Technische Hochschule Ingolstadt

Specialist area Computer Science
Bachelor's course Computer Science

Bachelor's thesis

Subject:	Conception, Implementation, and Evaluation of a Highly Scalable and Highly Available Kubernetes-Based SaaS Platform on Kubernetes Control Plane (KCP)
Name and Surname:	David Linhardt
Matriculation number:	00122706
Issued on:	2025–04–09
Submitted on:	2025–08–01
First examiner:	Prof. Dr. Bernd Hafenrichter
Second examiner:	Prof. Dr. Ludwig Lausser

Declaration in Accordance with § 30 Abs. 4 Nr. 7 APO THI

Declaration

I hereby declare that this thesis is my own work, that I have not presented it elsewhere for examination purposes and that I have not used any sources or aids other than those stated. I have marked verbatim and indirect quotations as such.

Ingolstadt, 2025–08–01

David Linhardt

Abstract

Acronyms

ABAC Attribute-Based Access Control. 7

API Application Programming Interface. 3, 7–9, 14–16, 18–20

B2B Business to Business. 11

B2C Business to Customer. 11

CD continuous deployment. 17

cgroups control groups. 6

CI continuous integration. 17

CPU central processing unit. 19

CRD Custom Resource Definition. 7, 8, 19

CRUD Create Read Update Delete. 14, 15, 20

DB database. 19–21

DevOps development and operations. 13

DIY do it yourself. 12

FE frontend. 20

HA high availability. 9, 16

HPA Horizontal Pod Autoscaler. 19, 20

HTML hypertext markup language. 19

I/O input / output. 14

IP Internet Protocol. 10

JS JavaScript. 19

JSON JavaScript Object Notation. 20

K8s Kubernetes. 1, 3, 4, 7, 21

KCP Kubernetes Control Plane. 3, 7–10, 12–16, 18, 19

MSP Managed Service Provider. 11

PV Persistent Volume. 21

PVC Persistent Volume Claim. 21

QPS queries per second. 19

RBAC Role-Based Access Control. 7, 8, 10, 17, 18

REST Representational State Transfer. 8, 19

RPO recovery point objective. 17

RTO recovery time objective. 17

SaaS Software as a Service. 1, 2, 11, 12, 14, 16

SLA Service Level Agreement. 3, 14

SLO service-level objective. 16

SMB small and medium sized businesses. 12–14, 16

SQL Structured Query Language. 15

SSH Secure Shell. 21

SSR server-side rendering. 19

TCP Transmission Control Protocol. 10

TTL time to live. 15, 20

UI user interface. 14, 20

URL Uniform Resource Locator. 8, 15

WAL write-ahead logging. 17

Glossary

Admission Webhook external validator/mutator called by the Application Programming Interface (API) server before objects are stored. 8

container A lightweight, portable, and isolated runtime environment that packages an application together with its dependencies and configuration. Containers share the host system's kernel but run in separate user spaces, enabling consistent execution across different environments.. 4–6

containerization packaging code and dependencies in Operating System (OS)-level containers. 5

data contract a *formal, version controlled agreement* between a data producer and its consumers, much like an API specification.. 12

Docker Docker is an open-source platform that enables developers to package applications and their dependencies into lightweight, portable containers that run consistently across different environments.. 20

etcd strongly-consistent key-value store that backs both Kubernetes and Kubernetes Control Plane (KCP) metadata. 7, 9, 10, 14

fan-out the pattern of sending one message, request, or event to many downstream consumers in parallel.. 13

high availability architectural and operational strategies employed to ensure that applications remain accessible and operational even in the face of failures, whether those are due to hardware malfunction, network issues, or other disruptions.. 4

Kubernetes Google-born container-orchestrator that underpins your whole platform. 1, 3–9, 17

Kubernetes Control Plane multi-tenant, horizontally-scalable control-plane project. 7

multi-tenancy many tenants sharing one platform while remaining logically isolated. 1, 3, 6, 7, 13

Next.js Next.js is an open-source web development framework created by the private company Vercel providing React-based web applications with server-side rendering and static rendering.. 19, 20

Node.js Node.js is a free, open-source, cross-platform JavaScript runtime environment that lets developers create servers, web apps, command line tools and scripts.. 19

performance isolation ensuring one noisy tenant can't violate another's Service Level Agreement (SLA). 3, 6

Redis Redis is an in-memory key-value data store for caching purposes.. 21

split-brain a phenomenon where the cluster is separated from communication but each part continues working as separate clusters, potentially writing to the same data and possibly causing corruption or loss.. 10

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2 Fundamentals

2.1 Kubernetes and Multi-Tenancy

2.1.1 Kubernetes as the Foundation for Cloud-Native Applications

As the de facto standard for deploying and managing *cloud-native applications*, Kubernetes, commonly referred to as Kubernetes (K8s) plays a pivotal role in modern cloud architecture (Poulton and Joglekar 2021, p. 7–8). Kubernetes works as an orchestrator for *containerized, cloud-native microservice* applications, meaning it can deploy apps and dynamically respond to changes (Poulton and Joglekar 2021, p. 3). It offers a platform for declarative configuration and automation for containerized workloads, enabling organizations to run distributed applications and services at scale (Kubernetes 2024; Red Hat 2024).

2.1.2 The Importance of Multi-Tenancy in Modern SaaS Platforms

Multi-tenancy plays a fundamental role in modern cloud computing. By allowing multiple tenants to share the same infrastructure through virtualization, it significantly increases resource utilization, reduces operational costs, and enables essential features such as VM mobility and dynamic resource allocation (AlJahdali et al. 2014, pp. 345–346). These benefits are crucial for cloud providers, as they make the cloud business model economically viable and scalable. In the context of modern Software as a Service (SaaS) platforms, multi-tenancy goes even further by enabling unified management, frictionless onboarding, and simplified operational processes that allow providers to add new tenants without introducing incremental complexity or cost (AWS 2022, pp. 9–11).

However, while multi-tenancy is indispensable for achieving efficiency, scalability, and cost-effectiveness, it simultaneously introduces complex security challenges, especially in shared environments where resource isolation is limited. In particular, the potential for cross-tenant access and side-channel attacks makes security in multi-tenant environments a primary concern (AlJahdali et al. 2014, pp. 345–346). As such, understanding and addressing multi-tenancy from

both operational and security perspectives is essential when designing and securing modern cloud-native platforms (AWS 2022, pp. 9–11; *Information technology - Cloud computing - Part 2: Concepts* 2023, p. 4).

2.1.3 The Challenges of Multi-Tenancy and the Need for Solutions

Multi-tenancy introduces a spectrum of technical and security challenges that need to be addressed.

[1]: *Residual-data exposure.* Shared infrastructures may expose tenants to data leakage and hardware-layer attacks. Because hardware resources are only virtually partitioned, residual data left in reusable memory or storage blocks, known as *data remanence*, can be inadvertently leaked or deliberately harvested by co-resident tenants (Zissis and Lekkas 2012, p. 586; AlJahdali et al. 2014, pp. 344–345).

[2]: *Control and transparency.* By design, SaaS moves both data storage and security controls out of the enterprise's boundary and into the provider's multi-tenant cloud, depriving organizations of direct oversight and assurance and thereby heightening concern over how their critical information is protected, replicated and kept available (Subashini and Kavitha 2011, pp. 3–4). To complicate matters further, the customer might have no way to evaluate the SaaS vendors security measures, meaning the pricing and feature set will most likely determine which service is used in practice, often disregarding security concerns (Everett 2009, p. 6; Khorshed, Ali, and Wasimi 2012, p. 836).

[3]: *Scheduling.* In multi-tenant architectures multiple tenants utilize the same hardware, thus creating the need for fair scheduling to ensure cost-effectiveness and performance (Simić et al. 2024, p. 32597). Achieving fair and efficient resource allocation in scheduling first requires a quantitative assessment of the system's existing unfairness (Ebrahimi et al. 2012, p. 7; Beltre, Saha, and Govindaraju 2019, p. 14; Ghodsi et al. 2011, pp. 2–3). Various scheduling algorithms and policies can be employed in practice to achieve fairness (Beltre, Saha, and Govindaraju 2019, pp. 14–16; Ghodsi et al. 2011, p. 4). To fully leverage the advantages of multi-tenant architectures, resources must not only be shared fairly, but also efficiently, not hindering performance (Beltre, Saha, and Govindaraju 2019, p. 14). As stated by Beltre, Saha, and Govindaraju 2019, p. 14 "Balancing both cluster utilization and fairness is challenging".

[4]: *Performance Isolation.* A single tenant is able to significantly degrade the performance of

other tenants working on the same hardware, if *performance isolation* is not given (Krebs and Mehta 2013, p. 195). The fundamental performance expectations of a system are commonly formalized in a Service Level Agreement (SLA).As noted by Krebs and Mehta 2013, p. 195 "A system is said to be performance isolated, if for tenants working within their quotas the performance is within the (response time) SLA while other tenants exceed their quotas (e.g., request rate)". As noted by Carrión 2022, p. 18 "Currently, it is difficult to achieve performance isolation for multi-tenancy on K8s clusters because this requires providing resource isolation and improving the abstraction of applications."

[5]: *Automation*. As noted by Nguyen and Y. Kim 2022, p. 651 "Presently, multi-tenant systems lack the facility of allowing clients to dynamic *[sic]*change their resources based on their business demands or create and allocate resources for new tenants. Multi-tenant system *[sic]*administrator manually does all the work of allocation or changing tenant's *[sic]*resources." However, to ensure efficiency and scalability, an API that allows automating deployments and dynamic changes in the application is needed.

A secure solution, keeping multi-tenancies advantages while also addressing security concerns is desperately needed (AlJahdali et al. 2014, p. 346; Şenel et al. 2023, pp. 14576–14577).

2.1.4 Kubernetes Control Plane (KCP) as a Promising Approach

Kubernetes Control Plane (KCP) offers three capabilities that map accurately onto today's multi-tenancy pain points.

[1]: *Workspaces*. KCP achieves strong resource isolation through the concept of *workspaces* (see subsubsection 2.2.1: *Workspaces*).

[2]: *API*. KCP offers an Kubernetes-like API that enables the use of standard tools and automation to a degree (see subsubsection 2.2.2: *API*).

[3]: *Sharding*. KCP offers sharding out of the box to manage high traffic and geo-distribution (see subsubsection 2.2.3: *Sharding*).

2.1.5 Background: The Evolution of Kubernetes

Kubernetes, an open-source container orchestration platform developed by Google, emerged from the need to manage the complexities of containerized applications effectively and to support large-scale deployments in a cloud-native environment (Google Cloud 2025; Kubernetes 2024).

It was originally developed at Google and released as open source in 2014 (Google Cloud 2025). Kubernetes was conceived as a successor to Google's internal container management system called Borg, and designed to streamline the process of deploying, scaling, and managing applications composed of microservices running in containers (Verma et al. 2015, pp. 13–14; Bernstein 2014, p. 84). The name Kubernetes originates from the Greek word κυβερνήτης meaning helmsman or pilot (Kubernetes 2024). The abbreviation K8s results from counting the eight letters in between the "K" and the "s" (Kubernetes 2024).

Since its inception, Kubernetes has gained traction among organizations because it provides robust features such as automated scaling, self-healing, and service discovery, which have made it the de facto standard for container orchestration in the tech industry (Damarapati 2025, pp. 855–858).

As noted by Moravcik et al. 2022, p. 457 almost 90% of organizations used Kubernetes as an orchestrator for managing containers and over 70% of organizations used it in production by 2021 (Shamim Choudhury 2025). The widespread adoption of Kubernetes is further underscored by Red Hat's latest (2024) report, which no longer asks survey respondents if they use Kubernetes for container orchestration, but rather **which** Kubernetes platform they use (Red Hat, Inc. 2024, p. 27). According to Damarapati 2025, pp. 855–856, Kubernetes has seen unprecedented industry adoption due to its vendor neutrality, strong community support, and flexible, extensible architecture in combination with readiness for enterprise use caused by high availability, disaster recovery and security.

Moreover Kubernetes enables faster time-to-market by providing a unified, declarative control plane that abstracts away infrastructure, guarantees consistent environments from development to production, and automates operational tasks such as scaling, rolling updates, and self-healing—advantages that translate directly into competitive delivery speed, increasing its appeal to organizations of every size (Damarapati 2025, pp. 858–859).

Over the years, Kubernetes — and the many orchestration solutions inspired by or built on it — has evolved to handle an increasingly diverse range of workloads, supporting everything from conventional applications in to emerging *edge-native* deployments (Biot et al. 2025, p. 21; Biot et al. 2025, pp. 1–4). Edge-native deployments are applications intended to run on computing resources located at or near the data source — the network *edge* — rather than in a central cloud (Satyanarayanan et al. 2019, p. 34). This adaptability reflects its fundamental design, which focuses on modularity and extensibility, allowing developers to customize their orchestration needs.

Overall, the history of Kubernetes showcases a transformative journey driven by the evolving demands of software architecture and the necessity for efficient application management in an increasingly complex technological landscape.

2.1.6 Background: Containerization as an Enabler of Kubernetes

Containerization is a way to bundle an application's code with all its dependencies to run on any infrastructure thus enhancing portability (AWS 2025; Docker 2025). The lightweight nature and isolation of containers can be leveraged by cloud-native software to enable both vertical and horizontal autoscaling, facilitated by fast startup times, as well as self-healing mechanisms and support for distributed, resilient infrastructures (Kubernetes 2025b; Kubernetes 2025d; AWS 2025; Davis 2019, pp. 58–59). Furthermore it complements the microservice architectural pattern by enabling isolated, low overhead deployments, ensuring consistent environments (Balalaie, Heydarnoori, and Jamshidi 2016, p. 209).

2.1.7 Background: The Role of Microservices in Cloud-Native Architectures

Microservices play a pivotal role in cloud-native architectures by promoting business agility, scalability, and maintainability of applications. By decomposing applications into independent, granular services, microservices facilitate development, testing, and deployment using diverse technology stacks, enhancing interoperability across platforms (Waseem, Liang, and Shahin 2020, p. 1; Larrucea et al. 2018, p. 1). Additionally, they help prevent failures in one component from propagating across the system by isolating functionality into distinct, self-contained services (Davis 2019, p. 62). This architectural style aligns well with cloud environments, as it allows services to evolve independently, effectively addressing challenges associated with scaling and maintenance without being tied to a singular technological framework (Balalaie, Heydarnoori, and Jamshidi 2016, pp. 202–203). Furthermore, the integration of microservices with platforms like Kubernetes enhances deployment automation and orchestration, thus providing substantial elasticity to accommodate fluctuating workloads (Haugeland et al. 2021, p. 170). Additionally, migrating legacy applications to microservices can foster modernization and efficiency, thus positioning organizations favorably in competitive landscapes (Balalaie, Heydarnoori, and Jamshidi 2016, p. 214). Overall, the synergy between microservices and cloud-native architectures stems from their inherent capability to optimize resource utilization and streamline continuous integration and deployment processes.

2.1.8 Background: Kubernetes Resource Isolation Mechanisms

Kubernetes employs several resource isolation mechanisms, primarily through the use of *control groups (cgroups)* and *namespaces* to limit resource allocation for containers. Cgroups are a Linux kernel feature that organizes processes into hierarchical groups for fine-grained resource limitation and monitoring via a pseudo-filesystem called *cgroupfs* (Kubernetes 2025a; Project

2024). *Namespaces* are a mechanism for isolating groups of resources within a single cluster and scoping resource names to prevent naming conflicts across different teams or projects (Kubernetes 2025e). However, these mechanisms may not always provide the sufficient isolation needed for multi-tenant architectures, because the logical segregation offered by namespaces does not address the fundamental security concerns associated with multi-tenancy (Nguyen and Y. Kim 2022, p. 651). Additionally, research indicates that the native isolation strategies can lead to performance interference, where containers that share nodes can experience significant degradation in performance due to CPU contention (E. Kim, Lee, and Yoo 2021, p. 158). Specifically, critical services may be adversely affected when non-critical services monopolize available resources, which undermines the quality of service in multi-tenant environments (Li et al. 2019, p. 30410).

Moreover, while Kubernetes allows for container orchestration and resource scheduling, it can lead to resource fragmentation, further exacerbating the issue of performance isolation (Jian et al. 2023, p. 1). A common approach in multi-tenant scenarios is to deploy separate clusters for each tenant, which incurs substantial overhead—particularly in environments utilizing virtual machines for isolation (Şenel et al. 2023, pp. 144574–144575). In summary, although Kubernetes offers essential isolation mechanisms, the complexities of resource sharing and performance consistency in multi-tenant applications highlight the need for enhanced strategies to ensure robust resource management and performance isolation (Nguyen and Y. Kim 2022, p. 651; Jian et al. 2023, p. 2; E. Kim, Lee, and Yoo 2021, p. 158).

2.1.9 Relevance to SaaS and this Thesis

2.2 Kubernetes Control Plane (KCP)

KCP is "An open source horizontally scalable control plane for Kubernetes-like APIs" (The kcp Authors 2025).

2.2.1 Workspaces

KCP introduces the concept of *workspaces* to implement multi-tenancy. In KCP, a workspace is a Kubernetes-cluster-like HTTPS endpoint exposed under `/clusters/<parent>:<name>`, that regular tools such as *kubectl*, *Helm* or *client-go* treat exactly like a real Kubernetes cluster. Every workspace is backed by its own logical cluster stored in an isolated **etcd prefix**, so objects in one workspace (including cluster-scoped resources like **CRDs**) are completely invisible to others, delivering hard multi-tenancy without spinning up separate control planes (kcp Docs 2025l).

As per the definition by the etcd Authors 2025, "**etcd** is a strongly consistent, distributed key-value store that provides a reliable way to store data that needs to be accessed by a distributed system or cluster of machines. It gracefully handles leader elections during network partitions and can tolerate machine failure, even in the leader node." etcd is the primary datastore used by KCP and K8s (kcp Docs 2025k; Sun et al. 2021, p. 214). **etcd prefixes** are a simple, inbuilt way to group keys using a prefix (etcd Docs 2025). This allows for resource isolation in KCP. A Custom Resource Definition (CRD) is a declaratively specified schema that registers a new resource, defined by its group, version, kind, and OpenAPI schema, into the Kubernetes Control Plane so the native API server stores and serves the objects as first-class resources (Kubernetes 2025c).

KCP implements the same Role-Based Access Control (RBAC)-based authorization mechanism and cluster role and cluster role binding principles as Kubernetes inside workspaces (kcp Docs 2025c). However unlike Kubernetes KCP does currently not support Attribute-Based Access Control (ABAC) (kcp Docs 2025c; Kubernetes 2025f). KCP likely supports only RBAC-based authorization because ABAC is considered overly complex, hard to audit, and increasingly deprecated in favor of RBAC, which offers a more structured and maintainable access control model (Cullen 2025). This allows for consistent access control and permission management across all workspaces, aligning with familiar Kubernetes patterns and simplifying multi-tenant environment administration.

Workspaces allow for a typed, parent-child tree, and each type can constrain which kind of workspaces it can contain or be contained by, giving platform teams a structured way to delegate environments while retaining policy control (kcp Docs 2025l).

This combination of strong isolation, familiar tooling, and hierarchical organization makes

workspaces offer an attractive solution to many of the problems commonly faced in multi-tenant environments: each tenant gets the freedom of a full dedicated cluster, yet operators manage only a single shared KCP control plane.

2.2.2 API

As previously noted, most Kubernetes based multi-tenant systems currently require manual intervention by an administrator to deploy new tenants or modify resource allocation. However KCP, other than similar frameworks, like Capsule or Kiosk, provides an API server to the customer, that provides an easy way to access their resources (Nguyen and Y. Kim 2022, p. 651; The kcp Authors 2025). This in turn enables a degree of automation (Nguyen and Y. Kim 2022, p. 651). Every workspace has its own API endpoint (kcp Docs 2025l). This ensures, that more control can be shifted back to the customer. KCP ships a curated set of built-in Kubernetes APIs, such as `Namespaces`, `ConfigMaps`, `Secrets` and RBAC objects, so tenants can start working with familiar primitives immediately (kcp Docs 2025d). Additional functionality can be added per workspace simply by installing a CRD, and KCP permits multiple independent versions of the same CRD to coexist across workspaces (kcp Docs 2025b).

To share an API with other tenants, a provider declares an `APIResourceSchema` and then exports it through an `APIExport`, while consumers attach that API to their workspace with an `APIBinding` (kcp Docs 2025f). This export/bind workflow lets platform teams evolve APIs centrally without touching each consumer workspace, reinforcing the system's self-service goal (kcp Docs 2025f).

KCP supports Admission Webhooks only through Uniform Resource Locator (URL)-based client configurations, while `service`-based webhooks and conversion webhooks are currently unsupported, so operators must host their hooks externally (kcp Docs 2025a).

Because admission requests include the logical-cluster name, webhook back ends can enforce policies per workspace and thus maintain strong tenant isolation (kcp Docs 2025c). Every Representational State Transfer (REST) call is scoped under the path pattern `/clusters/<workspace>`, ensuring that automation never leaks objects across workspaces (kcp Docs 2025h). API providers can also access consumer data through a virtual-workspace URL rooted at `/services/apiexport/`, enabling safe cross-workspace reconciliation loops without cluster-wide privileges (kcp Docs 2025h). Together, built-in APIs, CRDs, the APIExport / APIBinding model, admission controls and workspace-prefixed REST routing give tenants a rich yet safe surface for automation while keeping operational responsibility with the platform team.

2.2.3 Sharding

KCP employs sharding to **horizontally scale** the control-plane, letting an installation grow far beyond the limits of a single API-server/etcd pair (kcp Docs 2025i; kcp Docs 2025j).

Each shard hosts a set of logical clusters, so every workspace (and therefore every tenant) gets its own Kubernetes-compatible consistency domain on that shard (kcp Docs 2025j). Because "a set of known shards comprises a KCP installation", operators can add or remove shards at will, expanding or contracting capacity with no downtime for existing workspaces (kcp Docs 2025j). Cross-shard traffic is funneled through a dedicated **cache-server**, avoiding the $n \times (n-1)$ explosion of of direct links that would otherwise appear in large deployments (kcp Docs 2025e). This cache-server also underpins **workspace migration and object replication**, so tenants remain oblivious to topology changes while the platform evolves underneath them (kcp Docs 2025e).

Administrators can define **Partitions** that group shards, for example by region or load profile, giving schedulers a topology-aware API for controller placement (kcp Docs 2025g). Partitions therefore deliver **geo-proximity, load distribution, and fault isolation** for multi-tenant control-plane components (kcp Docs 2025g). Taken together, sharding provides the scalability, noisy-neighbor isolation, and topology flexibility required to run **large numbers of independent workspaces in a single multi-tenant KCP deployment**.

2.2.4 High Availability

As defined in *Guide to SSL VPNs – Recommendations of the National Institute of Standards and Technology* 2008, p. 3-3 high availability (HA) "is a failover feature to ensure availability during device or component interruptions".

KCP employs several mechanisms to ensure HA. Firstly to achieve this "failover feature" at the control-plane level, KCP relies heavily on its **cache-server layer** (kcp Docs 2025e). While individual shards can (and will) go offline, the cache server provides a logically-central, eventually-consistent replica of the small but critical objects that every shard must be able to see in order to keep tenant workspaces, API bindings or scheduling decisions functioning (kcp Docs 2025e). In essence, the cache server acts as a rendez-vous point that collapses the $n \times (n-1)$ mesh of direct shard-to-shard links into a single, well-known endpoint (kcp Docs 2025e). Instead of every shard having to maintain and re-establish dozens of peer connections after a failure, each shard needs only a single healthy path to any replica of the cache tier (kcp Docs 2025e). This single-hop topology is easier to debug, cheaper to secure, and—most importantly—continues to deliver the global metadata that controllers require even when one or several shards are offline (kcp Docs 2025e).

As described in kcp Docs 2025e, KCP uses a write-once / read-many replication model to populate and refresh that shared state:

[1]: *Write controllers* that run on every shard stream a selected set of objects, such as `APIExport`, `APIResourceSchema`, `Shard`, certain RBAC rules and more into the cache server. Because the controller keeps its own authoritative copy, it can re-push data after a transient outage without the risk of split-brain. As noted by Levine 2021, split-brain describes "a phenomenon where the cluster is separated from communication but each part continues working as separate clusters, potentially writing to the same data and possibly causing corruption or loss.".

[2]: *Read controllers* on all shards maintain informers that watch other shards' objects from the cache server. These informers are isolated from a shard's local etcd and can therefore start with a more tolerant back-off strategy: a shard may declare itself "ready" for tenant traffic even if cache connectivity has not yet been re-established, and will self-heal once the link returns.

Because objects in the cache server are stored per logical cluster but can be listed via wildcard paths, each controller needs only one LIST/WATCH stream per resource type rather than per cluster (kcp Docs 2025e). This dramatically reduces the number of long-lived Transmission Control Protocol (TCP) connections that must survive a fail-over and further increases control-plane availability.

Consequently, no individual shard becomes a single point of failure for global control-plane metadata. Only the cache tier must be deployed in a highly available configuration — something that can be achieved with standard Kubernetes Service + LoadBalancer constructs or by running two or more replicas behind a global Internet Protocol (IP) address. By funnelling cross-shard traffic through this purpose-built cache layer, KCP delivers the fail-over semantics described by *Guide to SSL VPNs – Recommendations of the National Institute of Standards and Technology* 2008: metadata remains available, and therefore the control plane remains operational, even when individual components fail.

2.3 SaaS Architecture and Automation

SaaS is, above all else, a **business and software-delivery model** in which a provider offers its solution through a low-friction, service-centric model that maximizes value for customers and providers surrounding all tenant environments with a single, unified experience (AWS 2022, pp. 3–4; AWS 2022, p. 11). According to AWS 2022, pp. 3-4, SaaS is associated with six major objectives:

[1]: *Agility*. SaaS companies prosper by designing for continuous adaptation to evolving markets, customer demands, competitive pressures, pricing models, and target segments.

[2]: *Operational efficiency*. SaaS companies grow and scale by fostering a culture of **operational efficiency** that unifies tooling, enables rapid collective deployment across all customer environments, and eliminates one-off customizations.

[3]: *Frictionless onboarding*. SaaS providers must minimize friction in onboarding for every Business to Business (B2B) and Business to Customer (B2C) tenant by creating repeatable, efficient processes that accelerate time-to-value.

[4]: *Innovation*. SaaS providers build a flexible foundation that lets them respond to current customer needs while using that same agility to innovate as well as unlock new markets, opportunities, and efficiencies.

[5]: *Market response*. SaaS replaces long-cycle releases with near-real-time agility, enabling organizations to pivot strategy in response to emerging market dynamics.

[6]: *Growth*. SaaS is a growth-oriented model that promotes agility and efficiency, enabling rapid adoption.

Automation is the foundation for the utilization of the scaling effects that come along with SaaS architectures. The onboarding service automatically orchestrates other services to create users, tenant, isolation policies, provision, and per-tenant resources (AWS 2022, p. 14). Once live, automated pipelines let new features roll to every tenant through a single, shared process, giving operators a single pane of glass for the whole estate (AWS 2022, p. 10). However merely automating the provisioning of each customer environment and offloading its management to an Managed Service Provider (MSP) still leaves tenants running potentially different, separately-operated versions (AWS 2022, pp. 23–24). Furthermore it distances the software provider from unified onboarding, operations, and customer insight—so automation alone creates an MSP

setup, whereas true SaaS requires one shared version and a single, provider-owned control plane for every tenant (AWS 2022, pp. 23–24).

Ultimately, SaaS depends on automated, repeatable workflows that remove internal and external friction, and ensure stability, efficiency and repeatability for this process (AWS 2022, p. 14).

3 State of the Art and Related Work

3.1 Zero-Downtime Deployment Strategies

3.2 Kubernetes Scaling Methods

3.3 Multi-Tenancy Concepts in the Cloud

3.4 KCP

4 Conceptual Design

4.1 Proposed Scenario

To demonstrate the conception, implementation, and evaluation of a highly-scalable, highly available SaaS platform on KCP, the thesis adopts a deliberately light-weight yet realistic **case study**:

A **small and medium sized businesses (SMB) Web-Presence-as-a-Service**, whose sole purpose is to give SMBs an instantly available, single-page web presence. The service sits between do it yourself (DIY) website builders and full custom agency work. Tenants enter their company facts, choose a theme, and receive a live, secure page, without touching infrastructure. A data contract is used to allow the frontend to be data-driven.

Actor	Responsibility	Interaction Pattern
SMB tenant	Enters or edits company information; chooses a theme	Write-heavy only at onboarding, then sporadic
End-User Visitor	Loads the generated page	Read-only; bursty traffic driven by marketing and search indexing
Platform Operator	Maintains themes, monitors capacity, rolls out new platform versions	development and operations (DevOps)

Table 1: Actors, their responsibilities, and interaction patterns in the case case study

This scenario is attractive for evaluating KCP because it combines high multi-tenancy (potentially tens on thousands of logically isolated sites) with skewed workload characteristics, like very high read fan-out combined with low per-tenant write rate. The workload stresses horizontal scalability, especially of the control plane, without the confounding complexity of rich business logic or deep data lineage. Moreover, the fact model is sufficiently small to allow *stateless* page rendering, enabling the data plane to be scaled independently of the rendering tier. The following subsection translates this narrative into concrete requirements.

4.2 System Requirements

Building on the foundation of (see subsection 4.1: *Proposed Scenario*), this Chapter formalizes *what* the platform must do and *how well* it must do it before any architectural choices are justified. Clear, measurable requirements serve three purposes in this Thesis:

[1]: *Design driver*. They constrain the solution space explored in (see subsection 4.3: *Architecture Design with KCP for SaaS*), ensuring that every architectural element demonstrably supports a stated need rather than an implicit assumption.

[2]: *Benchmark for implementation*. During prototyping ((see section 5: *Prototypical Implementation*)) the tables in this chapter become acceptance criteria that guide configuration, automation scripts, and performance-test baselines.

[3]: *Reference for evaluation*. The metrics used in (see section 6: *Evaluation*) map one-to-one to the service-level objectives, latency budgets, and scalability targets enumerated here, allowing an objective pass/fail discussion of the prototype's behavior.

The derivation methodology of the requirements can be characterized as follows:

[1]: *Actor analysis*. Each functional capability traces back to an interaction Table in (see Table 1: *Actors, their responsibilities, and interaction patterns in the case case study*).

[2]: *Service-level expectations*. Non-functional figures reflect common SaaS SLAs for SMB-facing products and align with KCP documentation on acceptable control-plane latency.

[3]: *Platform constraints*. Limits on etcd input / output (I/O), shard utilization, and workspace-list latency bind scalability goals to realistic thresholds.

By separating *function* from *quality*, the chapter provides a traceable checklist that threads through design, implementation, and evaluation, ultimately demonstrating whether KCP can underpin a highly-scalable, highly-available SaaS offering for the target market.

4.2.1 Functional Requirements

The prototype offers only a handful of end-to-end user journeys, yet each journey must be supported in a self-service and repeatable way across thousands of tenants. The purpose of this subsection is therefore to distill the actor interactions listed in Table 1 into a concise set of *functional* statements that can later be traced unambiguously to implementation artifacts and test cases.

To stay aligned with the thesis goals, a requirement is admitted into the list, only if it is **visible to at least one external actor**, it can be **validated through an API call or user interface (UI) action**, and it is **independent of any particular architectural decision**.

The resulting catalogue of functional requirements is intentionally short. I focuses on Create Read Update Delete (CRUD) operations for tenant data, delivery of the public page, and the minimal platform workflow required to provision, store and cache tenant configuration.

F ID	Scope	Title	Description
F-01	*Tenant*	Company Profile CRUD	A tenant owner shall be able to perform CRUD operations on the company profile (name, address, contact, logo, about-text) through the dashboard API.
F-02	*Tenant*	Service Catalog CRUD	A tenant owner shall be able to manage a list of services/products.
F-03	*Tenant*	Ratings CRUD	Public visitors shall be able to post 1-to-5-star ratings with comments; the public API shall list ratings.
F-04	*Tenant*	Public Page Delivery	The public Next.js frontend shall render the latest template and tenant data via the per-tenant API.
F-05	*Platform*	Tenant Provisioning	The dashboard shall create a new KCP workspace, deploy the tenant stack, allocate the Structured Query Language (SQL) schema and return a public URL in $\leq$ 60 s.
F-06	*Platform*	Config Storage and Retrieval	Template configuration for every tenant shall be stored under `/<tenant-id>/config.json` in the shared object bucket and fetched by the per-tenant API at start-up or cache miss.
F-07	*Tenant*	Config Caching	The per-tenant API shall cache configuration in-memory with a time to live (TTL) $\geq$ 24 h, falling back to the bucket on cache miss or version bump.

Table 2: Functional Requirements

These requirements cover the complete life-cycle of a tenant environment from **creation** over **serving** to **evolution**. Furthermore they define a simple yet measurable consistency contract between object storage and the API cache.

By keeping the scope this narrow, the thesis can focus evaluation on control-plane scalability,

HA, and page-delivery performance, without being distracted by edge functionality that would no exercise KCP in a meaningful way.

4.2.2 Non Functional Requirements

Where subsubsection 4.2.1 captured *what* the prototype must do, the present subsection specifies *how well* it must do it. Each requirement in Table 3 describes a service-level objective (SLO), that is:

[1]: *Observable*. It can be measured from outside the process boundary.

[2]: *Actionable*. It can be used as a pass/fail gate during architecture validation.

[3]: *Business aligned*. Its numeric target reflects viable SaaS expectations for SMB customers.

The SLOs can be summarized along the three quality dimensions **reliability and performance**, **scalability, consistency and security**, and **durability and operability**.
The following non-functional requirements provide the basis for the architecture design.

NF ID	Scope	Title	Description
NF-01	Tenant	Public Availability	The public page shall achieve $\geq$ 99.95 % monthly uptime; workspace moves or API pod restarts shall cause 0 failed GET requests.
NF-02	Platform	Dashboard Availability	The owner dashboard shall achieve $\geq$ 99.5 % monthly uptime (so brief maintenance windows are acceptable).
NF-03	Tenant	Page Performance	p95 full-page load time shall be $\leq$ 600 ms at 200 req/s from one region.
NF-04	Tenant	API Latency	p95 latency for GET `/api/config` and GET `/api/reviews` shall be $\leq$ 150 ms under the same load.
NF-05	Platform	Horizontal Scalability	The control plane shall handle at least 2 000 tenant workspaces with etcd IO $\leq$ 70 % and < 100 ms workspace-list latency.

NF ID	Scope	Title	Description
NF-06	Platform	Cache Consistency	Config cache shall reflect bucket changes within 5 min after a tenant triggers "publish" in the dashboard.
NF-07	Platform	Tenant Isolation and Security	Data and traffic from one tenant shall not be accessible to another (RBAC, row-level security, network policies).
NF-08	Platform	Data Durability	Reviews and config data shall have an recovery point objective (RPO) = 0 h (write-ahead logging (WAL)-based backups) and an recovery time objective (RTO) $\leq$ 2 h via cross-region restore.
NF-09	Platform	Disaster Recovery for Bucket	The shared bucket shall replicate to a secondary region with automatic fail-over; cached assets must remain available during a primary-region outage.
NF-10	Operator	Maintainability / continuous integration (CI)/continuous deployment (CD)	A full platform deployment (dashboard + initializer + tenant chart) shall complete via GitOps pipeline in $\leq$ 15 min.

Table 3: Non-Functional Requirements

4.3 Architecture Design with KCP for SaaS

4.3.1 Overview and Design Principles

The platform must host potentially thousands of small, largely independent sites, each with mostly predictable, read-heavy traffic and sporadic writes ((see subsection 4.1: *Proposed Scenario*)). Two architectural principles follow immediately:

[1]: *Isolation by Workspace.* A dedicated Kubernetes cluster per tenant is operationally inhibitive. Conversely, a flat namespace in a single cluster risks cross-tenant resource contention,

complicated RBAC, and a noisy neighbor problem. KCP's *workspace* abstraction offers the middle ground, providing strong boundaries at the API layer while keeping a single point to manage tenants.

[2]: *Push state to the edge, pull control to the centre*. All *public* traffic should terminate inside the tenant workspace (close to the cache and database), whereas *administrative* traffic aggregates in a central place, that can be rate-limited and protected.

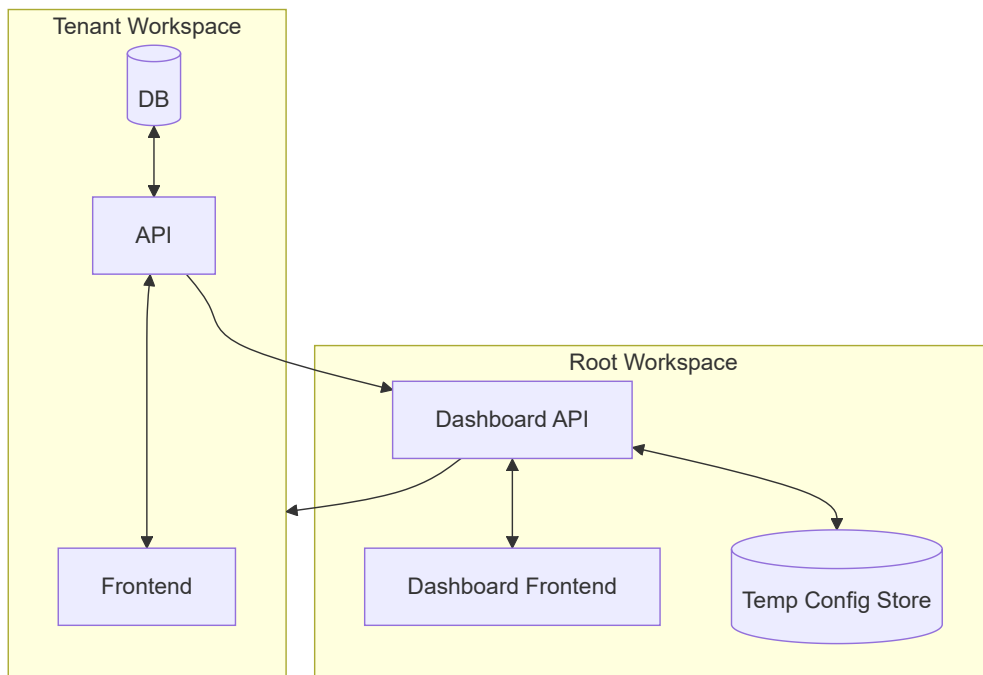These principles translate into the logical layout in Figure 1.

Figure 1: Overview of the system architecture

4.3.2 Workspace Topology and Multi-Tenancy model

Layer	KCP construct	Example resources	Provisioned Amount
Parent (control)	Workspace (`root`)	Deployment / dashboard, dashboard-API	1 (static)
Tenant (data)	Workspace (`root:<tenant-id>`)	Deployment / Frontend, tenant-API, stateful set	

Table 4: Layers overview

Each workspace is created via the Workspace CRD exposed by KCP's API. Creating a tenant in the Dashboard in turn creates a new KCP workspace for the tenant that is automatically provisioned. Deleting a workspace tears down all associated resources.

4.3.3 Tenant Workspace: Data Plane Components

Component	Scaling	Purpose
Frontend (Next.js)	Horizontal Pod Autoscaler (HPA) based on central processing unit (CPU) and queries per second (QPS)	Serves static hypertext markup language (HTML) / JavaScript (JS), does server-side rendering (SSR) for dynamic contents
API (Node.js)	HPA	Auth-less REST endpoints with cache consumed by the Next.js app.
database (DB)	StatefulSet	Stores ratings

Table 5: Per Tenant Components

The request flow of the visitor path can be summarized as follows:

[1]: *Frontend.* The Next.js frontend is called.

[2]: *Tenant API.* The Next.js frontend calls the tenant API to get dynamic data. The tenant API reads from the cache.

[3]: *Data sources.* The tenant API periodically renews its cache based of a TTL. The dynamic data (reviews) comes from the tenant DB while the data comes from the platform API.

This ensures, that for all customer interactions on the public website the workload remains local to the tenant workspace, thus improving the traceability.

4.3.4 Parent Workspace: Control Plane Components

Component	Scaling	Purpose
Dashboard	HPA	Authenticated UI for tenant owners; CRUD operations on tenant data
Parent API	HPA	validates input and writes JavaScript Object Notation (JSON); is polled by tenant API on cache miss

Table 6: Control Plane Components

4.3.5 Data Synchronization and Caching Strategy

4.3.6 Scalability, Isolation and Security

[1]: *Horizontal Scalability.* Inside the tenant workspace the frontend (FE) and the tenant-API replicate linearly.

[2]: *Tenant API.*

[3]: *Data sources.*

4.3.7 Rationale for Config Injection Strategy

The tenant-specific configuration is injected directly into the API container at build time using Docker `-build-arg`, and deployed into the tenant workspace. This decision favors strong

workspace isolation, avoids runtime complexities, and simplifies the tenant lifecycle.
The following alternatives were considered:

[1]: *Persistent Volume (PV)*. PVs offer cluster-wide storage, but they are bound to the underlying infrastructure and not scoped to individual workspaces. Since tenant data must remain fully isolated within its respective workspace, using a shared PV would have violated this design constraint.

[2]: *Persistent Volume Claim (PVC)*. PVCs are workspace-scoped and technically suitable for storing tenant configuration. However, managing their lifecycle dynamically per tenant (including updates and clean-up) would introduce significant operational complexity.

[3]: *ConfigMap*. A ConfigMap is a lightweight and K8s native way to inject configuration, but it has a very constraining size limit (typically 1 MiB) and is not designed for cross-workspace usage. Since KCP workspaces enforce strict isolation, injecting a ConfigMap from the parent workspace into the tenant workspace would violate boundary constraints, or require custom controllers.

[4]: *Git Repository*. Polling or pulling tenant configuration from a Git repository would offer central control and versioning, but would couple each tenant's runtime to an external dependency. It would also require embedding Git credentials or Secure Shell (SSH) keys within the workspace, raising security concerns and operational burden. Furthermore the data does not live inside the tenant violating isolation principles.

[5]: *initContainer + emptyDir*. This approach involves using an `initContainer` to write the config into an `emptyDir` shared volume before the main API container starts. While this ensures data locality, the config is ephemeral and lost on pod restart or rescheduling. Additionally, updates would require a full pod redeployment and controlled init re-execution, adding complexity.

[6]: *Tenant DB*. Storing the configuration in the tenant database would offer persistence and locality. However access control for the write operations and reaching out to the DB from the parent workspace are critical pain points.

[7]: *Redis*. A Redis store within the tenant workspace was considered for fast config access. However, this introduces a full additional service dependency per tenant, which contradicts the goals of lightweight and cost-efficient tenant deployments. Redis also requires

persistence management if configuration must survive restarts.

[8]: *Central Document Store* Maintaining a central document store in the root workspace (e.g. MongoDB) was ruled out due to isolation concerns. This would require the tenant API to reach out beyond its workspace boundary, which is explicitly avoided in the current architecture to enforce strict data sovereignty per tenant.

4.4 Automated Deployment Strategies

5 Prototypical Implementation

5.1 Infrastructure with KCP

5.2 Tenant Provisioning (Automation, Multi-Tenancy)

5.3 Scaling Mechanisms (Horizontal Pod Autoscaler)

5.4 Monitoring and Logging (Prometheus, Grafana)

6 Evaluation

6.1 Performance Measurements (Downtime, Latency, Scaling)

6.2 Scaling Scenarios and Optimizations

6.3 Discussion of Results

7 Conclusion and Outlook

7.1 Summary

7.2 Personal Conclusion

7.3 Future Outlook

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