in terms of unpredictability and dynamicity [21]. When it comes to automated policy analysis, the W3C community group is working on a formal semantics for the ODRL standard, which could potentially be used to facilitate the automated analysis needed to cater for system unpredictability and dynamicity. Unfortunately, the provision of a usage control framework, which provides a blueprint for the development of an architecture that leverages said formal semantics, is outside of the remit of the ODRL community group.

6.1.3 Usability. Based on our analysis of various usage control frameworks according to application domain, we observe that the operating systems, collaborative computer systems, and network security domains do not focus on the usability of the interfaces that they provide. That being said, generally speaking usability is a consideration when it comes to mobile computing and Industry 4.0 as these areas attempt to empower users to manage their own data and how it is used by data consumers. Since the entry into force of the GDPR in 2018, significant changes have been observed in the way personal data are processed and the rights afforded to data subjects. The empowerment of users implies facilitating user awareness via tools that enable users to: (i) give their consent for personal data processing; (ii) provide preferences concerning how their data are processed; (iii) have the ability to access, modify, and delete their personal data; and (iv) have the right to be informed about the processing of their personal data. The implementation of these rights requires the development of user-friendly interfaces that allow users to easily manage their preferences and to control how their data are used. To address these challenges, semantic technologies can be used to develop ontologies and vocabularies that provide a structured representation of preferences, policies, and rules. These ontologies and vocabularies can then be used to develop user-friendly interfaces that allows users to easily manage their preferences and to control how their data are used.

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4MPEG-21, https://mpeg.chiariglione.org/standards/mpeg-21
5ccREL, https://www.w3.org/Submission/ccREL/
6https://w3c.github.io/odrl/formal-semantics/
should be handled; (iii) benefit from data processing transparency; and (iv) profit from explainable policy decisions. For this, administration interfaces must be user-centered and user-friendly, thus enabling the user to understand their rights while at the same time guiding them in the protection of their data. In the case of the frameworks examined herein, most of them do not mention usability and/or human-computer interaction (HCI) as important design considerations. There is a broad body of literature that could potentially be used to enhance the usability of existing usage control systems. For instance, Mazumder and Das [70] propose usability principles that enable designers to consider the usability of a system early in the development cycle. Whereas, different works from privacy/legal researchers, such as [23, 71], could potentially be used to guide both usage control solution design and evaluation.

6.1.4 Verification and Validation. Usage control policy-based frameworks are intended to protect data from malicious use and prevent unwanted operations such as the sharing data with untrusted third parties. Usage control policies are usually based on high-level goals provided by data providers/owners that are then translated into machine-readable policies. The success of a usage control system relies heavily on the absence of discrepancies between policy specification and their intended high-level goals. A major drawback observed after comparing the various usage control frameworks is the lack of verification and validation tools that can be used to assess the accuracy and the correctness of the proposed usage control mechanisms. When it comes to the broader verification and validation literature, there are a number of possible techniques, such as those examined by Karafili et al. [47], which have already been successfully applied to systems that employ model checking, algebraic solutions, abductive reasoning, answer set programming solvers.

6.1.5 Benchmarking. As for evaluating the effectiveness of the various usage control solutions, the authors propose different evaluation schemes, which makes it difficult to compare the various proposals against one another. For example, in [112] the execution time metric is calculated based on the time required to update policy attributes, to interpret the policy rules, and to communicate with other components; whereas in [5] the metric depends on the type of actions performed by the users and the time needed to perform obligations and retrieve contextual or attribute information. Consequently, there is a need to develop a usage control benchmark that defines standardized characteristics, such as performance, scalability, etc. In their work, von Kistowski et al. [103] give important insights on how to build standardized benchmarks based on a set of quality criteria. The authors cite relevance, reproducibility, fairness, verifiability, and usability as key characteristics needed to build a benchmark. In our case, relevance implies choosing suitable and applicable characteristics for comparing different usage control frameworks. Based on our comparative analysis, we have already observed some common metrics for evaluating usage control frameworks, for instance, the time to process usage control policies and the memory usage needed to process policies. The remaining features imply that the benchmark is capable of: (i) reproducing similar results when the same test configuration is used; (ii) ensuring fair competition with other benchmarking tools; (iii) producing reliable and accurate results; and (iv) providing user-friendly tools that facilitate the execution of comparison experiments.

6.2 Decentralized Usage Control

Decentralized IoT-based use case scenarios, such as the motivating scenario which we introduced in Section 2, bring an additional set of considerations from a usage control perspective. Thus, we end our analysis with a discussion of the various usage control challenges and opportunities that have been derived from our motivating use case scenario.

6.2.1 Data sharing and Lack of Control. Once data are shared or accessed, they will move outside the premises of the data provider and therefore out of their control. For instance, users of the data
sharing platform in our IoT-based scenario, will no longer be able to control what happens to their data after they give their consent for stakeholders to use this data. Besides, different copies and derivations of the same data can be shared across the network, which makes it difficult to control how data are used [28, 109]. When it comes to the literature with respect to increasing control over data usage, proposals either involve employing information flow tracking tools or using sticky policies [22, 40, 72].

**Information Flow Tracking Tools.** Dynamic information flow tracking (IFT) involves the tagging and tracking of data as they propagate across network systems [40]. In distributed usage control, IFT is deemed complementary to policy enforcement, as it allows for the protection of the different data derivations shared across system nodes in a distributed environment [28, 50, 51, 91, 109]. IFT tools are often tailored for scenarios such as the web [33, 43, 111] and the cloud [29, 57, 85], among others, in order to cater for different aspects of data usage control, namely privacy preservation, regulatory compliance, and sensitive information protection. Generally speaking, IFT tools are either hardware-based or software-based. According to Hu et al. [40], most of the hardware IFT solutions can be vulnerable to security threats and are complex to debug. While, Demir et al. [22] point out that most IFT software solutions come with low security guarantees and high programmability impacts, which increases the reluctance to use such techniques.

**Sticky Policies.** Sticky policies represent restrictions on the use of data, which are directly attached to the corresponding data. Interest in sticky policies has increased with the emergence of new distributed technologies [72]. By using sticky policies in a decentralized environment, data consumers could potentially ensure that their usage policies are enforced after data are transferred from one system to another. In their survey, Miorandi et al. [72] compare and contrast sticky policy solutions for the cloud, the IoT, and context-aware applications, among others. Additionally, the authors outline several approaches for sticky policies, such as, encryption (e.g., public-Key encryption (PKE), identity-based encryption (IBE), and attribute-based encryption (ABE)), sticky policy languages (e.g., the enterprise privacy authorization language (EPAL) and the PrimeLife privacy policy language (PPL)), and sticky policy for access control (e.g., the purpose-aware role based access control (PuRBAC) model). They also provide a list of challenges that still need to be addressed before sticky policies can be adopted. For instance, the need for robust encryption techniques; the standardization of an expressive sticky policy language; and the adoption of mechanisms that are able to distribute and synchronize policies across decentralized systems in a controllable and secure way.

### 6.2.2 Distributed Trust Management

A distributed environment can be composed of heterogeneous entities and systems that interact with each other, which brings about trust issues in relation to dependability, security, and reliability [2]. Accordingly, in our IoT scenario, smart objects (e.g., sensors, phones, cars, and services) and entities (e.g., the marketing company, users, and manufacturers) can be of different forms and types, hence, the interaction between the different entities and devices should be trusted in order to ensure secure and reliable infrastructure. In their survey, Artz and Gil [4] compare and contrast different approaches for trust management in computer science, namely, policy-based trust, reputation-based trust, and general models of trust that could serve as interesting starting points. The establishment of trust can be facilitated via the use of trust negotiation solutions that are based on enforcing trust policies and/or the exchange of security credentials, among others. Different semantic languages have already built-in mechanisms for trust negotiation. For instance, the web services security (WS-Security) policy⁷, a standard introduced by the W3C, in order to provide ways to attach signatures and encryption headers or security

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⁷WS-Policy, https://www.w3.org/Submission/WS-Policy/
tokens during communication between system nodes, or the PeerTrust language [79] that involves automated trust negotiation. The exchange of credentials implies the presence of an authority that can verify the provided credentials. An example is the international data space (IDS) [83] initiative that specifies that all parties involved in data exchange need to use IDS certifications issued by the IDS certification body, which is a trusted third party. Another example concerns the use of blockchain smart contracts, where there is no need for a third party to verify identities. Smart contracts are very relevant in fields such as the IoT, where different parties are involved in data exchange, as they can be used to facilitate trusted and reliable transactions [65]. Several proposals that employ smart contracts in order to establish trust have already been proposed (cf., [25, 54, 97, 107]). When it comes to other approaches to trust management, reputation-based trust can be used to assess trust relationships, while general models of trust involve trust properties and relationships from different domains with different resources [72]. That being said, distributed applications impose challenges, such as the need for scalable trust management solutions that support an increasing number of nodes; the importance of considering different types of reputation metrics that vary from one domain to another; and the automation of trust management using trust policies.

6.2.3 Distributed Enforcement. In a usage control scenario, two main entities are always present: the data provider and the data consumer. In our IoT use case, the data consumer and data provider roles may be interchangeable, as a data consumer may be a data provider, and vice versa. For example, manufacturers can be data consumers of residents’ data. However, they can also be providers of residents’ data to other stakeholders, such as the marketing companies. Hence, a distributed system must not only enforce usage control policies on data leaving the providers domain, but also control the usage to resources or data in the consumers domain.

Policy Enforcement Point and Policy Decision Point. Using IFT to track data or sticky policies to enforce usage policies, or a combination of both, requires techniques that are capable of ensuring that policies and data usage are always observed and enforced in a decentralized environment. Kelbert and Pretschner [50] and Cirillo et al. [15] highlight the importance of using a reference architecture including a local policy enforcement point and a policy decision point at every site. In addition, mechanisms such as auditing should be put in place in order to trace the various interactions and transactions that occur within a system, but also to collect information provided by data monitoring tools.

Auditing. Pretschner et al. [89] state that detective mechanisms, particularly audit logs, are of particular interest in a usage control framework in order to verify that data consumers abide by usage control policies. Detective mechanisms are complementary to preventive mechanisms, especially if data are shared with third parties and the control of how data are used becomes more difficult. Moreover, according to Bonatti et al. [12], audit logs present the core of any transparency architecture as they can be used to both record data transactions and what happened to the data. In a decentralized usage control framework, the use of a hybrid approach involving a local internal ledger and a distributed ledger could be warranted. For instance, a local ledger could provide information about what happened inside the local component of the framework, while a distributed ledger could be used to trace what happened between services/ components and their relationships. However, this approach presents different challenges when it comes to the interoperability between ledgers from different consumers, and difficulties in retracing all events in a unified manner, which complicates compliance checking. Modeling events using semantic technologies could potentially resolve these issues by: (i) using a common schema to describe logs; and (ii) modeling and describing what happened to data using description vocabularies that represent and relate information from
different sources (i.e., data consumers) in an understandable and timely manner. There is already numerous vocabularies that could potentially be adapted to describe the provenance of data, such as PROV\textsuperscript{8}. Additionally, there are different vocabularies to describe the data processing events, such as Event\textsuperscript{9} and the LODE ontology\textsuperscript{10}.

7 Conclusion

This paper provides an overview of the usage control domain by comparing and contrasting the predominant usage control frameworks found in the literature. We started by examining various usage control concepts and providing a broad definition for usage control policies based on deontic concepts. Guided by an integrative research methodology, we collected and categorized requirements that have been used to guide the development of various usage control solutions. These requirements address both the “what” and “how” aspects of enforcing usage control policies, in particular, the specification, the enforcement, and the robustness of the proposed solution. We subsequently compared and contrasted the predominant usage control frameworks based on our resulting taxonomy of requirements.

We subsequently broadened the discussion to include opportunities and challenges that can guide future research directions. We highlighted that due to their flexibility and interoperability, semantic technologies are particularly suitable for encoding usage control policies. Following on from this, we discussed the key role played by reasoning when it comes to policy compliance, consistency, transparency, and system security. Additionally, we identified the need for additional research from a usability and a human computer interaction perspective in order to enable users to manage their data. We also highlighted the importance of benchmarking in order to systematically assess and validate the robustness of different usage control solutions. Finally, we showed the need to employ verification and testing tools in order to enhance the reliability and accuracy of usage control proposals.

Finally, we outlined further challenges and opportunities that arise with the emergence of modern decentralized and distributed environments. Key considerations include the potential brought about by information flow tracking tools and sticky policies when it comes to tackling issues with respect to controlling how data are shared and used. Additionally, we highlighted the key role played by distributed trust management approaches in order to establish dependable, secure, and reliable data sharing infrastructures. Finally, we underlined the need for preventive and detective enforcement mechanisms for ensuring the correct enforcement of usage policies.

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\textsuperscript{8}PROV, \url{https://www.w3.org/TR/prov-overview/}
\textsuperscript{9}Events, \url{http://motools.sourceforge.net/event/event.html}
\textsuperscript{10}LODE, \url{http://linkedevents.org/ontology/}
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