Engineering Self-adaptive Authorisation Infrastructures

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Abstract. As organisations expand and interconnect, authorisation infrastructures become increasingly difficult to manage. Several solutions have been proposed, including self-adaptive authorisation, where the access control policies are dynamically adapted at run-time to respond to misuse and malicious behaviour. The ultimate goal of self-adaptive authorisation is to reduce human intervention, make authorisation infrastructures more responsive to malicious behaviour, and manage access control in a more cost effective way. In this paper, we scope and define the emerging area of self-adaptive authorisation by describing some of its developments, trends and challenges. For that, we start by identifying key concepts related to access control and authorisation infrastructures, and provide a brief introduction to self-adaptive software systems, which provides the foundation for investigating how self-adaptation can enable the enforcement of authorisation policies. The outcome of this study is the identification of several technical challenges related to self-adaptive authorisation, which are classified according to the different stages of a feedback control loop.

1 Introduction

A critical concern for organisations surrounds the assurances of confidentiality, integrity, and availability of their computer based resources. To provide such assurances, organisations utilise access control to protect against unauthorised access. Regardless of adopting a fine grained approach to access control, abuse of access is still possible. Any form of access, no matter how restrictive, presents the risk of attacks due to uncertainty in user behaviour. To accommodate for this risk, organisations employ a range of methods \cite{42} to monitor and audit access within their systems and resources.

Traditionally, human administrators are relied upon to actively identify and drive changes in access control in response to detected abuse, natural organisational change, or identified errors in the criteria for access. It is challenging for human administrators to maintain a true awareness of the configuration of access, particularly within a run-time environment. With no complete view of access, obtaining assurances \cite{30} against changes made to mitigate the abuse of
access is limited. This potentially enables erroneous changes that cause a greater impact to the organisation over identified abuse. In addition, and as evident in case studies of historic insider attacks [16], the use of human administrators alone is inefficient in mitigating abuse in a timely manner. Improving on access control methodologies is one solution, yet such approaches [10,33,41,57] are unable to actively mitigate abuse, since they are constrained to a static definition of the criteria for access control at run-time.

Implementations of authorisation infrastructures [19] must be capable in handling the dynamic aspect of risk at run-time, driven by the uncertainty in user behaviour. It is therefore necessary for such systems to actively observe how access rights are being used, in order to infer whether the current criteria and assignment of access are enabling a user to conduct malicious activity. A promising solution for the provision of dynamic support to authorisation infrastructures is the incorporation of self-adaptation.

Self-adaptive systems are systems that are able to modify their behaviour and/or structure in response to changes that occur to the system itself, its environment, or even its goals [22]. Applying self-adaptive techniques to authorisation infrastructures enables the infrastructure to observe, reason, and act on its own configuration of access control. Through the use of a feedback loop [15], it is possible to employ a clear separation of concerns between the decision for access, and decision for a management change, therefore reducing the complexity in the criteria for access that dynamic access control approaches introduce.

The main contribution of this paper is identification of several technical challenges associated with the self-adaptation of authorisation infrastructures. The relevance of the identified challenges is discussed in the context of insider threat examples related to a Customer Energy Management System (EMS) case study. Another contribution is related to how the self-adaptation of authorisation infrastructures should be structured in order to handle parametric adaptations, i.e., the specification of access rights of subjects to resources, and structural adaptations, i.e., the enforcement of those specifications by controlling the subject’s access to a resource.

The rest of paper is organised as follows. Section 2 presents the concepts and terminology related to access control and authorisation infrastructures, and provides a brief introduction to self-adaptive software systems. In Section 3 we introduce a simple case study, based on NIST Smart Grid specification, that will be used as a basis for introducing self-adaptive authorisation infrastructures. We review the related work on dynamic access control in context of self-protection in Section 4. In Section 5 we map our perception of self-adaptive authorisation infrastructures into the modelling dimensions for self-adaptive software systems. Section 6 identifies, in terms of the key stages of a feedback control loop, like the MAPE-K loop, some challenges associated with the engineering self-adaptive authorisation infrastructures. Finally, Section 7 concludes the paper and indicates directions for future work.
2 Background

The focus of this paper is the application of self-adaptation in the management of privileges and the rendering of access control decisions, in order to reduce the need for human intervention, whilst reducing cost, and enabling systems to robustly adapt when responding to change. As such, the following section discusses some background topics, including, prominent access control models, authorisation infrastructures as a means to implement access control, static and dynamic access control, self-adaptive authorisation infrastructures that are capable of adapting themselves at run-time, and finally, insider threats that we employ as a motivation for managing access control.

2.1 Access Control Models

In the literature, the terms authorisation and access control are sometimes used interchangeably. In this paper, we define them as follows.

Definition 1 (Authorisation). Authorisation refers to the specification of whether a subject has access to a resource.

Definition 2 (Access control). Access control refers to the enforcement of authorisation by controlling (i.e., granting or denying) subject's access to a resource.

The goal of access control is to prevent unauthorised access to protected resources. A resource could be anything from a software system (e.g., web application and database) to an electronic device (e.g., electronic door lock and mobile phone). Through the specification of authorisation, captured in terms of policies, an organisation garners a certain level of protection from unwanted access.

Authorisation embodies two concepts: identities and permissions. An identity is a digital representation of a subject (a user), where a subject could be a human being, a system, or even a process [10]. An identity contains information about the subject, particularly relevant for authentication [58], where a subject must identify themselves, for example, entering in a username and password, or use of biometrics [61]. Most importantly, an identity contains a set of the subject's access rights (also referred to as privileges [20]). Access rights, as the name suggests, represent a subject’s right of access to a resource, used in accordance to a set of permissions. Once a subject obtains the required access right(s) to a resource, the subject is said to be authorised.

Access control models classify and define how permissions are expressed, who can define permissions, and what an access right looks like [53]. For example, Mandatory Access Control (MAC) [37] enables subjects with a set of security attributes to access resources in conformance to centrally specified permissions (i.e., defined by security administrators). In contrast, Discretionary Access Control (DAC) [37] enables subjects in a similar sense to MAC to access resources, however, permissions can be specified by the subjects themselves in relation to
the resources that they own. Another access control model is the Bell-LaPadula Model (BLP) [9] where permissions are based on labelled classifications, such as, Top Secret or Public, and a subject’s level of security clearance.

Arguably, the most adopted access control model in industry is the Role-Based Access Control (RBAC) model [50], where recently 50% of the 150 companies surveyed by the National Institute of Standards and Technology (NIST) had adopted RBAC by 2010 [54]. RBAC introduced the notion of roles, whereby a role is assigned a set of permissions that enable access to a resource. Finally, the Attribute-Based Access Control (ABAC) model [77] presents a more generic view of the RBAC model, where instead of roles, attributes (a type - value tuple) are used in order to collate and assign permissions.

Role Based Access Control (RBAC). The Role Based Access Control (RBAC) model is the culmination of work by Ferraiolo et al. [26] and Sandhu et al. [64] that led to the NIST RBAC standard [50]. The RBAC standard is defined by three layers, each layer extending the layer prior with additional features. These layers are referred to as Core, Hierarchical, and Constrained.

RBAC Core defines the fundamental elements that must exist within an implementation of RBAC model, namely: subjects (identities), roles, resources, actions, permissions, and sessions. Subjects are assigned a set of roles, where a role defines a function within an organisation (e.g., operations manager). Roles are assigned permissions, where each permission details the ability for a subject to execute an action (e.g., print) on a resource (e.g., printer). A subject’s session captures a set of roles that the subject has currently activated. RBAC Hierarchical extends RBAC Core by introducing the ability for roles to inherit permissions of another role. RBAC Constrained extends RBAC Core and RBAC Hierarchical by introducing constraints in regards to subjects and roles.

A limitation of the RBAC model is the focus on roles as access rights, which restricts the ability of a subject to access resources only via the subject’s organisational role(s). This both limits or overly exposes access to a resource since roles lack the granularity to final control access to resources. Potentially, organisations may have to create fictitious roles, not representative of the actual organisational structure, to ensure proper access to resources. In addition, the RBAC model provides no means to address multi-organisational access control, where access control is managed between several organisations. As a result, this could increase the complexity of roles and permission assignments within RBAC rules, making access more challenging to support.

Many proposals extend RBAC, highlighting not only RBAC’s popularity in industry, but also in research. Kalam et al. extend RBAC to include the notion of organisations in Organisation Based Access Control (OrBAC) [35]. Introducing organisations enables the specification of RBAC rules relevant to an organisation, where there are many sources of authority (SOAs) sharing access, and enabling organisations (and SOA) to define permissions solely for their own resources. Similar work by Demchenko et al. also address the problems caused by multiple sources of authority, proposing Role Based Access Control for Dis-
tributed Multidomain Applications (RBAC-DM) [24]. Demchenko et al. highlights limitations of RBAC in collaborative environments (containing multiple SOAs), and addresses them via the use of multi-domain authorisation sessions (where an RBAC session can span across several organisational domains). Lastly, Bertino et al.'s GEO-RBAC [21] introduces the notion of location, where a subject’s geographical location influences the activation of a subject’s assigned roles. GEO-RBAC addresses the need for spacial aware access control, where subjects may only access a resource depending on their location.

Attribute-Based Access Control (ABAC). Attribute Based Access Control (ABAC) is a recent development in access control models. There are a number of proposals [31], critiques [63], and implementations [19,36,2]. ABAC can be considered a natural progression from the RBAC model, whereby instead of permissions assigned to roles, permissions are assigned to attributes of a subject, resource, and their environment. An attribute describes some aspect of their associated entity, such as, a name or user group (for a subject), the number of active sessions (of a resource), or time of day and location (in the system’s environment). These attributes can be defined in such a way to create permissions with a fine granularity of access, where a permission may state that subjects only from user group ‘HR’ can access a resource with no more than 10 active sessions, between the hours of 9am and 5pm. In addition, ABAC is seen as a generalisation of RBAC, where RBAC roles are implemented as ABAC attributes assigned to subjects.

ABAC implementations and proposals have put forward additional criteria for access control, as opposed to simply replacing the notion of roles in RBAC with attributes. Notably, environment conditions are considered in order to provide additional context to a subject’s request for access. For example, a subject requesting access outside of normal office hours should not be granted access, despite having the necessary attributes to gain authorisation to the resource. The inclusion of environment conditions has the ability to expand the criteria necessary to award access, and further protect an organisation’s resources from attacks (e.g., credential stealing attacks [65], by blacklisting IP addresses based on location data observed in the environment).

Sandu has argued that the leap from RBAC roles to the use of attributes offers a number of benefits [63], highlighting the fact that ABAC unifies many access control models, for example, roles (RBAC), location (GEO-RBAC), security labels (Bell-LaPadula), and access control lists (DAC). However, the resulting benefits of ABAC come with increased complexity. Organisations now have to be more specific when utilising ABAC, as access rights could be represented as anything that might be owned by a subject, resource, or environment. This has the potential to lead to conflicts, or increased challenges when managing access, due to no clear representation of an access right.

Implementing Access Control Models. Traditionally, access control models have been implemented as bespoke components of information systems. Imple-
mentation concerns both ‘authorisation’ being how to capture and express identities, privileges, and permissions, and ‘access control’, referring to the process that can render access control decisions. A problem with this approach is the heterogeneous qualities of resources an organisation may wish to protect, often requiring each resource (e.g., a web application) to implement its own form of access control.

A solution to this problem is implementing access control models in a service orientated way, as demonstrated by the eXtensible Access Control Markup Language [52]. XACML is a popular standard for implementing ABAC and RBAC models, and provisions a reference architecture in which to guide implementation. XACML standardises the way in which identities and permissions are defined, communicated, and assessed in order for its reference architecture to render access control decisions. It does this through the use of authorisation policies (to express identities, privileges, and permissions as ‘attributes’ and ‘rules’), and the use of standardised protocols (e.g., SAML [53]). Authorisation policies embody the ‘authorisation’ aspect of an access control model, whereas the protocols support ‘access control’ via retrieval of privileges, and deliverance of access control decisions.

XACML’s reference architecture describes a set of components that exist to facilitate access to protected resources. The reference architecture defines a four tier process to access control: \textit{Enforce} requests and decisions to access, \textit{Decide} upon access, \textit{Support} retrieval of credentials and policies, and \textit{Manage} administration of policies. This process is implemented through a set of conceptual components that when combined achieves access control (Table 1). These components are the enabling factors for controlling access, whereby in real systems that implement such components, access control can easily be monitored and managed. A key selling point of the XACML reference architecture is the separation between access control and resources, where access control primarily becomes a service that resources and users can rely upon.

| Component                          | Description                                                                 |
|------------------------------------|-----------------------------------------------------------------------------|
| Policy enforcement point (PEP)     | Makes access requests and enforces access decisions                           |
| Policy decision point (PDP)        | Evaluates access requests against policies to provide access decisions       |
| Policy information point (PIP)     | Contains subject identity information (attributes)                           |
| Policy retrieval point (PRP)       | Contains ABAC authorisation policies to govern access decisions              |
| Policy administration point (PAP)  | The source of authority / system that issues access control policies         |

\textbf{Table 1.} XACML components
The XACML reference architecture has arguably sparked the rise of access control as a service, where we refer to such solutions as *authorisation infrastructures*.

### 2.2 Authorisation Infrastructures

An authorisation infrastructure [19] is a loose term for a collection of services and mechanisms that implement an access control model. There are a number of varying terms for authorisation infrastructures, such as, the ones defined by authentication and authorisation infrastructures (AAIs) [10], XACML’s reference authorisation architecture [52], and privilege management infrastructures [20]. We adopt the following rather simple definition for authorisation infrastructure.

**Definition 3 (Authorisation Infrastructure).** *Authorisation infrastructures facilitate the management of identities, privileges and policies, and render access control decisions.*

The key facet of authorisation infrastructures is the use of services that provide access control external to an organisation’s resources. This implies a separation of duties between provisioning of services by the resources, and the assessment of right to access [19, 27, 28]. Specifically, access control is implemented by the following key services:

**Identity services** responsible for the management of subject access rights, such as, access rights and subject identifiers.

**Authorisation services** responsible for the evaluation of access rights against access control rules, and decision of access.

The combination of both identity services and authorisation services should conform to an access control model (e.g., RBAC [50]). Based on existing implementations [19, 27, 28], identity services may authenticate subjects, and maintain, assign and release a subject’s access rights (i.e., privileges) to authorisation services based on policies (e.g., Shibboleth’s attribute release policy [43]). Examples of an identity service include directory services, such as, the Lightweight Directory Access Protocol (LDAP) [38]. Other forms of identity services include credential issuing services (such as, SimpleSAMLphp [67] and the Shibboleth identity provider [43]). These types of identity services not only maintain a subject’s access rights (privileges), but can be configured to decide what access rights can be issued and released to given services across multiple domains. Authorisation services may validate and evaluate a subject’s access rights against a set of policies (e.g., PERMIS’s access control and credential validation policies [3]). Examples of authorisation services include, the axiomatics policy server [1], PERMIS standalone authorisation service [3] (both of which utilise the XACML standard to define access control policies), and the community authorisation service (CAS) [60].

Figure 1 defines a general model of an authorisation infrastructure that abstracts away from its varying implementations. With reference to the flow of
communication to obtain authorisation, subjects (users) authenticate (1) with a
given identity service that maintains a set of access rights for each subject. The
authenticated subject can then request (2) access to a particular resource. The
resource’s policy enforcement point (PEP) communicates with an authorisation
service (3), which can first validate (4) the subject’s set of access rights, and then
decide upon access. The authorisation service sends a response back to the PEP
with a message indicating whether authorisation should be granted or denied
(5).

As already mentioned, authorisation infrastructures rely on policies to derive
access control decisions. Authorisation infrastructures may utilise a variety of
policy types, where an instance of a policy type will express rules relevant to
a particular service within an authorisation infrastructure. For example, poli-
cies within authorisation services are used to define the constraints of access
(i.e., RBAC role permission assignments), whereas policies and subject attribute
repositories (e.g., LDAP) within identity services contain or define what sub-
jects have in terms of assigned access. With this in mind, there are four types
of authorisation policies, which are defined as follows.

**Access Control Policy.** An access control policy specifies the security controls
of what credentials a subject must own in order to gain access to a set
of protected resources, what obligations they must conform to, and what
conditions they must meet.

**Credential Validation Policy.** A credential validation policy defines what
credentials an identity service is trusted to issue.

**Delegation Issuing Policy.** A delegation issuing policy defines the trust in
the extent of access a subject can delegate unto others.
Credential/Attribute Release Policy. A credential/attribute release policy defines what information an identity service will release on behalf of a subject to any requesting authorisation services or resources.

Associated with policies and access rights is the notion of source of authority (SOA) and issuer [19]. A source of authority is the owner of a resource that establishes the rules of access (as policies) to their resources. An issuer is the identity service or person responsible for issuing to a subject a set of access rights, which are either stored in an attribute repository as unsigned or signed attributes [32], or are generated at time of request [53].

Lastly, an additional quality of authorisation infrastructures is the ability to operate in federated environments (i.e., components of an authorisation infrastructure become component systems managed across multiple organisations). This is often referred to as federated identity management, or federated access control [24,31,35,70], and enables the sharing of access across multiple management domains (organisations). Various access control models are suitable for federated access control, demonstrated by several implementations [19,43,67].

Figure 2 conveys a high level overview of a federated environment, containing a service provider (SP) organisation and several identity provider (IdPs) organisations. An SP organisation offers access to their protected resources, whereas IdP organisations consume access to those protected resources. Subject identities managed by an identity provider component system can be assigned a set of attributes that are stored within an identity service (e.g., simpleSAMLphp [67]). Subjects can use their attributes to gain access to a SP’s resources given that the SP trusts the IdP. To control the release of attributes, some IdPs may define attribute release policies [43] to prevent certain types of information from being released to service providers. The service provider ultimately decides upon access through the use of authorisation services (which provide access control decisions local to the organisation).

![Fig. 2. Conceptual view of a federated authorisation infrastructure](image-url)
2.3 Static and Dynamic Access Control

We have seen how access control is a key element when implementing authorisation infrastructures. However, one thing not addressed is the distinction between traditional (static) approaches to access control, to more recent (dynamic) advanced approaches. In a static approach to access control, a user’s access rights are assessed against a set of security controls in order to determine access (e.g., RBAC [50]). This is limited since at time of access no additional context is assessed, such as, the user’s historical access, their location, time of day, or other external factors. With this in mind, static approaches are presumptuous in that, should a user have the necessary access rights, they should be awarded access.

Arguably, it is not always the case that access should be granted despite the user owning the necessary access rights. As such, there is a growing focus on dynamic approaches to access control that allow organisations to define a finer grain of control over access in response to varying risks, threats, and environment states. The definitions for static and dynamic access control are as follows.

Definition 4 (Static Access Control). Static access control refers to the evaluation of a subject’s access rights against a set of immutable authorisation policies for deciding the subject’s access to a resource, regardless of the context in which the request is made and evaluated.

Definition 5 (Dynamic Access Control). Dynamic access control refers to the evaluation of a subject’s access rights against a set of authorisation policies for deciding the subject’s access to a resource, taking into account the context in which the request is made and evaluated.

Dynamic access control differs from static access control because it is capable of employing various security controls that are related to changes in the state of the environment or protected resources, and user activity. As such, an authorisation policy may contain a diverse set of access control rules to accommodate a wide variety of scenarios (e.g., a rise in national security threat levels [41]). Appropriate access control rules are applied to requests for access in a mutually exclusive manner, given the context (i.e., state of the environment, such as, user activity or time of day) that surrounds the request.

The overall goal of dynamic access control is to reduce human intervention, make access control more responsive to attacks, and more cost effective. Several techniques have been proposed, including, resource usage [57], temporal properties [34], risk [41], and trust [12,65]. For example, in usage control [57] a perception of user activity is maintained over time and evaluated against thresholds of usage (e.g., a staff member may not print more than 100 pages per day), alongside traditional access control rules (e.g., a user must be assigned the role of staff to print). Additionally, ABAC can be seen as a dynamic access control model given its ability to define permissions that can be valid for a multitude of system states.
2.4 Self-adaptive Authorisation Infrastructures

With the goal of reducing human intervention, self-adaptation can be incorporated into existing authorisation infrastructures, thus enabling these infrastructures to manage themselves, at run-time, the definition of authorisation policies and process of access control. In particular, the focus of this paper is how self-adaptation can be integrated with authorisation infrastructures, and how authorisation infrastructures can self-protect against insider threats.

Self-adaptation. Self-adaptation enables a system to adjust itself in response to changes that might affect itself or its environment. Self-adaptive systems can be defined as follows.

Definition 6 (Self-Adaptive Systems [22]). “Systems that are able to modify their behaviour and/or structure in response changes that occur to the system itself, its environment, or even its goals.”

Although there are several reference models for self-adaptive systems [36,39,56], most of them share the common use of a feedback loop [14,25,29]. In this paper, we adopt as a feedback control loop, the Monitor, Analyse, Plan, Execute - Knowledge (MAPE-K) reference model [36], as shown in Figure 3.

In this diagram, the main feedback control loop, which embodies the stages of the MAPE-K reference model, observes (via probes) and adapts (via effectors) a target system. The Monitor stage enables to obtain the state of the target system and its environment. The Analyse stage analyses the state of the target system and its environment in order, first, to decide whether adaptation should be triggered (Solution Domain), and second, to identify the appropriate courses of action in case adaptation is required (Problem Domain). The Plan stage, first, selects amongst alternative course of action those that are the most appropriate (Decision Maker), and second, generates the plans that will realise the selected course of action (Plan Synthesis). The Execute stage executes the plans that deploy the course of action for adapting the system. Finally, Knowledge represents any information related to the perceived state of the target system and environment that enables the provision of self-adaptation.

Applying the MAPE-K reference model, we view an authorisation infrastructure as the target system, and all the rest, including the users and protected resources, as the environment. The role of a controller seeks to monitor both the target system and the environment in which to drive changes at run-time within the authorisation infrastructure. With this in mind, self-adaptation is capable of extending traditional approaches to access control, where such approaches become capable to respond to unplanned states, evolve to changing user needs, and maintain assurances in confidentiality, integrity, and availability of resources.

5 Also referred to as the self-adaptive layer.
Self-adaptive authorisation and self-adaptive access control. Self-adaptive authorisation has already been proposed by Bailey et al. [5, 6, 7], where legacy based authorisation infrastructures have been shown to mitigate, at run-time, attacks via the adaptation of authorisation (e.g., adaptation of authorisation policies and subject privileges). We define self-adaptive authorisation as follows.

Definition 7 (Self-Adaptive Authorisation). Self-adaptive authorisation refers to the run-time adaptation of the specification of whether a subject has access to resources.

The incorporation of self-adaptation into authorisation has highlighted a number of challenges that this paper aims to address, including the engineering of self-adaptive authorisation infrastructures, and practicalities of operating such systems at run-time. First, it is important to identify the differences between static approaches to access control (i.e., traditional, such as, RBAC), dynamic approaches (i.e., adaptive, such as, risk based), and self-adaptive ones.

Let us consider a subject requesting access to a resource outside of normal working hours, who then abuses such access in order to jeopardise the confidentiality of a resource. A static approach (i.e., static access control) will evaluate access based on purely the subject’s access rights alone, without considering the time of day, or the subject’s activity. A dynamic approach (i.e., dynamic access control) may select, from a pre-existing set of access control rules, a rule applicable for that time of day, using environmental attributes and the subject’s access rights. On the other hand, a self-adaptive approach may, at run-time, generate, modify, or remove the active set of access control rules (e.g., deploying a new authorisation policy, or revoking a set of user access rights) should a user be detected while abusing their access rights outside of normal working hours. Additionally, modifications instructed by a self-adaptive approach are based on a maintained perception of state of its target system and its environment.
Self-adaptive authorisation alone has some limitations. Specifically, it is limited to only mitigating attacks (e.g., insider threats) within the boundaries of an authorisation infrastructure’s implemented access control model, where adaptation is primarily parametric. Should services of an authorisation infrastructure suffer an attack, or the implemented access control model becomes vulnerable, an additional scope of adaptation is needed. As such, it is important to address the possibility of self-adaptive access control, which we define as follows.

**Definition 8 (Self-Adaptive Access Control).** Self-adaptive access control refers to the run-time adaptation of the enforcement of authorisation by controlling the subject’s access to a resource.

![Diagram of self-adaptive authorisation and self-adaptive access control](image)

**Fig. 4.** Self-adaptive authorisation and self-adaptive access control

Figure 4 emphasises the marriage of self-adaptive authorisation and self-adaptive access control, which allow us to mitigate attacks more effectively and efficiently, depending on the type of attack observed. Authorisation being the collection of policies that govern access, and access control being the process in how an access decision is achieved. From the diagram, we can see a distributed control topology of two controllers operating together in mitigating potential attacks originating from the environment of the authorisation infrastructure. The controller associated with self-adaptive authorisation observes activity of the authorisation infrastructure and its environment in order to gain a perception of malicious behaviour with relevance to the current state of authorisation policies. Should malicious behaviour be observed, this controller can adjust deployed authorisation policies to mitigate attacks. Similarly, the controller associated with self-adaptive access control may observe the authorisation infrastructure and its environment in order to identify if the current state of the employed access control model is fit for purpose. For example, external threats may warrant additional steps in validating subject credentials, and as such, the controller may
deploy credential validation services \[14\] between policy decision and policy enforcement points \[52\]. Based on the above, we define self-adaptive authorisation infrastructures as follows.

**Definition 9 (Self-Adaptive Authorisation Infrastructure).** Self-adaptive authorisation infrastructures refer to the run-time adaptation of the collection of authorisation policies and their enforcement.

**Self-protection.** Self-protection is of particular relevance since the goal of this work is to manage access control in order to mitigate abuse of access. Self-protecting systems can be defined as follows.

**Definition 10 (Self-Protecting System \[75\]).** “Self-protecting systems are a class of autonomic systems capable of detecting and mitigating security threats at run-time.”

There are various self-protective solutions that seek to detect and mitigate malicious behaviour. However, few works exist that are able to concretely address self-protection with a view to mitigate the abuse of access. Whilst many systems appear to be self-protective, such as, intrusion response systems \[44,69,71\], many are only adaptive and lack an awareness of ‘self’. A self-protecting system is clearly demonstrated by Yuan et al.’s architectural based self-protection framework \[76\], where a system maintains a modelled state of its own system architecture in which to guide mitigation of threats.

### 2.5 Insider Threats

Insider threat refers to an organisation’s risk of attack by their own users or employees. It is fast becoming a prominent topic that organisations need to address, as highlighted by recent scandals in the media \[8,14,71\]. This is particularly relevant to access control, where the active management of authorisation has the potential to mitigate and prevent users from abusing their own access rights to carry out attacks. The CERT Guide to Insider Threats (Cappelli et al.) \[16\] defines malicious insider threats as the following.

**Definition 11 (Insider Threat \[16\]).** “A malicious insider threat is a current or former employee, contractor, or business partner who has or had authorised access to an organisation’s network, system, or data and intentionally exceeded or misused that access in a manner that negatively affected the confidentiality, integrity, or availability of the organisation’s information or information systems.”

Cappelli et al. \[16\] classify three types of insider threat: *sabotage*, where malicious users attempt to damage or corrupt organisational resources, *theft* of intellectual property, where organisational resources are stolen and distributed, and *fraud*, where activity is covered up or information is used to commit crimes, such as, falsifying money transfers.
A common characteristic of insider threat is that malicious insiders utilise their knowledge of their organisation’s systems, and their assigned access rights, to conduct attacks. This places a malicious insider in a fortuitous position, whereby the insider (as an authorised user) can cause far greater damage than an external attacker, simply due to their access rights [17]. Such form of attack is representative of the attacks that many organisations consider to be most vulnerable from, being the abuse of privileged access rights by the employees of an organisation [55].

Unless additional measures are put into place, malicious insiders can abuse existing security measures, where current approaches fail to robustly adapt and respond to the unpredictable nature of users. For example, traditional approaches to access control assume that if a user has authenticated, and has the required access rights, access to resources should be given. Whilst there are a number of novel techniques that enable the detection of insider threat [2,51,68], there is little research that utilises such techniques within an automated setting. Many existing approaches require analysis by human agents to identify and execute resultant actions to mitigating attacks.

3 Case Study

In this section, we present a case study to illustrate the challenges in self-adaptive authorisation infrastructures, discussed in this paper. The case study is based on a subset of the NIST Smart Grid Cybersecurity specification [46].

3.1 The NIST Smart Grid Cybersecurity Specification

The NIST IR 7628 Guidelines for Smart Grid Cybersecurity [46] is an advisory report “intended to facilitate each organization’s efforts to develop a cybersecurity strategy effectively focused on prevention, detection, response, and recovery” [45], in the context of the transformation of the US electricity system into a smart grid. The report was released in three volumes: “Smart Grid Cyber Security Strategy, Architecture, and High-Level Requirements” [47], “Privacy and the Smart Grid” [48], and “Supportive Analyses and References” [49].

The first volume presents a high-level overview of the proposed framework, together with high-level security requirements. The report identifies 49 actors (including energy providers, customers, regulators, etc.) involved in the Smart Grid, and defines 22 logical interface categories, over 7 domains. The domains are transmission, bulk generation, operations, distribution, marketing, service provider, and customer. Due to the wide scope of the specification and its very high-level nature, we focused on a small subset of the framework, and constructed a more detailed architecture and requirements when necessary.
3.2 Smart Grid Cybersecurity: A Self-adaptive Authorization Infrastructure

The case study is centred around the Customer Energy Management System (EMS), an actor in the customer domain described as “an application service or device that communicates with devices in the home. The application service or device may have interfaces to the meter to read usage data or to the operations domain to get pricing or other information to make automated or manual decisions to control energy consumption more efficiently. The EMS may be a utility subscription service, a third-party offered service, a consumer-specific policy, a consumer-owned device, or a manual control by the utility or customer” [47]. In this case study, we assume a certain level of automation for the EMS, as an entirely manual control would not fit the purpose of our work.

The framework defines only the logical interfaces between the EMS and other actors in the customer, operations and service provider domains. Therefore, the scope of our case study will be restricted to those domains and actors, and only to the extend relevant to the operation of the EMS. The choice of the EMS, as the main focus of our case study, stems from the ability to involve a variety of possible scenarios involving several third-parties. Since the EMS has to deal with data flowing to and from those third-parties, as well as, to keep the data safe from unauthorised access, it is a good candidate for a case study focused on self-adaptive authorisation infrastructures.

**Actors** The following actors from the Smart Grid Cyber Security Specification [47] interact with the EMS, and are relevant to the case study:

**Customer Appliances and Equipment:** “A device or instrument designed to perform a specific function, especially an electrical device, such as a toaster, for household use. An electric appliance or machinery that may have the ability to be monitored, controlled, and/or displayed.”

**Customer Distributed Energy Resources (DER): Generation and Storage:** “Energy generation resources, such as solar or wind, used to generate and store energy (located on a customer site) [...]”

**Meter:** “Point of sale device used for the transfer of product and measuring usage from one domain/system to another.”

**Customer Premise Display:** “A device that enables customers to view their usage and cost data within their home or business.”

**Customer Information System:** “Enterprise-wide software applications that allow companies to manage aspects of their relationship with a customer.”

The EMS maintains authorisation policies that determine which actors can access which data, and under which conditions. Throughout the paper, the case study will be used to illustrate various self-adaptation techniques that can be applied to the adaptation authorisation policies.
**Goals** The system protects sensitive information, and allows selected actors to access some of that information. The goals of the system, at a high level, are the typical CIA properties:

**Confidentiality:** the system must guarantee that the data it protects cannot be used by a malicious subject. The system must also guarantee that legitimate users cannot use their privileges to access information that they are not meant to be able to access.

**Integrity:** the system must make sure that the data and commands it protects cannot be compromised.

**Availability:** the system must ensure that the data and commands are protected against malicious subjects that would try to make the system inaccessible.

The high level goals of the system are refined in the scenarios below (Sections 3.3 to 3.3).

**Initial State of the System** The system, in its initial state, involves the following actors:

**Customer energy management system (EMS):** a self-adaptive software system, running in the household, owned and controlled by the couple, that interfaces with all the actors below. The system exposes an API that allows authorised applications and web services to access data produced by the other actors, or to issue commands to said actors.

**Customer appliances and equipment:** an air conditioning unit, a water boiler, a thermostat, and an CCTV camera. They are all connected to a local network.

**Customer Distributed Energy Resources (DER):** solar panels, that can produce electricity. The electricity used can either be used in the household, fed to the grid, or wasted.

**Meter:** a smart meter, that can be queried remotely.

**Customer premise display:** an application running on the couple’s smartphones.

**Customer information system:** the software system, running on the energy retailer’s infrastructure, that allows the household to access, in real-time, data on their energy consumption, as well as information of whether, and when, they are allowed to feed energy to the grid.

The default authorisation policies, deployed on the EMS, can be summarised as follows:

- the EMS can read the temperature and humidity in the household from the thermostat;
- the EMS can turn the AC unit on and off, and switch it between the cooling and heating modes;
the EMS can turn the water boiler on and off, and read the temperature of
the water in the tank from the boiler’s sensor;
the EMS can find out the location of each member of the household, by
querying their smartphones’ location service;
the EMS can read the real-time energy production from the solar panels;
the EMS can query the meter to find out the current energy consumption;
the EMS can feed data to the customer premise display;
no third party apps or services are allowed to read or write any information
from or to the EMS;
the EMS can get real-time and historical data from the customer information
system;
the Customer Premise Displays (CPD) app running on the couple’s smartphones have read and write access to a range of data from the EMS, and
can issue commands to the connected devices in the household;
the customer information system can access the household’s meter data at
all times.

3.3 Scenarios

First Scenario: A Compromised Service The first scenario deals with com-
promised third party services, and the resulting risk of misuse of credentials.
In this scenario, the couple subscribes to an online service that uses their loca-
tion to automatically regulate the heating system in their home, as well as the
amount of hot water available. The application requires read access to the cou-
ple’s locations (through their smartphones’ location service), read access to the
thermostat and water boiler data, and write access to the AC/heating unit, and
water boiler. By using the service, the couple’s goal is to minimise their energy
bill, while still enjoying hot water and room temperature between 19-21°C when
home. The service should analyse the data it collects, and infer the best times
to turn the AC/heating unit and the water boiler on and off.
The specific authorisation goals for this scenarios are the following:

– the system must ensure that the data is only collected by the third-party
  service in a secure way, through an encrypted channel, and using state of
  the art authentication protocols.
– the system must monitor access to the data in order to detect any misuse.
  In particular, it must ensure that patterns of read and write requests do not
  suddenly change, which may indicate a compromised service.

We can envisage a scenario in which, after a few months on continuous use,
the service gets compromised, and starts issuing commands to the water boiler
and the AC/heating unit that do not achieve the goals. Furthermore, getting
location, water temperature and house temperature reading allows the attackers
to infer details about the couple’s habits and movements. The erratic behaviour
of the service is detected, the service’s credentials are temporarily revoked, and
the users are notified of the incident.
Second Scenario: Intrusive Energy Retailer  In the second scenario, the energy retailer is potentially threatening the couple’s privacy. The company has read access to the couple’s meter for billing their energy use. However, if the energy retailer queries the meter too often, it may be able to infer patterns about the couple’s life. By “too often”, we mean more than necessary for the operation of the service, and sufficiently to be able to make conjectures that would threaten the couple’s privacy, such as the study of their movements or habits. The frequency of making a query threatens the couple’s privacy for different reasons. It could be the energy retailer’s policy to snoop on its customers, but it could also be that the energy retailer’s infrastructure was compromised, either by an internal agent (such as a disgruntled employee) or by an external entity (such as a competitor or a spying agency).

The specific authorisation goals for this scenario are the same as for the first scenario. Instead of the third party, the queries are made by the energy retailer.

As the system is running, the self-adaptive authorisation infrastructure eventually detects that the energy retailer queries the meter too often, and chooses to reduce the number of times the energy retailer can query the meter every day, in order protect the couple’s privacy. The users are also notified of the incident.

Third Scenario: Data Deletion  The third scenario deals with integrity issues. In this scenario, the authorisation infrastructure monitors the use of the Customer Premise Displays (CPD) app. Part of the CPD app functionality is to allow the couple to selectively delete some data, such as their location at a certain point in time, either for privacy reasons, because of errors in the location data, or because they do not want some unusual data points to be taken into account in the decisions taken by the third party service described in the first scenario.

The specific authorisation goal for this scenario is the following extension of the integrity goal:

– the authorisation infrastructure must prevent malicious data destruction, by monitoring the usage of the CPD apps for pattern of suspicious behaviour, such as the deletion of vast quantities of data within a short time frame.

Once suspicious behaviour is detected by the authorisation infrastructure, the CPD app’s credentials are then revoked, and the users are notified. Furthermore, due to the wide access to data given to the CPD apps, they are required to follow a strict security protocol in order for the CPD app to regain its credentials.

Fourth Scenario: Stolen Credentials  The last scenario deals with stolen credentials, where an unauthorised subject managed to impersonate a legitimate subject to access the system. Depending on the legitimate subject’s credentials, such a scenario can threaten any or all of the CIA goals.

The specific authorisation goals for this scenario are the following:
– the authorisation infrastructure must detect the impersonation of legitimate credentials;
– the authorisation infrastructure must ban subjects impersonating legitimate users, and force the victims to reset their credentials securely.

In this scenario, a malicious subject manages to steal the couple’s credentials, and uses them to access the CPD app. The authorisation infrastructure detects that, while the couple is currently located on one continent, a new connection seems to originate from a different continent. The authorisation infrastructure then automatically shuts down the malicious subject’s access, as well as the access for the legitimate subject whose credentials were stolen. The legitimate subject then has to reset their password from an administration console provided by the EMS, which is only available from the household’s local network.

4 Related Work

In this section, we review some related work in the context of detection and mitigation of insider threat. Specifically, we discuss current approaches from three different solution areas. These being dynamic access control, intrusion detection, and self-protection. As such, it is intended to demonstrate the benefits and limitations of each solution area in mitigating insider threat, whilst arguing self-adaptation as a promising approach.

4.1 Mitigation through Dynamic Access Control

Approaches to dynamic access control \cite{1,12,13,33,57} are viewed as solutions to mitigating insider threat, due to their ability to enforce appropriate security controls given the state of the environment. Observation of changes in environment state, such as, a rise in threat to national security \cite{41}, a dynamic access control approach will select an appropriate security control from a pre-defined set of controls, in order to mitigate attacks. In the following, we discuss several notable approaches in dynamic access control, and their ability to mitigate insider attacks.

Usage Control (UCON) \cite{57} builds upon traditional access control models whereby obligations and conditions are used to assess a subject’s usage of a resource, as part of an access decision. A novel aspect of UCON is its ability to capture a subject’s state within a resource, and use this as a contributing factor within the access decision. Whilst the UCON model is sophisticated in identifying and managing a subject’s usage, it only allows for a transient solution to managing insider threat. For example, a subject could invalidate usage requirements for a particular resource, but go on to access other resources despite being seen as a threat. In addition, the UCON approach to access control has the potential to become complex because usage rules woven with traditional access control rules on a per resource basis.

A step forward from usage is the inclusion of trust and reputation when generating an access control decision, via a Trust Policy Decision Point \cite{13}. Here,
a weighting of trust is calculated based on the usage or feedback from resources, providing additional context to a subject’s usage. Serrano et al. [65] explores trust management to achieve access control. Within trust management, subjects and protected resources are given a level of trust, calculated from dimensions, such as, past behaviour of the subject, the access rights they already own, the issuer of access rights, and feedback from other subjects/resource owners.

In a similar work by Bistarelli et al. [12], a formal framework for trust policy negotiation is proposed. In contrast to Serrano et al. [65], access is awarded through the reasoning of access control policies, and a trust level generated from a subject’s given set of credentials. An interesting aspect of Bistarelli et al. work is that not all subjects will know the required credentials for access. Therefore, they propose an additional control that notifies the subject of the required credentials, providing the subject is deemed trustworthy. This adds an extra level of security, preventing the access requirements from being revealed unnecessarily, as they could be abused by a malicious subject.

There are other dynamic approaches specialised in expressing access control rules with a set of temporal constraints. For instance [33], access control policies contain a set of branch like rules, which are relevant to a set of system states. Given a state that conforms to a temporal constraint or one that exhibits a particular event, access control mechanisms are constrained to a branch of relevant access control rules. This approach to enabling dynamic access control (along with the aforementioned) is defined as dynamic policies.

In summary, approaches to dynamic access control are capable of mitigating insider attacks, which is achieved through actively selecting appropriate security controls depending on the environment. However, these approaches share a common limitation: it is necessary to maintain a comprehensive set of security controls in order to accommodate all potential risks of abuse. As such, dynamic access control is seen as an improvement on traditional approaches to access control, but lack robustness regarding deployments that may fail to offer the necessary (and appropriate) security control, in light of attack. In addition, dynamic access control requires fine grained security controls prescribed to particular states, which may prevent legitimate users from gaining access (due to constraints over time of access, or location) in order to prevent the prospect of malicious behaviour. Finally, given that security controls are bounded to particular states (e.g., time of day), approaches are open to potential subterfuge where prevention of access is viewed as a transitive measure that could be overcome. For example, if a subject abuses their credentials, from the viewpoint of a system administrator, one would expect that malicious subject’s ability to access is removed entirely, whereas a dynamic access control approach may only temporarily prevent access (e.g., due to the time of day).

4.2 Mitigation through Intruder Detection, Response, and Prevention

Intrusion detection systems are an established method of identifying and alerting system administrators to anomalous and malicious behaviour within a network.
For detecting anomalous activity, they use a mixture of signature based rules based on known patterns of malicious packets over a network [62], and machine learning techniques [72]. Whilst typically positioned for the detection of external attackers, recent works have demonstrated their use in detecting anomalous activity by malicious insiders [11].

Intrusion detection alone is limited by a strong reliance on human administrators interpreting alerts and actively responding to alerts in order to mitigate insider attacks. Several works aim to improve upon this limitation through automated response to attacks, and the ability to prevent attacks from even happening. These are known as intrusion response systems (IRSs), and intrusion prevention systems (IPSs), respectively.

Intrusion response systems (IRSs) [18] work alongside intrusion detection systems to automatically respond to raised alerts. Given the identification of certain types of attacks or alerts, an IRS will select a pre-determined response in order to mitigate any potential attacks. Many of these approaches rely on a static decision making approach, such as Mu et al.’s [44] approach based on a hierarchical planning of responses (adaptations). IRSs are capable in mitigating many forms of network based attacks, through both structural and parametric adaptation. Example adaptations include the reconfiguration of network devices, adaptation of firewall policies, and throttling bandwidth to networked devices.

Intrusion prevention systems (IPSs) [27] build upon IRSs, but sit within a network. Rather than act on alerts, they actively monitor network traffic and perform adaptations as attacks occur. IPSs have several advantages over IRSs. Specifically, they relate to the timeliness in mitigating attacks without relying on the input from external systems (i.e., IDSs). This in turn widens the scope of adaptations an IPS can perform over an IRS. For example, an IPS is capable of immediately mitigating network based attacks through dropping or altering malicious packets in transit, or resetting network connections.

The advantage of an IRS and IPS solution is the ability to respond and prevent unauthorised and external attacks, where many adaptations involve changes to architecture (structural) or firewall rules (parametric). IRSs and IPSs share similarities with self-adaptive approaches, yet are not explicitly classed as self-adaptive. A key distinction to this is the lack of reasoning about ‘self’, where many IRSs respond to alerts without considering the current state of the system and its environment. Whilst both approaches are capable in mitigating attacks via adaptation, it is important for such systems to maintain an awareness of system state before and after adaptation. This would allow for the selection of optimal adaptations that can be evaluated against the current state, whilst providing assurances against adaptations that may cause greater damage to an organisation as opposed to allowing an attack to continue.

With respect to the mitigation of insider attacks, whilst IRSs and IPSs are well positioned to mitigating both internal and external behaviour, they are limited in mitigating attacks only at the network layer. Internal attacks prolific of malicious insiders arguably offer different traits to that of external attackers intruding into a network, where there is a greater challenge in understanding the
context of an insider’s activity within a network, as well as their activity beyond the network layer.

Finally, one aspect of IRSs and IPSs that can benefit a self-adaptive approach is the use of dynamic decision making in selecting responses (adaptations). For example, some IRSs and IPSs make use of dynamic decision making in selecting adaptations to mitigate attacks. Stakhanova et al. [69] propose a dynamic decision making approach for IRSs where an IRS will analyse the results of a response to raised alerts. The success or failure of a response is then factored into future decisions. Ultimately, this can be extended to consider potential changes in perception of malicious or anomalous behaviour.

4.3 Mitigation through Self-protection

Self-protecting systems are a specialisation of self-adaptive systems with a goal to mitigating malicious behaviour. In the following, we discuss the few works that have demonstrated self-protection within the context of mitigating insider attacks. In particular, we discuss two self-protection approaches based on the state of access control, and one approach based on the state system architecture.

One of the approaches to self-protection via access control is SecuriTAS [59]. SecuriTAS is a tool that enables dynamic decisions in awarding access, which is based on a perceived state of the system and its environment. SecuriTAS is similar to dynamic access control approaches, such as RADac [41], in that it has a notion of risk (threat) to resources, and changes in threat leads to a change in access control decisions. However, it furthers the concepts in RADac to include the notion of utility, whereby given a perceived state of the system and its environment, the optimum set of security controls are used. This is achieved through an autonomic controller that updates and analyses a set of models (that define system objectives and vulnerabilities, threats to the system, and importance of resources in terms of a cost value) at run-time. The autonomic controller deploys optimal security controls (i.e., access control constraints) within the system, changing the conditions of access. A novel aspect of this work is that it is aimed towards physical security, whereby a resource (e.g., a computer terminal or hand held device) is stored within an office (also considered to be a resource), for example. SecuriTAS may change the conditions of access to the office based on the presence of high cost resources, or the presence of highly authorised staff.

Another form of self-protection in access control is positioned by SAAF [6], a Self-adaptive Authorisation Framework. SAAF’s goal is to make existing authorisation infrastructures self-adaptable, where an organisation can benefit from the properties of dynamic access control without the need to adopt new access control models. This is achieved through a globally centralised autonomic controller that monitors the distributed services of an authorisation infrastructure to build a modelled state of access at run-time (i.e., deployed access control rules, assigned subject privileges, and protected resources). Malicious user behaviour observed by a SAAF controller is mitigated through the generation and deployment of authorisation policies at run-time, preventing any identified abuse from continuing. Adaptation at the model layer enables assurances and verification
that abuse can no longer continue. In addition, model transformation has been shown to generate authorisation policies from an abstract model of access. This has the potential to enable the generation of policies specific to many different implementations of access control.

The main difference between SecuriTAS and SAAF, is that SecuriTAS positions its own bespoke access control model and authorisation infrastructure that incorporates self-adaptation by design. SAAF, on the other hand, is a framework that describes how existing access control models and authorisation infrastructures can be made self-adaptive, and as such, configured to actively mitigate insider threat. With that said, both approaches demonstrate an authorisation infrastructure’s robustness in mitigating insider attacks, by ensuring that authorisation remains relevant to system and environment states (and preventing continuation of attacks by adaptation of security controls).

In contrast to self-protection via access control, architectural-based self-protection (ABSP) [76] presents a general solution to detection and mitigation of security threats, via run-time structural adaptation. Rather than reason at the contextual layer of ‘access control’, ABSP utilises an architectural model of the running system to identify the extent of impact of identified attacks. Once attacks or security threats have been assessed, a self-adaptive architectural manager (Rainbow [28]) is used to perform adaptations to mitigate the attack. One adaptation example the approach offers is to throttle network connections to a server, in order to disrupt ongoing attacks. Another example is the deployment of application guards where a protective wrapper is deployed around architectural components (e.g., a web server). These provide mitigation measures that improve upon the integrity of architectural components (i.e., the encryption of session ids susceptible to hijacking). ABSP shares a number of similarities with intrusion response and prevention systems, particularly with the scope of adaptations that ABSP can perform (e.g., structural adaptation against network devices and connections). However, because ABSP maintains a notion of ‘self’, it is able to reason about the impact of adaptations and provide assurance over adaptation before adapting its target system.

5 Self-Adaptive Authorisation Infrastructures

In this section, in order to provide a basis for engineering self-adaptive authorisation infrastructures, we map our perception of self-adaptive authorisation infrastructures to the modelling dimensions for self-adaptive software systems, as described by Andersson et al. [4]. To clarify this mapping, examples will be taken from the case study’s scenarios introduced in Section 3. A summary of the mapping is presented in Table 2.

5.1 Goals

Evolution The main goals of the authorisation infrastructure, e.g., confidentiality, integrity, and availability, are inclined to be static, though they may change
**Table 2.** Summary of modelling dimensions for self-adaptive authorisation infrastructures

| Dimension   | Degree                                                                 |
|-------------|------------------------------------------------------------------------|
| **Goals**                                           |                                                                         |
| evolution   | dynamic (main goals) or specific (specific goals)                      |
| flexibility | rigid (main goals) or unconstrained (specific goals)                   |
| duration    | persistent (main goals), persistent temporary (specific goals)         |
| multiplicity| multiple                                                               |
| dependency  | independent or dependent                                               |
| **Change**                                         |                                                                         |
| source      | internal or external                                                   |
| type        | functional, non-functional or technological                           |
| frequency   | rare or frequent                                                       |
| anticipation| foreseen, foreseeable or unforeseen                                   |
| **Mechanisms**                                    |                                                                         |
| type        | parametric                                                             |
| autonomy    | mostly autonomous, but sometimes assisted                              |
| organisation| centralised                                                            |
| scope       | local or global                                                        |
| duration    | short, medium or long                                                  |
| timeliness  | best effort                                                            |
| triggering  | event-triggered                                                        |
| **Effects**                                       |                                                                         |
| criticality | harmless to mission-critical                                           |
| predictability | deterministic              |
| overhead    | insignificant to failure                                               |
| resilience  | ideally resilient, but this is hard to achieve                        |
during the infrastructure lifetime. This is the case when tradeoffs between goals need to be resolved, which may require the renegotiation of some of the main goals. However, specific goals may be more dynamic. For example, the goals in the first scenario (Section 3.3) pertain to protecting the infrastructure against misuse by the third party service. These goals are only valid from the moment the household subscribes to the service, until they end their subscription.

**Flexibility** Some of the main goals are rigid, as they prescribe that the infrastructure must preserve confidentiality and integrity, for example. However, some specific goals may be constrained or unconstrained. The third scenario (Section 3.3) provides a constrained goal, which is that the infrastructure should detect and act upon when the integrity of the data is compromised. Unconstrained goal are not fixed: they may be defined on a range of acceptable values, or as a particular situation that must be handled, but without specifying how it should be handled. The fourth scenario (Section 3.3) provides an example of an unconstrained goal, where the availability of the services that are neither mission- nor safety-critical should only be guaranteed according to a best-effort strategy. The goal does not define a minimal acceptable availability value, nor does it explicitly state how the goal should be satisfied.

**Duration** The main goals are persistent, as no breach in integrity or confidentiality should be tolerated. However, once again, specific goals may be either persistent or temporary. The first scenario provides temporary goals, in the sense that they are only valid whilst the service has access to the system, which can be revoked or granted at any time.

**Multiplicity** The system has multiple goals. There are the three main goals, availability, integrity, and confidentiality, which are common to all self-adaptive authorisation infrastructures. There are also the specific goals described in the case study scenarios, that are specific to each system or each deployment.

**Dependency** The dependency between goals vary. For example, the confidentiality and integrity goals are independent. However, there is a dependency between the confidentiality and availability goals, as well as between the integrity and availability goals. A system enforcing maximum availability may permit all requests, which would harm both the confidentiality and integrity goals. The goals in the second scenario (Section 3.3) mandate that the system must be protected against misuse by a third party service. These goals are complementary, and they also complement the confidentiality goal.

5.2 Change

**Source** The source of change in self-adaptive authorisation infrastructures can be external, internal, or both. A self-adaptive authorisation infrastructure that
uses intrusion detection techniques will monitor external changes, while a system that monitors users for patterns of misbehaviour will monitor internal changes. In the fourth scenario (Section 3.3), the detection that the geographical location from which request is made to access the CPD is different from the location in which the couple is known to be will be an external change. On the other hand, in the third scenario (Section 3.3), the detection of suspicious behaviour by the authorised CPD user will be triggered by internal changes, because it is likely the access logs on the EMS that will be monitored.

**Type** Non-functional changes can be exemplified by the case of policy updates, such as the removal of the energy saving service’s credentials when a confidentiality breach is detected in the first scenario. Functional changes can also happen when a new goal is incorporated into the system, for example when a new service is connected to the system, as in the first scenario. Finally, technological changes can also happen, if the system is able to change its policy language, or the policy evaluation engine, for example, when a security notice is issued for the running software.

**Frequency** The frequency of changes also varies widely depending on the type of change, and depending on the threats that the self-adaptive infrastructure needs to protect itself against. Changes such as new entries added to the authorisation log, that can be used in the first, second, and third scenarios, are frequent. Other changes, such as the stolen credentials of the fourth scenario, are likely to be less frequent. Finally, in the first scenario, the subscription to, or unsubscription from, the service, is a rare occurrence.

**Anticipation** The degree of anticipation can also vary. There will certainly be foreseen changes, and the second scenario provides a good example since any system connected to the internet can reasonably expect automated attacks to happen quickly. The system should be able to anticipate some of these attacks. Foreseeable examples can also be captured by the second scenario: many variants of attacks will eventually happen, and it is not possible to foresee each and every variation of them. However, classes of attacks can be recognised, and attacks that fall into such classes can be detected and dealt with, even if they were not specifically foreseen. Finally, there may be unforeseen changes, i.e., changes that the system has not been designed to handle. Those could be dealt with using automated improvement or modification of existing detection and response mechanisms (e.g. using genetic algorithms), or sometimes through chance alone.

5.3 Mechanisms

**Type** The type of mechanism regarding self-adaptive authorisation is parametric. It is the authorisation policy that is changed by the self-adaptive authorisation infrastructure. The authorisation policy is specific to each deployment of
the software: it contains the parameters that determine who can access what, under which circumstances. Regarding self-adaptive access control, the type of mechanisms is parametric because self-adaptive authorisation infrastructure can change how an access control model is implemented, which implies manipulating the deployment of the different services of a federated environment (Section 2.2).

**Autonomy** The self-adaptation mechanisms are preferably autonomous in self-adaptive authorisation, specially, if a potential intrusion is detected. The credentials should be updated quickly in order to satisfy the confidentiality goal. The fourth scenario, in particular, require an autonomous mechanism. Since attacks may happen at all times, waiting for the user’s input may take too long. The first scenario, however, may be implemented using both an autonomous or an assisted mechanism. If an assisted mechanism is chosen, the users may be notified that the service’s pattern of requests is unusual, and they can decide whether to unsubscribe from it or not.

**Organisation** The adaptation is centralised since there is a single component controlling all authorisation related services.

**Scope** The scope of adaptation can vary between local and global, depending on the change made. A change that affects a user’s ability to use a service is global when all the users are not able to use that service. The first scenario is such an example where the detection of suspicious behaviour of the application service can lead to the service’s credentials to be entirely revoked. However, a local change could only affect a user’s credentials for a specific service, without preventing the user from using other services.

**Duration** The duration of a change may vary from short to long. A subject could be barred from using the system for a short period of time, up to permanently. The fourth scenario provides a example of a short change duration: once the external attack is detected, the system can change to a more restricted access mode for a few minutes to a few hours, until the attack stops. The first scenario provides an example of a long change duration: once the application service subscription is cancelled and its credentials revoked, the change is permanent, unless a human intervention subscribes to the service again.

**Timeliness** The timeliness of changes is best-effort. It is difficult to offer guarantees when it comes to modifying the authorisation policy because any change may require extensive analysis. If many changes happen in a short period of time, it is unrealistic to hold any requests until the analysis has been done. Furthermore, all of our scenarios require the analysis of patterns of access, which requires the analysis to involve a number of changes.
**Triggering** The changes that initiate adaptation are always event-triggered. The authorisation policy changes are made in response to detected events, which can happen at any time.

### 5.4 Effects

**Criticality** The criticality of a failed self-adaptation may range from harmless to mission-critical. If the self-adaptation fails, then the system will still be vulnerable to the threat it was trying to protect itself against. The criticality of such a situation depends on the threat itself, and whether unauthorised access can indeed be obtained. In the third scenario, an external adversary may be able to penetrate the system and turn it off in which case the self-adaptation failure would have mission-critical consequences. But if the adversary does not manage to get into the system in the fourth scenario, then the failure is harmless.

**Predictability** The consequences of the self-adaptation are deterministic. It is always possible to find out what are the consequence in adapting a policy.

**Overheads** The overheads caused by self-adaptation on the system’s performance can also vary, from insignificant to system failure. This depends on the implementation of the system, as well as on the number of attacks detected by the system.

**Resilience** A self-adaptive authorisation infrastructure should be resilient. It is important to make sure that any adaptation to a policy, devised to resist a particular attack, will not make the system more vulnerable. Evidence should be provided that the self-adaptive authorisation infrastructure makes sound decisions that do not undermine the system resilience properties.

### 6 Challenges in Engineering Self-adaptive Authorisation Infrastructures

In this section, we identify some challenges for engineering self-adaptive authorisation infrastructures in the context of the MAPE-K loop. Specifically, for each of the stages of the MAPE-K loop, we discuss what are the challenges specifically associated with self-adaptive authorisation infrastructures, looking, in particular, into issues related to insider threats. For example, what type of probes are needed for the Monitor stage, how to generate dynamic plans in the Plan stage, and how to perform policy updates in Execution, etc. For each of the challenges, we identify and describe the challenge, discuss their relevance in the context of authorisation infrastructures regarding insider threats, and provide an example related to the scenarios identified for the case study previously defined (see Section 3).
6.1 Monitor

The size of what needs to be monitored, and the ability of the monitoring to adapt its own probes and gauges are the two dimensions that will influence the complexity of the Monitor stage. Since self-adaptive authorisation infrastructures have no control over their environment, it is impossible to foresee all the environment changes that might affect the system. Some changes can easily be detected by the probes and gauges of the self-adaptive authorisation infrastructure, while some others can remain oblivious if the appropriate probes and gauges are not provided. In order to avoid the risk of the infrastructure missing important information, it is necessary to dynamically adapt (1) what needs to be monitored, and (2) the type of probes and gauges required.

Active Monitoring With passive monitoring, static probes and gauges are set up at deployment time, to monitor the authorisation infrastructure and its environment. The probes and gauges are static since they cannot be re-deployed or removed at run-time, nor can they be re-configured.

While it may be tempting to monitor a wide range of environment resources, monitoring comes at a cost. It has an impact on performance, and may affect other requirements, such as the users’ privacy. Within a changing self-adaptive authorisation infrastructure and its environment, the right balance between data collection and performance or privacy is likely to evolve.

Challenge. The challenge is the provision of active (or pro-active) monitoring for reducing the amount of traffic related to monitoring considering that some of the analysis can be performed by the probes and gauges themselves, without sending the data to the controller for analysis. Moreover, pro-active monitoring requires the availability of smart probes and gauges, able to adapt to what they monitor.

Relevance. The key motivation for pro-active monitoring in self-adaptive authorisation infrastructures is to make dynamic access control more resilient to changes, thereby allowing the infrastructure to better detect and react to insider threats. The detection of insider threats relies on monitoring a wide range of resources from the environment of the authorisation service with the purpose of profiling the status and activity of subjects inside the organisation. As the monitoring might be outside the ownership of the authorisation service, special probes need to be synthesised and deployed that might be constrained by privacy issues, for instance.

Example. In the first scenario, the couple may fall into a routine, leaving and coming home around the same time every day. An active gauge is monitoring the users’ location, to turn the heating on and off. However, privacy considerations require to keep this to a minimum. The gauge identifies a pattern in the users’ location, and may choose to only query the users’ smartphones around the time where it expects a change in location. Upon detecting an unusual location, the
gauge itself decides to increase its monitoring frequency, in order to feed the system with more data to detect a potential insider threat.

**Run-time Synthesis of Probes and Gauges** The synthesis of probes and gauges at run-time is one way of achieving active monitoring. While the decision to synthesise probes and gauges may be out of the scope of the Monitor component of the MAPE-K loop, their synthesis, configuration, and deployment, are not.

**Challenge.** The challenge is the ability to synthesise probes and gauges at run-time, in response to new or emerging attacks. These probes and gauges, once deployed, should improve the resilience of the self-adaptive authorisation infrastructure against unexpected changes.

**Relevance.** The run-time synthesis and deployment of probes and gauges in self-adaptive authorisation infrastructures can help to cope with the unpredictable nature of an attack. There are no guarantees that what is being monitored is sufficient to identify a whole range of attacks, hence the need to autonomously synthesise and deploy a probe or a gauge that would be able to examine novel system attributes.

**Example.** The first scenario in the case study is a good illustration of this: when the users subscribe to the third party service, a new subject gets access to the system, thus this new subject must be monitored. A system that is not very resilient will rely on the user to create, configure and deploy a new set of probes and gauges to monitor the behaviour of the third party service. On the other hand, a resilient system should be able to extract a set of probes or gauges from a repository, before configuring and deploying them automatically. However, a more resilient system should be able to create a new set of probes and gauges tailored to the service to be monitored, and configure and deploy them automatically.

**Mutating Gauges** Mutating gauges are gauges that are able to change themselves, either randomly or guided, in order to identify unknown behavioural patterns that might be related to an attack. If the monitoring system needs to have the capability to detect autonomously previously unknown patterns of attack, one way to enable this is to generate new detectors by mutating existing ones.

**Challenge.** The challenge is to generate and deploy these mutating gauges for examining real-time or past data to identify unexpected interactions that an authorised subject might have with the system being protected. These mutating gauges can be used to provide additional evidence, with some degree of confidence, that an attack is, or has been, taking place.
Relevance. Since the environment of authorisation infrastructures are dynamic and unpredictable, one should not expect to know about all possible attacks before deploying the system. The ability to deploy mutating gauges would enable the detection of new forms of attack by simply looking for unknown anomalies, and this would be enabled by the random nature of these gauges, i.e., there is no implicit expectation of what they should be able to detect. Let's consider the case in which a gauge monitors the access to a service by authorised users. A possible change in the environment of this service is the deployment of a new version of the server providing the service, and this might result in changing the format of the logs that the gauge is supposed to monitor. Either the original gauge becomes ineffective, or it needs to be manually re-configured. Alternatively, once a change is detected in the log format, a mutating gauge may be able to automatically adapt itself in order to understand the new format. Another possible usage of mutating gauges would be to enable the perpetual analysis of logs in order to identify attacks. During run-time, as an offline activity, different gauges could be dynamically generated by mutation, and these would analyse the logs for identifying attacks previously unknown.

Example. The first scenario of the case study provides an appropriate context in which mutating gauges might be useful. A simple gauge could monitor the third party service when accessing the couple’s location by triggering an alert only if the location is accessed more than once during a specified time frame. Mutations of the gauge could record more complex data about the third party service’s queries. For example, a mutated gauge could keep track of the frequency of queries over time, and trigger an alert if it suddenly increases, which would provide the couple with a more precise way of finding out that their privacy is likely to be under threat.

Incomplete Information Incomplete information refers to the situation in which the Monitor stage is not able to provide all the information needed by the other stages of the control loop. This might be due to limited monitoring capabilities, and because of that, the monitoring stage has to find alternative ways of obtaining the missing information.

Challenge. Identify and select what to monitor in order to compensate the missing information, and know where it is safe to make assumptions about the unknown.

Relevance. Monitoring has a cost, especially when considering insider threats. The detection of insider threats relies mostly on data from the environment, and since the environment of an authorisation infrastructure is broad and fluid, in the sense that it is difficult to establish its clear boundaries, this has an effect on the data that is collected. Therefore, the system will likely have to deal with incomplete information, which in the Analyse stage might lead to more false positives regarding insider threats. One way to compensate for incomplete
information is for the gauges themselves to provide a level of confidence regarding the information that is forwarded to other stages of the control loop.

**Example.** The fourth scenario of the case study could benefit from such a feature in which a confidence level could be incorporated into the monitored information. The location of a user can be determined via several techniques, such as the IP address, triangulation from mobile network towers, or GPS signal. These techniques have varying levels of precision and reliability. Furthermore, a malicious user may also tamper with the readings in order to fool the system. If a gauge is able to attach a measure of confidence (obtained, for example, through several probes using different techniques to capture the user’s location), then it would help the other stages of the control loop in deciding whether the user credentials have likely been stolen or not.

**Automatic Feature Identification** During system operation certain probes may cease to function, either maliciously or accidentally. In order not to lose the features being monitored through that probes, the system should be able to recover some or all of those features by making use of the information provided by other probes. The assumption is that several features can be associated with a probe, and that these features can be extracted and combined with other features from other probes in order to reconstruct totally or partially the information lost from an unavailable probe.

**Challenge.** The challenge is for the system to be able to automatically extract features from its probes, and recombine those features as necessary, thus exploiting some intrinsic redundancy that may exist amongst the probes. At run-time, this should be achieved by combining and reconfiguring features that are associated with the information provided by several probes.

**Relevance.** This challenge is relevant to self-adaptive authorisation infrastructures because it helps to increase the system’s resilience against run-time threats to probes and gauges, whether they are intentional or accidental.

**Example.** The fourth scenario illustrates an application for automatic feature identification. In this scenario, if a denial of service attack is detected, the system can be reconfigured to ensure the availability of its critical services. The system reconfiguration does not have to be limited to protecting itself from an attack since the re-combination of the probes’ features may also allow the system to reduce the monitoring overhead. If probes themselves were affected by the denial of service attack, then recovering the affected probes’ features using the information from other probes would allow the system to maintain the same level of monitoring.

### 6.2 Analyse

The Analyse stage is made of two consecutive parts: the problem domain analysis and the solution domain analysis. The problem domain analyses the data
Anomaly Detection  Anomaly detection is related to the ability of the controller to identify any behaviour that deviates from what is perceived to be acceptable. Since we are essentially dealing with socio-technical systems for which it is almost impossible to establish, from the outset, all their possible behaviours, it is extremely challenging to clearly distinguish normal from abnormal behaviour, i.e., what is acceptable and what it is not. First, there is the uncertainty of the context of the system that might influence whether a particular behaviour is deemed to be normal or abnormal. Second, there are the previously unknown or unexpected behaviours that need to be classified according to profiles of similar class of behaviours.

Since there is no single technique that should be able to accurately detect a wide range of anomalies, one way of reducing the number of misclassifications is to use diverse techniques whose outcome should be fused for providing confidence in the classification. In the following, after introducing anomaly detection challenge, we present, as an example, two specific complementarity anomaly detection techniques that can be used for improving both the responsiveness and coverage when detecting anomalies.

Challenge. The key challenge in anomaly detection is to be accurate when detecting anomalies under uncertainty in order to reduce misclassifications, specifically in the context of insider threats. Since misclassifications cannot be eliminated, it is important to associate with those classifications levels of uncertainty.

Relevance. The ability of detecting anomalies should precede the system capability of handling insider threats. Since it is difficult to accurately identify an attack, uncertainty levels should be considered so the system can evaluate a particular detection against its context. The objective is to reduce the number of false positives and false negatives that might have detrimental consequences upon self-adaptive authorisation infrastructures.
**Example.** The first scenario, regarding reading and writing requests, motivates quite well the need for having accurate detection of a misuse. If a particular abuse is not detected in time, the privacy of the couple might be compromised. All the other scenarios also quite motivate the need for having an effective and efficiency means for detecting anomalies because the failure of not detecting an abuse might compromise the whole system.

**Signature-based Detection** Signature-based detection is a special case of anomaly detection (see Section 6.2), where domain analysis is performed by matching the data provided by the Monitor stage against signatures of known problems. A signature is a pattern that should be matched against the data provided by the Monitor stage, such as, an IP address, a particular regular expression in a log file, a URL, a version of some software, etc. Signature-based detection may require the matching of several individual signatures to identify a threat. They are relatively easy to automate. Since signatures refer to precise pieces of information, it is possible to completely automate their recognition, and therefore the identification of threats. With a sufficiently expressive language to write the signatures and their interactions, complex analysis can be performed to discover advanced threats. Administrators should also be allowed to define signatures, as well as, combinations of signatures, and associate them with threats.

**Challenge.** Since the signature-based detection is a static technique, the challenge is to be able to synthesise new signature-based detectors during run-time.

**Relevance.** Signature-based detection is best suited to detect threats that are known and well understood in advance. However, in the context of self-adaptive authorisation infrastructure the efficacy of static signature-based detectors is quite restrictive considering that both the attacks and the infrastructure can change. Thus the need for the self-adaptive authorisation infrastructure to be able to generate dynamically new signature-based detectors that are able to detect unknown threats efficiently at run-time.

**Example.** The second scenario provides an example for a simple signature-based detection algorithm. If the energy retailer is able to provide a wide range of services from different IP addresses, the self-adaptive authorisation infrastructure needs to identify those legitimate services that might abuse their privileges. For example, the authorisation infrastructure needs detects that a particular service from the energy retailer, originating from a particular IP address, reads the couple’s energy use too often, which may result in a potential threat to the couple’s privacy. The detection of the energy retailer’s behaviour can be implemented using signature-based detection, where the signature of the threat is a number of connections from the energy retailer’s IP address that exceeds a pre-determined threshold in a pre-determined time frame.
**Case-based Detection** Case-based detection is another special case of anomaly detection, where the focus is on observing subjects’ behaviours, which are harder to model, and hence, harder to automate. Where signature-based detection attempts to identify well-defined actions performed by malicious subjects, case-based detection observes the malicious behaviour of subject, and allows for decisions to be made based on the subject’s behaviour model. Moreover, instead of absolute thresholds for identifying anomaly detection, relative thresholds comparing users behaviours can be used.

**Challenge.** The challenge in case-based detection involves recognising a behaviour that may not be explicitly forbidden, but still suspicious.

**Relevance.** It may be the case that a subject will try to circumvent signature-based detection since signature-based detection works by using thresholds and precise patterns of attacks. This is where case-based detection becomes useful. The attacker may be slowed down because of their efforts to avoid detection, but that does not mean that the threat does not need to be addressed. Case-based detection is a good way to complement signature-based detection because of its ability to detect and act upon those types of threats, although it is more difficult to be fully automated.

**Example.** Since case-based detection can complement signature-based detection, we use the same example to illustrate both approaches. With signature-based detection, the intrusive energy retailer was detected when they read the couple’s energy consumption more than a pre-defined number of times during a given time frame. One way for the energy retailer to avoid detection by the signature-based detection system is to stay right under the threshold. Finding out what the threshold may have involved getting caught once. The case-based detection system may be looking at the history of the read operations by the energy retailer. This analysis may identify that the frequency went up until they got caught by the signature-based detection system, before staying just under the threshold. This may be constructed as suspicious behaviour, especially if the retailer had previously performed much less read operations per time period. Similarly, the detection of abuse could be related to a dynamic threshold instead of a static one. By profiling the number of times the energy retailer reads the energy consumption within particular time intervals, these can be compared for detecting an abuse. An administrator may be notified and shown a model of the retailer’s behaviour to decide whether is their can be characterised as intrusive.

**Diagnosis** When an attack is detected, the system may try to identify the source of the attack, how it was performed, what damage it caused or is causing, and which vulnerability was used to carry it out. Diagnosing an attack allows the system to better understand it, and therefore to make better decisions to defend against it.
**Challenge.** The challenge of diagnosing self-adaptive authorisation infrastructures is the ever changing type of attack, and the new vulnerabilities that might be introduced during adaptation.

**Relevance.** Identifying the source of the attack and the vulnerability exploited is key to stopping it to propagate, as well as making sure that it does not happen again. A self-adaptive authorisation infrastructure that can understand where attacks come from and how they are carried out will be more resilient than a system that can only identify them without understanding what caused them to be successful.

**Example.** The third scenario (Section 3.3) can be handled much better by a self-adaptive system capable of performing diagnosis on the attack. A system that does not attempt to understand the attack may restrict its actions to modifying the user’s credentials. However, if the attacker used a vulnerability in the system to gain the user’s credentials, they can run the attack again once the credentials have been re-configured. A system that would perform advanced diagnosis, however, may be able to identify how the attacker got hold of the credentials, and may be able to solve the root issue, or give the administrator useful data for them to do so manually.

**Resuming Normality** When an attack is over and a threat does not anymore pose danger, or when a particular risk that had previously identified has been mitigated, the system should be able to undo the restrictive measures that were taken for protecting the system against the attack, or the likelihood of an attack. This would be more relevant if the restrictive measures taken affected the system’s normal operation. This should be done without exposing the system to other attacks.

**Challenge.** After taking measures to protect the system against attacks, the challenge is when to undo some of the restrictive measures, and what measures should be put in place in order maintain a balance between usability and security.

**Relevance.** Measures taken to prevent or mitigate attacks, in the context of self-adaptive authorisation infrastructures, often take the form of reduced capabilities for users, or more stringent authorisation procedures. If the system were not able to scale back some of the measures taken after the event that triggered them has occurred, then the system would tend towards locking all the users out of the system. It is therefore crucial that the system is able to always strike the correct balance between usability and security.

**Example.** The second scenario (Section 3.3), where the intrusive energy retailer is prevented from reading energy consumption data if they have done it too often, requires for the counter-measure to be eventually lifted. This can be done after the self-adaptive authorisation infrastructures has assessed that the energy
provider’s behaviour does not pose a threat anymore. Failure to do so would prevent the provider from reading data that is essential to correctly billing the users.

**Perpetual Evaluation** When the controller is not adapting the target system, it can run background tasks to enhance the resilience of the self-adaptive authorisation infrastructure. Perpetual evaluation is one such task, which stands for the continuous analysis of either the problem or solution domains.

**Challenge.** The challenge associated with the perpetual evaluation of the problem domain is the identification of vulnerabilities and attacks that might affect the self-adaptive authorisation infrastructure. On the other hand, the challenge associated with the perpetual evaluation of the solution domain is the provision of assurances regarding the quality of services provided by the self-adaptive authorisation infrastructure.

**Relevance.** Perpetual evaluation can be used alongside traditional evaluation in order to improve the coverage in detecting insider attacks, localise vulnerabilities, and enhancing the provision of assurances. This can be done either proactively or reactively.

If insider attacks can be predicted to occur depending on some observable pattern of behaviour, adaptation can be proactive, and the same applies to evaluation. Since the proactive perpetual evaluation does not block any immediate adaptation, it can only inform future adaptations. While traditional evaluation can make fast, but imperfect, decisions, the reactive perpetual evaluation complements traditional evaluation by confirming that the adaptation satisfies the system goal, or point to issues that may require a rollback, or further adaptation. This is possible because the reactive perpetual evaluation can afford to take longer to complete, and consider more data or more stringent constraints. This is especially useful in scenarios where timeliness of adaptation is important, such as the response to insider threats.

**Example.** The third scenario (Section 3.3) illustrates the advantages of perpetual evaluation. Detecting suspicious deletions should be done very quickly, as one would like to minimise the data loss. Ideally, suspicious behaviours should be detected before any data loss happens. However, it may not be easy to tell the difference between legitimate and illegitimate deletion.

Proactive perpetual evaluation could monitor the system’s access logs, and compare each user’s actions to their behaviour profile, and the behaviour profile of similar users. If a user starts acting suspiciously, adaptation could be triggered before the user starts deleting sensitive data.

Using reactive perpetual evaluation could allow the system to suspend a user’s permissions when suspicious activity is detected, like the deletion of a large number of files. This can be achieved quickly using traditional evaluation techniques. The reactive perpetual evaluation could then consider more elements,
such as a longer history of the user’s access data, or access data for similar
users, to determine with more confidence whether the file deletions were likely
to be legitimate or not. If they were legitimate, a plan to reactivate the user
account can be made. If they were not, it confirms that the decision taken by
the traditional evaluation was the right one.

**Threat Management** There may be several simultaneous attacks detected
or vulnerabilities identified, and responses to these in the form of adaptations
should be prioritised. Furthermore, responses may increase the attack surface,
or weaken other security measures.

**Challenge.** In the problem domain, the ability to prioritise attacks and vulnera-
bilities is a challenge associated with threat management, which should take into
account the threats’ potential impact on the system’s operations, and attempt
to take preventive measures, to ensure that future threats can be addressed.

In the solution domain, the challenge associated with threat management is
the ability to rank alternative responses, and to ensure that a response does not
increase the system’s attack surface, or weakens its security measures.

**Relevance.** Any perceived attack or vulnerability should not be considered
in isolation from its current or historical contexts, otherwise problem domain
analysis might be incomplete, thus producing outcomes that might undermine
the mitigation of threats. Likewise, from the solution domain perspective, any
measure to handle the perceived attack or vulnerability should take into account
other measures either being processed or already processed. The goal is to reduce
the amount of resources needed for handling the attack or the vulnerability,
and minimise the risk of introducing new vulnerabilities. Moreover, considering
that known vulnerabilities might exist in the authorisation infrastructure, these
should be taken into account when analysing measures for mitigating a perceived
attack.

**Example.** The attack in the first scenario (Section 3.3) combined with the
attack of the second scenario (Section 3.3). In this situation, the self-adaptive
authorisation infrastructure should decide which one of the attacks is or higher
risk, respectively, the compromise of integrity in the services provided by the
third party, or the privacy violation by energy retailer.

**Risk Analysis** When perceived to be under attack, an authorisation infrastruc-
ture can be used risk levels to rank alternative responses and select the most
appropriate one. Factors that can influence the risk level include the coverage of
the evaluation, the severity of the attack and/or the vulnerability, but also the
impact of countermeasures on the system’s operations.
Challenge. The challenge of risk analysis in the problem domain is to determine the seriousness of an attack, which should establish the appropriate response level. Regarding the solution domain, risk analysis should guide the selection of the most appropriate response when several options are available.

Relevance. In the problem domain, depending on the perceived risk, attacks and vulnerabilities may need to be dealt with immediately, while others may allow for a delayed response, or no response at all, at little to no cost on the system’s security. Whether a self-adaptive authorisation infrastructure shall react to an attack should depend on the risk associated with the attack and/or vulnerability: the probability of an attack to be successful, and the impact the attack might have on the system in case is not mitigated.

Regarding the solution domain, adaptation may be expensive, whether in terms of time, computation resources, or inconvenience to legitimate users through degradation of the service. Therefore, a sophisticated authorisation infrastructure could use risk analysis to prioritise the order in which attacks should be addressed, and when and how to deal with them.

Example. A combination of the second and third scenarios (Sections 3.3 and 3.3, respectively) illustrate the need for risk analysis. In the second scenario, the system detects that the energy retailer reads data from the meter more often than agreed. This issue needs to be addressed, but might not be the most critical. The third scenario, however, deals with the detection of data being deleted by a malicious user. This should be stopped as soon as possible since more data will be lost until the issue is addressed. If issues arising from both scenarios are detected around the same time, and if the system is only able to deal with one issue after the other, then the data deletion attack should be addressed before the energy provider attack.

6.3 Plan

The Plan stage is made of two consecutive parts: decision making and plan synthesis. The purpose of decision making is to select the most appropriate solution amongst the alternatives provided by the solution domain analysis. Below, we have identified three challenges associated with decision making: decision making in a federated authorisation infrastructure, randomising decisions, and denial of service. The goal of plan synthesis is to generate a plan that implements the selected solution. We identified six challenges related to the plan synthesis: robust plans, controller capabilities, and infrastructure boundary.

Decision Making in a Federated Authorisation Infrastructure There are several benefits associated with federated authorisation infrastructures, being one of them the ability of authenticating users using third parties. However, these pose additional challenges to the planning phase, compare with a simpler, centralised infrastructure over which a single entity or user has complete control.
The selection of the best solution amongst alternatives, identified during the analysis problem domain, needs to consider the self-interests of the different parties of the federation. The component systems of a federated authorisation infrastructure may have conflicting interests and goals, and varying constraints (e.g., an identity provider service may conflict with a service provider). Yet it is important to be able to select the best solution amongst those identified in the analysis solution domain, while satisfying the goals and constraints of all the components in the federated authorisation infrastructure.

**Challenge.** Decision making in a federated authorisation infrastructure should take into account the potentially conflicting goals of all the parties in the infrastructure, and negotiate a solution that satisfies them all. This may require a solution that is not optimal, but “good enough”, and acceptable to all parties involved.

**Relevance.** In a self-adaptive federated authorisation infrastructure, it is expected for third parties to undergo some kind of change, for example, involving their goals or their deployment. This should have an impact on how the different parties collaborate in order to maximise each party self-interest. However, adaptation decisions that involve federated authorisation infrastructures may require negotiation between several stakeholders. If all the component systems’ goals cannot be satisfied, then a self-adaptive authorisation infrastructure may have to consider stopping its collaboration with some or all of the component systems with whom a compromise could not be reached.

**Example.** In the fourth scenario, user credentials are stolen by a malicious subject. If the resources under attack are protected by a federated authorisation infrastructure where identity management is handled by third parties, the self-adaptive system may have to negotiate with the identity providers in order for them to take action against the malicious subject. However, should the third party fail to meet the security expectations of the self-adaptive authorisation infrastructure, the infrastructure may decide to revoke its trust in the third party, and forbid all authentication tokens coming from it.

**Randomising Decisions** If the decision maker, for particular operational context, always selects the same strategy, then a new vulnerability is being introduced. If an attacker, while interacting with the system or observing its behaviour, is able to establish deterministically the response of the self-adaptive authorisation infrastructure, the attacker may be able to take advantage of this adaptation, and cause harm to the system.

**Challenge.** The selection of an adaptation solution among several more-or-less equally acceptable options should be randomised, in order to prevent an attacker from learning about the system’s response to a particular output, thus reducing the attack surface.
Relevance. Self-adaptive authorisation infrastructures could be targeted by attackers wishing to exploit a new vulnerability introduced by the controller. The nature of the adaptation measures that can be taken poses at least two threats. First, the attackers could trick the self-adaptive system into banning users, or groups of users, even if only for a limited amount of time, causing disruptions in the users’ ability to use the service. Second, the attackers could trigger a denial of service attack by forcing very frequent changes in the authorisation policies, which would overwhelm the system.

Example. In the first scenario, a compromised service gets access to the system. The compromised service could attempt to learn how the authorisation infrastructure adapts by purposefully attempting to trigger self-adaptation, and finding out how the system reacts to certain events through observation. If the response to specific threats is not always the same, it will be much more difficult for the compromised service to learn how the system works, and how it could be disrupted.

Denial of Service Denial-of-service (DoS) aims to make resource unavailable to their legitimate users, for example, by flooding a server with bogus requests that waste computing resources. An attacker could use the self-adaptation mechanism for this purpose, preventing legitimate users from using the service.

Challenge. As a challenge, the self-adaptive authorisation infrastructure should be able to analyse the triggers for self-adaptation, identify their source and frequency, and react accordingly in order to avoid the system to become unusable.

Relevance. Authorisation infrastructures for which the execution of self-adaptation requires reloading configuration files, restarting services, or interrupting or cancelling long-lived operations, are particularly vulnerable to DoS attacks. If the attacker finds a way to trigger self-adaptation often enough, the system may become unusable for legitimate users. In this case, the self-adaptation mechanism itself is the attack vector used by the attacker to perpetrate his attack. If the system detects a possible DoS attack, it may then switch to a less obtrusive means of self-adaptation if available, or disable self-adaptation for some time. Another option would be to cap the number of self-adaptation operations that disturb the service for a specified time period.

Example. The compromised service in the first example could use its credentials to trigger a DoS attack. It could find out which operations will likely trigger a self-adaptation that will render the service unavailable for some time, and then find a way to trigger that self-adaptation often enough that the system will be unusable by legitimate users. An attack that would trigger a restart of the authentication server and the revocation of user sessions would be a good example. Users would have to constantly re-authenticate and would not be able to use the system properly. If, however, the system were to be able to detect
such an attack, it could change its adaptation strategy so that legitimate users are not affected, for example, by banning the compromised service until it is manually re-activated by an administrator.

Robust Plans Some of the activities in a plan may be more likely to fail than others. This could be related to complex interactions between components of a federated authorisation infrastructure. This can be caused by software or hardware failures, or simply because assumptions made during the conceptualisation of the plan cease to be true during its execution.

Challenge. In a self-adaptive authorisation infrastructure, the challenge is to obtain a robust plan that should be able to handle failures in one or several of its activities, while minimising service interruptions. The plan should incorporate redundancy in its activities, or the ability to rollback to a previous working secure state, in case an activity fails.

Relevance. Authorisation infrastructures involve various component systems, as well as a number of policies whose interactions determine who gets access to what. If a plan is not robust enough, the infrastructure could be left in an intermediate insecure and unstable state, i.e., some authorisation decisions could allow unauthorised subjects access to sensitive data. If a plan is rolled back, then the infrastructure is again vulnerable to the insider threat that had triggered the (aborted) adaptation. None of these scenarios are acceptable, and therefore, the plan should be as robust as possible in order to deal with any unexpected issue arising during its execution. This can be achieved by enabling the controller to generate abstract plans (i.e., a plan that does not depend on any particular implementation, it can support several alternative implementations) that can be instantiated into concrete plans during their execution. In case a particular instantiation of an activity fails during its execution, the abstract plan should incorporate enough redundancy in order to activate an alternative instantiation.

Example. The first scenario illustrates the need for a robust plan. Once the compromised service has been detected, the self-adaptive authorisation infrastructure should synthesise a plan that would remove the service’s credentials from the authorisation policy, and would reload the new policy into the authorisation infrastructure. If, for some reason, the policy cannot be properly reloaded into the infrastructure, then the system is left into an intermediate state in which the compromised service still has access to the system. A plan that incorporates redundancies could, for example, force the whole authorisation infrastructure to be restarted using a restricted but trusted policy, if a new valid policy cannot be reloaded.

Controller Capabilities What a controller is able to achieve in a self-adaptive authorisation infrastructure is restricted by its capabilities. These capabilities are
related to what the controller is able to observe and control, and its computational and algorithm resources. Limitations on the controller’s capabilities might have an impact on the plans that a controller is able to synthesise, and these limitations should be incorporated into plans.

**Challenge.** In a self-adaptive authorisation infrastructure, because of its nature, it is difficult to forecast changes that might affect the system and its environment, the challenge is for the controller to be able to identify its own limitations. In case an operational boundary is reached, the controller should be able to act, either by shutting itself down or invoke another alternative controller, for example.

**Relevance.** While synthesising a plan, there is a risk that some implementations are not able to support activities of the plan. For example, the controller of a self-adaptive authorisation infrastructure is able to synthesise plans that only contain activities that rely on XACML implementation of Policy Enforcement Point (PEP), while the actual components of the infrastructure rely on other implementations rather than XACML.

**Example.** The first scenario illustrates the need for the controllers of self-adaptive authorisation infrastructures to be aware of their limitations. Once the compromised service has been detected, the self-adaptive authorisation infrastructure should synthesise a plan that would remove the service’s credentials from the authorisation policy, and would reload the new policy into the authorisation infrastructure. If PERMIS is used as an authorisation server, for example, policy cannot be reloaded without restarting the entire server. A plan that requires reloading a policy would fail, unless it allows for the server to be restarted as an alternative.

**Infrastructure Boundary** In a federated authorisation infrastructure, some components can be managed by third parties, and this should be captured by control boundaries that can be dynamic according to the role of the components of the infrastructure. These components may have different or even conflicting goals, hence negotiations between components are needed in order maximise their self-interest. In a self-adaptive authorisation infrastructure, the controller may only have partial control, or no control at all, over some of the components of the federated authorisation infrastructure. Considering that a controller needs to act on some components of the infrastructure that are owned by a third party, it is necessary that each party can trust each other in order to enable the negotiations.

**Challenge.** In a federated authorisation infrastructure in which self-adaptation underpins the authorisation services, the challenge is the ability of establishing boundaries of awareness and influence, and the ability of handling the dynamic nature of these boundaries.
Relevance. Control boundaries are particularly relevant in federated authorisation infrastructures, where the controller does not have direct control over the third party components. The controller may be able to request components of a federated authorisation framework to enact some changes, but these changes may only be accepted if they do not conflict with the goals of those components. In a federated authorisation infrastructure, boundaries can be related to what can be monitored and control, and to levels of trust, for example.

Example. The third scenario illustrates the issue of control boundary. If the subject deleting data at an alarming rate has authenticated using a third party service outside of the controller’s control boundary, the controller may devise a plan that first asks the third party service to ban the user for some time. However, the controller cannot force the third party service to enact this ban. Thus, the controller may also generate an alternative, which would ban the third party identity service entirely for some time.

6.4 Execute

The Execute stage is responsible for executing the adaptation plan generated during the Plan stage. However, the execution of the plan may not always be straightforward since it involves several distinct needs, including the following ones:

– meet the objectives of the adaptation plan (including, the synthesis of effectors, deployment of probes/gauges), and provide assurances that effectors have indeed carried out their actions (i.e., feedback of success);
– effectors must trust the controller of the self-adaptive authorisation infrastructure, in terms of authentication, authorisation, and non-repudiation;
– Execute stage is able to coordinate the effectors in issues, like, concurrency, rollbacks and commits, recovery from failed plans, and heterogeneity of effectors;
– adaptation plans incorporate redundancies for making its execution more resilient, and for supporting the provision of trust that resilience can be achieved;
– execution of the adaptation plan is secure in order to avoid exploitation of vulnerabilities;
– adaptation plans incorporate abstract commands since it should be down to the effector to decide how to implement a given action of the plan;
– synthesise and/or deploy probes, gauges and effectors, or even update its own adaptation strategy in order to respond to new threats being detected;
– ability to reloading adapted authorisation policies, or restarting authorisation services or other related services;
– ability to communicating with third-party identity providers, amongst other services, for example.

Underpinning all these needs, there is the fundamental need to provide assurances that the execution of the plan is according to its specifications. The
execution of a plan may involve checking post-conditions, and it should provide feedback of its progress. In the following, some of the above needs will be detailed in term of challenges.

**Deployment and Withdrawal of Probes, Gauges and Effectors** Although the deployment and withdrawal of probes, gauges and effectors might be outside the context of Execute stage of a self-adaptive authorisation infrastructure, these are an integral part of the adaptation plan and its execution. Probes, gauges and effectors could either be taken from a pool, which is populated at development-time, or synthesised at run-time for allowing the system to react to unforeseen changes (see Section 6.4). This dynamic deployment and withdrawal is different from the active monitoring challenge discussed in Section 6.1. In active monitoring, deployed gauges and probes have their own self-adaptive mechanism. In contrast, we discuss in this section the deploying and withdrawing of probes, gauges and effectors as the result of the evolution of self-adaptive authorisation infrastructures. As such, the deployment of new probes, gauges and effectors instead of being under the direct responsibility of a self-adaptive authorisation infrastructure, we could have a higher level entity responsible for controlling the evolution of the self-adaptive authorisation infrastructure.

**Challenge.** One of the challenges in self-adaptive authorisation infrastructures is the ability to deploy and withdraw probes, gauges and effectors because of the wide range, and volatile nature, of threats that the system has to protect itself against.

**Relevance.** In a self-adaptive authorisation infrastructure changes affecting the infrastructure or its environment should be handled by the controller, and the ensuing adaptations may have an impact on how the controller observes and effects the infrastructure and/or its environment. Consequently, this may affect the probes, gauges and effectors that are deployed. The complexity of the deployment can range from entirely pre-defined probes, gauges and effectors that simply need to be activated, to the synthesis of new ones (see Section 6.4). An intermediate solution would be the ability to configure pre-defined probes, gauges and effectors for a particular use.

**Example.** The first scenario provides an example of probe deployment and withdrawal. When the couple subscribes to the energy saving service, it is necessary to monitor the service’s behaviour through the deployment of probes and gauges. If the probes and gauges are simply pre-defined, they will already have been written for the particular service chosen by the couple. A more challenging option is for the self-adaptive authorisation infrastructure to configure the probes and gauges, depending on what the service has access to, what the system wants to monitor, and the implementation details of the chosen service.
Automated Synthesis of Probes, Gauges, and Effectors

It is not possible for the developers, at development-time, to foresee all the possible threats that the system could face. Too many of those depend on the environment in which the system operates, and this environment can change at any time. The synthesis of new probes, gauges and effectors at run-time allows the system to react to changes in the system or its environment that would otherwise affect the resilience of the self-adaptive authorisation infrastructure.

**Challenge.** The challenge of a self-adaptive authorisation infrastructure to react to changes that are not foreseen at development-time is to synthesise probes, gauges and effectors at run-time.

**Relevance.** Responding to threats that had not been foreseen during development-time is essential for self-adaptive authorisation infrastructures. Occasionally, handling some of these threats may require probes, gauges and effectors that are not yet available. In particular, the self-adaptive authorisation infrastructure may require new probes or gauges for monitoring new features of the system or its environment. The ability to synthesise probes, gauges and effectors during run-time will broaden the range of unforeseen threats that the system can protect itself against.

**Example.** To demonstrate the automated synthesis of effectors, we postulate the deployment of a new identity provider. Such a deployment could be part of the response to the compromised service described in the first scenario. The identity provider that was used to carry out the initial attack might have been banned, and a new one may need to be deployed. The deployment of a new identity provider requires the self-adaptive authorisation infrastructure to deploy new effectors to communicate with the new identity provider, e.g., to ask it to ban a particular user for a given amount of time. It may also be necessary to synthesise new probes if the infrastructure needs to monitor the new identity provider.

**Trust**

Trust is necessary between the parties in a federated authorisation infrastructure. The controller should trust that the other parties will carry out the plan as expected, and the other parties must trust that the controller acts in their advantage.

**Challenge.** A key challenge in a self-adaptive authorisation infrastructure is to maintain trust between the parties by ensuring all parties behave as agreed. This is not restricted to techniques that ensure trust is maintained, but also associated with strategies that are used when reacting to a breach of trust.

**Relevance.** If a malicious user has been detected and reported to the identity service, but the identity service fails to take action to suspend the malicious user, then the trust between the authorisation infrastructure and the identity
service should be reevaluated. As authentication is a critical component in access control. It is crucial for the authorisation infrastructure to be able to react to such breaches of trust, as they may harm the protected system.

**Example.** The second scenario provides a good example regarding trust. In this scenario, the authorisation infrastructure detects that the energy company is acting against the users’ interest by attempting to collect too much data, and too often. The self-adaptive authorisation infrastructure is able to detect this as a breach of trust. The controller reacts by requesting to the identity services to revoke the credentials of the energy company, which should affect its ability to gather any further data.

**Update or Redeployment of Policies, and Sessions** Self-adaptive authorisation infrastructures can adapt authorisation policies in various ways. The adaptation could either take the form of an update of the current policy, where the controller sends the modifications to the policy decision point (PDP). Alternatively, the controller may create a whole new policy, and instruct the PDP to deploy it instead of the previous one.

When adapting authorisation policies, the infrastructure should also consider the sessions that are currently open by a particular user, and which may carry permissions that the user should not be assigned anymore sessions. All sessions could be revoked every time adaptation occurs. Alternatively, sessions could be amended in order to reflect the changes made in the authorisation policy.

**Challenge.** During the execution of the plan, the challenge is to reduce the system vulnerability while policies are updated or redeployed.

**Relevance.** The adaptation of an authorisation policy is an important part of a self-adaptive authorisation infrastructure’s reaction to an internal threat. It is important that the adaptation is completed in a timely manner, in order to minimise the amount of time during which an attacker can cause damage to the system. The choice between updating the existing policy or deploying a new one should take into account the amount of time required for the new policy to be effective. Updating an existing policy requires the controller to communicate to the PDP only the changes to be made to the current policy. It is then the PDP’s responsibility to enact those changes. Deploying a new policy, however, requires the controller to prepare a complete, updated policy, and to communicate it to the PDP, which only needs to deploy it to replace the previous one.

Existing sessions should also be taken care of in order to adapt the permissions given to the users that are logged on to the system while the adaptation takes place. Terminating all sessions is a simple solution, but it will require each user to authenticate again. In some circumstances this may not be ideal, especially if adaptation occurs often. The alternative is to modify user sessions at run-time, which may be more difficult to implement.
A similar challenge could be associated with the deployment of new probes and effectors, in particular those that are third party. The heterogeneity and the inflexibility of such devices may introduce vulnerabilities during adaptation.

**Example.** The third scenario illustrates the importance of handling existing sessions when updating or redeploying the authorisation policy. In this scenario, data is being deleted by an attacker using stolen, legitimate credentials. Once the attack has been detected by the Analyse stage, and the policy adapted by the Execute stage, the session used by the attacker must be taken care of. Depending on the infrastructure’s implementation, two alternatives are available. First, the session can be terminated entirely, forcing the attacker to attempt to authenticate again using the stolen credentials. Second, the privileges afforded to the session may be reduced, in such a way that the attacker would be unable to continue deleting data, but without terminating the session.

**Redundancy** Introducing redundancy in the Execute stage is one way to increase the resilience of the system. In case an effector fails to properly execute a portion of the plan, the plan should incorporate redundancies, using other effectors, alternative solutions, or workarounds, that would allow to tolerate the failed execution.

Whilst the incorporation of redundancies in case of failure may be, in part, the responsibility of Plan stage, it is the responsibility of the Execute stage to monitor the execution of that plan, and to trigger the redundancy measures when necessary.

**Challenge.** The challenge is to include sufficient redundancies in the execution of the plan in order to make adaptation more resilient against potential threats, being these either internal attacks or faults.

**Relevance.** The consequences of a failure during the execution of a plan while adapting an authorisation policy can be disastrous. At best, the old policy will still be in place, and the system will not be protected against the newly identified threat. At worst, the authorisation infrastructure could fail, either by locking all users out, or by letting everyone access everything. Implementing redundant mechanisms to update policies will increase the service’s resilience.

**Example.** All the scenarios in the case study could provide an example of the importance of reacting to failures during Execute stage. In the second scenario, the inability of the infrastructure to reduce the energy company’s rate of data collection will directly harm the users’ privacy. The plan can include contingency provisions that handle this particular issue, and an alternative strategy, which is an integral part of the plan being executed, can then be deployed, such as, giving the energy company empty readings when they try to collect data too often.
6.5 Models

There are several types of models relevant to authorisation infrastructures, as well as, many ways of using them for self-adaptation. In this section, we first categorise models for authorisation infrastructures into four types: authorisation policies, access control, threat, and adaptation. We then focus on the challenges that stem from the use of these models, which include: portability, facilitating negotiation, history of models, uncertainty and conflicts in models, and model drift.

The examples in this section differ from those in the previous section. Instead of using the scenarios from our case study to highlight challenges, we will instead discuss the case study in general. This is because models are the same in the application, and do not depend on specific scenarios.

Modelling authorisation policies Authorisation policies are a central component of authorisation infrastructures, where rules or assignments are defined, and whose evaluation determines whether requests for access to protected assets are granted or denied. Policies can be very large, and they can be distributed across several documents, using various technologies, or, in the case of federated authorisation infrastructures, under the control of different entities.

Challenge. Models of authorisation policies should be understandable yet precise for facilitating their manipulation by both the controller and system administrators.

Relevance. For supporting the automated manipulation of models, these need to be precise, and at the same time, in order to allow the validation of the models against their respective policies, these models need to be accessible to users. The reason being that, since authorisation policies determine the rendering of access control decisions, the authorisation policies models should be consistent with the actual authorisation policies in order to avoid discrepancies between the authorisation infrastructure and its controller. So whatever changes are made on the authorisation policies, either by users or automated tools, these need to be accurately reflected on their corresponding models.

Example. In our case study, the Customer Energy Management System (EMS) maintains the authorisation policies. In order to present a coherent view of the policies to the user, the EMS must be able to collect all the policies, which may be expressed in different languages or using different access control models, and collate them in a way that is easy for users to make sense of them. Furthermore, since third parties or service providers, such as the energy provider, may have some control over parts of the authorisation policies, their correspondent models should be able to capture any changes made on the policies. On the top of this, there is the controller, which should be able to manipulate the different control models.
Modelling access control  Authorisation infrastructures often involve several key components that are connected for rendering access control decisions. For example, the XACML standard recommends that an authorisation infrastructure should be separated into the following distinct components [52]: Policy Decision Points (PDP), Policy Enforcement Points (PEP), Policy Information Points (PIP), and Policy Administration Points (PAP). Architectural models at the controller should be able to capture the components of an authorisation infrastructure, and how these components are connected.

Challenge. Architectural models should be dynamic because the infrastructure is expected to change, and these should be capture by the models. Such dynamic architectural models should be able to capture issues, such as, the unavailability of components. In the context of federated authorisation infrastructures, architectural models should also be able to support access control and provide assurances of this ability.

Relevance. In self-adaptive authorisation infrastructures, dynamic architectural models are essential for enabling the controller to handle changes affecting the infrastructure. Architectural models enable to analyse the consequence of threats to the infrastructure, and investigate potential architectural solutions for mitigating those threats. For example, if an identity service fails to revoke credentials from subjects that are perceived as persistent attackers, the self-adaptive authorisation infrastructure may chose to disconnect that identity service from its infrastructure. However, before implementing that solution, the authorisation infrastructure may evaluate the impact of such a measure towards its users.

Example. In our case study, the EMS is at the centre of the federated authorisation infrastructure, and its architecture should include the third party service provider and the energy provider, both sharing the EMS control over the smart meter. When adaptation occurs, the self-adaptive authorisation infrastructure must be aware of all those components in order to effect changes across the infrastructure.

Modelling threats  The purpose of self-adaptive authorisation infrastructures is to defend the system against threats. Since threats can change throughout the life time of an infrastructure, threat models should be dynamic, i.e., models that are able to change according to the threats to the infrastructure.

Challenge. For reasoning about threats in self-adaptive infrastructures, a modelling language for expressing dynamic threat models is needed. In addition to representing threats, threat models should capture the likelihood of their occurrence, the potential harm they can cause to the infrastructure’s assets, and which countermeasures can be taken to address them. If the self-adaptive infrastructure is capable of discovering previously unknown threats, then the threat model should be adaptable at run-time.
Relevance. Threats, whether internal or external, are what self-adaptive authorisation infrastructures try to defend the system against. This can only be done if these infrastructures have a suitable model of threats, and if these models cannot be adapted according to ever changing threats a vulnerability will ensue.

Example. A threat model for our case study could represent, for example, abuse regarding smart meter’s queries. A possible threat and its response is discussed in the second scenario. A model of the threat is necessary for the infrastructure to realise that an attack is taking place. The model could simply be a counter representing the number of queries from the energy retailer over a set period of time, with a threshold above which the attack is deemed to happen. A more complex model could maintain a historical distribution of the queries’ frequency, together with a variation limit that, once reached, would represent an attack taking place.

Modelling adaptation The various models supporting self-adaptive authorisation infrastructures should take into account the run-time adaptation capabilities of the infrastructure. In particular, adaption models should represent what parts of the authorisation infrastructure can be adapted, how the adaptation can be executed and in which order, and when or under which conditions adaptation can happen.

Challenge. There is the need to specify adaptation models that would be able to coordinate adaptations taking at different levels of an authorisation infrastructure, and to identify what kind of assurances those models can provide.

Relevance. Considering that both authorisation infrastructures and their environments are intrinsically dynamic, adaptation models should be related to the architectural models of the infrastructure, models of the authorisation policies, and threat models. Adaption models should also capture how the controller communicates with the authorisation infrastructure, which includes the monitoring and controlling of the infrastructure. If adaptation models do not related to all models that enable the support of self-adaptation of authorisation infrastructures then inconsistencies might arise regarding the how self-adaptation is enacted.

Example. In our example, adaptation models should be able to capture the different aspects of adapting an authorisation infrastructure, which includes adapting its architectural configuration or the components that are part of that configuration. An example of component adaptation would be its ability of adapting authorisation policies in order to modify users’ ability to perform certain operations, for example, restricting the amount of smart meter readings. An adaptation model, that would be part of Customer Energy Management System (EMS), should specify which parts of the authorisation policy can be adapted and how. It should also specify how the adapted policy can be deployed in the
infrastructure. For example, it might be the case that the component responsible for the authorisation service must be restarted, as it is not possible to reload the authorisation policy without restarting the component.

**Portability** Portability can take different forms in self-adaptive authorisation infrastructures. It could mean that the system can be deployed on various types of infrastructures. It could also mean that the system should be able to function in an heterogeneous environments, where different subsystems can communicate with each other. The former requires some form of vertical transformation, where abstract elements can be concretised in various ways, depending on the underlying infrastructure. The latter requires some form of horizontal transformation, where models and data can be communicated between subsystems that use different representations.

**Challenge.** The need for developing self-adaptive authorisation infrastructures that can be vertically and horizontally portable. Vertically portable self-adaptive authorisation infrastructures can easily be redeployed on different environments or implementations of components. Horizontally portable self-adaptive authorisation infrastructures have components that may use different data formats and protocols, but are still able to communicate with each other.

**Relevance.** Federated authorisation infrastructures have components controlled by various entities, system they use. Components of these infrastructures may run different technologies, or different versions of the same technology. They may also evolve and change at any time. Therefore, it is necessary for the self-adaptive authorisation infrastructure to be designed in a portable way.

**Example.** In our case study, the self-adaptive authorisation infrastructure may be federated, with different entities handling parts of the authorisation and/or authentication infrastructure. For example, the owner may delegate the authentication to OAuth providers, such as, Google or Twitter, while the household owners and the energy provider may have share responsibility over authorisation for the access to the smart meter readings.

**Facilitating negotiation** Federated authorisation infrastructures require several components working together. However, these components may be owned and controlled by different entities, who may have conflicting goals and interests. Therefore, it may be necessary for multiple components to negotiate a solution that satisfies all parties.

**Challenge.** Models are required to facilitate negotiation between several components of a federated authorisation infrastructure. In self-adaptive authorisation architectures, these models should allow components to understand the consequences of the proposed changes on users’ ability to use the system, and should allow components to express agreement or disagreement with some of those changes.
Relevance. Self-adaptive federated authorisation infrastructures must be able to handle negotiation between several of their components. They must be able to exchange proposed solutions to problems, and indicate agreement or preferences. The solutions will contain models of the proposed changes, in order for the components to make informed decisions about the proposals they are presented with.

Example. In our case study, the EMS and the energy company share access to the smart meter readings. It is in the household’s interest to minimise the energy company’s data collection frequency, and the amount of data it can collect. However, there is a minimum amount of data that the energy company needs to collect in order to guarantee its service, and to be able to correctly invoice the household. Since both the household’s and the energy company’s requirements can change, they may have to re-negotiate the data collection frequency. A suitable model for such a negotiation would represent the amount of data that can be collected and its frequency, and would allow each party to express agreement or disagreement, in whole or in part, and to propose alternatives until a solution can be found.

Capturing the history of models Capturing the history of models allows for the analysis of changes that happened in the past. The detection of long-running attacks, forensics analysis, and the detection of the entry point of an attacker all require access to historical data about the state of the system.

Challenge. Self-adaptive authorisation infrastructures should be able to keep a history of the models that they maintain, in such a way that does not degrade performance, yet allows for efficient analysis of past events. The ability to correlate changes to different models is especially important.

Relevance. Attacks can be carried out over long periods of time. Hence, understanding them may require to analyse the past states of the self-adaptive authorisation infrastructure, both in order to detect and prevent attacks, but also in order to identify patterns of suspicious behaviour over a long period of time.

Example. The infrastructure in our case study focuses on the detection of internal threats, which means that, before carrying out their attacks, the attacker must have been authenticated. In order to find out whether an attack was enacted by the legitimate holder of the credentials in question, or by an external attacker who managed to impersonate them, it requires analysing the state of the infrastructure at the time of authentication, how the authentication was carried out, as well as, compare the behavioural patterns of the user at different points in time.
Analysis capabilities The Analyse Stage of a self-adaptive system depend on the available models in the knowledge base. If these models cannot completely reflect the reality they represent, the Analyse stage may not be able to always come to the correct conclusion, or even come to a conclusion at all. Therefore, analysis on incomplete models may lead to uncertainty. If several analysis components are used, this may also lead to conflicting results.

Challenge. Self-adaptive authorisation infrastructures should be able to deal with uncertainty and conflicts, and these may need to be encoded in the models.

Relevance. Detection of insider threats is difficult because a smart malevolent insider will attempt to try and pass their usage as legitimate. Therefore, there is often no clear-cut distinction between legitimate and malicious users, making their detection difficult and ambiguous. Moreover, in a federated self-adaptive authorisation infrastructure, various Analyse stages may reach different conclusions, even when considering the same data.

Example. The authorisation infrastructure may use models of users’ access to resources to detect insider threats. One such model may represent each access request, its timestamp, the resources requested, and the authorisation infrastructure’s response. One analysis may use the number of failed requests per hour, and classify users as legitimate if the number of failed requests is smaller than a threshold $x$, suspicious if between $x$ and $y$ (with $x < y$), and a threat if the number of failed requests is higher than $y$. In this case, suspicious users are an uncertain result: the analysis was not able to give a definite answer.

Another analysis could use the same data, but perform different operations to detect insider threats. It could look at the total number of requests, whether they were denied or not by the authorisation infrastructure. Similarly to the first analysis component, if a user produces less than $a$ requests per hour, it is considered legitimate; between $a$ and $b$ ($a < b$) requests per hour, it is considered suspicious, and over $b$ requests per hour, it is considered a threat. It is possible that the two analysis will disagree on the nature of a particular user. The self-adaptive authorisation infrastructure needs to deal with this conflict. For example, it could run more analysis components over the same data until it finds sufficient confirmation, or it could take a conservative approach and treat the user as a threat if at least one the analyses has identified it as a threat.

Model drift Dynamic models are at risk of drift over time. Model drift is the progressive increase in the discrepancy between the model and what the model represents. In self-adaptive authorisation infrastructures, dynamic models are used to represent the target system, as well as its environment. If the models do not correctly reflect the reality, this may lead to sub-optimal, or harmful, adaptation decisions.

Challenge. In self-adaptive authorisation infrastructures, model drift should be avoided in order to reliably detect suspicious activity and identify malicious actors.
Relevance. Attackers are likely to try and masquerade their actions as legitimate in order to escape security measures. Therefore, it is important for self-adaptive authorisation infrastructures to keep models that are very close to reality - even a small drift may be used by the attacker to cover their tracks.

Example. In our case study, the self-adaptive authorisation infrastructure maintains a model of the target system, which may include distributed access control policies over several components of the authorisation infrastructure. If the self-adaptive authorisation infrastructure cannot keep an accurate representation of these policies, then it may believe that an authorisation request that the target system will accept would be rejected, or vice-versa, leading to incorrect adaptation decisions. For example, the self-adaptive authorisation infrastructure may recognise that a user who is acting suspiciously has less permissions than he actually has, and decide to treat it as a low priority threat, where in reality, the user’s level of access should warrant a high priority resolution of the issue.

7 Conclusions

The provision of self-adaptive authorisation infrastructures is a promising solution to protect systems against the dynamic nature of attacks and uncertainties associated with them, such as, insider threats. In this paper, we have presented how this could be achieved architecturally by separating the specification of policies (i.e., self-adaptive authorisation) from the enforcement of these policies (i.e., self-adaptive access control). We have also presented several technical challenges associated with the self-adaptation of authorisation infrastructures, which followed the stages of the MAPE-K feedback control loop. Each of the technical challenges was presented in terms of their relevance, and an example was provided for demonstrating their pertinence. Of course, the list of technical challenges was not exhaustive since several of them were not included in the description due to space constraints. Moreover, in addition to the identified technical challenges, restricted by our experience in building and deploying self-adaptive authorisation infrastructures, one would expect new technical challenges to arise, depending on authorisation infrastructure and their deployment.

For presentation purposes, it was natural to follow the MAPE-K feedback control loop for identifying the technical challenges, however, questions may be asked about the appropriateness of MAPE-K loop when finding solutions to the wide range of identified challenges. Authorisation infrastructure are inherently quite complex infrastructures, which can be geographically distributed, and this might require architectural solutions for the controller that might go beyond what the classical MAPE-K loop can offer. For example, if perpetual evaluations are needed in order to obtained assurances of the confidentiality, integrity, and availability of computer based resources regarding the adaptations performed to the authorisation infrastructure, then new ways of enforcing separation of concerns are needed at the controller level. This of course will
raise a new set of technical challenges that should be specific to the provision of assurances.

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