

MASTER THESIS

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Kubernetes on the Edge

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Vienna, April 29, 2022



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Kurzfassung

Kubernetes wird als das Schweizer Armeemesser der Container-Orchestrierung bezeichnet. Auch im Bereich edge-computing bietet der Dienst eine Vielzahl an unterschiedlichen Werkzeugen und Tools, welche teils unterschiedliche Strategien und Ansätze verfolgen. Zum einen ist der Einsatz einer herkömmlichen Kubernetes Architektur möglich, zum anderen können jedoch auch verteilte und unabhängig agierende Kubernetes Cluster betrieben werden. Die richtige Architektur für ein individuelles Einsatzgebiet zu wählen ist eine herausfordernde Entscheidung. Ziel dieser Arbeit ist es, genau diese Frage zu beantworten. Dazu werden die beiden Varianten in Form eines Proof-of-Concepts unter Einsatz der "Design Science Research" Methode aufgebaut und untersucht. Die daraus gewonnenen Daten bilden die Basis eines Vergleichs der beiden Möglichkeiten. Als Produkt entsteht ein Kriterienkatalog der für die Entscheidungsfindung herangezogen werden kann. Die Daten zeigen, dass je nach Anwendungsfall Vor- und auch Nachteile mit der jeweiligen Architektur entstehen. Durchläuft man den Katalog kann wissenschaftlich belegt die präferierte Variante gewählt werden. Eine weitere Möglichkeit, welche aus der Forschung resultiert, ist die Kombination beider Architekturen zu einer Art "Hybrid Kubernetes" Umgebung.

Schlagworte: Kubernetes, edge-computing, distributed System, Proof-of-Concept

Abstract

Kubernetes is the de facto swiss-army-knife for orchestrating container-platforms. Beyond that, the tool can also be used to distribute workloads and manage nodes in an edge-computing environment. However, there are different methods regarding the architecture for achieving comparable results. On the one hand a possible solution is to build a central instance managing small distributed and independent cluster, on the other hand a centralized master controlling associated edge-nodes could be used. Making the right architectural decision is crucial. The goal of this thesis is therefore to answer the question of which architecture is more suitable for an individually defined scenario. To answer this question the "Design Science Research" method is used in order to build a proof-of-concept and record the necessary findings. These data serve as a basis for developing a catalogue of criteria to support decision-makers in the selection process. The results show that the two architectures can serve certain requirements or goals differently. In addition to certain peculiarities, the respective strengths were also pointed out. The characteristics can be evaluated in the criteria catalogue itself in order to be able to determine the optimal target architecture for individual needs. Lastly, the expansion in the form of a hybrid environment is described as a possible future-work.

Keywords: Kubernetes, edge-computing, geo-distribution, proof-of-concept

Contents

1	Introduction	1
1.1	Problem area	1
1.2	Research question	2
1.3	Expected Contribution	2
1.4	Structure	2
2	State of the Art	3
2.1	Technology	3
2.1.1	Kubernetes	3
2.1.2	Edge-Computing	6
2.2	Architecture	7
2.2.1	Default	7
2.2.2	Distributed K8s	10
2.3	General Challenges	11
3	Methodology	13
3.1	Design Science Research	13
3.2	Requirements	13
3.2.1	Functional requirements	13
3.2.2	Non-functional requirements	14
3.2.3	Security requirements	14
3.3	Testing and Research	15
3.4	Main categories covered	15
4	Proof-of-concept	16
4.1	Environment	16
4.1.1	General	16
4.1.2	KubeEdge	18
4.1.3	KubeFed	18
4.2	Use-Case	19
4.2.1	KubeEdge	21
4.2.2	KubeFed	24

5 PoC - Research	26
5.1 Performed Tests	26
5.1.1 Ressource usage	26
5.1.2 Network connectivity	30
5.1.3 Application stability	35
5.1.4 Security bechmark	38
5.2 Discussion	42
5.2.1 Handling	42
5.2.2 Limitations	43
5.2.3 Delimitations	44
5.2.4 Outcome	44
6 Catalogue	45
6.1 Decision Variables	45
6.1.1 Installation	45
6.1.2 Operation	47
6.1.3 Application deployment	48
6.1.4 IT-Security	49
6.1.5 Community and support	53
6.1.6 Future proof	54
6.2 Criteria catalogue	56
6.2.1 Properties overview	57
6.2.2 Rating	58
6.3 Exclusions and Special Cases	58
7 Related Work	59
7.1 Kubernetes and the Edge	59
7.2 Extend Cloud to Edge with KubeEdge	59
7.3 Sharpening Kubernetes for the Edge	59
7.4 Ultra-Reliable and Low-Latency Computing with K8s	59
8 Conclusion	61
8.1 Findings	61
8.2 Results	61
8.3 General advice	62
8.4 Future Work	62
Bibliography	63
List of Figures	68
List of Tables	69

List of Code	70
List of Abbreviations	71
A Appendix	73

1 Introduction

Because of internet-of-things (IoT) devices becoming more and more common, the number of devices capable of communicating with the world wide web (WWW) increases rapidly. Consequently, the overall traffic generated as well as the amount of data which must be processed increases accordingly. Regarding this development edge-computing is the rising star trying to solve these issues. Thereby data is not processed centrally like in traditional datacenters, but effort is made to handle these data close to the user within several distributed systems. Because of this methodology only really necessary data is transmitted to a central instance for further treatment and thus the processing-power as well as the bandwidth necessary for processing required data is reduced significant.

It is expected, that the number of IoT devices will continue to grow fast [1] over the coming years. In connection with this, edge computing will also gain in importance in the future and play an important role in modern information technology (IT) architectures..

To be able to control distributed systems effectively, Kubernetes (K8s) provides useful tools and functions. Fundamentally there are two different approaches regarding the architecture of how to build an edge-computing environment making use of K8s:

- **Default:** A centralized K8s Cluster controlling many leaf-devices (workers) on the Edge.
- **Distributed:** Small and distributed K8s Clusters running independent on the Edge controlled by a centralized Master-Instance.

Another upcoming approach of solving that issue is making use of the service mesh [2]. This ultimately uses or builds on both of the aforementioned technologies. However, since this thesis concentrates on the two main architectures and their differentiation, the service mesh is not the main focus and just mentioned for the sake of completeness.

1.1 Problem area

Problems arise when trying to find the proper architecture for a specific use-case. There is no clear winner when comparing the above-mentioned different variants. Each of them has their own pros and cons and may decide whether a project is successful or not. It is therefore all the more important to choose the proper architecture right before starting, changing the strategy in retrospect would take a lot of time and effort. However, there is no clear guidance on how to find the proper target environment, at least none which applies in general. Occasionally one finds

recommendations for a very specific use case, however the chance is very low this findings fit your goals respectively enlighten the decisions. This leads to the following research questions.

1.2 Research question

This paper is going to answer the subsequent research questions:

1. What are the main differences of the architectures mentioned in chapter 1 regarding functionality, scalability and security aspects?
2. Which decision criteria must be defined respectively examined to create a catalogue capable of choosing the proper architecture easier for IT managers as well as administrators?
3. Is there a trend of which technology is most likely to be used?

1.3 Expected Contribution

The general objective of this thesis is to highlight the pros and cons for each of the architectures defined in the Introduction. The focus will be mainly on the geo-distribution aspect. Although IoT is playing a major role in pushing the development forward, it is not considered further in the present work. To find the proper architecture, or at least recommendations what could fit best for different desired use-cases, a catalogue will be defined. An important part will be the decision criteria catalogue helping people making comprehensible decisions based on scientific research. The main characteristics which are taken into account are scalability, state-of-the-art, handling as well as security. A template for using the catalogue yourself can be found in the appendix.

1.4 Structure

In the first part of the paper, the current state of research is presented based on a literature search. Products and solutions are outlined for the various target platforms, which are then developed in the course of a proof-of-concept (PoC) using the design science research (DSR) method. Tests show the respective behaviour and possible areas of application. This results in properties that flow into the following catalogue. This catalogue of criteria, in the form of a utility value analysis, can then be used to find the optimal target environment for individual areas of application. A point system is used to evaluate the respective criteria. Finally, outlooks are given and related works and extensions are cited.

2 State of the Art

2.1 Technology

The present chapter provides an introduction to the general thematic. The main components and objects of K8s are explained as well as the layers of edge-computing are highlighted.

2.1.1 Kubernetes

To promote modern development and be able to implement continuous deployment pipelines, cumbersome monolithic applications are divided into many smaller units. Each of these units provides only one function. In order to establish the overall functionality, these units are communicating with each other and thus provide services or make use of other ones. This new method of delivering applications brings many advantages in terms of development but also introduce some new challenges and complexities regarding operation. To simplify the tasks around the management of this architecture, K8s has established itself as the de facto standard [3]. K8s was initially developed by Google and later donated to the opensource community. Over the course of time, a broad community has developed around K8s and a number of additional tools and extensions have emerged as a result. The most promising solutions regarding geo-distribution respectively edge-computing are highlighted in the subsequent section 2.2 "architecture". In order to be able to interpret the results of the use-cases, as well as building the necessary basic understanding, the following functionalities and components of K8s are of relevance.

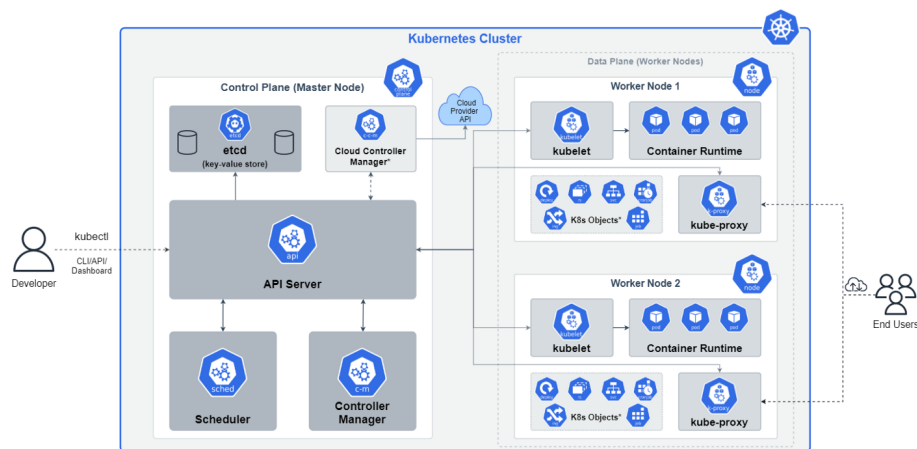


Figure 1: K8s architecture overview[4]

Master Nodes run the so-called *Control Plane* which is responsible for controlling the cluster itself and all the resources within. The Control Plane consist of the following components [5]:

- *API Server* - acts as frontend web-interface responsible for controlling the K8s cluster as well as the objects inside the cluster. Tools like *kubectl* abstract the *OpenAPI v2* endpoint and provide access in form of a simply understandable and usable commandline interface (CLI).
- *etcd* - represents a high-available and consistent key value store responsible for storing the actual state as well as the desired configuration of the cluster.
- *Scheduler* - is responsible for scheduling pods on the available worker nodes. Decision variables such as available resources, affinity-rules and constraints are taken into account. However, the default *kube-scheduler* ist not aware of any latency between the worker nodes nor the pods communicating with each other. As discovered in the following chapters, this appears to be an important variable for edge-deployments. However, some available white-papers are already trying to address those issues and show possible solutions by adopting a custom scheduler taking care of those values. More details on this can be found in the chapter 7 "related work".
- *Controller Manager* - consists of a single compiled binary controlling the status of nodes, jobs, service-accounts and endpoints as well as creating or removing them.
- *Cloud Controller Manager* - represents the interface to the underlying cloud-platform. This allows kubernetes to create and configure load-balancers, routes and persistent-volumes on the underlying cloud-infrastructure. In local environments or at edge-locations, this part of K8s is not needed or would not have any functionality. K3s therefore does without cloud-integration by default[6].

Worker Nodes manage the workload, i.e. run the actual application(s). These nodes are composed of the following parts [5]:

- *kubelet* - is an agent which assures that the container is executed properly inside their associated pods according to its specifications defined via *PodSpec*. Also *kubelet* is responsible for monitoring the healthy state of the containers.
- *kube-proxy* - uses the packet filters of the operating system underneath to forward traffic to the desired destination. The resulting access points, also called *Services* in K8s-jargon, can be made available either internally or externally.
- *container runtime* - is the part that finally executes the containers. The default runtime at time of writing is *containerd*, however any runtime is supported that complies with the CRI specification [7].

It should be mentioned, that those components are also executing on the *Master Nodes*, because some of the core-componentes are containerized (pods) themself.

Kubernetes Objects are persistent properties inside the K8s ecosystem representing the state of a cluster. The most important feature of those objects is to describe the target environment in a declarative way. For this purpose, most of the time, YAML files are used. Kubernetes now ensures that the desired state of the environment is actually achieved and continuously monitors the required objects to meet those defined requirements. This mechanism is also ideal for distributed systems, such as edge computing, as availability can be monitored at any-time and an action can be taken if necessary. Subsequently the main objects are cited starting with the smallest unit [8]:

- *Containers* - decouple the actual application and its dependencies from the underlying infrastructure. The main properties of those containers are immutability and repeatability. This means that the container can be rebuilt anytime resulting in an identical clone. Likewise, the code of a running container cannot be modified subsequently.
- *Pods* include at least one or more *Containers*. In the most scenarios a single pod consists of a single container, in some cases a so-called sidecar container is used increasing the number of containers inside a pod. A side-car supports the main container with additional functionalities. Containers which are in the same *Pod* share the same local Socks as well as volumes mounted.
- *Deployments*, *Statefulsets* and *Daemonsets* - are responsible for ensuring the actual workload is provided; to achieve this they control and scale the assigned *Pods*. When creating an application for K8s, it is most likely to create one of those objects. The *Pods* and *Containers* are merely an end product that is derived from these objects.
- *Services* - provide an abstract way to make a set of *Pods* available on the network via a single endpoint. Additional deployed pods will automatically be added to the responsible *Services*. Thereby K8s is an excellent choice when it comes to scaling applications without any manual intervention. This also applies for deploying applications to the edge of the network, as illuminated in the course of this thesis. Closely related to the *Services* - is the *Ingress* resource, which is taking care of making the aforementioned objects available outside the cluster. An optional reverse-proxy (*Ingress-Controller*) must be installed in order to make use of the latter.

A new feature, which is of relevance regarding edge-computing, currently in beta phase, is the so-called *Topology Aware Hint*. Basically it is meta-data added to the endpoints defined previously advising the connecting client on how to reach the destination efficiently; e.g. zones aware of different locations can be defined. In simple terms, short latency connections are preferred, K8s automatically optimises for this.
- *ConfigMaps* and *Secrets* - are pieces of information which can be mounted into *Containers* to adjust their configuration at runtime. Even whole files can be replaced using one of them. *Secrets* are only different in the sense that they decode the content, however technically they are the same.

- *Volumes* - provide persistent storage which extends beyond the life cycle of the pods. Volumes can be mounted at any defined position inside the pods. The disadvantage is that the data written to those *Volumes* resides out of the K8s ecosystem and therefore the operator must take care of data security and replication. This becomes even more complicated in an edge-computing environment where nodes have higher latency between them.

Security Although this is not directly an object or component of K8s, the principles regarding IT-Security are nevertheless of important significance. A distinction is made between security at different levels, as illustrated by the "4Cs" of cloud native computing [9]:

- *Cloud* - as well as Co-location includes all locations and physical devices.
- *Cluster* - refers to the entire K8s cluster itself.
- *Container* - represents the unit that performs the workload.
- *Code* - the actual application, which is located in the containers.

In order to create a holistic security concept, all layers must be considered and taken into account. Due to the diversity, these efforts are usually quite extensive and time-consuming and should not be underestimated. Nevertheless, Kubernetes offers many tools and methods to harden and secure the environment accordingly.

2.1.2 Edge-Computing

Edge-computing is the model that extends cloud services to the edge of the network. The computing resources on the edge act as a layer between the entity, who provides or wants to process data, and the centralized datacenter (e.g. the cloud). Because data can be processed earlier respective closer to the source, latency and amount of data transferred can be reduced [10]. Also, the required computing-resources in the datacenter can be minimized as data can be processed at the edge. A major driver of the subsequent technology is IoT. The amount of devices and resulting data volume, which must be processed, is increasing exponentially [1]. Another technology which depends on it are low-latency applications like video-streaming.

Hierarchy describes the layers of the architecture. The following list enumerates the most important layers from top to bottom [10]:

1. *Cloud* - centralized datacenter
2. *Fog* - distributed "smaller" datacenters
3. *Edge* - the closest unit to the end-user

4. *IoT* - device at the edge put into use

The main focus of this work is to efficiently combine the two layers *Cloud* and *Edge* and orchestrate between them using K8s. The layer *Fog* is skipped because it is often seen to be "the same" as the *Edge*. Also, current K8s based solutions do not make use of it.

Geo-Distribution characterises the aspect of the geographical propagation of the edge resources. The goal is to provide computing power over wide areas, each close to the users. By establishing many of these locations in different regions, network latency can be significantly reduced from the user's perspective. However, the latency between the edge-nodes and the centralized cloud still remain.

2.2 Architecture

This chapter focuses on the two different architecture approaches which can be used for edge computing. After an general overview, the advantages and disadvantages of the individual architectures and possible solutions are examined.

2.2.1 Default

In order to be able to manage resources at the edge, a traditional architecture can be used. This is divided into a centralized control plane hosted in the cloud and distributed worker nodes near the edge. The same K8s architecture is commonly used when deploying to a single location as well as inside the cloud. Figure 2 illustrates the architecture.

Although the conventional components can communicate with each other over long distances, there are challenges that need to be taken into account. An important role in this context is played by the container network interface (CNI). This part of K8s, which can be selected in the form of a plugin, is responsible for the cluster-internal network traffic. Most of these plugin providers offer advanced features that facilitate geographical distribution. Some of the most used CNI providers are [11]:

- Calico
- Canal
- Cilium
- Flannel
- Weave

Another issue that needs to be considered is the replication of metadata held by the control planes. Because of the higher latency, and/or unstable connection at the edge site, data cannot always be retrieved reliably. To circumvent this problem, asynchronous replication can be used

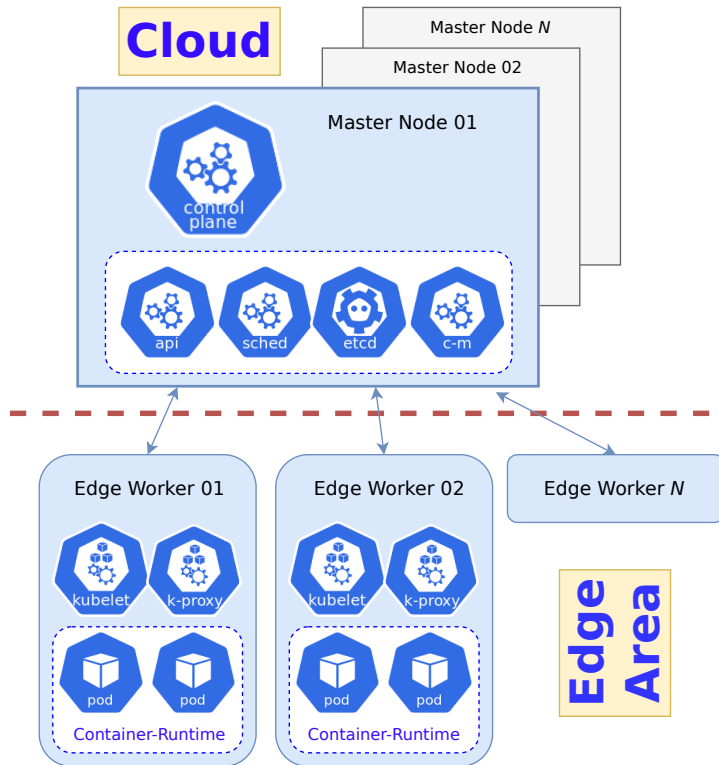


Figure 2: Default K8s architecture

for replicating metadata. The important part of the metadata store are domain namesystem (DNS) entries, because K8s heavily relies on them for service discovery. NodeLocal DNS is the recommended way [12] to hold a copy of the entries in the DNS (cache) on the worker nodes. Another solution is to make the environments independent of each other, thereby no big data chunks are requested respectively synchronized at all.

Another challenge regarding storage ist the handling of persistent volumes. Those logical data chunks must be replicated in an asynchronous manner because of the latency between the nodes. As this is not always possible and data management is a general challenge, making services stateless is the recommended way to work around this issue. In contrast to this, forwarding data to the cloud is not an issue most of the time when using suitable message queues. For that purpose, eg. KubeEdge, is making use of message queuing telemetry transport (MQTT).

In addition there is no awariness of where workloads are running and the level of latency between nodes when using vanilla kubernetes. There are some developments in this area, but they have not caught on yet [13, 14, 15].

KubeEdge is an open-source Cloud Native Computing Foundation (CNCF) project [16] that already comes with many of these functions respectively requirements pre-charged. Likewise, this tool was explicitly developed for edge-computing. Worker nodes can therefore be distributed across the whole globe without any major adjustments. To make this possible, some

components were added or exchanged [17]:

- *CloudHub* - websocket endpoint responsible for sending data to the edge-nodes.
- *Edged* - kubelet is replaced with a lightweight custom agent, the EdgeCore. Thereby even devices with very limited resources, e.g. a Raspberry Pi, can be used for running workloads.
- *EdgeController* - a K8s controller responsible for managing and distributing metadata.
- *EdgeHub* - the counterpart to the Edgecontroller; uses a websocket server for syning updates to and from the cloud.
- *MetaManager* - Message processor, coordinating datatraffic as well as tasks to be run between edgehub and edged. Can also store information in an SQLite database. In case of connectivity issues this database is used so that services can continue to run continuously.
- *EdgeMesh* - responsible for replacing the K8s default network functionalities such as the kube-proxy, DNS and CNI, making them fit for edge scenarios. The main goal was to achieve high availability, reliability and the agent to be as lightweight as possible. However, this agent also has some disadvantages, as we will discover in the use-cases later. It should also be mentioned that this agent is not installed per default and is being developed in a separate project. That iss also why this component is not part of Figure 3. A more detailed description as well as a figure can be found in subsection 4.2.1.

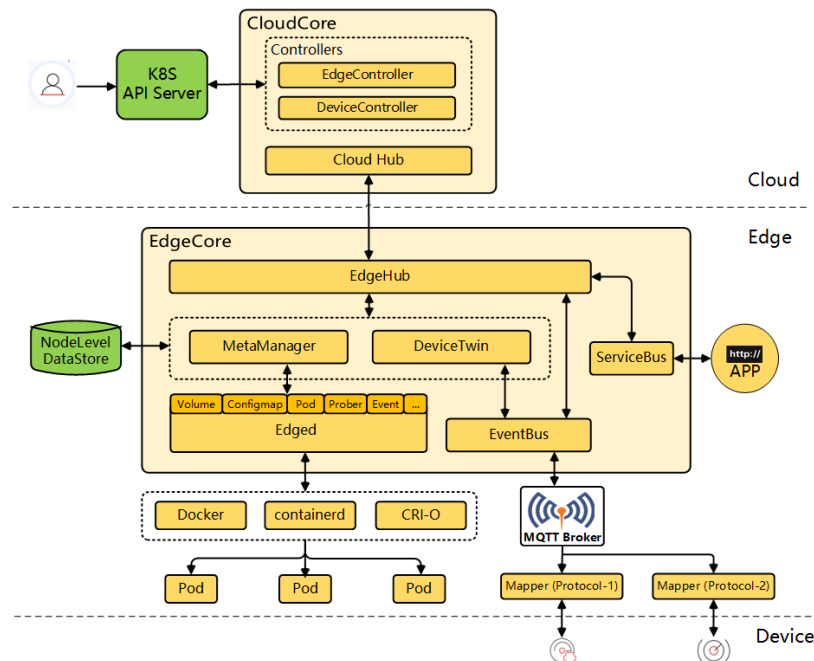


Figure 3: KubeEdge architecture[18]

Figure 3 illustrates the interaction of the components.

In addition components (DeviceTwin, EventBus and ServiceBus) for device and IoT management are shown in Figure 3. Also a seamless integration with MQTT is built-in to KubeEdge[16]. However, because this thesis focuses on the geo-distribution aspect, these parts are not researched any further.

2.2.2 Distributed K8s

In this case, a different approach is chosen and, in contrast to the previous architecture, fully-fledged clusters are also operated at the edge. The obvious advantage is that they can operate autonomously. There is basically no dependence on the other nodes or their workloads.

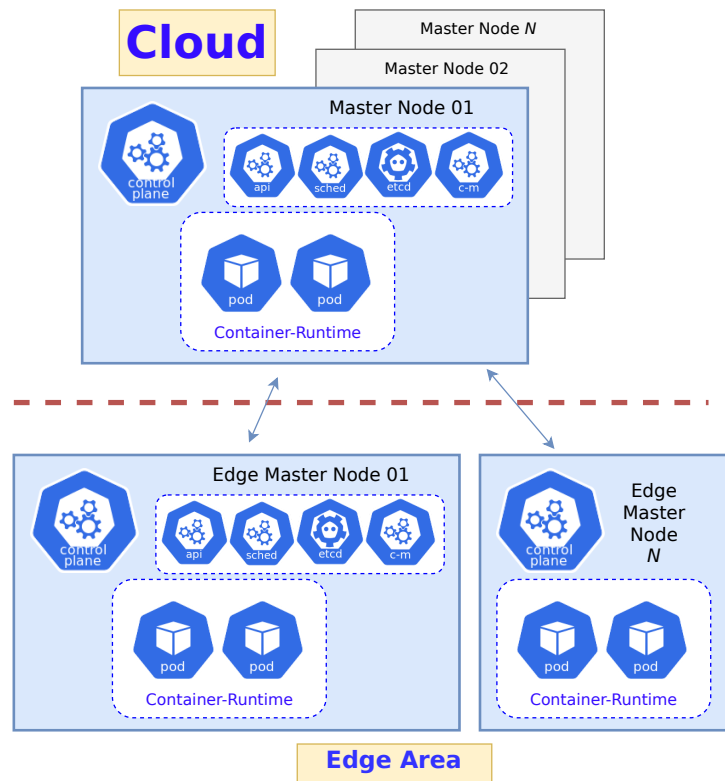


Figure 4: Distributed K8s architecture

However, this also creates new challenges such as the distribution and coordination of workloads. Without additional functionality added, the workload running on the clusters does not know about their neighbours. To overcome this gap, the division "multi-cluster deployment" has excelled in recent years. Even Google, who is the original developer of K8s, offers such a service [19] in their public cloud. Due to the increased demand, the Kubernetes cluster federation (KubeFed) tool is officially being maintained and further developed by the K8s project[20]. Although the tool is still in beta, it is a very good choice for our field of application. One possible alternative would be the K8s manager by Rancher Labs.

KubeFed consists of a central hosting cluster which controls subordinate clusters via application programming interface (API) delegation. Within KubeFed it can be defined which configuration should be managed by the hosting cluster. The methods used are intentionally low-level and can thus be expanded well for different edge-deployment variants. Two different types of information are used to configure KubeFed[20]:

- *Type configuration* - determines which API types are handled.
- *Cluster configuration* - determines which clusters should be targeted.

The type configuration itself consists of three main parts:

- *Templates* - defines a common resources across the clusters.
- *Placement* - defines which destination-cluster the workload should run on.
- *Overrides* - defines variation of the templates on a per cluster level.

One disadvantage of KubeFed is the lack of network integration. Workloads running on distributed clusters cannot communicate with their neighbours. The integration of the standard CNIs listed above is not possible. However, additional components or configurations can now solve this problem, as Cilium demonstrates [21]. However, since this paper focuses on the comparison of the two architectures themselves, such extensions are not considered.

2.3 General Challenges

Challenges that appear when creating respectively operating such infrastructures are diverse, as can be seen in the following list [10]:

- *Variety* - a lot of different locations, technologies as well as methods on how to control devices on the edge is challenging for both development and operation. The better these different factors can be abstracted and simplified, the more effectively the infrastructure can be used.
- *Integration* - edge-computing evolves very quickly, thereby things could change quickly. It is important to keep the provided interfaces extensible. This way, new devices or application can be put in use swiftly.
- *Awareness* - the devices and/or end-user do not care about how their traffic is routed, or their data is processed. However, the architecture needs to take care of that to use the topology in the best possible way.
- *Resources* - scaling Resources like central processing unit (CPU), random access memory (RAM) and disk space at the edge is by far more elaborate than in a datacenter or in the cloud.

- *quality of service (QoS)* - The service provided at the edge should be reliable and provide a good user experience. Availability and performance play a central role in this context. As the availability can not be guaranteed to some extent, an appropriate failover mechanism should be in place.
- *Security* - physical access control as well as isolating applications from each other is a difficult task. Also, the data traffic must be separated accordingly. In general, IT security is a hot topic, and especially at the edge, it requires appropriate consideration for hardening the environment.
- *Monitoring* - another important factor is how to capture metrics and events (logs) from the edge. They need to be indexed on a centralized instance in order to get a general overview on what's happening. Because of the dynamic and rapid changes some kind of automatic discovery should be used for that purpose.
- *Environment* - Some locations may have to deal with difficult conditions regarding their surroundings. Poor internet connections or recurring power outages can be some of these factors. The system must be able to cushion or parry such failures accordingly.

The above-mentioned challenges provide a good starting point for defining the necessary tests to find the matching target architecture. Details about this test can be found in the chapter 3 "methodology".

3 Methodology

3.1 Design Science Research

DSR is used as a scientific method to create the PoC. DSR describes itself as follows: "A common topic when performing research in technical disciplines is to design some kind of artefact, such as a model, an information system, or a method for performing a certain task. To address this topic in a systematic and scientific way, Design Science Research (DSR) has established itself as an appropriate research method" [22]. Following the paradigm two environments are built as described in section 4.1, each representing one of the architectures listed in section 2.2. A test-deployment is then applied to both environments and tested against specific use-cases to be found in section 4.2. The findings are finally interpreted and summarised in section 5.2 and serve as a basis for the catalog in chapter 6.

It is essential in the procedure that the environments can be refined and adapted during the execution of the test scenarios. This is listed and described in the respective chapters insofar as adaptations have been made. The starting point is always the simplest form of implementation or the standard version without any adaptations for both architectures.

3.2 Requirements

3.2.1 Functional requirements

Technical aspects that should be solved in the course of the PoC.

Distribution The goal is to provide a web application that can be deployed across many nodes that are geographically spread out. It should be possible to carry out the distribution in an essentially automated manner.

Connectivity The service should be made accessible locally as well as within the cluster itself. The possibility of releasing services to the Internet should also be examined.

Compatibility The more different devices are supported, the more flexible the environment can be. A high level of diversity is therefore the main focus.

Scalability If necessary, the service should be able to be quickly adapted to load changes. The scaling of the application will be evaluated accordingly.

Operation Easy handling as well as high stability can simplify the operation accordingly. Activities such as those that can occur in daily business are also examined.

3.2.2 Non-functional requirements

Other non-technical requirements which should be covered accordingly. The focus in this section is on the dependencies around the products.

Community An active community can be an important attribute. Sharing experiences can help to build up know-how more quickly.

Support Especially in the business environment, support from the manufacturer can be an important means.

Future-proof The further development or the roadmap of the respective solutions also play an important role in the choice. The background of the two projects should therefore be illuminated accordingly.

3.2.3 Security requirements

The security requirements are defined according to the security measures or recommendations defined by OWASP CheatSheetSeries [23]. The model of the "4C's" [9] also has an influence in order to be able to cover all safety aspects. The work is divided into the following categories and respective requirements.

Encryption Encryption of data transferred between workers and masters is an absolute requirement. Data should generally no longer be transmitted unencrypted on the public internet at the time of writing.

Logging The central collection of log data is an important factor in making attacks detectable in the first place. Such functionality is therefore being evaluated.

Workload The workload itself should be appropriately hardened according to OWASP specifications [23]. For this purpose, different guidelines that can secure the system are examined.

Architecture The basic security architecture of the environments is also checked for compliance with standards and best practices. The focus is also on the behaviour during operation. The highest possible standard should be achieved.

3.3 Testing and Research

In order to fully check the requirements, tests are carried out at the PoC in the following categories: resource utilisation, network and connectivity, application stability and IT-Security. The focus is on exploring the peculiarities and behaviour of the respective environment. As far as possible, quantitative data is collected, which is then evaluated. The focus is not on implementing the most complicated applications available, but on testing the main functionalities of K8s itself. Therefore, using the most commonly used configuration objects is sufficient.

3.4 Main categories covered

Based on the requirements and including the results collected in the PoC, the following categories are considered in the catalogue:

- Installation
- Operation
- Application
- IT-Security
- Community
- Support
- Future-proof

4 Proof-of-concept

All details about the code or the configurations are not listed in the appendix but on the Github repository [24] of the project, which is linked in the relevant places. The work itself only shows fragments that are relevant to the currently discussed topic to ensure the best possible reading flow.

4.1 Environment

4.1.1 General

The main goal is to create both of the aimed architectures in a similar environment. The target environment should provide good coverage of the diversity encountered in edge environments. For that purpose the PoC is build across [Hetzner Cloud](#) [25] and a local site connected via 4G mobile internet.

Coverage The following properties are taken into account for the environment:

- *Geographical distribution* - Hetzner Cloud offers location in Germany, Finland and the U.S for deployments. This allows communication to take place over long distances.
- *Scalability* - On the Hetzner Cloud scaling nodes can be realised quickly via API.
- *network address translation (NAT)* - At the local site, nearby Vienna, no public IP is available for each of the nodes. Therefore, NAT is used to map a dynamic changing IP to the nodes downstream.
- *advanced RISC machines (ARM)* - Also at the local site, a Raspberry Pi is used as an edge-node to emulate devices with minimal resources.
- *Unstable* - The connection at the local site may be unstable from time to time because the connection is established over the public 4G network using mobile technology.

Locations Table 1 lists all of the nodes that are used for each of the both test environments, followed by Figure 5 showing the locations on a map.

Node	Location	IP	CPU	Cores	RAM	Latency
Master	Nürnberg, DE	dedicated	AMD64	2	4GB	0ms
Edge-1	Ashburn, US	dedicated	AMD64	2	2GB	95ms
Edge-2	Helsinki, FI	dedicated	AMD64	2	2GB	24ms
Raspberry	Kirchberg, AT	dynamic	ARM64	4	4GB	40ms

Table 1: PoC nodes specification



Figure 5: Map of the PoC[26]

OS The operating system (OS) used on all cloud nodes is Ubuntu 20.04.3 LTS. For the local site on the Raspberry Pi the OS Raspberry Pi Lite, without graphical user interface (GUI), is used.

K8s For simplicity, the tool of choice for installing K8s is [K3s](#). This is a lightweight K8s distribution optimized for IoT and deployments at the edge. All necessary features are supported, only the dependencies have been reduced to the essentials. In actual use, insofar as resources in the cloud only play a subordinate role, the standard K8s can also be used analogously. However, at the edge K3s is a perfect match. To illustrate the simplicity, the installation command used is shown below.

```
curl -sfL https://get.k3s.io | INSTALL_K3S_EXEC="--disable traefik
--disable-cloud-controller" sh -s -
```

Code 1: K3s installation

VPN No virtual private network (VPN) is used for either environment. Although a VPN can increase security and services can communicate more easily, its use in a widely distributed edge environment with many nodes can be problematic. Traditional VPNs are not designed for unstable connections with high latency and possibly rapidly changing internet protocol (IP)

addresses. The tools used in both architectures therefore use alternative approaches via HTTPs and RPC respectively.

4.1.2 KubeEdge

For the default architecture respectively KubeEdge variant, only a K8s installation on the master node is required. The edge-nodes need be to equipped with a supported container runtime as well as the KubeEdge installation binary. In our specific PoC Docker is used. KubeEdge takes over the roles of the kubelet and the kube-proxy as shown in Figure 2. The single binary (keadm) is used to initialise KubeEdge. The KubeEdge installation is carried out on the master according to the default routine. If the process has been successfully completed, X.509 certificates are generated with which the edge-nodes can then authenticate themselves. To simplify this, a token is also generated from the certificates. On the edge-nodes, only the public facing IP of the master and the token must be entered during the installation in order to make them join automatically.

Challenges The most important steps and challenges encountered during the installation are listed below.

- *CloudStream* - While the standard installation can be done easily, activating logs is much more challenging. Activities such as generating certificates, setting environment variables and adapting configuration files must be carried out manually.
- *K8s Networking* - As will become clear in the next subsection 4.2.1, no CNI is installed per default, which is why it must be post-installed, if this functionality is required.

Version KubeEdge v1.9.2, released on 21.03.2022

Installation Steps for installation can be found in the file "kubeeedge-install"[27] in the project repository.

4.1.3 KubeFed

In contrast to KubeEdge, as also noted in subsection 2.2.2, KubeFed relies on individually acting clusters that are controlled by a central instance. Because of this, each node must be equipped with a fully functional K8s cluster. Usually, the installation is associated with greater effort, but K3s simplifies this process enormously, as described in section 4.1.

Challenges The most important steps and challenges encountered during the installation are listed below.

- *Hosting Cluster* - The challenges arise when it comes to connecting all instances from the central cluster. The kubeconfig for each of them must be modified, to include the public ip or full qualified domain name (FQDN) of the node, and transmitted to the central hosting cluster. There, the configuration must be added as an additional context. Finally, a custom binary is used to add each of the defined contexts to KubeFed, as shown below.

```
kubefedctl join edge1 --cluster-context edge1 --host-cluster-context  
default --v=2
```

Code 2: KubeFed join context

- *Dynamic IP* - Because the central hosting cluster is initialising the connection to the nodes at the edge, these nodes must be reachable over a static address. In most cases the use of static ips is not a problem. However, especially in edge-environments, the use of dynamic ip-addresses may be necessary. To circumvent this problem, a so-called dynamic DNS service is used to establish the connection. Although such a service can be set up relatively quickly, it does mean that an additional component has to be installed and maintained. In contrast, KubeEdge works without such a workaround.
- *dNAT* - As long as the target node is behind a router and connected with a private ip, destination NAT must be configured to forward the necessary port. Alternatively, a reverse-proxy can be used to publish the internal service. This step is only required for the KubeFed variant.

Version KubeFed v0.9.1, released on 15.02.2022

Installation Steps for installation can be found on the Github: [Berndinox/K8sEdge](#) [28]

4.2 Use-Case

As a test, a web-application is distributed over several egde-nodes which is to be made accessible locally as well as via ClusterIP. The goal here is not to develop a complex application, but to uncover the behaviour of the environments. A ready-made nginx container, which is available for both arm and x86, is used as the test pod. The name of the docker image, available in the DockerHub, is: [nginxdemos/hello](#). The K8s objects used are composed of a service definition and a deployment file. The most important parts are listed in the example Code 3.

```

kind: Deployment
spec:
  selector:
    matchLabels:
      app: nginx1
  spec:
    containers:
      - image: nginxdemos/hello
        ports:
          - containerPort: 80
---
kind: Service
spec:
  ports:
    - name: http
      port: 8000
      targetPort: 80
  selector:
    app: nginx1

```

Code 3: Web-application code

It is important to note that the above configuration only contains parts to increase readability and cannot be applied in this form. The full configuration can be found in the Github repository under the folder [DOCs](#) [29].

Relevance The example provides a good basis for the tests carried out. The object "Deployment" is used, which allows the pods defined to be scaled accordingly. This is a fundamental part of any environment at the edge. A "Service" is also defined that allows any network functionalities to be tested. Many of the applications that are specifically designed for the edge are based on these two mechanisms.

Connectivity Basically, the service can be made available via two different methods. The first variant makes it possible to use the services from the local network. For this purpose, either a HostPort or NodePort is defined in the service object. For example, IoT devices could send or retrieve data via this interface. The second method publishes the service via ClusterIP or Ingress. This variant is only supported by KubeEdge because it is dependent on the CNI. With this variant, it would be possible to operate a CDN or distributed web service. For this purpose, the use of an anycast IP or a GeoDNS would be required.

Goals The main objectives to be achieved with the use-case are as follows.

- K8s Objects
 - Create the defined objects (YAML configuration) across the edge-nodes
 - Achieve a high scalability through multiple pods (nginx)

- Networking
 - Publish the services locally on each edge-nodes networking
 - Publish the services on the internal K8s network
- Operation
 - Collect logs of the edge-nodes
 - Stability should be guaranteed

4.2.1 KubeEdge

Starting the web-application on the KubeEdge environment, without any further modification on the K8s stack, the deployment fails. This is manifested as follows: If the deployment and the service definition is created via `kubectl`, the job looks successful at first. The service is created and pods are scheduled accordingly. However, the goal is to follow the native approach and make the service accessible via ClusterIP using the Kubernetes network functionality. However, connecting the service was not possible as a test, making use of `curl`, proves. Another problem that arises is that the pods cannot be accessed either directly on the exposed port or via `kubectl exec`.

Research has shown that KubeEdge does not use any CNI plugin to offer network-connectivity per default. However, a specially developed Kube-API endpoint is used for this, which takes over the functionalities (see below) and improve them for the requirements of an edge environment. This endpoint does not currently cover all functionalities, which is why our deployment needs to be modified accordingly [30]. The following list represents the available

Kube-API verbs:

- Get
- List
- Watch
- Create
- Update
- Patch

Not implemented at time of writing is the verb "**Proxy**", which prevents us from connecting directly to the pod via `kubectl exec`. Other commands that rely on the proxy verb are `attach`, `top`, and `logs`. For the latter, there is already a solution in the official documentation, also noted in the code base of this thesis.

Three variants are available to solve the problem of missing network connectivity.

- *Without network* - the first approach is to simply omit the network part and make your deployment independent of each other, comparable to how KubeFed handles its workloads. However, this means that the actual added value of the default architecture is lost; network communication can not take place as it would within a traditional K8s cluster. Also the description found in the docs of KubeEdge seem not to be very accurate, when not using additional tools: "With KubeEdge, users can orchestrate apps, manage devices and monitor app and device status on Edge nodes just like a traditional Kubernetes cluster in the Cloud." [18]
- *CNI* - the next logical step seems to use a CNI, which would make all the required functionalities available. However, this means that many of the advantages promised by KubeEdge are gone: The support of private-ip addresses behind NAT, high availability and resilience as well as latency-independence. In addition, a developer from KubeEdge points out that making use of a CNI is not a recommended solution [31].
- *EdgeMesh* - as described in subsection 2.2.1 is an additional component which has to be installed manually. Although EdgeMesh is part of KubeEdge and integrates seamlessly, it is seen as a separate project whose development is independent. EdgeMesh functions similarly to the CNI described above and is based on the same mechanisms, but is equipped with additional functions for use at the edge. It should be noted that the project was still in a fairly young status at the time of the research, when comparing the statistics of the Github repository.

In the course of solving the problem, two variants were examined in detail, firstly the one that does without all additional tools and secondly the variant with EdgeMesh. The variant with post-installed CNI is not considered further; in this case, one could fall back directly on vanilla K8s. The following graphic illustrates the differences. The green access is via ClusterIP using the internal network component EdgeMesh, whereas the call in purple is made directly to the Pod without an internal network.

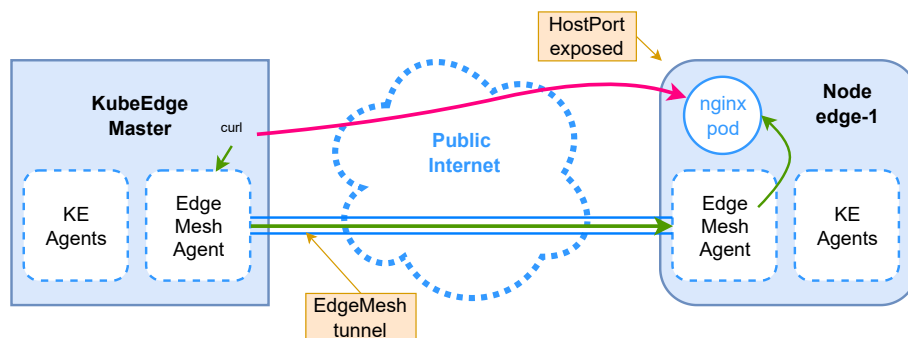


Figure 6: KubeEdge networking

Figure 6 illustrates the both connection methodes. "KE Agents" refers to the componentes of KubeEdge as shown in Figure 3.

Without network As long as there is no need for complex network communication between the pods, this variant offers a simple solution. Deployments, StatefulSets and DaemonSets can be distributed and scheduled via K8s to the edge-nodes. The services can then be made available for local services only. This is achieved through the configuration of a so-called HostPort. It is important to note that making the port available cannot be done via NodePort, as in this case the port would be made accessible at all nodes, which in turn requires a functioning cluster network. The following is the modified deployment that makes the application accessible on the edge-location. Please note that the object service was removed entirely, only relevant parts are cited.

```
spec:
  hostNetwork: true
  containers:
  - image: nginxdemos/hello
    ports:
    - containerPort: 80
    - hostPort: 8000
```

Code 4: Web-application HostPort

One possibility to establish the connection between the edge-locations in this variant would be the exchange via MQTT on the application level via the cloud component. However, this increases the complexity tremendously. In this case, one of the other two solutions is to be preferred at the current state of affairs.

EdgeMesh As already noted, this component must be installed before it can be used. Before the actual installation, which takes place within the K8s system, the KubeEdge configuration must be adapted. The installation is divided into the following steps.

1. *Load* - Download the EdgeMesh sources from Github
2. *CRDs* - Create the custom resource definition (CRD) necessary
3. *KubeEdge* - Configure KubeEdge components
4. *Agent* - Apply the YAMLs provided by EdgeMesh
5. *Restart* - and verify your system-changes.

The complete process is available in the following document: [Berndinox/K8sEdge](#) [32]. Please note that the project may change rapidly, the installation-process linked above is just a snapshot of the current state. As long as EdgeMesh could be installed without errors, the deployment and service object described above can be distributed and scheduled without any modification. With this solution, the native K8s approach is fully followed and ensured.

What is certain is that the documentation at this point is not sufficiently well formulated. It advertises native K8s support, which cannot be met with a default KubeEdge installation. Although it is pointed out that logging has to be configured separately, the networking section receives little or no attention. It was only through intensive testing and tracking of issues on Github that the above behaviour regarding connectivity could be uncovered. This fact is taken into account in the later evaluation.

4.2.2 KubeFed

In principle, the same considerations must be made for deploying on KubeFed as for those on KubeEdge without network support. The application must be designed so that no communication can take place between the clusters. However, the native approach of K8s can be followed within the respective clusters at the edge. It would also be possible to operate several nodes at the respective edge-locations in the form of a cluster. Within this cluster, communication between the workloads would be possible without restrictions. Due to these properties, KubeFed is always particularly suitable when fewer and better developed locations are to be connected, which must be able to act independently. In order to roll out the deployment mentioned in the introduction of the chapter to the federated clusters, some adaptations are nevertheless necessary, which are illustrated below.

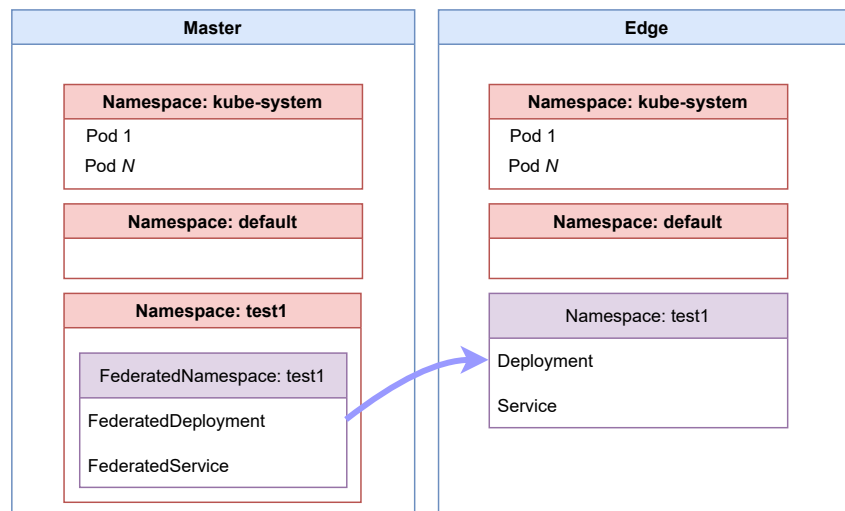


Figure 7: KubeFed objects

1. *Enable API-Ressource* - On the master instance, the resources earmarked for distribution must be enabled. Per-default KubeFed does not distribute any resources. In this specific case, we have to enable the deployment and service object as follows.

```
kubefedctl enable deployments.apps, services --kubefed-namespace
kube-federation-system
```

Code 5: Enable federation

2. *Create Namespace* - The first step is to create a namespace at the master, which then contains all the resources that are distributed to the clusters at the edge. In our first specific use-case the namespace is called "test1".
3. *Create Resources* - At this point it is crucial to understand that KubeFed distinguishes between two types of objects. The normal objects, which are however only executed and managed on the master, and specially federated objects which will be deployed on the edge-clusters. Figure 7 illustrates the interaction between the components. The conventional objects are simply preceded by the abbreviation "Federation". If the API-resource is also delegated, the objects are passed to the edge-clusters and scheduled there in form of the default objects. The environment at the edge does not even know about the existence of these special federated resources, because they are scheduled in form of a default object. The service and deployment mentioned at the beginning is therefore expanded as shown in Code 6.

```
apiVersion: types.kubefed.io/v1beta1
kind: FederatedDeployment
spec:
  ...
placement:
  clusters:
    - name: edge1
    - name: edge2
```

Code 6: Federated Object

The same approach applies for the service object. An important part of the configuration is the placement part, which defines on which edge clusters the respective object is to be created. The complete configuration, can be found in following file saved in the Github Repository: [Berndinox/K8sEdge - KubeFed usecase](#) [33].

5 PoC - Research

This part examines the previously created use-case through a scientific method. The results from the tests are analysed in section 5.2.

5.1 Performed Tests

In addition to the previously described feasibility, the operation of the respective environment is also of great importance. In the following section, tests are therefore carried out on connectivity, resource utilisation and the application itself. If problems arise or environments do not function as expected, adjustments can be made in accordance with DSR guidelines. These adjustments are documented and described accordingly and can be regarded as best-practice.

5.1.1 Ressource usage

As already described in the section 2.3, the efficient use of resources is an important characteristic in the edge-computing environment. Due to the fact that we rely on K3s as K8s distribution for KubeFed, which is known for using few resources, comparable results can be expected. In principle, however, KubeEdge should be more lightweight, since only the Docker agent as well as EdgeMesh is used on the edge-nodes. Unknown at this point is how many resources are consumed by the EdgeMesh containers. The tests are performed on the edge-side choosing node "edge-1" located in US. The uptime of the nodes for both environments, at time of the measurements, is exactly the same, approximately 15 minutes.

Idle

The first parameter to be considered is the CPU and Memory load while system is idle or under no significant load. The first test is carried out using the tool `cpustat`. "Cpustat is a program that dumps the CPU utilization of current running tasks (that is, processes or kernel threads). `cpustat` is useful to monitor the activity of long lived processes in a system, such as daemons, kernel threads as well as typical user processes" [34].

CPU The deployment created in the usecase is scaled to one pod per node, then the first measurement is performed in idle mode using the command: `cpustat -x -D -a 1 30 -r export.csv`. The utilisation of the CPU by the applications is measured every second for a

duration of 30 seconds and exportet in a CSV. To provide a simple overview, the top 5 processes that caused the highest CPU load are shown based on their ticks consumed. "The processor clock coordinates all CPU and memory operations by periodically generating a time reference signal called a clock cycle or tick" [35].

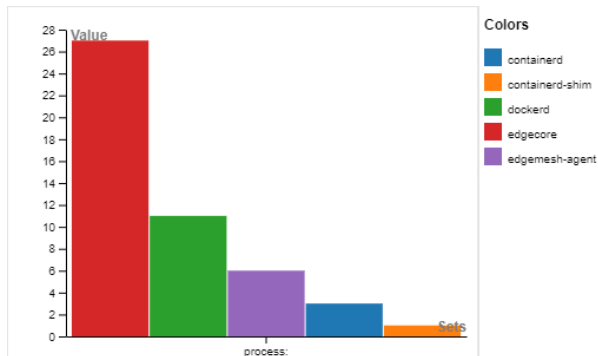


Figure 8: KubeEdge CPU without load

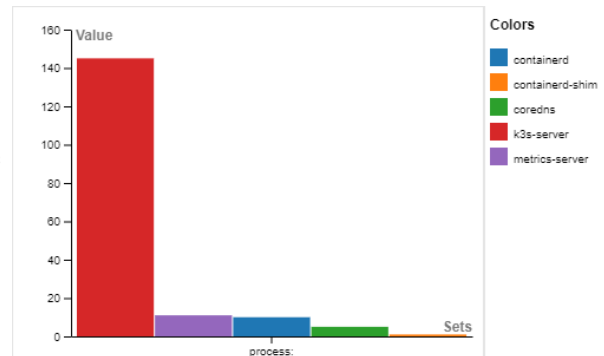


Figure 9: KubeFed CPU without load

In the diagram above, the process of cpustats itself and that of the SSH agent were not taken into account. Neither of them have any direct concern about the test performed. Basically, the result can be interpreted in such a way that the load is low for both systems and no significant jumps were recognisable. Nevertheless, it must be noted that KubeEdge caused many times fewer CPU compared to KubeFed, while both system idle. The full CSV can be viewed in the designated folder on Github. The link is given at the end of the chapter.

Memory Htop[36] and Ansi HTML adapter (Aha)[37] were used to check the memory utilisation in idle mode. The measurement is carried out under the same conditions as the CPU test described above. The deployment was scaled to 1 on the corresponding node, no increased load must or had to be processed. The uptime of both system is 2 hours 15 minutes at time of testing. Since the memory behaves less erratically than the CPU, only one sample were taken. The total consumption for the both systems are:

- *KubeEdge* - 239 MB
- *KubeFed* - 600 MB

The following table lists, in descending order, the 5 processes with the most RAM usage and their percentage share of the total utilisation.

As the data shows, KubeEdge consumes less RAM. KubeFed, on the other hand, uses almost three times as much. Although 600 MB may not seem much in today's times, this can be important in some scenarios, especially in the context of edge-computing.

Disk The last resource to be examined in this section is that of hard disk usage. The CLI tool "df" provided by Ubuntu shows the respective space allocated.

Process	Usage in %
dockerd	4,5
edgecore	4,2
systemd-journald	3,2
edgemesh-agent	2,6
containerd	2.2

Table 2: KubeEdge: RAM usage

Process	Usage in %
k3s	24,0
containerd	6,9
metrics-server	2,4
systemd-journald	2,2
coredns	2.2

Table 3: KubeFed: RAM usage

- *KubeEdge* - 3.5 GB allocated
- *KubeFed* - 4.1 GB allocated

Similar to the results before, KubeEdge is also more efficient in this area.

Load

In the next part of the tests-series, the behaviour during increased CPU and memory load is examined. Since we are only concentrating on the performance part of individual nodes and its effects in this section, no horizontal pod autoscaler (HPA) is used but only a pod that simulates high load. The behaviour of the overall system, when distributing and scaling application load is examined in the subsection 5.1.3. The same environment as for the previous tests is assumed as the basis for conducting the test. To test the described scenario, the tool "kube-stresscheck"[38] is used. This tool creates a pod on one of the available edge-nodes which, on the one hand, occupies the entire RAM and, on the other hand, utilises all available CPU cores.

It should be noted that the standard QoS of K8s is applied or maintained for system pods[39]. This mechanism provides three different levels of execution: Guaranteed, Burstable, BestEffort. As the name suggests, pods with the level guaranteed are assigned the highest priority. The test that is carried out is only assigned the level BestEffort and should therefore theoretically not be able to influence system pods that are assigned a higher level. In real operation, high loads can still cause considerable problems under certain circumstances. In productive settings, such tests should be refrained from.

KubeEdge Due to the K8s native support KubeEdge comes with, the configuration provided by kube-stresscheck does not need to be adjusted. The version selected is the one that only occupies one node with full load. In order to test the node that was selected as the input for the tests before, the other nodes are temporarily drained. Although the developers of the test application describe it as follows: "Usually pods like kube-proxy, nginx-ingress-controller, calico-node are crashlooping. If kubelet or docker was affected by stress test then node will become

NotReady"[38]. However, no such effects could be observed in the test run carried out. The following values were observed and recorded during the stress test on the affected node.

- *Memory usage: 100%* - a flickering was noticed because the underlying OS is trying to free-up unused allocated memory. On the other hand, the pod fills the RAM directly again.
- *CPU usage: 100%* throughout on both cpu cores during the test periode.

The following behaviour was observed during the test, which was carried out over a period of one minute.

- *Stability* - All functionalities of the environment were maintained during the test. Also all pods were available during the entire run and did not get re-scheduled or exited. All local services and agents at the edge-node also performed their services unhindered.
- *Logs* - No errors could be read in the local logs of the respective nodes or in the kubernetes-specific logs. No indication of any problems that could be traced back to the load tests could be found within the test pods either.
- *Responsiveness* - The test deployment responds and is fully available during the test period. The response times are increased, as described in the following subsection 5.1.2.
- *Recovery* - After the end of the test, operation was continued without any consequences. The CPU as well as RAM utilisation go back to the initial level.

In summary, KubeEdge has done exceptionally well. No failures or noteworthy events were detected during the tests. Although the performance of the services that are located on the same node suffers, these effects were within limits and to some extent predictable. The effective use of QoS could further improve overall performance.

KubeFed The test is carried out under the same conditions as the test above. The test deployment is scaled to a pod on the target system, edge-1. However, since KubeFed does not offer an CNI for intra-cluster service communication, the port is changed from ClusterIP to NodePort. This allows the connection test to be carried out using curl with the same conditions. The following values were observed and recorded during the stress test on the affected node.

- *Memory usage: 100%* - similar to the behaviour with KubeEdge, a flickering was noticed.
- *CPU usage: 100%* throughout on both cpu cores during the test periode.

The following behaviour was observed during the test, which was carried out over a period of one minute. With the exception of the response times, the same results were achieved. For the sake of completeness, these are listed again below.

- *Stability* - All functionalities of the environment were maintained during the test. Also all pods were available during the entire run and did not get re-scheduled or exited. All local services and agents at the edge-node also performed their services unhindered.
- *Logs* - No errors could be read in the local logs of the respective nodes or in the kubernetes-specific logs. No indication of any problems that could be traced back to the load tests could be found within the test pods either.
- *Responsiveness* - Similar to the test before, the deployment of the test pod was reachable during the test. Details of this test, as mentioned earlier, can be found in the network-section in subsection 5.1.2.
- *Recovery* - After the end of the test, operation was continued without any consequences. The CPU as well as RAM utilisation go back to the initial values.

In summary, KubeFed behaved very well during the tests. Even under heavy load, our test service performs well and only stands out due to slightly higher response times. As with KubeEdge, this could be further improved through the use of QoS.

Result and interpretation

Both systems can be considered resource efficient. KubeFed benefits from the use of K3s instead of vanilla K8s. Nevertheless, KubeEdge is the winner in terms of minimum requirements and may be preferable for edge locations with weak devices. Under high load, both environments could prove high stability.

5.1.2 Network connectivity

Response time

In the course of the performance tests, which can be found in the subsection 5.1.1, network tests were also carried out to test the behaviour both under load and without load. For this purpose the tool curl is used which can measure time values via output parameters. The test-command is shown below.

```
curl -w "@curl-output.txt" -o /dev/null -s IP:8000
```

Code 7: Curl command

The [curl-output.txt](#)[40] file defines the processing and output specifications. The call via curl is made from the respective master node located in Germany. The list of the locations can be found in Table 1. The target in each case is the node edge-1 which is hosted in the US and performs our target deployment. Due to the differences within the architecture of the two environments, different methods are used at this point. While the internal ClusterIP can be addressed for KubeEdge, which brings the data transfer to the target pod internally via

EdgeMesh, a NodePort must be made accessible via the internet for KubeFed. This means that in the case of KubeFed, the curl command must be issued against the public IP of the target node. The service object of our usecase, describe in section 4.2, was therefore modified as follows for KubeFed.

```
type: NodePort
ports:
- name: http
  port: 8000
  targetPort: 80
  NodePort: 30298
```

Code 8: Curl command

It should be noted that the default port-range for NodePorts is from 30000 to 32767.

KubeEdge based on the command declared above, the following data could be obtained.

Measuring point	Time
time_namelookup	0.000059s
time_connect	0.000581s
time_pretransfer	0.000663s
time_starttransfer	0.192938s
time_total	0.193011s

Table 4: KubeEdge: curl no load (ClusterIP)

Measuring point	Time
time_namelookup	0.000070s
time_connect	0.000245s
time_pretransfer	0.000316s
time_starttransfer	0.338320s
time_total	0.338480s

Table 5: KubeEdge: curl with load (ClusterIP)

The total time to complete a call increased by about 75% in the test conducted. While this may sound like a large increase at first, it must be mentioned again that the node was under absolute full load. In this respect, this value is relativised and could even be considered quite good.

In order to provide a complete overview KubeEdge was also tested via HostPort. This variant is more comparable with the NodePort described above.

The test via NodePort, which bypasses the internal network structure based on EdgeMesh, is similar to the following test of KubeFed. However, this variant also means that a benefit of KubeEdge is lost. This shows that EdgeMesh brings with it a certain overhead that should not go unnoticed.

KubeFed under the same conditions, except for the adjustments to the service, the test was run through for KubeFed. The result is displayed below.

The test only shows an increase of 25%. Considering that the target node is under full load, this is an enormously good value and exceeds expectations. Especially under heavy load,

Measuring point	Time
time_namelookup	0.000079s
time_connect	0.093761s
time_pretransfer	0.093832s
time_starttransfer	0.187626s
time_total	0.188056s

Table 6: KubeEdge: curl no load (HostPort)

Measuring point	Time
time_namelookup	0.000033s
time_connect	0.093475s
time_pretransfer	0.093552s
time_starttransfer	0.201756s
time_total	0.201889s

Table 7: KubeEdge: curl with load (HostPort)

Measuring point	Time
time_namelookup	0.000085s
time_connect	0.089800s
time_pretransfer	0.089906s
time_starttransfer	0.180030s
time_total	0.180333s

Table 8: KubeFed: curl without load

Measuring point	Time
time_namelookup	0.000042s
time_connect	0.089541s
time_pretransfer	0.089756s
time_starttransfer	0.225031s
time_total	0.225544s

Table 9: KubeFed: curl with load

Kubefed resp. a single target cluster, can process the request faster compared to KubeEdge and the EdgheMesh-agent.

Connection restoring

In addition to the ability to keep services available under heavy load, seamless restoration of availability is also important in the event of a disconnection. As with the previous runs, the test-deployment for this setup is scaled to a single pod on the node edge-1. The connection between the master and the node is then disconnected via the firewall function provided by Hetzner. This allows the connection to be cut without manipulating the nodes themselves. In summary, the steps are as listed below in an orderly sequence for each environment.

1. Disconnect "edge-1" for at least 30 minutes with Hetzner firewall.
2. Verify the availability of the pod via NodePort or HostPort
3. Query the status of the node on the master
4. Scaling of the test-deployment on the (unavailable) target node to two pods
5. Restore the connection; disable the firewall rule
6. Verify if the node is marked as available again without any action being taken
7. Check if the deployment has been scaled accordingly

During the entire run, any anomalies in the underlying system and within K8s ecosystem are observed. The time until the system is fully restored and the deployment is scaled is also measured. Likewise, during disconnection, the service should continue to be available through HostPort for KubeEdge or NodePort in case of KubeFed.

KubeEdge The features advertised on the KubeEdge homepage, especially those concerning the handling of network interruptions, could not be proven or confirmed in the tests carried out. The first four steps of the above procedure were completed without any issues. The affected node is marked as "NotReady", as expected when the link goes down and the pod that is exposed via HostPort is still accessible. However, the edge-node could not reconnect to the cluster and mark itself as "Ready" after restoring the connection. In the course of the problem, all error messages in the logs were searched through, leading to the following findings.

First of all, the EdgeMesh-Agent, running inside a pod could establish the connection. This source of error can therefore be excluded. Then the EdgeCore component was examined, where the following error stood out.

```
Apr 02 17:37:20 edge-1 edgecore[583]: W0402 17:37:20.670742      583
context_channel.go:180] The module websocket message channel is full,
message: {Header:{ID:183c3a0f-3c6f-40f7-ade9-2ec0b9f0e8dd ParentID:
Timestamp:1648921040658 ResourceVersion: Sync:true MessageType:}
Router:{Source:>
```

Code 9: EdgeCore Error

This error occurs because the MetaManager still wants to transmit the status of the node and the pods. The messages are accepted by the local EdgeHub process, but cannot then be forwarded to the Cloudcore component because of the connection being cut off. Instead the messages are saved in a message queue, so that the messages can be transmitted after restoration of the connection. While it seems like a good idea in principle to cache local status and events so that they can be processed later, the implementation is obviously failing.

However, the problems continue to accumulate as all messages are passed in one go to the CloudCore queue, after reconnecting the node, which also overruns it. In this status, not only one node is now affected, but all of them, as a status query illustrates.

```
kubectl get nodes
```

NAME	STATUS	ROLES	AGE
edge-2	NotReady,SchedulingDisabled	agent,edge	3d5h
edge-1	NotReady	agent,edge	3d5h
raspberrypi	NotReady,SchedulingDisabled	agent,edge	3d5h
kubeedge-master	Ready	control-plane,master	3d5h

Code 10: EdgeCore nodes unavailable

Code 10 illustrates the effects of the overflowing queue. All nodes at the edge, except the master, are in the "NotReady" state. The nodes cannot be served with K8s relevant updates or

changes in this state. It is therefore important to correct the problem quickly.

The functionality could not be restored without manual intervention. Both the component on node edge-1 and on the master had to be restarted manually. It must be mentioned that at least the distributed pods were recognised without any further action and our service was available during the hole test. Furthermore, the problem only occurs after longer network disconnections, because the queue has to fill up first. However, depending on the environment and workload, this period can change considerably.

In another test, with only 5 minutes of disconnection, the problem could not be provoked.

Researching the issue described above leads us to the following [issue #3576](#)[41] which has already been reported in the Github repository of kubeEdge. Unfortunately, it must be noted that the problem has been open for over two months without any feedback. Considering the challenges from section 2.3, that connections at the edge are often of poor quality and terminations have to be compensated accordingly, KubeEdge does not seem very suitable for such scenarios. The full logs and commands run through during the test could be found in the thesis [repository hosted on Github](#) [42].

In addition, the pods of the deployment could not be removed cleanly after the test. This problem has already been reported as [Issue 3736](#) [43]. At least the KubeEdge team is already working on fixing this issue.

KubeFed Due to the nature of the architecture, no such problems were detected during the test on the KubeFed environment. In simple terms, a kubectl hosted in the central cluster controls other clusters. Each cluster functions completely independently of the others and can therefore remain separated for hours without any problems. This is also confirmed by tests that have been carried out. After reconnecting, the disconnected instance was recognised almost instantly and was again controllable from the central unit. It must also be mentioned that the separated cluster remains locally operable during the time of separation. This remains even if the connection is no longer established at all. In this case, one could simply continue to use the K8s cluster as a singular instance.

Result and interpretation

Fulfilling expectations, KubeFed is characterised by particularly good error resistance in the network area. Both under load and complete disconnection, services remain well accessible. KubeEdge also offers good response times under increased load, although those over the internal CNI has somewhat increased latency. However, this is due to the architecture itself and is within acceptable limits. However, the fact that the local message queue overflows if the connection is interrupted is problematic and, as a result, also causes the master component

to crash. Although the functionality could be restored by restarting the services, a larger environment with many edge-nodes cannot be operated sensibly in this form. However, it can be assumed that a fix will be provided for this.

5.1.3 Application stability

This part of the test focuses on the scalability of the environment and the stability achieved in the process. For this purpose the test-deployment from the previous chapters is reused. The first step is to scale from 0 to 100 pods, then all events of the namespace and start-times are evaluated and compared. Any system-relevant peculiarities or problems are also examined and recorded. All the steps performed during the test for both environments are listed below.

1. Scale test-deployment to zero pods
2. Scale up the test-deployment to 100 pods
 - KubeFed: the pods are evenly distributed over the nodes
 - KubeEdge: the decision is left to the Scheduler
3. Recording of the following events
 - Namespace events
 - Pod status and startup times
 - Cluster events and behaviour
4. Scale test-deployment down to zero pods

The command to monitor the state of the pods is as easy as:

```
watch -n 2 'echo $(echo -n $(kubectl get pods -n=test1 | grep "Pending" | wc -l)
&& echo -n "/" && echo $( kubectl get pods -n=test1 | grep "Running" | wc
-1)) | ts >> running.log'
```

Code 11: Pods status

The code displayed above queries every two seconds the count of the pods in pending and running state and is writing those information as well as an added timestamp to the file called "running.log". It should also be noted that the image (nginxdemo/hello) is already cached on all nodes, and the same image is used for each pod.

KubeEdge After just under one and a half minutes, KubeEdge starts all 100 pods and completes the task flawlessly. The following command confirms that the deployment scaled properly.

```
kubectl get deployment -n=test1
```

NAME	READY	UP-TO-DATE	AVAILABLE	AGE
nginx1	100/100	100	100	3d23h

Code 12: KubeEdge scaling proof

Besides the evidence that the procedure has worked, however, efficiency is also an important variable. Therefore, as previously described, the pods were monitored during the test and the state of each was recorded with a timestamp. The evaluated data can be presented graphically as follows.

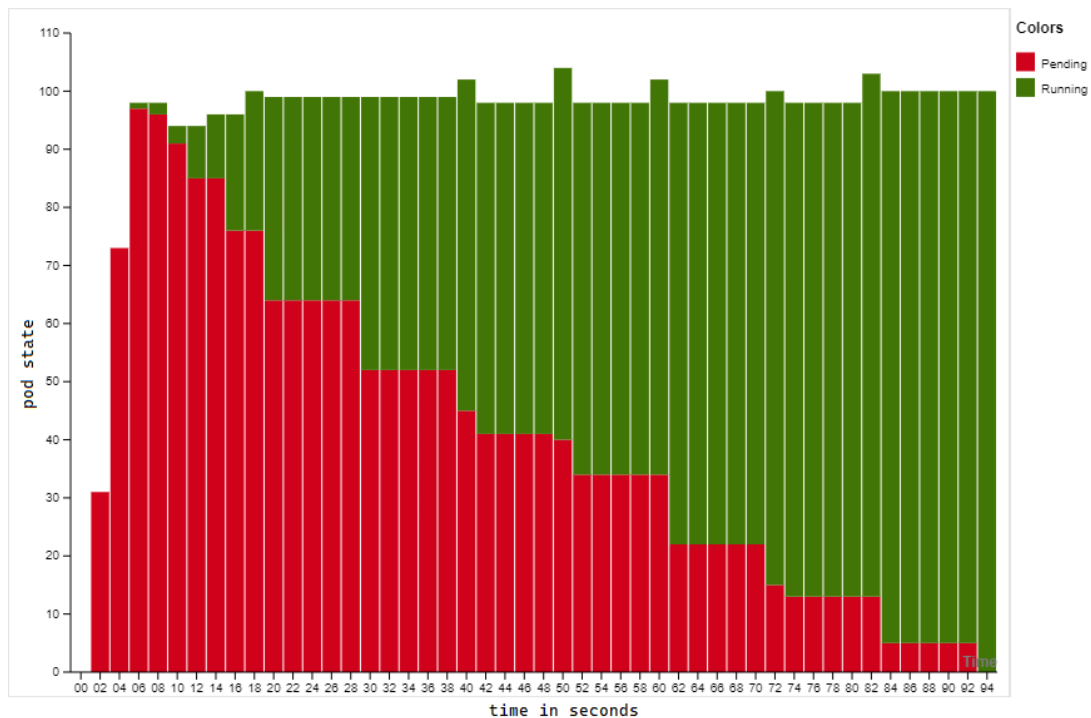


Figure 10: KubeEdge scale

It only takes 8 seconds for all pods to reach the "pending" state, the pods are then started linearly in tranches and are all in the "running" status after exactly 94 seconds. While these values are considered quite positive, considering that the test environment only uses low-resource nodes, the results regarding distribution are less convincing. The following table illustrates the distribution of the pods across the nodes on the edge.

The exact causes of the uneven distribution could not be determined exactly, a connection with the respective latency of the nodes would be quite conceivable, as Table 1 illustrates. The node with the lowest latency to the master was able to launch significantly more pods in the tests. An actual connection could not be proven.

Node	Pods
Edge-1	6
Edge-2	82
Raspberry	13

Table 10: KubeEdge: scale distribution

KubeFed Due to the different mode of operation, the distribution of the pods for KubeFed is done manually in the configuration, which is why a more even distribution is achieved. While this behaviour may be advantageous for the test at hand, the functions of a dynamic scheduler may work more efficiently in environments with rapidly changing conditions and a variety of different deployments.

In order to scale to exactly 100 pods for the KubeFed environment, the deployment was adapted as follows.

```
spec:
  replicas: 33
...
placement:
  clusters:
    - name: edge1, edge2, edge3 // simplified line
overrides:
  - clusterName: edge2
    clusterOverrides:
      - path: "/spec/replicas"
        value: 34
```

Code 13: KubeFed scale adaptations

Since an uneven number of edge-nodes is used, one node must be loaded with an additional pod via override. Similar to KubeEdge, the node with the lowest latency was selected. The deployment was then distributed and the following values were determined. In the course of the distribution of the above-mentioned deployment, the following values were collected. For ease of classification, the values are also shown in Figure 11.

After only 20 seconds, all pods could be started successfully. KubeFed thus takes just under a third of the time as KubeEdge. This is also where the performance efficiency of the RaspberryPi node comes into play, requiring only 12 seconds for 33 pods. Nevertheless, it is important to note that KubeEdge started almost all pods on the same node. Assuming linearity and starting all pods in the KubeFed environment on one node, the start time would be about 60 seconds. That would still be faster. The gaps in the above diagram are caused by the "waiting" status,

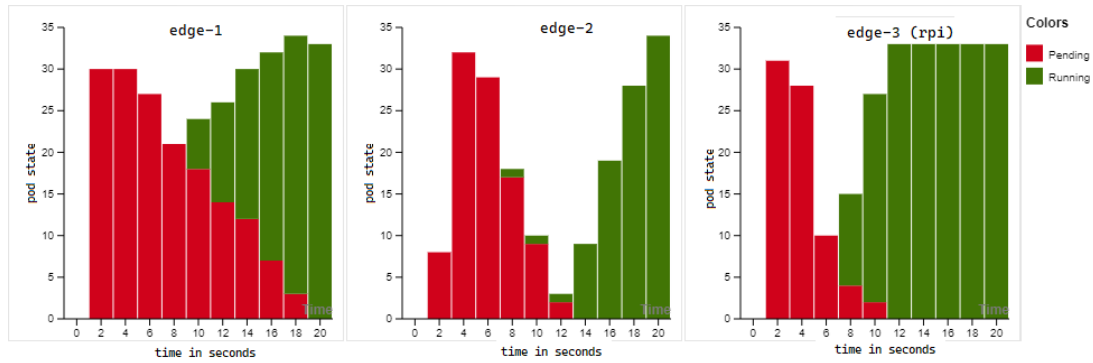


Figure 11: KubeFed scale

which is not covered by the monitoring command. However, this is only an intermediate status which has no relevance for measuring the total time.

Result and interpretation

Both architectures, KubeEdge and KubeFed were able to scale without major problems. Due to the manually performed symmetrical distribution of the pods on KubeFed nodes, the start-up process is significantly faster overall. KubeEdge, on the other hand, has problems with distribution and starts most pods on the node with the supposedly lowest latency. In the specific case, this leads to a disadvantage of KubeEdge, but in larger environments with increased dynamic and complexity, the use of a dynamic scheduler still brings great advantages. The more detailed study of scheduling is reserved for future work.

5.1.4 Security bechmark

In the course of the tests carried out, security scans were also executed in order to identify any problems with the two environments. The following output shows the results of the test framework "falco" [44], which serves as a particularly prominent tool for finding vulnerabilities within K8s. The complete results for each scan including details are deposited in the [Github project](#) [45, 46].

```
== Summary node ==  
2 checks PASS  
11 checks FAIL  
10 checks WARN  
0 checks INFO  
== Summary policies ==  
0 checks PASS  
0 checks FAIL  
26 checks WARN  
0 checks INFO  
== Summary total ==  
2 checks PASS  
11 checks FAIL  
36 checks WARN  
0 checks INFO
```

Code 14: KubeEdge & KubeFed bench

At first glance, the above results do not meet expectations. Both environments have the same result, only two tests can be passed successfully. If one analyses the details, however, one quickly comes to the conclusion that many of the tests carried out are not valid for the present environment. The first part of the test focuses on the analysis of the component "kubelet". The two environments used, however, rely on K3s as K8s distribution in the cloud, or for KubeFed also on the edge-nodes. K3s uses different default paths for kubelet and offers its own configuration parameters [47] to customise the agent. KubeEdge goes one step further on the edge-nodes and dispenses with the standard agent altogether. The result of the first part is not that the environments are not able to fulfill safety aspects, but rather that the standard procedures used within the security benchmark are not, or only slightly, suitable for this type of environments.

KubeFed For this reason, Rancher has published its own guide [48], which clarifies these points accordingly. In the following, the tests modified especially for K3s are therefore run through in order to obtain a meaningful result. The following tests concern the nodes:

- KubeFed: Master
- KubeFed: Edge-Nodes
- KubeEdge: Master

The tests carried out take into account the following components:

- File permissions
- Kubernetes-API
- Kube-Scheduler

- PodSecurityPolicies
- NetworkPolicies

The complete test is stored at the thesis repo [24] in the file "[k3s-test.md](#)" [49]. In the course of the test run, all requirements were met, except for two weak points. The first part that did not go through successfully concerns the PodSecurityPolicies (PSP). The PSP are an important part of the cluster, responsible for hardening pods. Control mechanisms for volumes, networking or even apparmor or selinux can be used with it. The following code excerpt proves that the extension is not installed.

```
journalctl -D /var/log/journal -u k3s | grep 'Running kube-apiserver' | tail -n1
| grep 'enable-admission-plugins'

--enable-admission-plugins=NodeRestriction
```

Code 15: K3s PSP test

The first line of code queries the installed extensions, the last line returns the results where the PSP extension should also appear. As it turns out, the default configuration of K3s does not install this part. To fix this, the following parameter should be used during installation.

```
--kube-apiserver-arg="enable-admission-plugins=NodeRestriction,PodSecurityPolicy,ServiceAccount"
```

Code 16: K3s PSP install

The second part, which is not covered by K3s, is the use of NetworkPolicies. By default, the CNI "Flannel"[50] is used for K3s, which does not support such a function. At this point, the question arises why such a function is required, after all, the nodes in the distributed K8s version do not communicate with each other. This is correct, but NetworkPolicies can also be used to control communications between namespaces. The functionality can therefore also increase local security on individual nodes. It is also easy to replace the standard CNI plugin during installation, which is why the use of a plugin with appropriate support should be chosen. Flannel can be skip as follows while installing K3s:

```
--flannel-backend=none
```

Code 17: K3s no Flannel

Afterwards, a freely selectable plug-in such as Calico, Canal or Cilium can be installed [51].

KubeEdge As mentioned in the introduction to this section, most of the tests listed above simply cannot be transferred to the KubeEdge environment. This is because the agents used by K8s are completely replaced by custom developments on the edge-side, as also shown in Figure 3. Unfortunately, KubeEdge does not provide documentation explicitly dedicated to security, which is why more intensive research is necessary. In order to take into account as many vectors as possible, the components that are executed on the edge nodes are listed below:

- Docker
- MQTT Broker
- EdgeCore
- EdgeMesh

Due to the use of EdgeMesh, only Docker can be used as a container runtime. K3s, on the other hand, is making use of containerd, which has developed as a newer standard. However, both runtimes are generally considered secure. As defined in the introduction, this thesis does not focus on advanced functionalities such as message queues or managing IoT devices. Nevertheless, it should be mentioned that the MQTT broker binds a public port[52] and is therefore accessible from the local network as well the public internet, provided it is not blocked on the firewall. This can pose a safety risk. With regard to the security of the workloads on EdgeCore, it should be noted that no PodSecurity policies can be applied. For this, however, there is a separate framework, called "SPIFFE" that offers comparable functionalities[53]. However, the implementation requires additional software and server components and entails a much higher level of complexity. Concerning the last component, EdgeMesh, important insights could be gained. The security section of the official EdgeMesh documentation describes: "The EdgeMesh service does not turn on security by default, and edgemesh-server establishes a connection with edgemesh-agent without any authentication" [54]. This means that once the ["Getting Started"](#) [55] instructions have been followed, the nodes communicate with each other without encryption. There is no special note on this page which highlights that. In order to enable the encryption of the communication a certificate authority is required. The CloudCore component, which runs on the central instance, can fulfil this role. The following adjustments should therefore be carried out in any case for the ConfigMaps of the EdgeMesh agent and server.

```
modules:
  tunnel:
    security:
      enable: true
      httpServer: https://KubeEdge-Master:10002
```

Code 18: EdgeMesh security[52]

Policies The second part, of the test using "falco" [44] in the beginning of the chapter, focuses mainly on the policies that affect security within the cluster. Since no hardening of the workloads has taken place, and the tests were carried out with full administrative rights, warnings also appear here. According to the "4Cs" of security, this mainly concerns the container part. Further safeguarding considerations and recommendations, although not the main focus of this work, can be found in the document subsection 6.1.4.

Security by default The very highest security standard is not achieved with the standard installation for either architecture. In the case of KubeFed, a comparatively good level is achieved. Nevertheless some extended functionalities are missing, which allow additional protection of the workload. But, these are mainly optional features. In the case of KubeEdge, however, there are serious deficiencies. If you follow the normal installation routine, no encryption is used between the nodes. All K8s traffic is sent unencrypted over the internet. A customisation to encrypt the communication is highly recommended.

Result and interpretation

Conventional security tests for K8s are only conditionally suitable for the two environments. If one looks at the environments in detail, especially if the installation routine has not been explicitly adapted, problems regarding security can be uncovered. K3s, or indirectly KubeFed, offers its own documentation for this, a good safety standard can be achieved by simple measures. With regard to KubeEdge, the procedure is more difficult. Standard configurations have granular deficiencies. Adaptations to achieve a higher security standard are possible but also require more effort and know-how.

5.2 Discussion

This chapter deals with or analyses the previously conducted test. Characteristics or attributes that have no direct relation to the tests but were indirectly relevant are also described in the following subsections. Likewise, the overall result of the previous practical tests is analysed in more detail and documented.

5.2.1 Handling

Deployment As the previous tests have shown, the way in which deployments can be distributed varies. While KubeEdge can process the same configuration files as on a conventional K8s cluster and thus follows the native approach, modifications are necessary for KubeFed. To improve handling, KubeFed also offers functionality to automatically convert standard K8s resources into federated resources. Nevertheless, a further step is necessary and the seamless integration of an existing CI/CD pipeline may not be possible as the conversion has to be taken into account.

Scaling As mentioned briefly above, KubeFed distributes a number of pods over a number of connected clusters at the edge when they are listed in the deployment. To find out the total number of pods, all pods across all clusters must be added together, which is not possible with a single command. Alternatively, the deployment file can be interpreted accordingly, but the pods must also be totalled here. KubeEdge, on the other hand, uses a scheduler that

performs the distribution independently or dynamically [56]. In this respect, variants offer both advantages and disadvantages. In a smaller, manageable environment with clearly defined locations and workloads each running, KubeFed provides the necessary tools. However, in larger environments, with thousands of nodes and rapidly changing conditions, the scheduler approach is the better choice. Although the distribution did not function optimally in the test conducted above, the potential should not be disregarded. After all, the scheduler can be extended relatively easily and other parameters, such as latency, can be taken into account. Possible extensions of the scheduler are described in the related works in section 7.3 and section 7.4.

Operation KubeEdge performs all tests successfully in the end, but in case of network disconnection, manual intervention was necessary. A pod that was stuck in the "ContainerCreating" status also had to be removed manually. So while the service is basically working, manual intervention may be necessary during operation. This also has to do with the rapid development and the fast growing exosystem. In this context, it must be mentioned that KubeEdge is made up of far more components than KubeFed and therefore has an increased complexity. KubeFed, on the other hand, does an excellent job and comes up with no surprises.

5.2.2 Limitations

During the tests, the following limitations and challenges came to light.

KubeEdge makes it hard to operate disconnected nodes locally, because custom agents and services are used at the edge. Although the environment can be manipulated via docker cli, this may cause so-called zombie containers, that must be cleaned up after use. Similarly, a deployment cannot be scaled up on the nodes if a hostPort is used; a port can only be used once on the system. Another limitation that arises from the use of EdgeMesh is that currently only Docker containers are supported.

KubeFed Although KubeFed does not have many of the limitations of KubeEdge, other drawbacks are to be expected. Thus, due to the architecture itself, no network is available for the data of the pods between the clusters. If the applications themselves only take on local tasks, this is not a problem, but if you want to implement more complex systems with interdependencies, limits are reached quickly. Accesses from one cluster to the other must therefore be solved in the application itself. In concrete terms, this means that existing Kubernetes deployments may have to be revised.

5.2.3 Delimitations

At the present time, the operation of such environments is only possible with the help of experts. The development of edge-computing and K8s is progressing rapidly and therefore makes adjustments, updates and extensions of the environment inevitably necessary. The necessary commitment, know-how and time must be taken into account. If this is neglected, instabilities, security or safety deficiencies can quickly occur.

5.2.4 Outcome

The two architectures are fundamentally different. While KubeEdge offers the native Kubernetes approach and existing applications can be used 1:1 for edge-computing, the configurations for KubeFed have to be revised. On the other hand, KubeEdge itself has a more complex structure and some teething troubles were discovered during the test. KubeFed shines with stability and seems to be the perfect choice for smaller controllable environments with simple applications. As far as the detected errors can be fixed, KubeEdge can fit well when complex applications have to be distributed dynamically over many, up to thousands, edge-nodes.

6 Catalogue

6.1 Decision Variables

6.1.1 Installation

The first decision variable that is examined is the effort required for the installation and the associated complexity. According to the KISS principle[57], those solutions with less complexity should be preferred. If one investigates the installation routine, described in the section 4.1 "environment", very different steps and necessary tools were discovered.

Dependencies The first important variable we look at in this context are the dependencies. This paragraph considers requirements that must be met in order for the installation to proceed successfully.

- *Connectivity* - While KubeEdge works with literally any connection when combined with EdgeMesh, even behind carrier-grade NAT[58], important conditions must be checked for KubeFed, as described in subsection 4.1.3 under the paragraph "challenges". For the sake of completeness, the requirements for KubeFed are listed subsequent.
 - Static IP or dyn DNS agent if dynamic assigned
 - NAT rule if the device is located behind a router
- *Device Support* - Both solutions offer a wide selection of different types of devices supported, like: ARM64, ARMv7, x86 or x64 based systems. However, because KubeFed relies on a full functional K8s cluster those extensive support is provided by the use of K3s and the container-runtime packaged within. In contrast, KubeEdge only requires on one of the supported container-runtimes as well as the KubeEdge binary. Because KubeEdge is taking special care of implementing lightweight agents compatible with container runtime interface (CRI)[59, 60], an even wider range of devices can be supported. Due to the design, even edge-devices with fewer resources can be used effectively. In summary, both solutions support a wide range of devices. KubeEdge, however, goes one step further and is therefore slightly in the lead.
- *Other dependencies* - Other requirements such as bandwidth, connection quality and e.g. storage space have little or no influence on the installation itself and are therefore only considered in the following operational part.

Configuration The second step is to examine the installation routine respectively the configuration steps itself.

- *Required Tools* - One important part is the number of tools and binaries used respectively required to be able to run the environments. The fewer components are used, the less complex the installation and operation. The fewer components used, the greater the tendency to keep the environment simple. Although individual components can also involve quite a high degree of complexity, this variable must not be disregarded. The individual configuration steps are evaluated in the following sections. All tools are listed for each environment subsequent.

- *KubeEdge*

- * CRI (e.g. Docker)
 - * KubeEdge binaries
 - * K3s (Master only)
 - * EdgeMesh (Master only)

- *KubeFed*

- * K3s
 - * KubeFed binaries (Master only)
 - * Helm (Master only)

It should be noted that K3s includes or builds on CRI.

- *Configuration steps* - This property describes the necessary steps that were required during the installation without additional tools. For KubeEdge the basic installation, without any logging capability and a working CNI, is done by using a single binary. However, if logging is necessary (in almost all cases it should be), some adaptations must be made. The same applies to the installation of EdgeMesh, as described in subsection 4.1.2. As the documentation is not clear enough, increased complexity and the associated effort are to be expected. For KubeFed, in contrast, the respective kubeconfig must be transferred to the master and added there as a custom context. This context is then added via kubefed binary. If one only examines the steps that are necessary to operate the two architectures in a meaningful way, these are much easier to accomplish for KubeFed. On the other hand, KubeEdge requires additional configurations and tools to be installed in order to be able to use the full range of functions. If you are looking for a simple and straightforward solution, KubeFed is the winner in this section.
- *Documentation* - Both documentations appear well maintained and kept up to date. The KubeEdge updates seem a little more recent according to the Github history. The KubeFed documentation can only be read in the form of markdown files within Github, but there is a separate web page for KubeEdge. It must be noted, however, that the part concerning network and connectivity is unclear or not sufficiently described. After research,

the extension EdgeMesh, which offers its own documentation, could be found. However, the interaction between the components KubeEdge or the Autonomic Kube-API Endpoint, the MetaManager and EdgMesh is insufficiently described. Even the encryption that has to be activated manually, which is absolutely necessary for security, is only mentioned on a sub-page. Overall, therefore, the KubeFed documentation is easier to read and understand.

Summarised assessment The following table presents the above facts in a clear form.

Category	Criteria	Property	KubeEdge	KubeFed
dependency	connectivity	w/o static IP	✓	✗
dependency	connectivity	w/o dNAT	✓	✗
dependency	device support	extensive support	✓	✓
dependency	device support	resources efficiency	high	moderate
configuration	required tools	master/edge	4/2	4/2
configuration	handling	necessary effort	high	moderate
configuration	documentation	clarity/actuality	moderate	good

Table 11: Installation complexitiy overview

6.1.2 Operation

The next variable that is defined concerns the operation of the respective environments. For example, increased effort in the installation routine can be justified by better downstream operation. In order to be able to make a clear statement regarding the two environments, the results of the tests, performed in section 5.1, are evaluated in the following 4 sections.

Stability As the tests showed, both environments were able to create the test application and distribute it accordingly and keep it available. For KubeEdge, however, problems occurred in the course of the connectivity test, described in subsection 5.1.2, which could only be solved by restarting the services both at the master and at the edge node concerned. Also, due to the complexity of KubeEdge, the susceptibility to errors is generally higher, also because the system is in active development. However, it can be assumed that the problem discovered will be remedied in the coming releases. If the stability of the environment is an absolute requirement, only KubeFed can be recommended at this point, considering the facts at hand.

Handling As already mentioned in subsection 5.2.1, KubeEdge offers the native approach to use K8s. Deployments running on a "normal" K8s environment can simply be transferred

to KubeEdge without modification. Administrators who are familiar with K8s can thus perform simple tasks or even solve problems without having to deal with the system in detail. If, on the other hand, deeper-seated problems occur, expertise regarding KubeEdge is unavoidable. In order to operate KubeFed, some new API objects have to be created or operated. However, the learning curve is low, also because there is a tool-supported translation option for K8s Objects. In principle, no additional skills are required if major problems occur, as these are basically "only" individual K8s clusters.

Scalability This paragraph focuses on the scalability of the environment itself, not that of the applications running on it. No official data could be found for either variant. For KubeEdge, the default values of Kubernetes itself could be considered, which are 5,000 nodes [61]. How accurate this information is has not been checked in detail and is explicitly marked as subjective. KubeFed cannot be equated with these specifications due to the different operating method. The fact alone that the respective configuration of the individual clusters has to be imported into the master shows that the limitations with regard to scaling occur much earlier. Of course, such tasks can be automated, but if the clearly stated goal is to operate thousands of nodes, the use of KubeFed cannot be recommended on the basis of the available data.

Summarised assesment the following table illustrates the facts collected.

Category	Criteria	Property	KubeEdge	KubeFed
operation	stability	error-free test	x	✓
operation	stability	product complexity	high	low
operation	handling	learning curve	moderate	low
operation	handling	troubleshooting	hard	easy
operation	scaling	environment nodes	thousands	hundreds
operation	scaling	limitations	no statement	no statement

Table 12: Operationt overview

6.1.3 Application deployment

As in the Handling chapter outlined above, which deals with general handling, this section explains and delves into the details of the application deployment. The results of the tests carried out previously are also included in the evaluation, in particular those from subsection 5.1.3.

Transformation For KubeEdge, no transformation is required; for KubeFed, the objects to be distributed must first be activated and packed into a "wrapper". Normal Kubernetes objects are

extended with the abbreviation "Federated" in front. Normal Kubernetes objects are extended with the abbreviation "Federated" and some additional properties such as clusters or overrides are added.

CI/CD Both environments can receive and run applications via continuous integration / continuous delivery (CI/CD) pipeline. Due to the transformation, more work may be necessary for KubeFed. However, in the case of a KubeFed environment with only a few nodes and a ready integration of a CI/CD pipeline, the question arises whether it is not more sensible to distribute directly to the clusters without KubeFed.

Deployment scaling As can be read in the subsection 5.1.3, the manual distribution is contrasted with the dynamic scheduling across all nodes. Since the dynamic scheduler, through the use of annotations, can achieve a similar behaviour as of the manual distribution on KubeFed, it offers the wider range of functionality. In terms of adaptability, KubeEdge is therefore the preferred variant.

Summarised assesment the above facts can be clearly presented as follows.

Category	Criteria	Property	KubeEdge	KubeFed
application	deployment	transformation	✓ <i>not required</i>	✗ <i>required</i>
application	deployment	CI/CD	✓	✓
application	scaling	method	dynamic	manual
application	scaling	adaptability	high	moderate

Table 13: Application deployment overview

6.1.4 IT-Security

As almost all statistics and reports show, IT-Security is more important than ever [62, 63, 64] and there is no sign of this dangerous development abating [65, 66]. This makes it all the more important to always consider the IT-Security factor when setting up new environments or existing ones are expanded. In order to obtain a complete view, this chapter is oriented towards the CIA triad [67]. The part of the availability has already been examined respectively described in subsection 6.1.2. The chapter therefore concentrates on the confidentiality and integrity part of the CIA triad.

Key components

The first subsection builds on section 2.1 and is dedicated to further information regarding K8s and its security architecture. The most important features respectively mechanics are listed below in no particular order.

API The API is used for control, which can be called via HTTPs and authenticates as well as authorises users respectively admins accordingly. Both variants, KubeEdge and KubeFed, offer this interface. To authenticate users, the API supports static tokens, X.509 certificates and service account tokens. As a developer who is to roll out or maintain an application on a system, the use of service tokens is the recommended method of authentication. In contrast to the previously mentioned variants, these tokens can be easily recalled and equipped with the necessary authorisations[23]. Understanding this is relevant when comparing the two environments in terms of interaction with the API. While for KubeEdge a central interface controls the entire system, KubeFed has a multi-level structure. The central KubeFed cluster does not control the edge nodes directly, but also via their shared API. Conversely, this means that the central KubeFed instance can be granted the exact necessary rights on the edge nodes. The authorisations can also be different or withdrawn if necessary, which makes the environment very flexible, but also entails an increased configuration effort.

In order to omit fine-grained permissions K8s is making use of role based accesscontrol (RBAC). "Role-based access control (RBAC) is a method of regulating access to computer or network resources based on the roles of individual users within your organization"[68]. The default behaviour is to block requests, commonly referred to "fail-secure", if not explicit allowed. In the context of the CIA triad, this represents the area of authorization.

ETCD is the default database for K8s. K3s replaces this with a local SQLite database, but the same recommendations apply[47]. As a general rule, the data contained therein must be particularly well protected. Write access is equivalent to full root rights on the cluster, even read access opens the doors to various privilege escalations[23]. This is where KubeEdge has an advantage, as only one such database needs to be protected. KubeFed, on the other hand, uses a separate instance on each edge-node respectively K8s cluster. Security measures must therefore be taken individually for each node, which causes increased effort.

Networking & Firewall Due to the implementation, different characteristics can be achieved. In the case of KubeEdge, all ports on a firewall can be closed; no active access from the outside is necessary. This is due to the fact that EdgeHube, the component responsible for communication between master and edge-nodes, supports NAT-traversal without restrictions. With KubeFed, however, the API port 6443 (default) must be accessible from the central instance. This makes the individual nodes publicly accessible and easier to attack. However, in the event of a complete disconnection from the network, KubeFed can be controlled locally and

continue to be operated. For KubeEdge, continued operation is also provided for, but taking control is not possible. It should be noted, however, that the network solution (EdgeMesh) used for KubeEdge must be specially configured to encrypt traffic, as subsection 5.1.4 points out. Minor adjustments are also necessary for KubeFed respectively the underframe K3s.

Workload

Previous points focused on securing the environment itself, or its main components. The Workload section is dedicated to protect the containers respectively applications executed inside each of the solutions. Although the most important points are presented, this thesis focuses on the two architectures themselves and their distinctions, which is why this section can only be understood as an introduction.

• Build phase

- Unnecessary stuff inside containers like build tools or even shells should be avoided. Distroless or "from Scratch" Images are the preferred way to create container images.
- The use of recent software packages or containers tagged as "latest" is recommended. Although this can cause problems in the productive environment, it ensures that the latest version is always used. If specific versions are chosen, a corresponding update mechanism should be implemented.
- Images should be checked for vulnerabilities on an ongoing basis. A number of plug-ins integrate seamlessly into the CI/CD pipeline offering this functionality.
- Configurations that describe the workload (YAML Files) must meet certain security standards. Tools that can carry out these checks automatically are also available for this purpose. One of these tools offering such functionality is [kubesecc](#) [69].

• Running workload

- Collect and export K8s logging events.
- Separate different applications making use of Namespaces
- Limit CPU and RAM for containers or at least the Namespace
- Apply suitable NetworkPolicies
- Apply appropriate PSPs
- Execute containers as non-root

Securing

In order to secure the environment accordingly, taking into account the points mentioned above, and to follow the recommendations of the "4Cs", the following procedure, at a high level, is recommended:

1. *Nodes* - Starting with the node itself, software should kept up to date
 - OS
 - Container-runtime
 - K8s distribution
 - Additional softwarepackages
2. *Networking* - The component must be appropriately secured.
 - Firewall
 - Encryption
3. *Cluster* - Implementing the hardening guides recommended by K8s
 - PodSecurityPolicies
 - NetworkPolicies
 - RBAC enabled
4. *Workload* - make sure your workload runs safeguard
 - this can be found in subsubsection 6.1.4
5. *Application* - verify the code itself inside the containers
 - opensource
 - trusted source
6. *User* - Apply least privilege principle
 - RBAC

Findings

The following paragraphs summarises the results obtained in Chapter subsection 5.1.4.

KubeEdge Functionalities such as NetworkPolicies or PSP are not supported by KubeEdge. An alternative framework, SPIFFE [53], is available for this purpose. Thus, while it can be used to check and restrict many security-related aspects such as the integrity of the application and workloads or even the nodes, it also requires more effort to implement. Since specially developed components are used, conventional security tests cannot be applied or have no significance. KubeEdge does not provide a guide or recommendations for hardening. The EdgeMesh component has a serious gap; if encryption is not explicitly activated, all communications take place without these security safeguards. Finally, it is important to note that KubeEdge only supports Kubernetes up to version 1.21. The most recent version at the time of the survey was version 1.23.

KubeFed Since KubeFed is based on K3s, some parameters must be specified during installation. PSP must be activated, the NetworkPolicies cannot be used with the standard CNI plugin and must therefore be replaced. Otherwise, due to the simplified architecture, no noteworthy problems could be detected during the tests.

Summarised assesment The following table shows the most important factors with regard to IT-security.

Category	Criteria	Property	KubeEdge	KubeFed
it-security	communication	firewalling all ports	✓	✗
it-security	communication	encrypted	TLS	TLS
it-security	communication	configuration effort	high	low
it-security	logging	enabled on install	✗	✓
it-security	logging	cluster-wide	✓	✗ ₁
it-security	workload	K8s security addons	default ₂	SPIFFE [53]
it-security	workload	configuration effort	high	moderate
it-security	architecture	seperation possible ₃	✗	✓
it-security	architecture	centralized controll	fully	partiali
it-security	architecture	default security level	low	moderate

Table 14: IT-Security overview

Additions to Table 14:

1. possible through the use of thirdparty
2. PSP, NetworkPolicies
3. An edge-node can be separated and converted into an independently acting cluster easily

6.1.5 Community and support

Another important factor is the support and the community for the respective application. Especially with relatively new software, it is important to either have access to the community to exchange ideas and discuss problems, or to have a manufacturer who can provide support if needed. This is even more true if you want to use the environment productively and commercially.

Community Both products offer an active community with regular meetings, an mailing list and Slack channel. The open source approach promotes the formation of these open com-

munities. KubeEdge is somewhat more active in research than KubeFed, but this does not necessarily mean that you will be better with one or the other.

Support At time of writing, no official company offering commercial support for the products could be found. This is also, as mentioned above, due to the opensource approach. For KubeEdge, however, there is a list of companies that already use the product and support it accordingly. Among them are well-known companies such as Huawei, Orange and ARM. For KubeFed such a list is not disclosed. The project is managed by Jeremy Olmsted-Thompson (Google) and Paul Morie (Apple) for this purpose. For both projects, issues can be submitted via Github.

Activity During the investigation of the topic, KubeEdge seems to be a bit more hyped than KubeFed. This indirectly also leads to getting the necessary support faster. Details on the topicality can be found in the next subsection "future proof".

Summarised assessment The properties revealed above are tabulated below.

Category	Criteria	Property	KubeEdge	KubeFed
community	communication-channel	Slack	✓	✓
community	communication-channel	mailing-list	✓	✓
community	communication-channel	regular meeting	✓	✓
support	commercial	maintenance	✗	✗
support	non-commercial	Github issues	✓	✓
support	sponsors	official list	✓	✗
activity	hype	movement	high	medium

Table 15: Community and support overview

6.1.6 Future proof

Another important element when deciding between the two options is how promising each is for the future. Especially, as in our case, when the project is mainly supported and developed by the community. In the following, the background of the projects, the actuality of the software updates as well as the media impact will be examined. The companies that use or support the project also play an important role in this context.

Releases An important factor are the release cycles and the associated update frequency. An overview of all versions and updates can be found in the "Releases" site of each Github project.

Both projects offer new versions on a regular basis, but KubeEde has slightly shorter cycles. Since the beginning of the year (2022), KubeEde has released two versions and KubeEdge has released one [70, 71]. The difference is only small at this point, both products shine with actuality.

Github Stats Other characteristics that can define the future viability are the current stats from Github. The following table compares the two projects.

Github Stat	KubeEdge	KubeFed
Stars	4800	2100
Forks	1300	470
Releases	30	32
Contributors	229	87
Open issues	147	23
Open pull-requests	34	8

Table 16: Github stats overview

It should be noted that the table shown above is only a snapshot. The values may change accordingly. It must also be stated that the higher number of reported problems may also result from more frequent use. Therefore, the correct interpretation is important.

Membership KubeEdge is listed as a CNCF project in the incubation phase. CNCF is a central home for the fastest growing projects in the cloud native category. Even K8s itself was part of it. In contrast, KubeFed is supported and further developed by the K8s oriented special interests group (SIG). It stands out that due to the group membership, clear rules concerning the further development have to be observed.

Sponsors As already mentioned in section "community and support", KubeEdge is officially sponsored by some well-known companies. It should be noted, however, that these are mainly Chinese companies.

Independence A final important characteristic with regard to future-proofing is the extent to which a solution can be used without further development of the respective application. Although this assumption represents a worst-case scenario that seems rather unlikely in the foreseeable future, it should nevertheless be taken into account. KubeEdge uses a completely self-developed solution on the worker nodes. To replace it, all nodes must be reinstalled with the vanilla component of K8s. Besides the effort involved, important functions concerning edge-computing are lost. KubeFed offers a better solution here, due to its different architecture. Each

node on the edge is a complete and independent worker. If KubeFed is no longer used, applications continue to run for the time being; no new installation is necessary on the nodes. The control could be taken over by alternative approaches, e.g. via CI/CD pipelines. KubeFed thus offers better independence.

Summarised assessment The characteristics relating to future viability are summarised below.

Category	Criteria	Property	KubeEdge	KubeFed
future-proof	releases	frequency	very-high	high
future-proof	Github	stars	5k	2k
future-proof	Github	activities	high	moderate
future-proof	membership	development programm	CNCF	SIG
future-proof	sponsors	companies	✓	✗
future-proof	independencie	alternative option	✗	✓

Table 17: Future-proof overview

6.2 Criteria catalogue

The following catalogue of criteria can be compiled on the basis of the data obtained in section 6.1. Zangemeister defines the method as follows: "Utility analysis is the analysis of a set of complex alternative actions with the purpose of ordering the elements of this set according to the preferences of the decision maker with respect to a multidimensional goal system" [72]. By awarding points for each sub-area, the target environment with the highest effectiveness can be selected. The multiattribute value function is used for this purpose. The sum of the calculated individual attributes results in the total value per solution.

$$v(a) = \sum_{r=0}^m w_r v_r(a_r)$$

$w(r)$ must be greater than 0 and the condition of validity of the value function must be fulfilled.

$$\sum_{r=0}^m w_r = 1$$

Provided that the above mathematical principles are followed, individual weightings can be assigned. This achieves a high degree of flexibility of the catalogue.

6.2.1 Properties overview

The following table acts as a criteria catalogue. Based on the previous qualitative research using the DSR method, the values were obtained. Due to the many different areas of application or objectives that are targeted, this table can be adapted according to one's own requirements. However, the values given serve as orientation points or generalised starting values. There is an empty table in the Appendix A that serves as a template so that adjustments can be made easily.

Category		Criteria		Rating		Weighted rating	
Name	Weight	Criteria	Weight	KubeEdge	KubeFed	KubeEdge	KubeFed
Installation	30%	connectivity	10%	5	1	0,5	0,1
		device support	10%	5	4	0,5	0,4
		required tools	2%	3	3	0,06	0,06
		configuration	2%	2	4	0,04	0,08
		documentation	6%	2	4	0,12	0,24
Operation	17%	stability	10%	1	5	0,1	0,5
		handling	3%	2	5	0,06	0,15
		scaling nodes	4%	5	3	0,2	0,08
Application	17%	deployment	10%	5	4	0,5	0,4
		scaling	7%	5	2	0,35	0,14
IT-security	10%	communication	3%	3	4	0,09	0,12
		logging	2%	4	3	0,08	0,06
		workload	2%	2	4	0,04	0,08
		architecture	3%	3	4	0,09	0,12
Commuity	6%	communication channels	3%	5	5	0,15	0,15
		actual hype	3%	4	3	0,12	0,09
Support	10%	commercial maintenance	5%	0	0	0	0
		bug reporting	4%	5	5	0,2	0,2
		sponsor-list	1%	5	0	0,05	0
Future-proof	10%	Github stats	3%	4	3	0,12	0,09
		release cycles	3%	4	3	0,12	0,09
		independencie	3%	1	4	0,03	0,09
		commercial sponsors	1%	5	0	0,05	0
Result	100%		100%	80	73	3,57	3,24

Table 18: Criteria catalogue table

To define your own values, proceed as follows. First, the categories are given the appropriate weighting. The total value of all categories must amount to 100%. The more important a category is or is to be included in the evaluation, the higher the percentage value assigned

should be. Then the percentage value of a category is divided into the criteria below it. So if the category is rated 20%, two criteria can be assigned 10% each, for example. The next step is to evaluate the respective criteria for the two environments. The pre-filled values above serve as an initial value respectively approximation. A value between 1 (low, bad) and 5 (high, good) is indicated. The weight is then calculated using the following formula.

$$\frac{CriteriaWeight}{100} * Rating$$

The permitted value range for the rating must be taken into account.

$$Rating = \{1, 2, 3, 4, 5\}$$

6.2.2 Rating

The awarding of points for the individual rubrics or characteristics is carried out in the course of a qualitative evaluation based on the research results of the previous chapters. Since a certain subjectivity could be assumed, the results given are only to be understood as a first approximation. An adjustment of the assessment to cover individual requirements is therefore recommended. The template from the Appendix A can be used for this purpose.

6.3 Exclusions and Special Cases

It must be explicitly emphasised that properties with greater priority must be weighted correspondingly higher. Certain areas or functions can also be declared as absolutely necessary, which directly excludes the respective solution insofar as these are not supported. To check this, details of the variables defined in the catalogue can be found in the respective paragraph in section 6.1.

Furthermore, it is also possible to supplement the properties or variables with your own. This thesis concentrates primarily on the most important key data, which is why special functions may not be included. In contrast to this, however, the template (Appendix A) also offers the option of omitting elements.

7 Related Work

This chapter explains or enumerates work on which this thesis is based as well as papers which can function as an extension of the respective architecture.

7.1 Kubernetes and the Edge

The paper [16] provides an introduction to the topic and offers the necessary basics. However, it mainly examines the vanilla K8s, which is only slightly suitable for use in edge-computing without additional tools. In the related work chapter, the paper refers to the use of KubeEdge and KubeFed, on which the present thesis is based on. These theses are therefore to be understood as an extension of the cited paper.

7.2 Extend Cloud to Edge with KubeEdge

The whitepaper [17] provides a good insight into the internals of KubeEde. However, some components of KubeEdge have since been revised or even replaced. KubeBus, for example, has been replaced by EdgeMesh. Also, no realworld example is tested on the environment in the paper. Nevertheless, many mechanisms remain unchanged, which is why the paper is still of great relevance.

7.3 Sharpening Kubernetes for the Edge

As shown in this scientific paper, schedulers do not always work as desired. An approach to solving this problem is described in the white paper "Sharpening Kubernetes for the Edge" [13]. The authors describe the function of a scheduler that takes into account the respective latencies between the nodes and can thus make intelligent decisions. This could be a well-functioning extension for K8s at the edge, however this is reserved for future research.

7.4 Ultra-Reliable and Low-Latency Computing with K8s

In the research paper "Ultra-Reliable and Low-Latency Computing in the Edge with Kubernetes" [73] the approach of the latency aware scheduler, described in section 7.3, is pushed one step

further. However, logical regions can be defined and pods can be launched preferentially in these. A re-scheduler has also been implemented, which makes it possible to automatically redistribute deployment when the environment changes in order to achieve optimum results.

8 Conclusion

8.1 Findings

Both environments each offer different and individual advantages and enable different operating models. The environments are characterised in particular as follows.

KubeEdge offers the native K8s approach. Existing objects such as deployments, pods or configmaps can be run on the system without any transformation. Due to the good abstraction, the system acts like a conventional cluster. Functionalities such as central logging, communication encryption via TLS and support for a diverse range of different hardware types round off the product. It should be noted that the development is still at an early stage. Many configurations have to be done by hand and there are gaps in the documentation. The stability is also not completely convincing, as tests have shown, because components may have to be restarted. The hype towards KubeEdge seems to be unbroken, as the Github statistics show.

KubeFed offers high stability and the distribution of workloads via proven interfaces. This is characterised by less complexity and easier handling. Especially in smaller static environments where applications are rolled out in a controlled way, the solution shines. Edge-nodes can be controlled and operated locally in case of disconnection from the central unit. Even the conversion into an independent instance, which no longer has any dependencies, is possible. On the other hand, K8s objects have to be transformed before they can be scheduled. The solution also does not offer the possibility to use the internal K8s network via CNI. This must be taken into account when creating applications for the environment.

8.2 Results

In principle, edge environments can be set up and operated with both variants. In smaller, less complex environments where internal network communication of the applications is not absolutely necessary, KubeFed is a solid solution. If the environment is to scale strongly and the workload is dynamically distributed as well as native K8s network is required, KubeEdge provides the better toolset. In addition to these main criteria, however, there are a large number of other properties that need to be assessed individually depending on the requirements. Insofar as a comprehensible and fact-based decision on architecture is to be aimed for, it is recommended to go through the criteria catalogue accordingly.

8.3 General advice

If no clear decision can be made even after going through the criteria catalogue, or if both environments can realise a target architecture, the recommendation goes in the direction of KubeEdge. Considering the functions examined as well as the native approach during operation, KubeEdge offers an excellent environment. Even though some problems arose regarding stability, the technology offers the more promising basis. Research into future developments clearly point in the direction of default K8s architecture such as KubeEdge.

8.4 Future Work

Kubernetes provides the abstraction of an underlying system into a logical entity. KubeEdge follows this paradigm, while KubeFed offers more separation. A combination of both models would also be conceivable. For example, one could delegate at country or continent level via KubeFed and control the individual nodes below via KubeEdge. This would allow the advantages of both architectures to be combined in the form of a "distributed hybrid environment". The environment can also be equipped with an improved scheduler, which can take into account aspects such as latency and geographical distribution, as described in chapter 7. In any case, it must be considered that such solutions are partly still in an early stage of development and that errors are to be expected, as our tests have shown. Nevertheless, the use of Kubernetes for edge computing is a hot topic that already offers excellent solutions and functions. Further options and functions can also be provided by the use of a service mesh. Some modern solutions offer functions for multiple distributed clusters as well as within a cluster itself.

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List of Figures

Figure 1	K8s architerture overview[4]	3
Figure 2	Default K8s architerture	8
Figure 3	KubeEdge architecture[18]	9
Figure 4	Distributed K8s architecture	10
Figure 5	Map of the PoC[26]	17
Figure 6	KubeEdge networking	22
Figure 7	KubeFed objects	24
Figure 8	KubeEdge CPU without load	27
Figure 9	KubeFed CPU without load	27
Figure 10	KubeEdge scale	36
Figure 11	KubeFed scale	38

List of Tables

Table 1	PoC nodes specification	17
Table 2	KubeEdge: RAM usage	28
Table 3	KubeFed: RAM usage	28
Table 4	KubeEdge: curl no load (ClusterIP)	31
Table 5	KubeEdge: curl with load (ClusterIP)	31
Table 6	KubeEdge: curl no load (HostPort)	32
Table 7	KubeEdge: curl with load (HostPort)	32
Table 8	KubeFed: curl without load	32
Table 9	KubeFed: curl with load	32
Table 10	KubeEdge: scale distribution	37
Table 11	Installation complexitiy overview	47
Table 12	Operationt overview	48
Table 13	Application deployment overview	49
Table 14	IT-Security overview	53
Table 15	Community and support overview	54
Table 16	Github stats overview	55
Table 17	Future-proof overview	56
Table 18	Criteria catalogue table	57
Table 19	Criteria catalogue template	73

List of Code

Code 1	K3s installation	17
Code 2	KubeFed join context	19
Code 3	Web-application code	20
Code 4	Web-application HostPort	23
Code 5	Enable federation	24
Code 6	Federated Object	25
Code 7	Curl command	30
Code 8	Curl command	31
Code 9	EdgeCore Error	33
Code 10	EdgeCore nodes unavailable	33
Code 11	Pods status	35
Code 12	KubeEdge scaling proof	36
Code 13	KubeFed scale adaptations	37
Code 14	KubeEdge & KubeFed bench	39
Code 15	K3s PSP test	40
Code 16	K3s PSP install	40
Code 17	K3s no Flannel	40
Code 18	EdgeMesh security[52]	41

List of Abbreviations

Aha	Ansi HTML adapter
API	application programming interface
ARM	advanced RISC machines
CI/CD	continuous integration / continuous delivery
CLI	commandline interface
CNCF	Cloud Native Computing Foundation
CNI	container network interface
CPU	central processing unit
CRD	costum ressource definition
CRI	container runtime interface
DNS	domain namesystem
DSR	design science research
FQDN	full qualified domain name
GUI	graphical user interface
HPA	horizontal pod autoscaler
IoT	internet-of-things
IP	internet protocol
IT	information technology
K8s	Kubernetes
KubeFed	Kubernetes cluster federation
MQTT	message queuing telemetry transport
NAT	network address translation

OS	operating system
PoC	proof-of-concept
PSP	PodSecurityPolicies
QoS	quality of service
RAM	random access memory
RBAC	role based accesscontrol
SIG	special interessts group
VPN	virtual private network
WWW	world wide web

A Appendix

Category		Criteria		Rating		Weighted rating	
Name	Weight	Criteria	Weight	KubeEdge	KubeFed	KubeEdge	KubeFed
Installation	x%	connectivity	x%	1-5	1-5	x	x
		device support	x%	1-5	1-5	x	x
		required tools	x%	1-5	1-5	x	x
		configuration	x%	1-5	1-5	x	x
		documentation	x%	1-5	1-5	x	x
Commuity	x%	communication channels	x%	1-5	1-5	x	x
		actual hype	x%	1-5	1-5	x	x
Support	x%	commercial maintenance	x%	1-5	1-5	x	x
		bug reporting	x%	1-5	1-5	x	x
		sponsor-list	x%	1-5	1-5	x	x
Future-proof	x%	Github stats	x%	1-5	1-5	x	x
		release cycles	x%	1-5	1-5	x	x
		independencie	x%	1-5	1-5	x	x
		commercial sponsors	x%	1-5	1-5	x	x
Application	x%	deployment	x%	1-5	1-5	x	x
		scaling	x%	1-5	1-5	x	x
Operation	x%	stability	x%	1-5	1-5	x	x
		handling	x%	1-5	1-5	x	x
		scaling nodes	x%	1-5	1-5	x	x
IT-security	x%	commuication	x%	1-5	1-5	x	x
		logging	x%	1-5	1-5	x	x
		workload	x%	1-5	1-5	x	x
		architecture	x%	1-5	1-5	x	x
Result	100%		100%	x	x	x	x

Table 19: Criteria catalogue template