

# **Postgres Lifecycle Management Operators in Kubernetes**

Miroslav Šiřina

---

Bachelor's thesis  
2023



Tomas Bata University in Zlín  
Faculty of Applied Informatics

Univerzita Tomáše Bati ve Zlíně  
Fakulta aplikované informatiky  
Ústav informatiky a umělé inteligence

Akademický rok: 2022/2023

# ZADÁNÍ BAKALÁŘSKÉ PRÁCE

(projektu, uměleckého díla, uměleckého výkonu)

Jméno a příjmení: Miroslav Šířina  
Osobní číslo: A20079  
Studijní program: B0613A140020 Softwarové inženýrství  
Forma studia: Kombinovaná  
Téma práce: Správa životního cyklu Postgres v Kubernetes pomocí operátorů  
Téma práce anglicky: Postgres Lifecycle Management Operators in Kubernetes

## Zásady pro vypracování

1. Seznamte se s operátory v Kubernetes a Postgres databázovým systémem.
2. Definujte životní cyklus databázového serveru.
3. Vyberte vhodné operátory a popište je.
4. Sestavte metodiku testování jednotlivých operátorů.
5. Na základě sestavené metodiky otestujte vybrané operátory.
6. Proveďte zhodnocení.

Forma zpracování bakalářské práce: **tištěná/elektronická**  
Jazyk zpracování: **Angličtina**

**Seznam doporučené literatury:**

1. SAYFAN, Gigi, 2020. Mastering Kubernetes: level up your container orchestration skills with Kubernetes to build, run, secure, and observe large-scale distributed apps. Third edition. Birmingham: Packt Publishing. ISBN 9781839211256.
2. RIGGS, Simon a Gianni CIOLLI, 2022. PostgreSQL 14 Administration Cookbook. Birmingham: Packt publishing. ISBN 9781803248974.
3. DOBIES, Jason a Joshua WOOD. Kubernetes operators: automating the container orchestration platform. Sebastopol, CA: O'Reilly Media, 2020. ISBN 9781492048046.
4. FARLEY, David, 2021. Modern software engineering: doing what really works to build better software faster. Boston: Addison-Wesley. ISBN 9780137314911.
5. DAME, Michael, 2022. The Kubernetes Operator Framework Book. Birmingham: Packt Publishing. ISBN 9781803232850.

Vedoucí bakalářské práce: **Ing. Peter Janků, Ph.D.**  
Ústav informatiky a umělé inteligence

Datum zadání bakalářské práce: **2. prosince 2022**  
Termín odevzdání bakalářské práce: **26. května 2023**

**doc. Ing. Jiří Vojtěšek, Ph.D. v.r.**  
děkan



**prof. Mgr. Roman Jašek, Ph.D., DBA v.r.**  
ředitel ústavu

Ve Zlíně dne 7. prosince 2022

**I hereby declare that:**

- I understand that by submitting my Bachelor's thesis, I agree to the publication of my work according to Law No. 111/1998, Coll., On Universities and on changes and amendments to other acts (e.g. the Universities Act), as amended by subsequent legislation, without regard to the results of the defence of the thesis.
- I understand that my Bachelor's Thesis will be stored electronically in the university information system and be made available for on-site inspection, and that a copy of the Bachelor's Thesis will be stored in the Reference Library of the Faculty of Applied Informatics, Tomas Bata University in Zlín.
- I am aware of the fact that my Bachelor's Thesis is fully covered by Act No. 121/2000 Coll. On Copyright, and Rights Related to Copyright, as amended by some other laws (e.g. the Copyright Act), as amended by subsequent legislation; and especially, by §35, Para. 3.
- I understand that, according to §60, Para. 1 of the Copyright Act, Tomas Bata University in Zlín has the right to conclude licensing agreements relating to the use of scholastic work within the full extent of §12, Para. 4, of the Copyright Act.
- I understand that, according to §60, Para. 2, and Para. 3, of the Copyright Act, I may use my work – Bachelor's Thesis, or grant a license for its use, only if permitted by the licensing agreement concluded between myself and Tomas Bata University in Zlín with a view to the fact that Tomas Bata University in Zlín must be compensated for any reasonable contribution to covering such expenses/costs as invested by them in the creation of the thesis (up until the full actual amount) shall also be a subject of this licensing agreement.
- I understand that, should the elaboration of the Bachelor's Thesis include the use of software provided by Tomas Bata University in Zlín or other such entities strictly for study and research purposes (i.e. only for non-commercial use), the results of my Bachelor's Thesis cannot be used for commercial purposes.
- I understand that, if the output of my Bachelor's Thesis is any software product(s), this/these shall equally be considered as part of the thesis, as well as any source codes, or files from which the project is composed. Not submitting any part of this/these component(s) may be a reason for the non-defence of my thesis.

**I herewith declare that:**

- I have worked on my thesis alone and duly cited any literature I have used. In the case of the publication of the results of my thesis, I shall be listed as co-author.
- The submitted version of the thesis and its electronic version uploaded to IS/STAG are both identical.

In Zlín; dated:

.....

Student's Signature

## **ABSTRAKT**

Text abstraktu česky

Klíčová slova: Přehled klíčových slov

## **ABSTRACT**

Text of the abstract

Keywords: Some keywords

Zde je místo pro případné poděkování, motto, úryvky knih, básní atp.

## TABLE OF CONTENTS

<b>INTRODUCTION.....</b>	<b>10</b>
<b>I THEORY .....</b>	<b>11</b>
<b>1 BACKGROUND .....</b>	<b>12</b>
1.1 POSTGRES.....	12
1.1.1 Write Ahead Log .....	13
1.1.2 Backup and restore .....	14
1.1.3 High Availability .....	14
1.1.4 Load Balancing and Connection Pooling .....	15
1.2 KUBERNETES .....	15
1.2.1 Kubernetes Components.....	17
1.2.2 Kubernetes Concepts .....	18
1.3 RUNNING POSTGRES IN KUBERNETES.....	20
1.4 DATABASE SYSTEM LIFECYCLE .....	20
1.5 OPERATORS .....	22
<b>2 THESIS OBJECTIVE .....</b>	<b>26</b>
<b>3 RESOURCE QUESTIONS .....</b>	<b>27</b>
<b>4 OPERATORS FOR LIFECYCLE MANAGEMENT IN KUBERNETES</b>	<b>28</b>
4.1 CRUNCHY POSTGRES FOR KUBERNETES .....	29
4.2 EDB POSTGRES FOR KUBERNETES .....	30
4.3 CLOUDNATIVEPG .....	31
4.4 STACKGRES OPERATOR .....	32
4.5 PERCONA OPERATOR FOR POSTGRESQL.....	35
4.6 SUMMARY .....	36
4.7 KEY DIFFERENCES.....	36
<b>5 METRICS.....</b>	<b>37</b>
5.1 PERFORMANCE.....	37
5.2 RELIABILITY .....	37
5.2.1 Maturity.....	37
5.3 USABILITY .....	38
5.3.1 Learnability .....	38
5.3.2 Operabilitiy .....	38
5.4 MAINTENANCE .....	38
5.4.1 Renewal .....	38

5.5 SECURITY .....	38
5.5.1 Vulnerabilities .....	39
<b>6 TESTING METHODOLOGY .....</b>	<b>40</b>
6.1 NOTICE .....	40
6.2 CRITERIA.....	40
6.3 TEST MANAGEMENT PROCESS .....	41
6.4 TEST STRATEGY AND PLANNING .....	42
6.5 TEST PLAN .....	42
6.6 TEST MONITORING AND CONTROL PROCESS .....	43
6.7 TEST COMPLETION PROCESS .....	44
6.8 DYNAMIC AND STATIC TEST PROCESSES .....	44
6.9 TEST DESIGN AND IMPLEMENTATION PROCESSES .....	44
6.10 TEST ENVIRONMENT AND DATA MANAGEMENT PROCESSES.....	45
6.11 TEST EXECUTION PROCESS .....	45
6.12 TEST INCIDENT REPORT PROCESS .....	45
6.13 LEVEL OF DETAIL.....	46
<b>II APPLICATION OF THEORY .....</b>	<b>47</b>
<b>7 TEST PROCESS .....</b>	<b>48</b>
7.1 STATIC TEST PROCESS .....	48
7.1.1 Reliability and maintenance.....	48
<b>8 EVALUATION .....</b>	<b>49</b>
8.1 RELIABILITY AND MAINTENANCE .....	49
8.1.1 Popularity .....	49
8.1.2 Fixed issues .....	49
8.1.3 Renewal .....	50
8.2 LEARNABILITY .....	51
8.2.1 Required training .....	51
8.2.2 Documentation examples.....	52
8.3 SECURITY .....	53
8.4 OPERABILITY .....	54
8.4.1 Ease of use .....	55
8.4.2 Monitoring.....	55
8.5 PERFORMANCE.....	56
8.5.1 Issues with CNPGO.....	59

8.5.2	Issues with SPGO.....	59
8.5.3	Issues with PPO.....	60
8.6	USABILITY .....	61
<b>9</b>	<b>EVALUATION .....</b>	<b>62</b>
	<b>ZÁVĚR.....</b>	<b>63</b>
	<b>REFERENCES .....</b>	<b>64</b>
	<b>LIST OF ABBREVIATIONS.....</b>	<b>73</b>
	<b>LIST OF FIGURES.....</b>	<b>74</b>
	<b>LIST OF TABLES.....</b>	<b>75</b>
	<b>LIST OF APPENDICES .....</b>	<b>77</b>

## INTRODUCTION

It is essential for the database server to be as close as possible to the applications that are using it. This reduces the number of men in the middle between the database and the application, which reduces database access latency and thus reduces overall application latency and increases security. The mass migration of applications to Kubernetes clusters implies a necessary shift of Postgres to Kubernetes. This thesis defines Postgres, Kubernetes, and their Operators. It then further describes the lifecycle of a Postgres cluster, and searches for Operators capable of managing this lifecycle. It establishes metrics by which it tests and evaluates these Operators. The result of this thesis is the recommendation of a suitable Operator based on the defined metrics.

TBD - remove

The cloud has made our work easier. We no longer have to physically connect new machines to the network, configure network connections, add disks, or even plug in virtual ones. Kubernetes, together with the cloud, can automatically allocate new resources for our applications and, thanks to operators, can even create entire database clusters with high availability. Thanks to operators, it can also automatically set up scaling or backups. It can even restore an entire database system from a backup. This paper is focused on Kubernetes operators for the popular Postgres database management system. Its goal is to find Operators for Postgres. To evaluate their pros and cons. To test them and recommend the best one.

TBD - remove end

TBD - fix footnotes numbering

TBD - switch to Czech layout

TBD - Motto

TBD - Czech abstract, English abstract

TBD - Poděkování, motto

TBD - adjust the test theory to test process

TBD - cíl práce, navrhout doporučení, rozhodovací strom

## I. THEORY

## 1 BACKGROUND

This chapter introduces the key technologies used in this thesis including Postgres, Kubernetes, and Kubernetes Operators.

### 1.1 Postgres

TBD: Connect image with text

PostgreSQL is a powerful object-relational database management system (ORDBMS) derived from the POSTGRES package written at the University of California at Berkeley. [1] [2] The first version of POSTGRES was released in June 1989. POSTGRES has been used in many applications, including financial data analysis systems, asteroid tracking databases, medical information database, and several geographic information systems. The size of external community users has nearly doubled by 1993. [3]

POSTGRES was using its POSTQUEL query language from version, until Andrew Yu and Jolly Chen introduced SQL to POSTGRES in 1995. The name has changed to Postgres95. Postgres95 was completely ANSI C code reduced by 25 % and was 30 – 50 % faster than Postgres 4.2. [3]

It was clear by 1996 that the name would not stand the test of time therefore it has been renamed to PostgreSQL. As stated by PostgreSQL documentation [3]: “Many people continue to refer to PostgreSQL as “Postgres” (now rarely in all capital letters) because of tradition or because it is easier to pronounce. This usage is widely accepted as a nickname or alias.“ This thesis will use Postgres as an alias for PostgreSQL as well.

More than 30 years after the first version Postgres has been considered the most used ORDBMS for professional developers by Stack Overflow survey [4]. According to Riggs and Ciolfi [2]: “The PostgreSQL feature set attracts serious users who have serious applications. Financial services companies may be PostgreSQL’s largest user group, although governments, telecommunication companies, and many other segments are strong users as well.“ It is fully ACID compliant [5] and supports many kinds of data models such as relational, document, and key/value. [2]

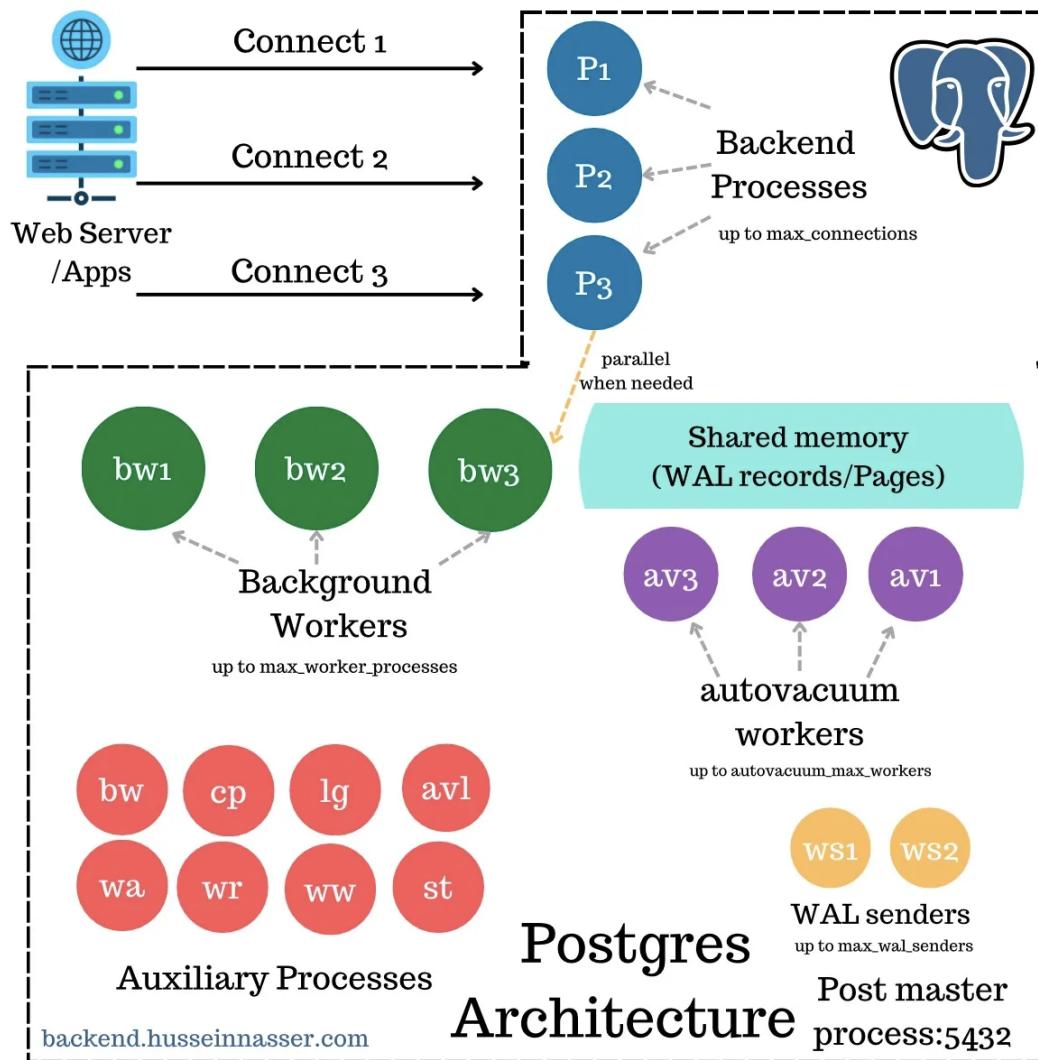


Figure 1.1 Postgres Architecture [6]

### 1.1.1 Write Ahead Log

Write-ahead Logging (WAL) used by Postgres is a standard technique to ensure data integrity. Its main concept is that changes in data files (where tables and indexes are stored) must only be written after they are logged (saved to a log file). That means the database is updated after the changes are written to disk. In the event of a system crash, all transactions will be recovered from the disk. [7]

Although WAL is primarily designed for recovery after a database server crash, its design also allows any changes to the database server state to be replayed backward. A copy of the log is also a form of backup. Thus, for recovery to a point in time, only logs that have been saved to that point in time can be restored. This technique

is called Point-In-Time Recovery (PITR). [8] These log files can also be streamed to other nodes to serve as a replica or remote backup. [9]

TBD: describe synchronous and asynchronous replication

### 1.1.2 Backup and restore

A full set of backup commands is included in Postgres. Among the simple backup commands are pg\_dump and pg\_dumpall, which enable one or more databases to be saved in SQL format. A wide range of configuration options are available for these commands, including compression for large databases or exporting only the database schema. To restore a database from a file at a later time, the psql command can be used, which is capable of restoring a database from its dump. [10] These commands are also helpful with migration from one major Postgres version to another because the dumped files are plain SQL commands.

The backup options in Postgres are quite limited. Postgres allows to set up of a backup command that runs after the next log file is created, database dumps, and log streaming. For more advanced backup techniques, additional software such as PgBackRest must be used. [8]

**PgBackRest** PgBackRest is a reliable and simple backup and restore solution that provides many features on top of classic Postgres backup and restore tools like parallel backup options with compression, local or remote backups, cloud backup (S3, Azure and Google Cloud), or backup encryption. Full, incremental, or differential backup is also supported. [11]

TBD: why is it here? Connect to crunhy and operatores

### 1.1.3 High Availability

The basic structure of a database cluster consists of one or more database servers, which can be called nodes. In Postgres there are two types of nodes, Primary node and Standby node. A Primary node is such a node that allows reading and writing information. The newly written information is then streamed to the Standby nodes. Standby nodes are read-only, they do not allow writing. [9]

Achieving high availability with Postgres is possible by using more than one node in the cluster. Two options are possible here. A single Primary node option, where the Primary node is read and write enabled, and the other nodes are Standby nodes. If the Primary node is unavailable, then the Standby node is promoted to the Primary node. This event is called failover. In this variant, the Primary node streams the logs to the Standby nodes. The second option is to use multiple Primary nodes. However, conflicts can occur because all Primary nodes allow concurrent writes. [12]

**Patroni** Since Postgres does not provide any software that can detect that a node is unavailable, it is necessary to use software outside of Postgres [13], such as Patroni. Patroni is a popular open-source tool created by Zalando to achieve high availability of Postgres clusters. Patroni uses a distributed configuration source such as ZooKeeper, Etcd, Consul, or Kubernetes for its operation. Patroni can automatically adjust the settings of all managed nodes, therefore it can automate failover and make it seamless. [14] [15]

#### 1.1.4 Load Balancing and Connection Pooling

Using more than one node allows to direct traffic to a node that is less busy and thus achieve load balancing. Postgres doesn't come with any software that allows splitting the load on different nodes, so it is necessary to use an external load balancer such as HA Proxy or pgBouncer. The load balancer then acts as an intermediary between the database and the client and directs the traffic to the available nodes according to the set rules. These load balancers also enable connection pooling which is a technique for managing and reusing database connections to increase performance and reduce overhead. Connection pooling involves creating a pool of pre-created connections that can be shared and reused by multiple client requests, instead of creating a new connection for each request. This removes the overhead of creating a new process each time a client connects to Postgres and allows the client to use resources that would otherwise be used to service multiple requests (or complete them faster). [16]

## 1.2 Kubernetes

Kubernetes, also known as K8s, is an open-source platform for automating deployment, scaling, and management of containerized applications. It provides a way to manage and orchestrate containers, which are units of software that package up an application

and its dependencies into a single, isolated package that can run consistently on any infrastructure. [17]

As described by Kubernetes Documentation [18] Kubernetes provides several key features, including:

- **Service discovery:** A container can be exposed by Kubernetes either through its DNS name or its own IP address.
- **Load balancing:** In the case of high traffic to a container, stability of the deployment can be ensured by Kubernetes load balancing and distributing the network traffic.
- **Storage Orchestration:** Storage orchestration in Kubernetes allows for the automatic mounting of a storage system of choice, including local storage, public cloud providers, and others.
- **Automated rollouts and rollbacks:** The desired state of deployed containers can be described using Kubernetes, and the actual state can be changed to the desired state at a controlled rate. For instance, the automation of Kubernetes can be utilized to create new containers for the deployment, remove existing containers, and transfer all their resources to the newly created container.
- **Automatic bin packing:** A cluster of nodes for running containerized tasks is provided to Kubernetes. The amount of CPU and memory required by each container is specified to Kubernetes. The optimal utilization of resources can be achieved by Kubernetes fitting the containers onto the nodes.
- **Self healing:** Containers that fail are restarted by Kubernetes, those that do not respond to the user-defined health check are replaced or killed, and they are not advertised to clients until they are deemed ready to serve.
- **Secret and configuration management:** Sensitive information, such as passwords, OAuth tokens, and SSH keys, can be stored and managed by Kubernetes. The deployment and updating of secrets and application configuration can be done without the need to rebuild container images and without the exposure of secrets in the stack configuration.

### 1.2.1 Kubernetes Components

Kubernetes cluster is composed of a set of worker machines that run containerized applications called nodes. Each cluster must have at least one node. [18]

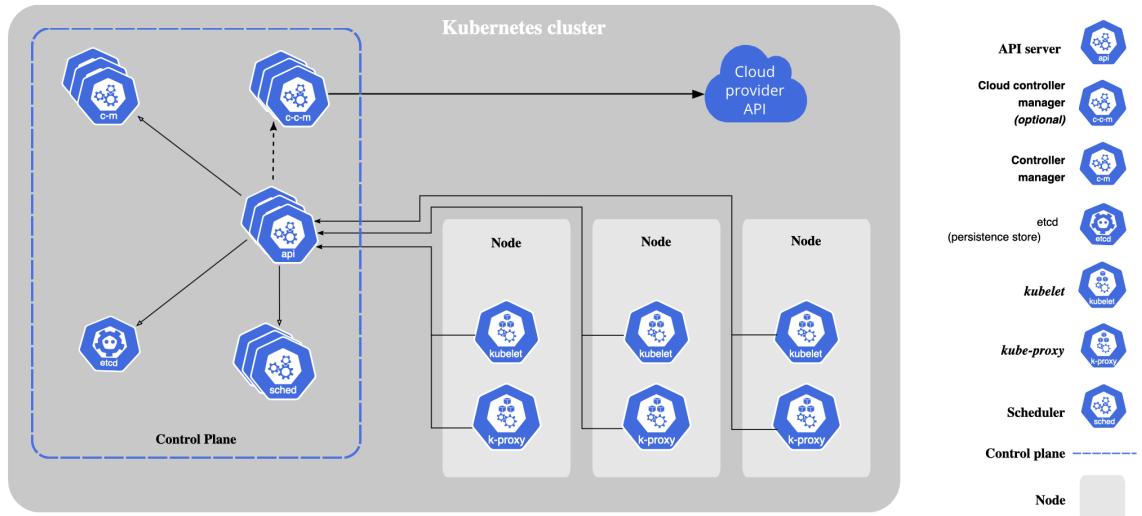


Figure 1.2 The components of a Kubernetes cluster [18]

The Kubernetes control plane is the management system of a Kubernetes cluster, responsible for maintaining the desired state of the cluster. It consists of multiple components that work together to manage the cluster and its resources, including pods, services, and volumes. The key components of control plane are [19]:

- **kube-APIserver:** Acts as the front-end for the Kubernetes API and exposes the API to other components. [18]
- **Etcd:** Highly available distributed key-value store that serves as the backing store for the cluster's configuration data. [20]
- **kube-scheduler:** Assigns work to nodes in the cluster, such as scheduling pods to run on nodes. [21]
- **kube-controller-manager:** Monitors the cluster's state and makes adjustments as necessary to maintain the desired state. [19]
- **cloud-controller-manager:** Manages cloud-related tasks such as node creation and management, volume management, and load balancing, allowing the other components of the control plane to focus on their specific responsibilities. Cloud manager is optional. Can be avoided when Kubernetes not used in cloud. [18]

**Node components:** Node components in a Kubernetes cluster run on each node and provide crucial functionality for the operation of containers on that node. [18]

- **kubelet:** Is responsible for communicating with the control plane and ensuring that containers are running and healthy. [22]
- **kube-proxy:** Is responsible for maintaining network rules on the nodes, allowing network communication to the containers. It enables the containers in a pod to communicate with other containers and the outside world, and performs tasks such as load balancing and traffic routing. [22]
- **container runtime:** Is responsible for running containers. [18]

### 1.2.2 Kubernetes Concepts

ReplicaSet extension - Operators p. 28 (Replica is general and application agnostic)

Pod is the smallest deployable unit that can be created in Kubernetes. [23] A Pod in Kubernetes is comprised of multiple containers and storage volumes that are run together within the same execution environment. As a result, all containers included in a single Pod will always run on the same machine. [21] A Pod's specifications are outlined in a Pod manifest, which is simply a JSON or YAML text file that represents the Kubernetes API object. Kubernetes follows a declarative configuration approach, where the system's desired state is defined in a configuration file, and the service then implements the necessary changes to make the desired state a reality. [24]

ReplicaSet's purpose is to ensure a consistent number of replica Pods are running at all times. It is commonly used to guarantee a specified number of identical Pods are available. However, a Deployment is a more advanced concept that oversees ReplicaSets and provides a more streamlined way to make updates to Pods. It also offers additional features. As a result, it's advisable to use Deployments instead of directly utilizing ReplicaSets, unless you have specific update requirements or don't need to make updates at all. [25]

Service is an abstraction layer and defines a group of Pods and the method to access them (often referred to as a micro-service). The group of Pods targeted by a Service is usually specified through a selector. The Service abstraction makes this possible by enabling the decoupling of components. [26] Kubernetes includes built-in service discovery mechanisms. When a service is created in Kubernetes, it is automatically

assigned an IP address and DNS name. Clients and other services can use this name or address to access the service within the Kubernetes cluster. [26]

Containers and pods in Kubernetes are ephemeral. When a container is terminated, any data it has written to its own filesystem is lost. In Kubernetes, storage is represented by a basic abstraction called "volumes". Containers use these volumes by binding them to their respective pods, and can then access the storage regardless of its physical location as if it were a part of their local filesystem. [27]

Kubernetes version 1.5 came with a new object called StatefulSet that allows a set of stateful pods to be deployed and managed. Each pod has a unique, stable network identity and a persistent storage volume. This enables stateful applications like databases to be run on Kubernetes. Advantages of using StatefulSets include predictable naming schemes, ordered pod creation and deletion, and unique persistent storage. [28] [29]

In version 1.7, Kubernetes introduced the Custom Resources extension to its API. [30] This extension allows Kubernetes to use user-defined resources that are not native to Kubernetes as if they were native. [31] Custom resources (CR) is an extension to the Kubernetes API that extends the deployment with additional parameters that are not part of it. CR stores these parameters and allows the API server to access them just like the native Kubernetes parts. CR is created in the Kubernetes cluster using a definition called Custom Resource Definition (CRD). [32]

Kubernetes controllers are control loops<sup>1)</sup> that constantly check the state of their controlled objects. If the controlled objects are not in the desired state, the controller performs actions to get the controlled objects into that state. For example, restart a crashed node, add a new replica, modify settings, etc. [33] However, to work with CR, custom controllers that can work with these resources must be created, these controllers are called Custom Controllers. [34]

TBD - show that Kubernetes can run stateless very well, maybe from Operator book

TBD - Read <https://containerjournal.com/kubecon-cnc-eu-2022/why-run-postgres-in-Kubernetes/>

TBD - Read data on Kubernetes <https://dok.community/dokc-2021-report/>

---

<sup>1)</sup>A control loop is a process that continuously monitors the state of a system, compares it to a desired state, and makes adjustments to bring the system closer to the desired state.

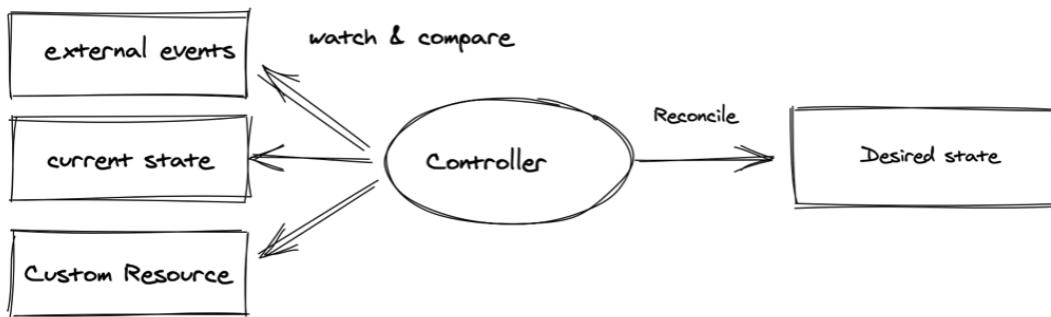


Figure 1.3 Kubernetes controller [35]

### 1.3 Running Postgres in Kubernetes

Kubernetes cannot know all complex stateful applications, which can contain a large number of nodes and have a wide range of uses while remaining general-purpose. The goal of Kubernetes is to provide an abstraction covering basic application concepts and providing options for extensions for more complex applications and their specific operations. Kubernetes cannot and should not know all the possible settings and operations that, for example, a Postgres cluster needs to run. [36]

The easiest way to run Postgres in Kubernetes is through the StatefulSet just mentioned. This StatefulSet can start a Postgres pod, create a persistent volume, and connect this volume to the pod. A stateful set can do this for all replicas set in its configuration. It can also scale up or down. Unfortunately, however, all independent Postgres instances created by StatefulSet controller are not synchronized in any manner.

This basic setup may be sufficient for running a single node, but it is no longer sufficient for managing the whole Postgres lifecycle. For managing whole Postgres lifecycle it is necessary to install other applications in the Kubernetes cluster and then configure the entire Postgres cluster to work with them. This represents a large amount of work and subsequent maintenance that Kubernetes Operators can facilitate.

### 1.4 Database System Lifecycle

The database system itself is a software like any other. It is therefore also subject to the same life cycle as software. As depicted in figure 1.4 application lifecycle consists of three main parts. It is the governance part, development, and operations. For this thesis, only the operations part is relevant because it is the only part we are able to control.

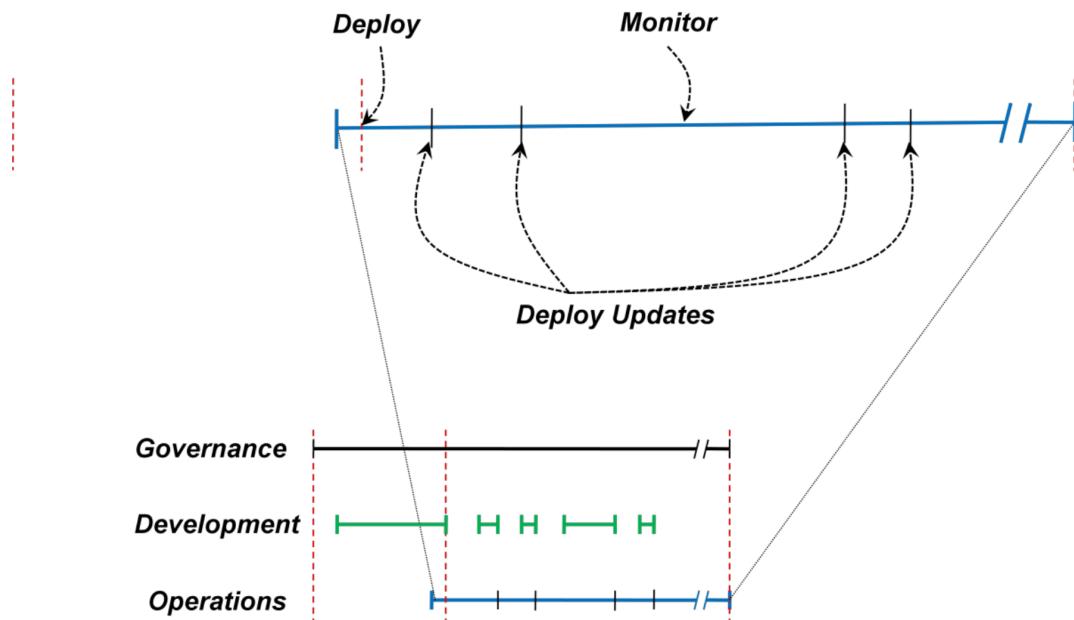


Figure 1.4 Application Life Cycle [37]

Operation is the process of running and managing the application, which starts with deployment and continues until the application is taken out of service. This aspect of the application lifecycle management covers the release of the application into production, ongoing monitoring, and other related tasks. [37]

Therefore the complete database life cycle can be outlined by following events:

- System installation
- System upgrade to a newer version (major and minor)
- System backup
- System restore
- System monitoring
- System scaling (vertical and horizontal)
- System configuration update
- System uninstall

## 1.5 Operators

As described in chapter 1.3, Kubernetes can run stateless applications very well. But its general purpose makes running complex stateful applications on top of it quite challenging.

This has changed in 2016 when CoreOS came up with Operators as a way to deploy complex applications with state such as databases, caches, or monitoring systems. [38]

An operator is a special kind of software that extends the Kubernetes API and has a particular knowledge of managed resource that Kubernetes does not have. The Operator also serves as a packaging mechanism for distributing applications including their dependencies in Kubernetes. The Operator can manage, restore, update or monitor the resource. It can also manage very complex applications. The Kubernetes Operator thus replaces the human operator after which it is named, who would otherwise take care of these tasks. [39] [38]

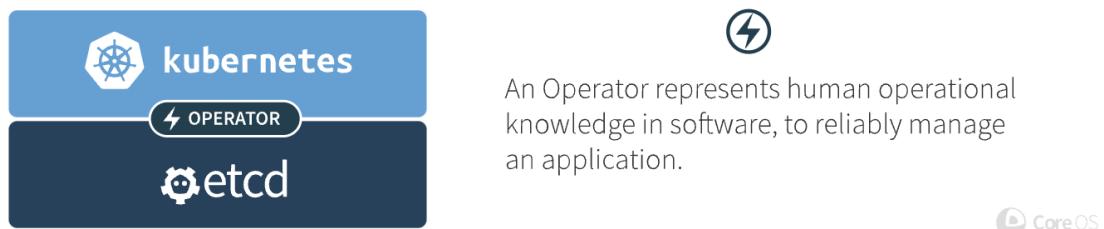


Figure 1.5 Definition of Kubernetes Operator [38]

CoreOS demonstrated the use of its Operator on Etcd (described in the Kubernetes Components chapter). When new Etcd nodes are created, it is necessary to give them a DNS names and use the Etcd cluster management tools to add the new nodes to an existing cluster. CoreOS has automated these tasks with the Etcd Operator so that all that is required is to increase the number of replicas in the Operator CRD and the Etcd Operator will perform these tasks instead of a human operator. [38] By embedding the human operator's operational knowledge into the code, this ensures that these tasks are repeatable, testable and upgradable. It also ensures that the necessary operations are always performed, executed in the order in which they are supposed to be performed, and none are skipped. This reduces the number of hours spent on dull but essential work such as backups. [35]

As described by Operator White Paper [35] and depicted in figure 1.6, Operator consists

of the following parts

- The managed application or infrastructure
- Software that has some specific knowledge of the managed application or infrastructure and allows the user to declaratively set the desired state
- Custom Controller, which is responsible for achieving the desired state

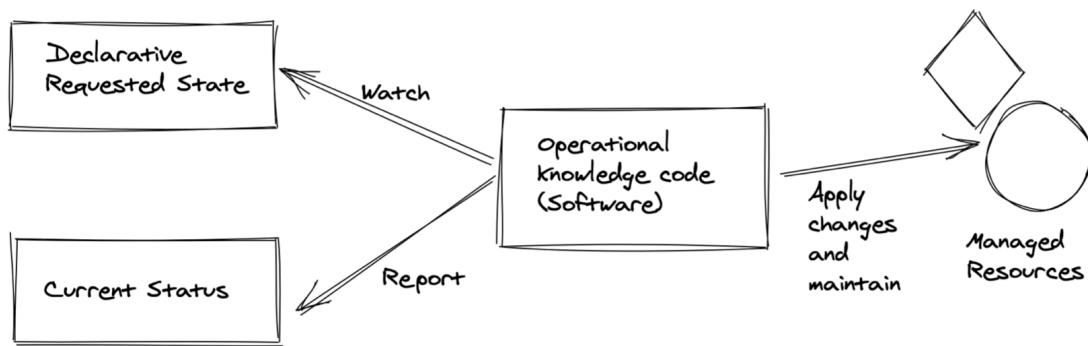


Figure 1.6 Operator pattern [35]

Like human operators, Kubernetes Operators can have a level of manual skill ranging from basic software installation and setup skills to a high level where they can scale software vertically or horizontally to automatically change the configuration or detect abnormalities. All Operator maturity levels are depicted in the figure 1.7. The highest level can only be reached by programming the Operator in the GO programming language or by using the Ansible automation tool. [40]

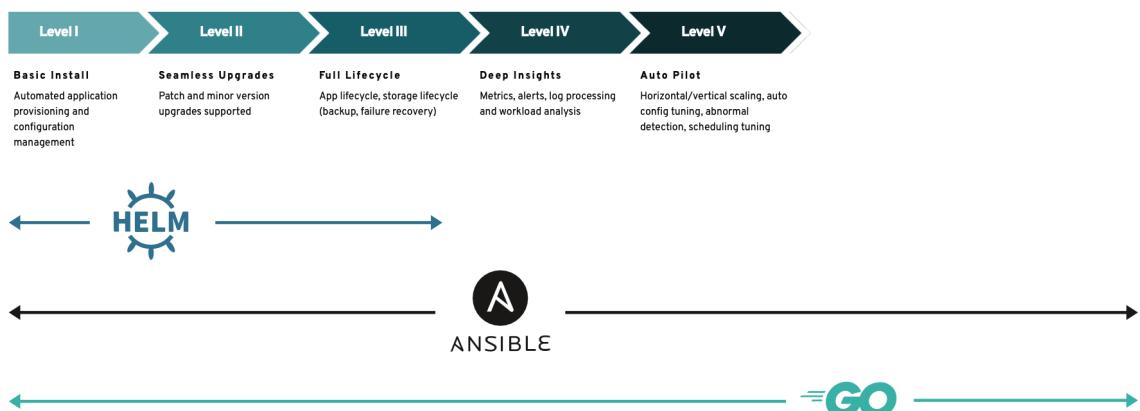


Figure 1.7 Operator maturity levels described by Operator Framework [41]

As stated in the Operator white paper, [35] the Operator should be able to cover the complete life cycle of the managed resource as defined in the previous chapter without the need for external installation or upgrade intervention. Specifically as follows:

- Install or take ownership of the controlled application.
- Upgrade the managed application, including the monitoring of the upgrade process. It should also be able to roll back in case of failure. He should record the status of the upgrade.
- Back up the managed application and log when the application was last backed up and the status of that backup.
- Restore the application from the backup.
- Provide monitoring of the managed application.
- Scale the application.
- Automatically adapt the configuration of the application.
- Uninstall or disconnect from the application.

These are all capabilities that an Operator should have at the highest level No. 5 - Autopilot. For lifecycle management described in previous chapter, the minimum level of Operator capabilities must be at least level No. 4 - Deep Insights with an option to scale.

The Kubernetes cluster is divided into individual namespaces that separate the objects and names in the cluster and can have constraints applied to them. This partitioning makes it easier to share the cluster between users or entire teams. The object name must be unique within a namespace, but not between namespaces. An operator usually operates in its own namespace so it has a Namespace Scope, but it can also operate in the whole cluster in which case it will be a Cluster Scope Operator. Namespace Scope Operators are more flexible and easier to upgrade due to their independence from the rest of the cluster. Operator rights are further restricted by the so-called Role-Based Access Control (RBAC), which grants the rights assigned to the Operator. [32]

The following options are advised by the Operator white paper [35] in case the Operator is to be used for controlling the resource:

- Consultation with the creator of the resource to be controlled about the possibilities of using the Operator.
- The search for public Operator registries that provide a platform for publishing Operators and the underlying documentation.

- The creation of own Operator.

## 2 THESIS OBJECTIVE

The objective of this thesis is to conduct an extensive evaluation of various Kubernetes Operators available for Postgres lifecycle management.

The ultimate aim is to provide clear and comprehensive recommendations on which Operators are best suited to meet different stakeholder needs and preferences. This thesis intends to serve as a valuable resource that can guide stakeholders in making informed decisions about choosing the right Operator for their specific operational context and requirements.

Furthermore, it aims to contribute to the broader knowledge base about Kubernetes Operators and their application in managing Postgres databases in a cloud-native environment.

### 3 RESOURCE QUESTIONS

Having defined the thesis objective and established a thorough understanding of PostgreSQL, Kubernetes, the PostgreSQL lifecycle, and Operators in previous chapters, we are now in a position to formulate research questions. These questions are designed to enable a deeper exploration into the complexities of managing Postgres in a Kubernetes environment via Operators.

1. What Operators exist for lifecycle management of Postgres in Kubernetes?
2. What metrics are suitable for comparing Operators for lifecycle management in Kubernetes?
3. What approach should be taken to determine the degree to which the metrics are met?
4. How do the Operators perform when evaluated according to the chosen metrics?

## 4 OPERATORS FOR LIFECYCLE MANAGEMENT IN KUBERNETES

This chapter aims to answer the first research question: 'What Operators exist for lifecycle management of Postgres in Kubernetes?" As recommended in chapter 1.5 the selection of the Operator should first be consulted with the manufacturer of the controlled source. Postgres offers the following Kubernetes Operators in its software catalog [42]: CloudNativePG, EDB Postgres for Kubernetes a Kubegres.

The next step involved a search of the Operators' registers. In particular the Operator Hub. [43] Operator Hub presents nine operators with varying levels of capabilities, including Crunchy Postgres for Kubernetes by Crunchy Data, EDB Postgres for Kubernetes by EnterpriseDB Corporation, Ext Postgres Operator by movetokube.com, Percona Operator for PostgreSQL by Percona, Postgres-Operator by Zalando SE, Postgresql Operator by Openlabs, PostgreSQL Operator by Dev4Ddevs.com and StackGres by OnGres.

A deeper internet search revealed Stolon Operator. [44]

Of the thirteen operators available, only five meet the minimum capability requirement of Deep Insight, namely: Crunchy Postgres for Kubernetes, EDB Postgres for Kubernetes, Percona Operator for PostgreSQL, CloudNativePG Operator, and StackGres Operator. As a result, only these five will be subjected to deeper research, testing, and evaluation.

## 4.1 Crunchy Postgres for Kubernetes

Crunchy Postgres for Kubernetes (PGO) is a Postgres Operator provided by Crunchy Data, which offers a declarative solution for the management of PostgreSQL clusters, with a focus on automation. Crunchy Data is a company that specializes in providing open-source software solutions for Postgres. The company also provides a range of support, consulting, and training services to help organizations implement and optimize their Postgres deployment. [45]

PGO's capabilities are the following:

- **Postgres Cluster Provisioning:** PGO is able to create [46], update [47] or delete Postgres cluster [48]
- **High Availability:** High availability is achieved by adding additional nodes. PGO uses a synchronous replication technique with Primary and Standby architecture. [49]
- **Postgres updates:** PGO is able to apply minor patches [50], and major upgrades since version 5.1. [51]
- **Backups:** PGO backup capabilities features: automatic backup schedules, backup to multiple locations, backup to cloud providers (AWS S3, Google Cloud Storage, Azure Blob), ad hoc backups, backup compression, and backup encryption. [52]
- **Disaster Recovery:** PGO is capable of Point In Time recovery, in place Point in Time Recovery, restore of an individual database. [53]
- **Cloning:** PGO is able to clone cluster. [53]
- **Monitoring:** Monitoring is provided by Prometheus, Grafana, and Alertmanager. [54]
- **Connection Pooling:** PgBouncer connection pooler from Postgres is part of PGO. [55]
- **Customization:** PGO provides a wide area of Postgres customization. [56]

PGO consists of the following key components [57]:

- High Availability: Patroni

- Backups: PgBackRest
- Connection Pooler: PgBouncer
- Monitoring: PgMonitor, Prometheus, Grafana, and Alertmanager

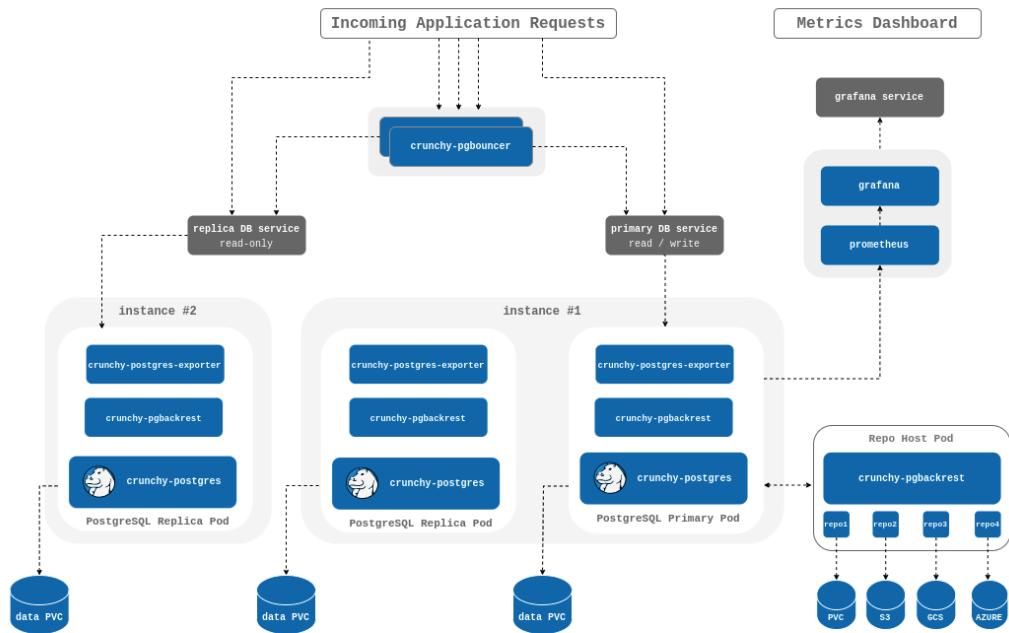


Figure 4.1 PGO's architecture [58]

The current stable version of PGO is 5.3.1 was released on 17th February 2023. [59]

PGO is distributed under the Apache License 2.0, an open-source license that allows for both commercial and non-commercial use. With regards to capability, PGO is considered to have the highest capability level, labeled as Autopilot. [60]

## 4.2 EDB Postgres for Kubernetes

The EDB Postgres for Kubernetes (EDBO) is a fully supported operator that has been designed, developed, and maintained by EnterpriseDB Corporation. It provides comprehensive coverage of the entire lifecycle of highly available PostgreSQL database clusters with a Primary/Standby architecture, utilizing native streaming replication. The operator is based on the open-source CloudNativePG operator and offers additional benefits. [61]

EDBO is distributed under the EDB Limited Usage License Agreement, a proprietary license that is specific to software provided by EnterpriseDB Corporation. A license key is always required for the operator to work longer than 30 days. [62] Due to the restrictive nature of the license EDBO will no longer be subject to testing and evaluation but its key component CloudNativePG will.

### 4.3 CloudNativePG

The CloudNativePG operator (CNPGO) is an operator that is available as an open-source solution and aims to manage PostgreSQL workloads across various Kubernetes clusters running in private, public, hybrid, or multi-cloud environments. The Operator aligns with DevOps principles and concepts like immutable infrastructure and declarative configuration. [63]

Initially developed by EDB, CNPGO was later made available to the public as an open-source software under the Apache License 2.0. In April 2022, the project was submitted to CNCF Sandbox for further development and community engagement. [63]

CNPGO's capabilities are the following:

- **Postgres Cluster Provisioning:** CNPGO is able to create, update or delete Postgres cluster. [64]
- **High Availability:** High availability is achieved by adding additional nodes. PGO uses a synchronous replication technique with Primary and Standby architecture. [65]
- **Direct database imports:** CNPGO provides direct database import from remote Postgres server by using pg\_dump and pg\_restore even on different Postgres versions. [66]
- **Postgres updates:** CNPGO is able to apply minor patches. [67] Major updates are possible by Direct database imports<sup>1)</sup>.
- **Backups:** CNPGO backup capabilities features: automatic backup schedules, backup to multiple locations, backup to cloud providers (AWS S3, Google Cloud Storage, Azure Blob), on-demand backups, and backup encryption [68][69]. Due to EDB's backup software Barman backup compression is available also. [68]

---

<sup>1)</sup>Due to its nature Direct database imports cannot be considered as major upgrade option.

- **Disaster Recovery:** CNPGO is capable of Point In Time recovery. [68]
- **Cloning:** CNPGO is able to create cluster replicas. [65]
- **Monitoring:** Monitoring can be provided by the additional installation of Prometheus, and Grafana, and Alertmanager. [70]
- **Connection Pooling:** Provided by native Postgres pooler PgBouncer. [71]
- **Customization:** CNPGO provides a wide area of Postgres customization such as max parallel workers tuning or WAL configuration [72]

TBD: footnotes numbering

CNPGO consists of the following key components [73] [70]:

- High Availability: Postgres instance manager
- Backups: Barman
- Connection Pooler: PgBouncer
- Monitoring: Prometheus, Grafana, and Alertmanager

The current major stable version of CNPGO is 1.20.0 was released on 27th April 2023. [74] CNPGO is distributed under the Apache License 2.0 open-source license. CNPGO is considered to have the highest capability level, labeled as Autopilot. [63]

#### 4.4 StackGres Operator

StackGres (SPGO) is a comprehensive distribution of Postgres for Kubernetes, delivered in a user-friendly deployment package. The distribution includes a set of Postgres components that have been carefully selected and optimized to work seamlessly with each other. [75]

SPGO is developed by OnGres that was established as a result of years of experience in working with and creating products based on Postgres and supporting clients with their Postgres infrastructures. Postgres databases are at the heart of the company's business, as the name suggests. [76]

SPGO's capabilities are the following [76]:

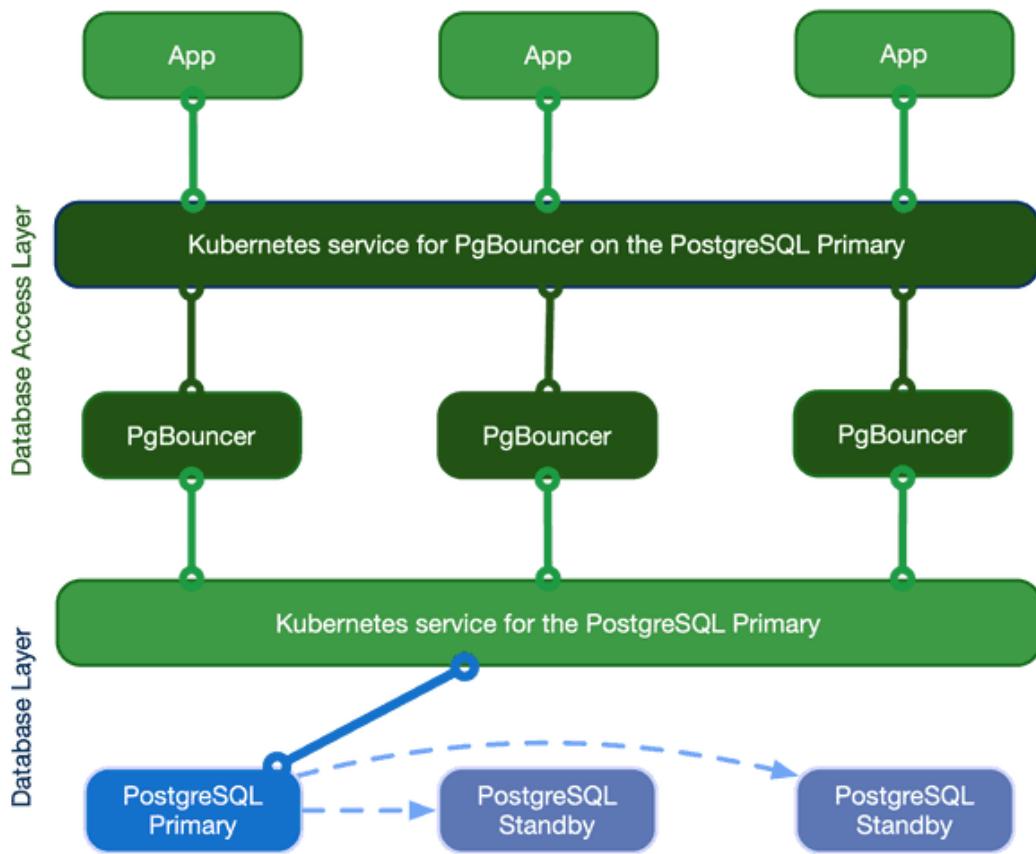


Figure 4.2 CNPGO's architecture [71]

- **Postgres Cluster Provisioning:** SPGO is able to create, update or delete Postgres cluster.
- **High Availability:** High availability is achieved by adding additional nodes with Primary and Standby architecture.
- **Postgres updates:** SPGO is able to apply minor patches. Major updates are possible by SGDbOps [77].
- **Backups:** SPGO backup capabilities features: automatic backup schedules, backup to multiple locations, backup to cloud providers (AWS S3, Google Cloud Storage, Azure Blob)
- **Disaster Recovery:** SPGO is capable of Point In Time recovery.
- **Cloning:** SPGO is able to create cluster replicas.
- **Monitoring:** Monitoring is provided by Prometheus, Grafana, and Alertmanager.

- **Connection Pooling:** Is provided by PgBouncer.
- **Customization:** SPGO provides a wide area of Postgres customization such as WAL configuration, archive mode, vacuum, etc. [78]
- **Management Console:** SPGO provides a fully featured management web console.

SPGO consists of the following key components [73]:

- High Availability: Patroni
- Backups: WAL-G
- Connection Pooler: PgBouncer
- Monitoring: Prometheus, Grafana, and Alertmanager.

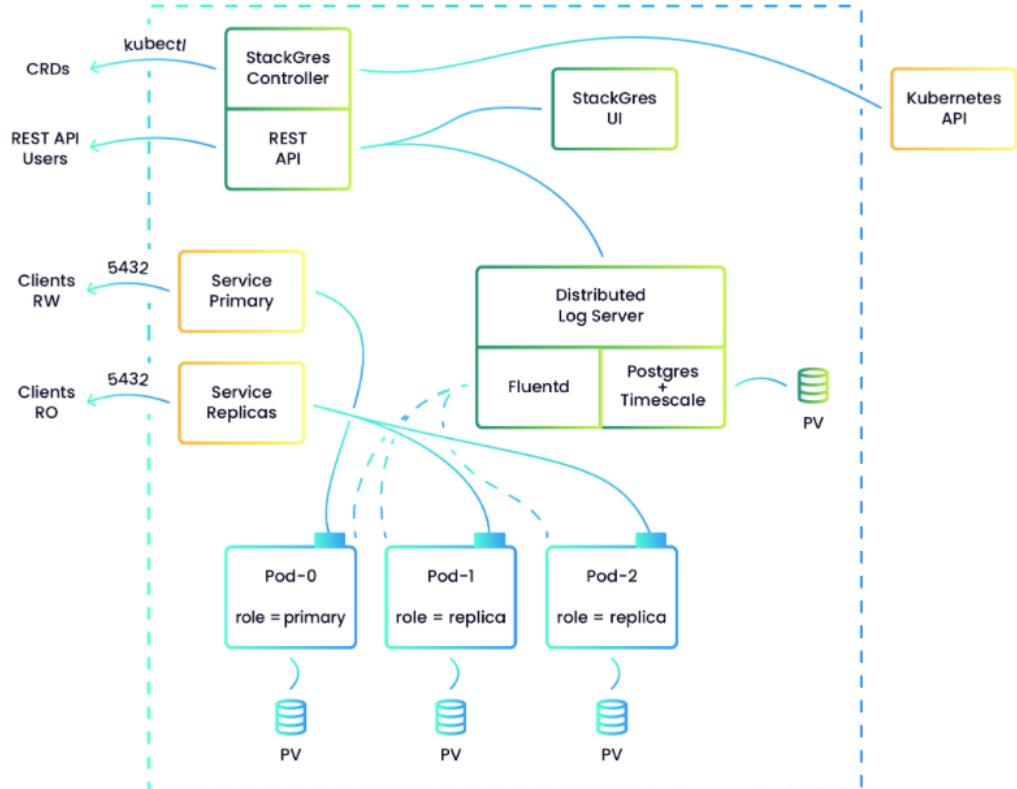


Figure 4.3 SPGO's architecture [79]

The current stable version of SPGO is 1.4.3<sup>2)</sup> was released on 24th January 2022. [80] SPGO is distributed under the AGPL3 open-source license. [81] With regards to capability, SPGO is considered to have the second highest capability level, labeled as Deep Insights. [82]

#### 4.5 Percona Operator for PostgreSQL

Percona is a company that provides services and solutions for open-source database technologies. It offers expertise, support, and software for MySQL, MongoDB, and PostgreSQL. The company's offerings help organizations manage their open-source databases and ensure optimal performance, security, and scalability. [83]

Percona Operator for PostgreSQL (PPO) is based on Crunchy Postgres for Kubernetes. Percona forked PGO v 4.7 and has added enhancements for monitoring, upgradability, and flexibility. [84]

Differences between PGO and PPO are the following:

- **Postgres updates:** PPO provides automatic Postgres updates for minor and major versions of Postgres. [85]
- **Backups:** PPO is not able to back up to Azure. [86] Although it uses Patroni, which has this ability.
- **Disaster Recovery:** PPO documentation does not mention the possibility of restoring a single database from a backup. [87]
- **Monitoring:** PPO is not using the usual monitoring stack consisting of Prometheus and Grafana but their own Percona Monitoring and Management. [88]

The current stable version of PPO is 1.4.0 was released on 31st March 2023<sup>3)</sup>. [89] PPO is distributed under the Apache License 2.0, an open-source license that allows for both commercial and non-commercial use. With regards to capability, PPO is considered to have the second highest capability level, labeled as Deep Insights. [90]

---

<sup>2)</sup>Version 1.5.0 has also been released, it is not yet production-ready yet. Therefore will not be tested or evaluated.

<sup>3)</sup>Version 2.0.0 has also been released, it is not yet production-ready yet. Therefore will not be tested or evaluated.

## 4.6 Summary

Table 4.1 Summary of selected Operators

Operator	Maturity level	Current production version	Release date
PGO	Autopilot	5.3.1	17th February 2023
CNPGO	Autopilot	1.20.0	27th April 2023
SPGO	Deep Insights	1.4.3	23th February 2022
PPO	Deep Insights	1.4.0	31st March 2023

## 4.7 Key differences

Table 4.2 Key differences between selected Operators

Feature	PGO	CNPGO	SPGO	PPO
In place Point in time recovery	Yes	No	No	No
Individual database restore	Yes	No	No	No
Operator user interface	No	No	Yes	No
Major version upgrade	Yes	No	Yes	Yes
Supported Postgres versions	v11 - v15	v11 - v15	v12 - v15	v12 - v14

## 5 METRICS

This chapter aims to answer the second research question: 'What metrics are suitable for comparing Operators for lifecycle management in Kubernetes?" According to Tom Gilb [91], the main issue in software attribute requirements is identified not in their functionality, but in their quality. Gilb differentiates these attribute requirements into two categories: Resources (people, time, money), which are always finite, and qualities or benefits, which are always fewer than desired. Knowledge about the functionality that an Operator must provide to achieve a certain level of capabilities is obtained from Chapter 1.5. The most significant functional properties of Operators have been detailed in Chapter 4. With the lifecycle of Postgres and the capabilities of operators now understood, what remains to be examined are their qualitative properties. The upcoming testing will be focused on the proposed qualitative metrics.

### 5.1 Performance

Performance is a qualitative parameter of a system, defined by the efficiency with which the system utilizes allocated resources. In the case of Postgres, performance can be expressed as the number of transactions executed per unit of time. A higher transaction rate is indicative of superior performance.

### 5.2 Reliability

Reliability is a qualitative parameter that determines the degree of system dependability. If a system cannot be relied upon, it cannot be utilized effectively. Therefore, reliability is a critical parameter of any system.

#### 5.2.1 Maturity

Maturity in the context of software refers to the degree to which a system is fully developed, perfected and reliable. A mature system is typically characterized by stability, reliability, robustness, and well-defined, predictable behavior based on its previous operation and iterations.

## 5.3 Usability

Usability is a key aspect of software design that focuses on user experience. It refers to the ability of a system to achieve certain goals for certain users in a particular context of use.

### 5.3.1 Learnability

How easy it is for users to learn how to use the system.

### 5.3.2 Operabilitiy

How easy is it for users to successfully use the system.

## 5.4 Maintenance

Activities that are performed after the software is deployed to ensure its correct functionality and performance. Maintenance may include bug fixes, adding new features, performance optimization, updates for compatibility with new systems, etc. Ignoring software maintenance can lead to increased repair costs and reduced system performance over time. Additionally, it can cause system instability, increased vulnerability to security threats, and eventually, potential system failure.

### 5.4.1 Renewal

Renewal is considered a crucial aspect of software maintenance, playing a significant role in maintaining the relevance of a software system over time. Essentially, this process ensures that the software is consistently updated to align with current standards and technologies.

## 5.5 Security

Security refers to the measures, practices, and technologies employed to protect the system and its data from threats and attacks.

### 5.5.1 Vulnerabilities

Vulnerability refers to a weakness in a system that can be exploited by a threat actor, such as a hacker, to perform unauthorized actions within a computer system. This can involve gaining access to the system's features and data, or disrupting the system's normal functioning.

## 6 TESTING METHODOLOGY

This chapter aims to answer the third research question: 'What approach should be taken to determine the degree to which the metrics are met?" and presents a high-level overview of the testing methodology. The goal of the methodology is to deliver rules and guidance for test process that produces test reports forming the basis of this evaluation.

### 6.1 Notice

It is important to notice at the beginning of this chapter that testing as described in [92] has following seven testing principles:

1. Testing shows the presence of defects, not their absence
2. Exhausting testing is impossible
3. Early testing saves time and money
4. Defects clusters together
5. Beware of pesticide paradox
6. Testing is context dependent
7. Absence of errors is fallacy

Therefore, the test process derived from this methodology as every test process will not exhaustively test the Operators and will be depended on thesis context, author bias, and author skills. Because The objective of this thesis is to conduct an extensive evaluation of various Kubernetes Operators available for Postgres lifecycle management the main scope of this methodology is to deliver test process that will produce test reports that will form the base for this evaluation.

### 6.2 Criteria

The following criteria described in Chapter 5 will be subjected to testing. These criteria should provide a solid basis for the decision-making process. To keep track of these criteria, each one has been assigned an ID. The list of identified criteria is as follows:

- CP: Performance
  - CP1: Maturity
- CR: Reliability
- CU: Usability
  - CU1: Learnability
  - CU2: Operability
- CM: Maintenance
  - CM1: Renewal
- CS: Security

### 6.3 Test management process

According to the IEEE Standard for Software Test Documentation [93], test management processes have three main test processes: test strategy and planning, test monitoring and control, and test completion. As depicted in Figure 6.1 testing has more than one management test process. The main process is the Organizational process which is further divided into Test management processes that are then devided into Dynamic test processes.

Thesis test process will consist of one management process that will create two managed subprocesses, one for static testing and one for dynamic testing. This test management process will monitor and control subprocesses. Subprocesses will deliver all their deliverables to this main process.

The main management consist of following tasks:

- High-level test strategy
- High-level test planning

Subprocess consist of following tasks:

- Test strategy
- Test test planning

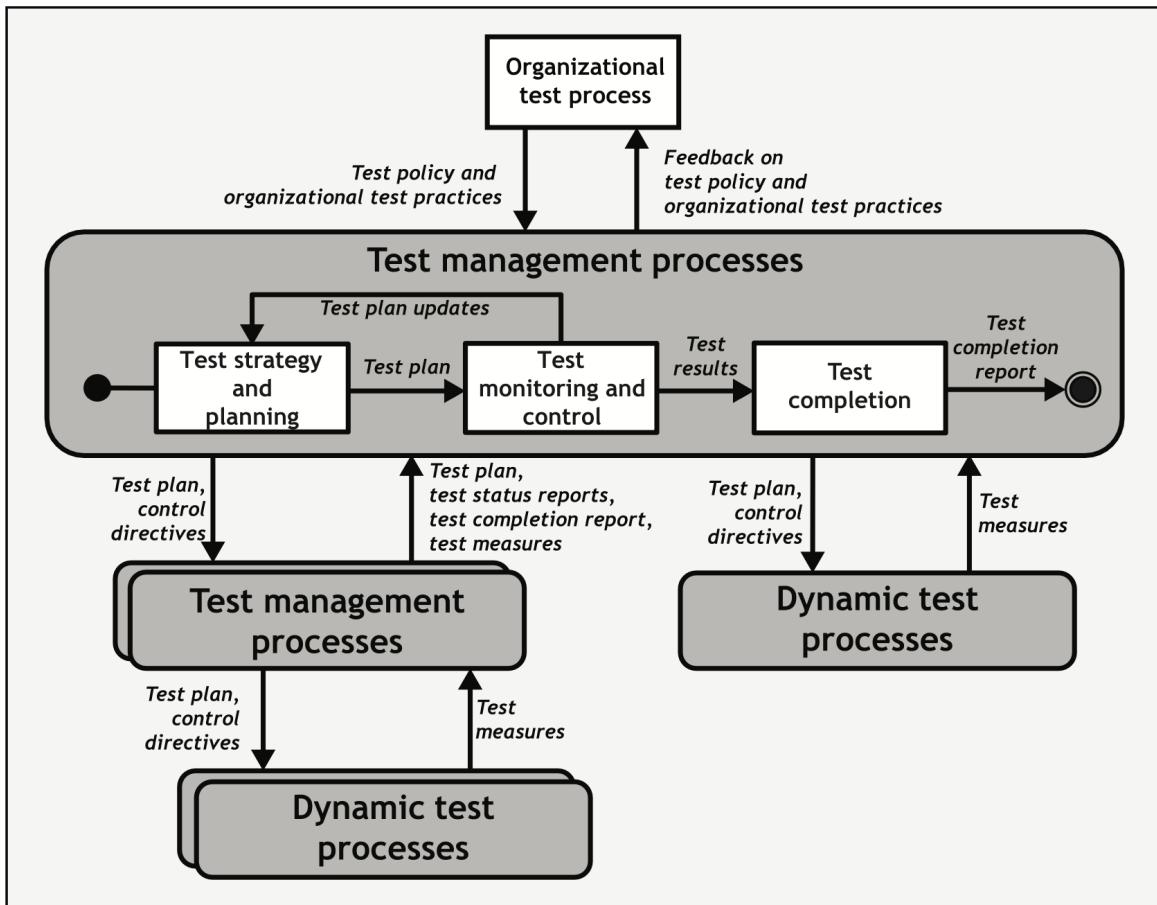


Figure 6.1 Test management process relationships [93]

#### 6.4 Test strategy and planning

The output of the test strategy and planning will be the test plan, as the basis for its creation will be the requirements created earlier. Details about activities are described by ISO/IEC/IEEE 29119-3.

As depicted on 6.1 test plan is not static but it changes according to monitoring.

#### 6.5 Test plan

In order to create a test plan, IEEE proposes the following procedure shown in the figure 6.2 with the idea that some activities can be repeated.

The result of a properly designed test plan should be:

- Scope of testing

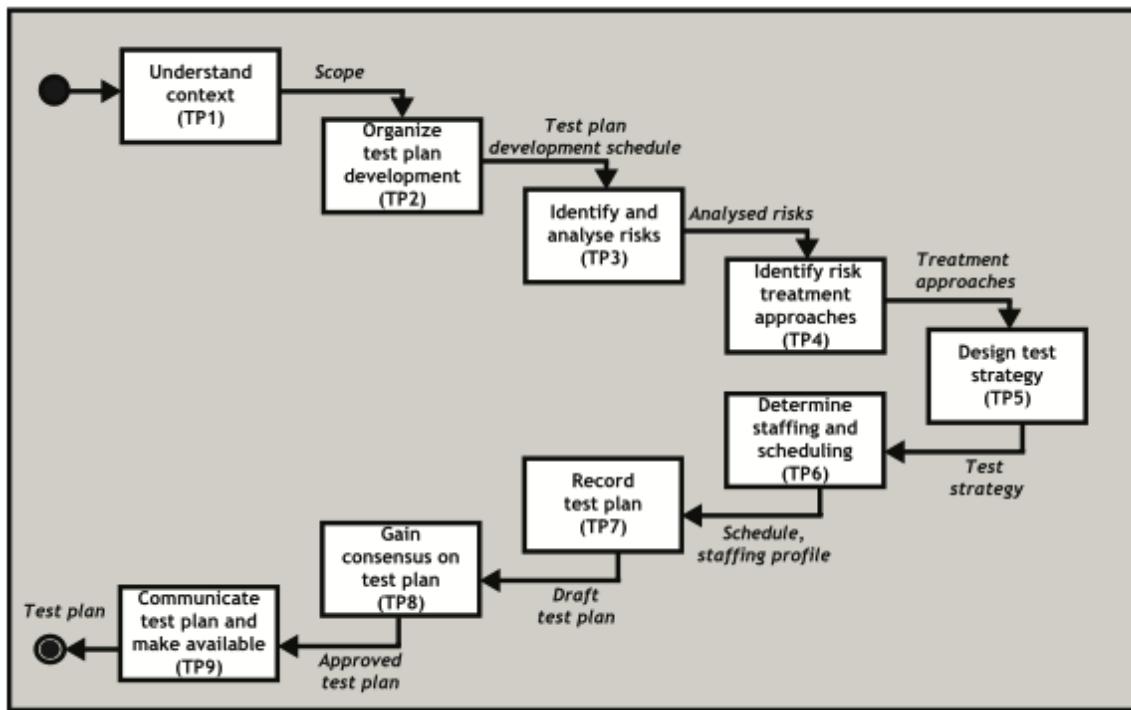


Figure 6.2 Test plan creation activities [93]

- List of identified risks
- Testing strategy
- Test environment
- Test tools
- Test data
- Staffing
- Scheduling
- Required training
- Estimates of time and resources
- Compliance with all stakeholders

## 6.6 Test monitoring and control process

The role of the test monitoring and control process is to observe the test process and detect deviations from the plan. This process controls the test process throughout its duration. The findings are then used to modify the test plan.

To avoid unnecessary bureaucracy, where the manager and tester are the same person, and consequently the testing progress would be reported to the person who is also filing it, there will be no status reports during this process.

### 6.7 Test completion process

The test completion process as depicted in the figure 6.3 will be used in testing after each test the test competition report will be created and delivered to a higher level.

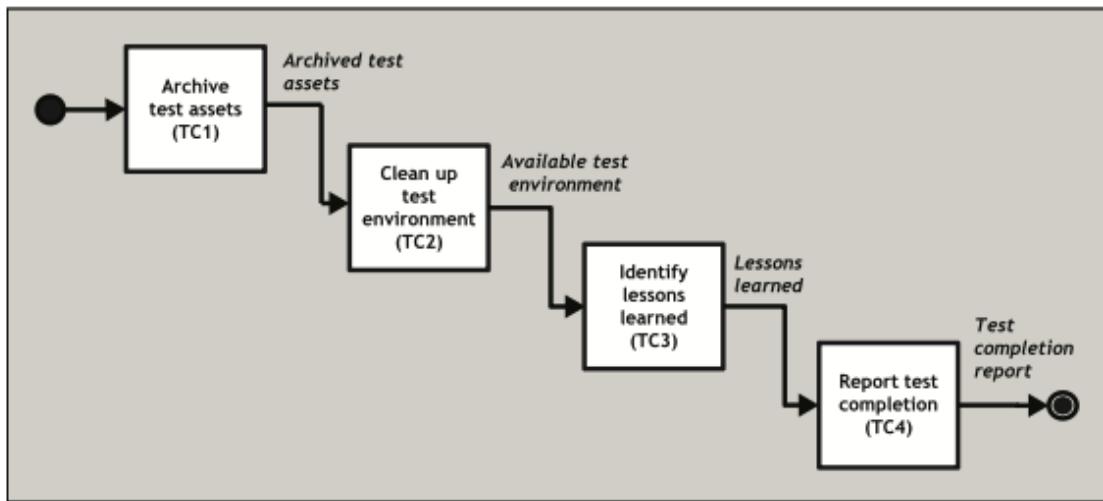


Figure 6.3 Test completion process [93]

### 6.8 Dynamic and static Test processes

According to ISTQB [92] there are two types of tests. Static and dynamic. The main difference is that the static technique does not execute the tested software, but the dynamic does. The testing process will utilize both techniques using the dynamic testing process depicted in figure 6.4.

### 6.9 Test design and implementation processes

Test design and implementation process must follow the process depicted in the figure 6.5. Test design techniques should be used to derive test cases. Test cases must be traceable to requirements and must meet the ISO/IEC/IEEE 29119-3 requirements. This process can be reentered multiple times and must meet the completion criteria specified in the test plan.

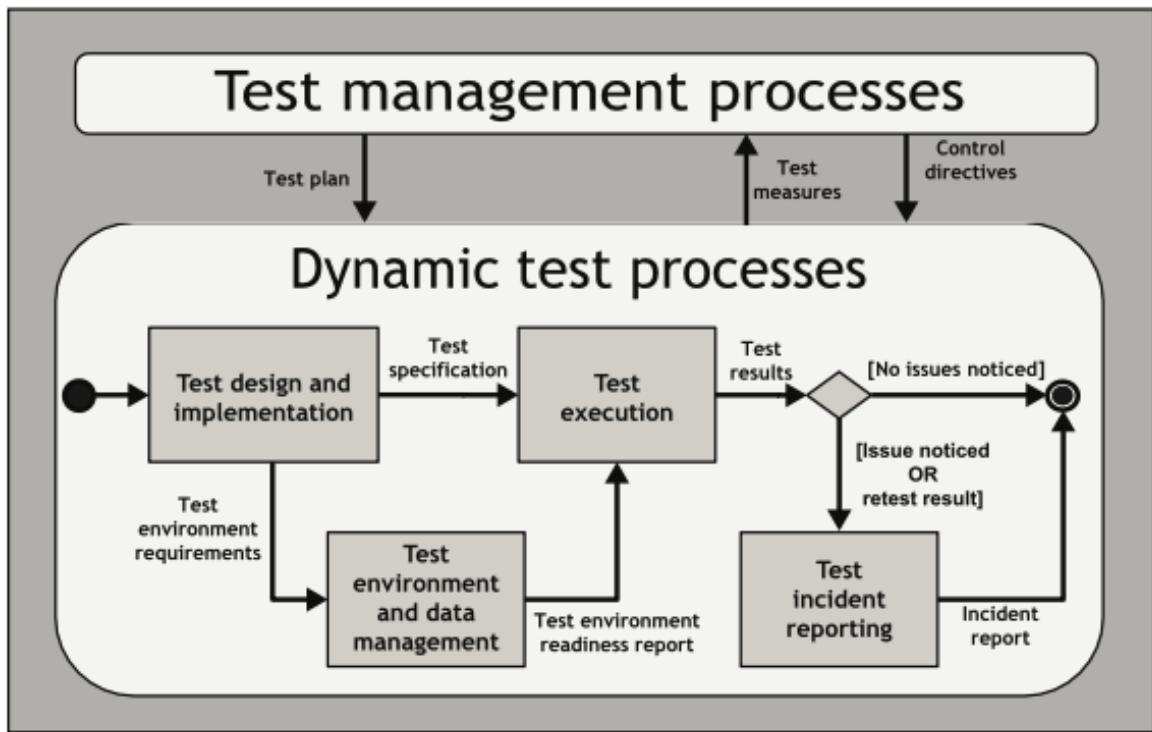


Figure 6.4 Dynamic test processes [93]

## 6.10 Test environment and data management processes

Based on the test plan all the environments must be established and well maintained.

## 6.11 Test execution process

Test execution process depicted in 6.6 must be followed. After the test execution, the execution log must be delivered. Details about activities are described by ISO/IEC/IEEE 29119-3.

## 6.12 Test incident report process

The process for reporting test incidents, as depicted in Figure 6.6, must be followed. It is important to note that the purpose of testing is not to simply find incidents, but rather to test the capabilities of the system. As such, the term "finding" will be used in cases where it is more appropriate.

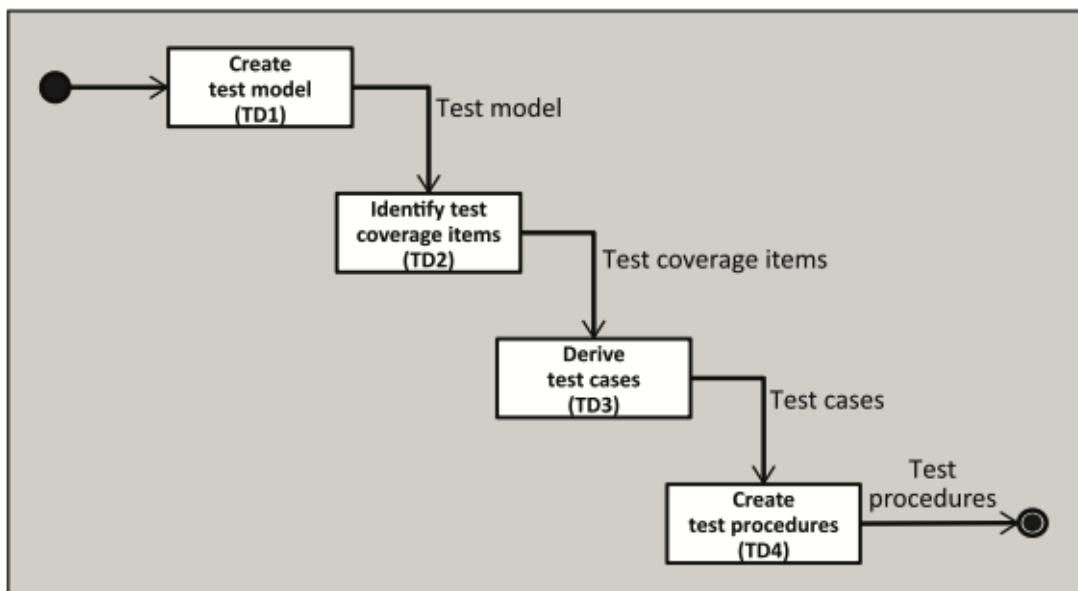


Figure 6.5 Test design and implementation [93]

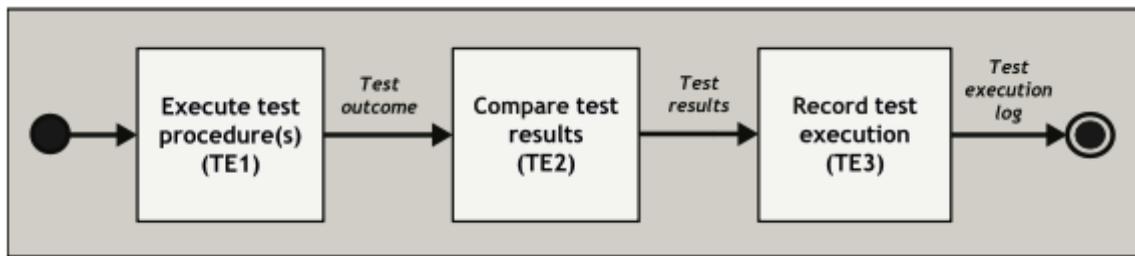


Figure 6.6 Test execution process [93]

### 6.13 Level of detail

Please note that this chapter provides only a high-level overview of the testing methodology. More detailed information can be found in ISO/IEC/IEEE 29119-2<sup>5)</sup>. If there are any doubts regarding the testing process, this standard should be used as a guide to ensure that all necessary aspects of testing are properly addressed.

<sup>5)</sup><https://standards.ieee.org/ieee/29119-2/7498/>

## II. APPLICATION OF THEORY

## 7 TEST PROCESS

As stated in the methodology, the main test process with a general test plan was created. The general test plan can be seen in Appendix A I. This process was divided into two subprocesses: one for static testing and one for dynamic testing.

According to the priorities stated in the general test plan, the first test process to be conducted was the static test process.

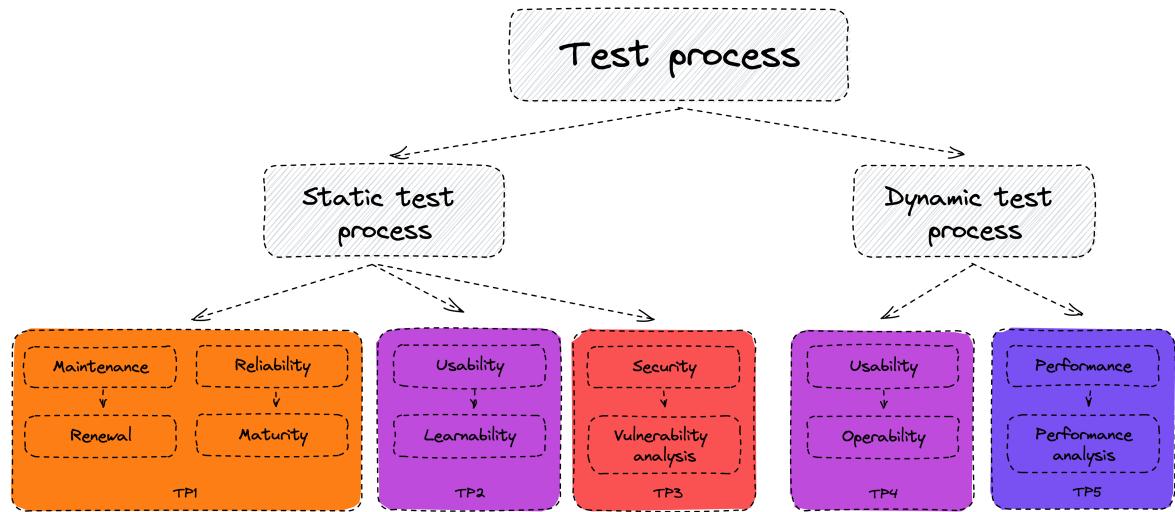


Figure 7.1 Test process

### 7.1 Static test process

The static test process was divided into three separate subprocesses, each with its own testing procedures.

#### 7.1.1 Reliability and maintenance

PLAN

MODEL

INCIDENT REPORT

Test Plan No. 1, which includes reliability and maintenance, can be found along with the Test Completion Report in Appendix A II. The subsequent sections will present the results of the test.

## 8 EVALUATION

### 8.1 Reliability and maintenance

In order to determine the maturity of the system, data was statically collected from the repositories of each operator. This included the popularity of the operators, the number of issues they had, and the number of issues that were resolved. The maturity was then determined based on the popularity of the operators and the ratio of resolved issues.

#### 8.1.1 Popularity

Popularity can be considered an indicator of maturity because broad recognition and use of a product often suggest that the product is reliable, efficient, and capable of meeting user requirements. In the context of software, popular software tends to be more thoroughly tested, leading to the identification and correction of bugs, and therefore greater stability and maturity.

The operator with the highest number of stars, and therefore the most popular, is the PGO operator. To compare operators, the most popular one was assigned a popularity score of 100%, and the others were assigned a score relative to their share of the maximum.

Table 8.1 Popularity of Operators

	PGO	CNPGO	SPGO	PPO
Popularity (stars)	3258	1198	84	149
Popularity ratio	100%	37%	3%	5%

#### 8.1.2 Fixed issues

The number of issues resolved is often considered a sign of a software project's maturity, as it indicates that the developers are actively maintaining the software, responding to user feedback, and fixing problems as they arise. A high number of resolved issues indicates that the project has faced and overcome challenges, which may indicate that the software has been "battle tested" and improved over time.

The operator with the highest proportion of resolved issues is PGO, which has suc-

cessfully addressed 93% of its reported issues. CNPGO and PPO exhibit a reasonable performance level in this area. However, SPGO, despite being less popular and more recent than PGO, has more reported issues and a large number of unresolved issues (445 in total). This could suggest that SPGO is still underdeveloped.

Table 8.2 Operators issues

	PGO	CNPGO	SPGO	PPO
Total issues	1884	764	1959	317
Issues fixed	1755	691	1514	282
Fixed issues ratio	93%	90%	77%	89%

The overall maturity of the operators was calculated as an average of popularity and the ratio of fixed issues. The results can be seen in Table 8.3. As maturity is the only subtest under reliability, it is considered as a measure of reliability.

Table 8.3 Operators maturity

	PGO	CNPGO	SPGO	PPO
Overall maturity / reliability	97%	64%	40%	47%

### 8.1.3 Renewal

Software renewal, a key aspect of software maintenance, is often essential to ensure that the software continues to be effective and efficient in light of changing user needs, technological progress, and evolving industry standards. Commits to the repository represent incremental changes in the project. Therefore, the number of commits per unit of time indicates the rate at which the software is being renewed.

The overall renewal rate of the operators depicted in Table 8.4 was calculated as the number of commits since the day of repository creation. The highest ratio of commits per day was achieved by SPGO with an average of 5.03 commits per day, earning it a score of 100%, while the other operators were assigned scores relative to their share of this maximum.

Interestingly, this contrasts with the Operator issues where SPGO scored the lowest and was therefore considered underdeveloped. A possible explanation for this could be that SPGO uses issues for its own project management, rather than solely for issue tracking. As renewal is the only subtest under maintenance, it is considered as a measure of maintenance.

Table 8.4 Operators renewal

	PGO	CNPGO	SPGO	PPO
Repo creation	27th Feb 2017	18th Feb 2020	29th May 2019	27th Feb 2017
Test date	1st May 2023	1st May 2023	1st May 2023	1st May 2023
Sum of commits	5582	3362	7208	4689
Commits/day	2.48	2.88	5.03	2.08
Renewal / maintenance	49%	57%	100%	41%

## 8.2 Learnability

Learnability testing, which is one part of usability, aims to assess the ease with which new users can understand and use a product. This particular testing was conducted with two primary objectives. The first objective was to identify the presence of examples in the documentation, as learning facilitated by examples is generally more effective than without. The second objective was to gauge the level of learning required to operate the system effectively. This was accomplished through a detailed analysis of the provided examples.

Test Plan No. 2, which includes learnability, can be found along with the Test Completion Report, checklist and gathered examples in Appendix A III. The subsequent sections will present the results of the test.

### 8.2.1 Required training

The training required depicted in Table 8.5 was calculated as the additional training needed to work with each operator, over and above knowledge of Kubectl (the Kubernetes command-line tool). Each additional tool required to work successfully with the operator resulted in a 5% score decrease. In this regard, CNPGO was at a disadvantage because, according to its documentation, the Cnpg plugin is necessary to uninstall it. PGO also faced a similar issue as it utilizes the simple Kustomize tool to customize its manifest with a namespace.

Additional training needs were identified during the Ease of Use testing, where both CNPGO and PPO required the use of Helm for the deployment of monitoring. During these tests, the CNPGO cluster was easily uninstalled using Kubectl, indicating that the CNPGO plugin isn't necessary for utilizing CNPGO.

Overall, the learnability scores are quite high, suggesting that all of the operators are relatively easy to learn. If monitoring is not a requirement, knowledge of Kubectl commands is sufficient to work with the CNPGO, SPGO, and PPO Operators. However, to install monitoring, Helm is necessary for these operators. For PGO, learning Kustomize for cluster operations is sufficient, and no additional tool is needed for monitoring.

Table 8.5 Training needed

	PGO	CNPGO	SPGO	PPO
1st training	Kubectl	Kubectl	Kubectl	Kubectl
2nd training	Kustomize	Helm	Helm	Helm
Required Training	95%	95%	95%	95%

### 8.2.2 Documentation examples

As depicted in Table 8.6, documentation examples were prevalent across all operators. SPGO, however, is at a disadvantage here due to its own UI, which is capable of managing the entire cluster and can easily handle all cluster operations. Surprisingly, it does not provide examples for major and minor updates, which can be easily configured via the UI. Considering that there are ten examples, each example was assigned a value of 10% towards the total score.

Table 8.6 Documentation examples

	PGO	CNPGO	SPGO	PPO
Cluster creation	Yes	Yes	Yes	Yes
Minor upgrade	Yes	Yes	No	Yes
Major upgrade	Yes	No	No	Yes
Backup	Yes	Yes	Yes	Yes
Restore	Yes	Yes	Yes	Yes
Monitoring	Yes	Yes	Yes	Yes
Vertical scaling	Yes	Yes	Yes	No
Horizontal scaling	Yes	Yes	Yes	Yes
Configuration Update	Yes	Yes	Yes	Yes
Uninstall	Yes	Yes	Yes	No
Documentation examples	100%	90%	80%	80%

The overall learnability rating of the Operators, as depicted in Table 8.7, was calculated as the average of the scores from the required training and the documentation examples. Given the high level of overall learnability among the operators, it can be derived that these operators should be relatively easy to learn.

Table 8.7 Learnability of Operators

	PGO	CNPGO	SPGO	PPO
Learnability	98%	93%	88%	88%

### 8.3 Security

In order to perform the vulnerability analysis, the Docker images of each operator were scanned using the Trivy security scanner. To replicate these tests, please refer to the repository directory `tests/vulnerability_analysis`, which contains subdirectories for each operator with the corresponding commands used together with complete results.

Each operator is deployed as a Docker image, which can be scanned for vulnerabilities. With this test, the main issue for the operators was the quality of the underlying operating system used in the image. CNPG is utilizing Debian 11.6, where Trivy was unable to detect any vulnerabilities. The rest of the operators are using the Red Hat 8.7 underlying Docker image, which resulted in almost identical vulnerability scores. Unfortunately, the implementation of Red Hat 8.7 in both PGO and SPGO has a high vulnerability with `openssl-libs` (CVE-2023-0286). More details about this vulnerability can be found here: <https://avd.aquasec.com/nvd/2023/cve-2023-0286/>.

The results depicted in Table 8.8 were quantified in the following manner: the presence of a critical vulnerability was scored as 0%, a high severity vulnerability as 20%, medium as 40%, low as 60%, unknown as 80%, and no vulnerabilities as 100%. CNPGO was the only operator with zero detected vulnerabilities, thus achieving a full score and can be considered secure. PPO, having only medium and lower severity vulnerabilities, can also be considered reasonably secure. However, both PGO and SPGO, which had high severity vulnerabilities, can be seen as less secure compared to CNPGO and PPO.

Test Plan No. 3, which includes security, can be found along with the Test Completion Report in Appendix A IV.

Table 8.8 Vulnerability analysis

	PGO	CNPGO	SPGO	PPO
Critical	0	0	0	0
High	1	0	1	0
Medium	40	0	41	35
Low	36	0	36	36
Unknown	0	0	0	0
Security	20%	100%	20%	40%

## 8.4 Operability

To evaluate the ease of working with each Operator, use cases derived from the Postgres lifecycle (as described in chapter 1.4) were created. A separate test case was developed for each use case, and the Operators were evaluated accordingly. Testing was conducted on a local Kind Kubernetes cluster set up on a first generation M1 Macbook Air with 8GB of RAM and a 500GB disk size.

For specific test cases, such as cluster monitoring for SPGO and PPO, and cluster restore for CNPGO, SPGO, and PPO, the Operators could not proceed with the local Kind cluster. Therefore, Google Kubernetes Engine (GKE) cluster was utilized. The configurations for both GKE and Kind clusters can be located in the repository folder at `tests/environments`. Use cases, their scenarios, and the test plan can be found in Appendix A V.

Operability depicted in Table 8.9 was evaluated based on two aspects. The first aspect, 'ease of use,' evaluated the number of command executions needed to achieve each goal. The second aspect focused on the quality of the Operator's monitoring capabilities.

Table 8.9 Operability

	PGO	CNPGO	SPGO	PPO
Ease of use	32%	25%	100%	17%
Monitoring	83%	75%	50%	75%
Operability	58%	50%	75%	46%

#### 8.4.1 Ease of use

The number of commands executed to achieve the goal was counted for each test case. If an Operator did not provide the necessary functionality, the number of steps required was designated as 10. This is because realizing this functionality would require significant effort, or it might not be achievable at all. Test procedures can be found in the repository folder at `tests/operability/ease_of_use`.

The operator with the fewest steps was assigned a score of 100%. The scores for the other operators were calculated relative to this maximum. The results are depicted in Table 8.10.

**SPGO** The reason SPGO scored the highest is due to its user-friendly interface. Most tasks can be accomplished directly within this interface, eliminating the need for using the terminal. Even complex tasks, such as performing a major version upgrade, can be easily carried out via this user interface. An example of this user interface is shown in Figure 8.1. Additional images can be found in the repository folder at `doc/graphics/monitoring/SPGO`.

**Cluster major version upgrade** The upgrade to a new major version appears to be the most challenging task for each Operator. While SPGO handled the cluster upgrade seamlessly, PGO required four steps to proceed with the major version upgrade. On the other hand, CNPGO claimed to be capable of an "Offline import of existing PostgreSQL databases, including major upgrades of PostgreSQL". This process involves dumping the database and restoring it to a new cluster, which can be done with any cluster and is not considered a major upgrade. PPO declared in their documentation that they are capable of automatic updates even between versions. However, this Jira issue (<https://jira.percona.com/projects/K8SPG/issues/K8SPG-254?filter=allopenissues>) suggests otherwise.

#### 8.4.2 Monitoring

To evaluate the monitoring capabilities of each operator, a set of necessary monitoring parameters was created. During the monitoring deployment test case, screenshots of each monitoring system were taken. These screenshots can be found in the repository folder at `doc/graphics/monitoring`. Each operator's score was determined based on

the number of parameters covered by its monitoring system.

All of the operators, except for PPO, use the traditional Grafana Prometheus monitoring stack, while PPO uses the Percona Monitoring and Management solution. This Percona monitoring system is quite extensive, but its coverage of parameters is comparable to that of the less extensive CNPGO monitoring system.

It can be derived that all operators, with the exception of SPGO, offer high-quality monitoring. While SPGO is easy to operate, it is difficult to monitor effectively.

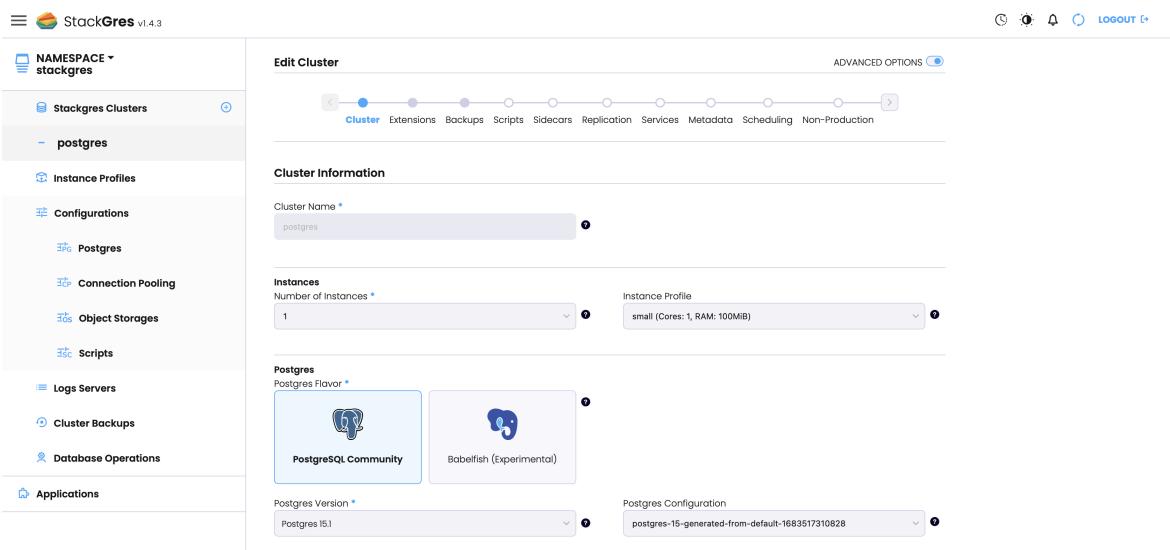


Figure 8.1 SPGO’s user interface

## 8.5 Performance

In order to perform performance testing, it was necessary to create a more robust cluster than the Kind cluster on MacBook Air. This was achieved by creating a Google Kubernetes Engine cluster with three e2-standard-2 nodes. Each node was equipped with 2 virtual CPUs and 8 GB of RAM. A standalone Postgres node with pgbench was also deployed to the cluster. A simplified version of this cluster is depicted in Figure 8.2. The Terraform plans for this deployment can be found in the `tests/environments/gke` repository directory.

For each Operator test, the Kubernetes cluster was recreated to ensure a clean starting point. A Postgres cluster with three nodes (one primary and two replicas) was deployed, along with three connection pooler instances.

Cluster configurations were also adjusted according to the recommendations from the

Table 8.10 Ease of use

	PGO	CNPGO	SPGO	PPO
Operator installation	2	1	2	3
Cluster installation	1	2	0	1
Cluster monitoring	2	4	3	5
Cluster vertical scaling	1	1	0	1
Cluster horizontal scaling	1	1	0	1
Cluster connection pooling	1	1	0	0
Cluster extension install	1	1	0	10
Cluster number of connections increase	1	1	0	2
Cluster max_wall_size increase	1	1	0	3
Cluster scheduled backup	1	1	0	1
Cluster ad-hoc backup	2	1	0	1
Cluster restore	2	1	1	1
Cluster minor version upgrade	1	1	0	1
Cluster major version upgrade	4	10	0	10
Operator uninstall	1	1	1	1
Cluster uninstall	1	1	0	1
Overall	22	28	7	41
Ease of use	32%	25%	100%	17%

pgTune website. The adjusted settings were as follows:

- max\_connections: 200
- shared\_buffers: 1536MB
- effective\_cache\_size: 4608MB
- maintenance\_work\_mem: 384MB
- checkpoint\_completion\_target: 0.9
- wal\_buffers: 16MB
- default\_statistics\_target: 100

Table 8.11 Monitoring

	PGO	CNPGO	SPGO	PPO
Health	Yes	Yes	Yes	Yes
Query performance	Yes	Yes	No	Yes
Number of connections	Yes	Yes	Yes	Yes
Locks	Yes	Yes	Yes	Yes
Index hit	No	No	No	No
Cache hit	Yes	No	Yes	Yes
Disk space usage	Yes	Yes	No	Yes
CPU and memory usage	Yes	Yes	Yes	Yes
WAL generation rate	Yes	Yes	No	Yes
Replication lag	Yes	Yes	No	No
Errors and logs	No	No	No	Yes
Backup and recovery	Yes	Yes	Yes	No
Monitoring	83%	75%	50%	75%

- random\_page\_cost: 4
- effective\_ioConcurrency: 2
- work\_mem: 3932kB
- min\_wal\_size: 1GB
- max\_wal\_size: 4GB

This configuration was implemented to standardize each cluster configuration.

After the deployment of the Postgres cluster, each Operator was tested using the pgBench tool, a PostgreSQL benchmarking utility. This tool was configured to execute 10,000 transactions across 25 concurrent clients and utilizing 10 threads. This benchmark was directed towards the Postgres cluster's pooler service. This procedure was replicated twice more for thoroughness.

The results depicted in Table 8.12 only display the transactions per second, as these offer a sufficient indication of the operators' performance. For a comprehensive view of

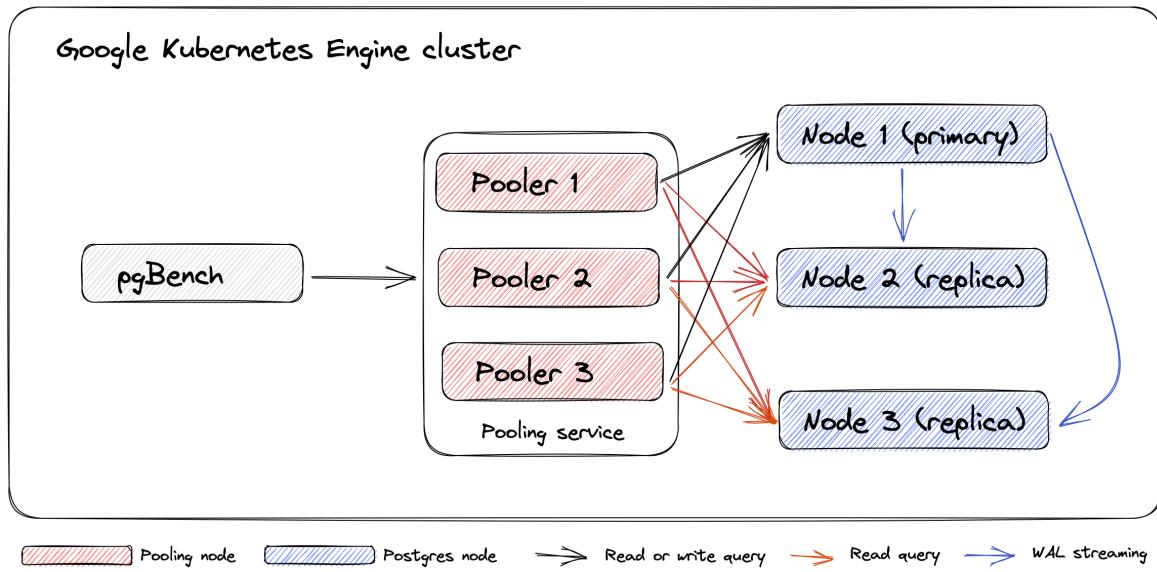


Figure 8.2 Kubernetes performance setup

the results from this benchmark, along with the Test Completion Report, please refer to Appendix A VI.

The commands executed throughout this procedure, along with the complete configuration of the operators, can be located in the `tests/performance` directory in the repository.

### 8.5.1 Issues with CNPGO

CNPGO was the only one unable to execute 250,000 transactions in each run due to an error (client 6 script 0 aborted in command 4 query 0: FATAL: query wait timeout, SSL connection has been closed unexpectedly). This error usually occurs when a query takes too long to execute, leading to a timeout. The SSL connection is then closed unexpectedly, causing the transaction to fail. This might suggest that CNPGO is struggling with performance or network stability in this particular scenario.

### 8.5.2 Issues with SPGO

The possible reason for SPGO's low transactions per second score is that a cluster profile is needed to deploy an SPGO cluster. When this profile was correctly set, Google Kubernetes Engine was unable to deploy the cluster. By gradually reducing these values, the available resources were eventually found, but these settings were probably too low for optimal performance (500m CPU and 2Gi RAM). Despite the

cluster showing that it had more memory and CPU allocable, as may be seen in Figure 8.3, the reduced resource allocation might have constrained SPGO's performance.

### 8.5.3 Issues with PPO

As described in Chapter 8.4, changes to PPO's configuration do not affect the cluster, therefore, the cluster was not modified during this test. This means that the performance results for PPO are based on its default configuration settings.

Table 8.12 Performance analysis

	PGO	CNPGO	SPGO	PPO
First run	544.91 tps	403.70 tps	284.39 tps	401.46 tps
Second run	543.29 tps	402.54 tps	279.89 tps	392.04 tps
Third run	538.51 tps	392.63 tps	309.16 tps	387.79 tps
Mean	542.24 tps	399.62 tps	291.15 tps	393.77 tps
Performance	100%	74%	54%	73%

The most performant Operator PGO received a score of 100% in this test, while the other operators were assigned scores proportionally based on their performance.

Nodes							
Name	Status	CPU requested	CPU allocatable	Memory requested	Memory allocatable	Storage requested	Storage allocatable
gke-operators-e2-standard-2-8a273e24-1vhq	Ready	289 mCPU	1.93 CPU	560.99 MB	6.33 GB	0 B	
gke-operators-e2-standard-2-8a273e24-d2mn	Ready	481 mCPU	1.93 CPU	503.32 MB	6.33 GB	0 B	
gke-operators-e2-standard-2-8a273e24-j33v	Ready	531 mCPU	1.93 CPU	576.23 MB	6.33 GB	0 B	

Figure 8.3 GKE nodes details

## 8.6 Usability

The overall usability was calculated as the average of learnability, as shown in Table 8.5, and operability, as presented in Table 8.9. The results are shown in Table 8.13.

Table 8.13 Usability

	PGO	CNPGO	SPGO	PPO
Learnability	98%	93%	88%	88%
Operability	58%	50%	75%	46%
Usability	78%	72%	82%	67%

## 9 EVALUATION

Table 9.1 Overall quality of Operators

	PGO	CNPGO	SPGO	PPO
Performance	100%	74%	54%	73%
Reliability	97%	64%	40%	47%
Usability	78%	72%	82%	67%
Maintenance	49%	57%	100%	41%
Security	20%	100%	20%	40%
Quality	68.8%	73.4%	59.2%	53.6%

## ZÁVĚR

Text závěru.

## REFERENCES

- [1] Group, T. P. G. D.: PostgreSQL 15.1 Documentation - What Is PostgreSQL? [visited 2023-02-08].  
URL <https://www.postgresql.org/docs/15/intro-whatis.html>
- [2] Riggs, S.; Ciolli, G.: *PostgreSQL 14 Administration Cookbook*, chapter Introducing PostgreSQL 14. Birmingham: Packt publishing, 1st edition, 2022, ISBN 9781803248974, pp. 2–8.
- [3] Group, T. P. G. D.: PostgreSQL 15.1 Documentation - History. [visited 2023-02-08].  
URL <https://www.postgresql.org/docs/15/history.html>
- [4] Inc., S. E.: Stack Overflow 2022 Developer Survey. [visited 2023-02-07].  
URL <https://survey.stackoverflow.co/2022/>
- [5] Juba, S.; Vannahme, A.; Volkov, A.: *Learning PostgreSQL*, chapter Relational databases. Packt Publishing Ltd, 1st edition, 2015, ISBN 9781783989188, pp. 1–4.
- [6] Nasser, H.: PostgreSQL Process Architecture. Creating a listener on the backend.... 2023, [visited 2023-03-16].  
URL <https://medium.com/@hnasr/postgresql-process-architecture-f21e16459907>
- [7] Group, T. P. G. D.: PostgreSQL: Documentation: 15: 30.3. Write-Ahead Logging (WAL). [visited 2023-02-21].  
URL <https://www.postgresql.org/docs/current/wal-intro.html>
- [8] Group, T. P. G. D.: PostgreSQL: Documentation: 15: 26.3. Continuous Archiving and Point-in-Time Recovery (PITR). [visited 2023-02-23].  
URL <https://www.postgresql.org/docs/15/continuous-archiving.html>
- [9] Riggs, S.; Ciolli, G.: *PostgreSQL 14 Administration Cookbook*, chapter Replication and Upgrades. Birmingham: Packt publishing, 1st edition, 2022, ISBN 9781803248974, pp. 499–557.
- [10] Group, T. P. G. D.: PostgreSQL: Documentation: 15: 26.1. SQL Dump. [visited 2023-02-23].  
URL <https://www.postgresql.org/docs/15/backup-dump.html>
- [11] Group, T. P. G. D.: Reliable PostgreSQL Backup and Restore. [visited 2023-02-23].  
URL <https://pgbackrest.org>

- [12] Group, T. P. G. D.: PostgreSQL: Documentation: 15: 27. High Availability, Load Balancing, and Replication. [visited 2023-02-23].  
URL <https://www.postgresql.org/docs/15/high-availability.html>
- [13] Group, T. P. G. D.: PostgreSQL: Documentation: 15: 27.3. Failover. [visited 2023-02-23].  
URL <https://www.postgresql.org/docs/15/warm-standby-failover.html>
- [14] Stratnev, P.: Migrating a PostgreSQL database cluster managed by Patroni. [visited 2023-02-24].  
URL <https://blog.palark.com/migrating-a-postgresql-cluster-managed-by-patroni>
- [15] SE, Z.: Introduction — Patroni 3.0.1 documentation. [visited 2023-02-24].  
URL <https://patroni.readthedocs.io/en/latest/>
- [16] Avinash Vallarapu, F. L. C., Jobin Augustine: Scaling PostgreSQL using Connection Poolers and Load Balancers for an Enterprise Grade environment. [visited 2023-02-24].  
URL <https://www.percona.com/blog/scaling-postgresql-using-connection-poolers-and-load-balancers-for-an-enterprise-grade-environment>
- [17] Vayghan, L. A.; Saied, M. A.; Toeroe, M.; et al.: Kubernetes as an availability manager for microservice applications. *arXiv preprint arXiv:1901.04946*, 2019.
- [18] Authors, T. K.: Kubernetes Components. [visited 2023-02-07].  
URL <https://kubernetes.io/docs/concepts/overview/components/>
- [19] Sayfan, G.: *Mastering Kubernetes*, chapter Kubernetes concepts. Birmingham: Packt Publishing, third edition edition, [2020]., ISBN 978-183-9211-256.
- [20] Dobies, J.; Wood, J.: *Kubernetes operators*. Sebastopol, CA: O'Reilly Media, 2020, ISBN 978-149-2048-046.
- [21] Burns, B.; Beda, J.; Hightower, K.; et al.: *Kubernetes: up and running*, chapter Pods. " O'Reilly Media, Inc.", third edition edition, 2022.
- [22] Burns, B.; Beda, J.; Hightower, K.; et al.: *Kubernetes: up and running*. " O'Reilly Media, Inc.", third edition edition, 2022.
- [23] Authors, T. K.: Pods. [visited 2023-02-07].  
URL <https://kubernetes.io/docs/concepts/workloads/pods/>
- [24] Authors, T. K.: Create static Pods. [visited 2023-02-07].  
URL <https://kubernetes.io/docs/tasks/configure-pod-container/static-pod/>

- [25] Authors, T. K.: ReplicaSet. [visited 2023-02-07].  
URL <https://kubernetes.io/docs/concepts/workloads/controllers/replicaset/>
- [26] Authors, T. K.: Service. [visited 2023-02-07].  
URL <https://kubernetes.io/docs/concepts/services-networking/service/>
- [27] Sayfan, G.: *Mastering Kubernetes*, chapter Managing Storage. Birmingham: Packt Publishing, third edition edition, [2020]., ISBN 978-183-9211-256, pp. 175–219.
- [28] Authors, T. K.: StatefulSets. [visited 2023-02-24].  
URL <https://kubernetes.io/docs/concepts/workloads/controllers/statefulset/>
- [29] Foundaution, C. N.: kubernetes/CHANGELOG-1.5.md at master · a0x8o/kubernetes. [visited 2023-02-24].  
URL <https://github.com/a0x8o/kubernetes/blob/master/CHANGELOG-1.5.md>
- [30] Foundaution, C. N.: Custom Resource (CR). [visited 2023-03-02].  
URL <https://ibm.github.io/kubernetes-operators/lab1/>
- [31] Ziolkowski, D.: Kubernetes CRDs: What They Are and Why They Are Useful. [visited 2023-03-01].  
URL <https://thenewstack.io/kubernetes-crds-what-they-are-and-why-they-are-useful/>
- [32] Dobies, J.; Wood, J.: *Kubernetes operators*. Sebastopol, CA: O'Reilly Media, 2020, ISBN 978-149-2048-046, pp. 27–32.
- [33] Authors, T. K.: Controllers. [visited 2023-03-02].  
URL <https://kubernetes.io/docs/concepts/architecture/controller/>
- [34] Authors, T. K.: Custom Resources. [visited 2023-03-02].  
URL <https://kubernetes.io/docs/concepts/extend-kubernetes/api-extension/custom-resources/>
- [35] Kahani, O.; Strejevitch, J.; Schuetz, T.; et al.: CNCF Operator White Paper - Final Version. 2023.  
URL [https://github.com/cncf/tag-app-delivery/blob/main/operator-wg/whitepaper/Operator-WhitePaper\\_v1-0.md](https://github.com/cncf/tag-app-delivery/blob/main/operator-wg/whitepaper/Operator-WhitePaper_v1-0.md)
- [36] Dobies, J.; Wood, J.: *Kubernetes operators*. Sebastopol, CA: O'Reilly Media, 2020, ISBN 978-149-2048-046, pp. 4–8.

- [37] David, C.: WHAT IS APPLICATION LIFECYCLE MANAGEMENT? [visited 2023-02-07].  
URL [http://davidchappell.com/writing/white\\_papers/What\\_is\\_ALM\\_v2.0--Chappell.pdf](http://davidchappell.com/writing/white_papers/What_is_ALM_v2.0--Chappell.pdf)
- [38] Philips, B.: Introducing Operators: Putting Operational Knowledge into Software. [visited 2023-03-01].  
URL <https://web.archive.org/web/20170129131616/https://coreos.com/blog/introducing-operators.html>
- [39] Dobies, J.; Wood, J.: *Kubernetes operators*. Sebastopol, CA: O'Reilly Media, 2020, ISBN 978-149-2048-046, pp. XIII–XVI.
- [40] Dobies, J.; Wood, J.: *Kubernetes operators*. Sebastopol, CA: O'Reilly Media, 2020, ISBN 978-149-2048-046, pp. 27–32.
- [41] Framework, T. O.: Welcome to Operator framework. [visited 2023-03-03].  
URL <https://operatorframework.io/operator-capabilities/>
- [42] Group, T. P. G. D.: PostgreSQL: Software Catalogue - Clustering/replication. [visited 2023-03-10].  
URL <https://www.postgresql.org/docs/15/warm-standby-failover.html>
- [43] OperatorHub.io: OperatorHub.io | The registry for Kubernetes Operators. [visited 2023-03-10].  
URL <https://operatorhub.io/?keyword=postgres>
- [44] Bogdanov, N.: Comparing Kubernetes operators for PostgreSQL. [visited 2023-02-20].  
URL <https://blog.palark.com/comparing-kubernetes-operators-for-postgresql/>
- [45] Crunchy Data Solutions, I.: Trusted Open Source PostgreSQL and Commercial Support for the Enterprise. [visited 2023-02-07].  
URL <https://www.crunchydata.com>
- [46] Crunchy Data Solutions, I.: PGO, the Postgres Operator from Crunchy Data. [visited 2023-02-15].  
URL <https://access.crunchydata.com/documentation/postgres-operator/5.3.0/tutorial/create-cluster/>
- [47] Crunchy Data Solutions, I.: PGO, the Postgres Operator from Crunchy Data. [visited 2023-02-15].

- URL <https://access.crunchydata.com/documentation/postgres-operator/5.3.0/tutorial/customize-cluster/>
- [48] Crunchy Data Solutions, I.: PGO, the Postgres Operator from Crunchy Data. [visited 2023-02-15].  
URL <https://access.crunchydata.com/documentation/postgres-operator/5.3.0/tutorial/delete-cluster/>
- [49] Crunchy Data Solutions, I.: PGO, the Postgres Operator from Crunchy Data. [visited 2023-02-15].  
URL <https://access.crunchydata.com/documentation/postgres-operator/5.3.0/tutorial/high-availability/>
- [50] Crunchy Data Solutions, I.: PGO, the Postgres Operator from Crunchy Data. [visited 2023-02-15].  
URL <https://access.crunchydata.com/documentation/postgres-operator/5.3.0/tutorial/update-cluster/>
- [51] Crunchy Data Solutions, I.: PGO, the Postgres Operator from Crunchy Data. [visited 2023-02-17].  
URL <https://www.crunchydata.com/blog/easy-major-postgresql-upgrades-using-pg>
- [52] Crunchy Data Solutions, I.: PGO, the Postgres Operator from Crunchy Data. [visited 2023-02-15].  
URL <https://access.crunchydata.com/documentation/postgres-operator/5.3.0/tutorial/backups/>
- [53] Crunchy Data Solutions, I.: PGO, the Postgres Operator from Crunchy Data. [visited 2023-02-15].  
URL <https://access.crunchydata.com/documentation/postgres-operator/5.3.0/tutorial/disaster-recovery/>
- [54] Crunchy Data Solutions, I.: PGO, the Postgres Operator from Crunchy Data. [visited 2023-02-15].  
URL <https://access.crunchydata.com/documentation/postgres-operator/5.3.0/tutorial/monitoring/>
- [55] Crunchy Data Solutions, I.: PGO, the Postgres Operator from Crunchy Data. [visited 2023-02-15].  
URL <https://access.crunchydata.com/documentation/postgres-operator/5.3.0/tutorial/connection-pooling/>

- [56] Crunchy Data Solutions, I.: Customize a Postgres Cluster. [visited 2023-03-10].  
URL <https://access.crunchydata.com/documentation/postgres-operator/v5/tutorial/customize-cluster/>
- [57] Crunchy Data Solutions, I.: PGO, the Postgres Operator from Crunchy Data. [visited 2023-02-15].  
URL <https://github.com/CrunchyData/postgres-operator>
- [58] L'Ecuyer, A.: Easy Postgres Major Version Upgrades Using PGO v5.1. [visited 2023-02-15].  
URL <https://access.crunchydata.com/documentation/postgres-operator/5.3.0/architecture/overview/>
- [59] Crunchy Data Solutions, I.: Customize a Postgres Cluster. [visited 2023-04-15].  
URL <https://access.crunchydata.com/documentation/postgres-operator/5.3.1/releases/5.3.1/>
- [60] OperatorHub.io: OperatorHub.io | The registry for Kubernetes Operators. [visited 2023-02-07].  
URL <https://operatorhub.io/operator/postgresql>
- [61] OperatorHub.io: OperatorHub.io | The registry for Kubernetes Operators. [visited 2023-02-13].  
URL <https://operatorhub.io/operator/cloud-native-postgresql>
- [62] Corporation, E.: EDB Postgres for Kubernetes v1. [visited 2023-02-17].  
URL [https://www.enterprisedb.com/docs/postgres\\_for\\_kubernetes/latest/license\\_keys](https://www.enterprisedb.com/docs/postgres_for_kubernetes/latest/license_keys)
- [63] Contributors, T. C.: CloudNativePG. [visited 2023-02-17].  
URL <https://cloudnative-pg.io/documentation/1.19/>
- [64] Contributors, T. C.: CloudNativePG. [visited 2023-02-17].  
URL [https://cloudnative-pg.io/documentation/1.19/postgres\\_for\\_kubernetes/latest/replica\\_cluster/](https://cloudnative-pg.io/documentation/1.19/postgres_for_kubernetes/latest/replica_cluster/)
- [65] Contributors, T. C.: CloudNativePG. [visited 2023-02-17].  
URL <https://cloudnative-pg.io/documentation/1.19/replication/>
- [66] Contributors, T. C.: CloudNativePG. [visited 2023-02-17].  
URL [https://cloudnative-pg.io/documentation/1.19/database\\_import/](https://cloudnative-pg.io/documentation/1.19/database_import/)

- [67] Contributors, T. C.: CloudNativePG. [visited 2023-02-17].  
URL [https://cloudnative-pg.io/documentation/1.19/rolling\\_update/#rolling-updates](https://cloudnative-pg.io/documentation/1.19/rolling_update/#rolling-updates)
- [68] Corporation, E.: EDB Postgres for Kubernetes v1. [visited 2023-02-16].  
URL [https://cloudnative-pg.io/documentation/1.19/postgres\\_for\\_kubernetes/latest/backup\\_recovery/](https://cloudnative-pg.io/documentation/1.19/postgres_for_kubernetes/latest/backup_recovery/)
- [69] Contributors, T. C.: CloudNativePG. [visited 2023-02-17].  
URL [https://cloudnative-pg.io/documentation/1.19/postgres\\_for\\_kubernetes/latest/tde/](https://cloudnative-pg.io/documentation/1.19/postgres_for_kubernetes/latest/tde/)
- [70] Contributors, T. C.: CloudNativePG. [visited 2023-02-17].  
URL <https://cloudnative-pg.io/documentation/1.19/quickstart/>
- [71] Contributors, T. C.: CloudNativePG. [visited 2023-02-17].  
URL [https://cloudnative-pg.io/documentation/1.19/postgres\\_for\\_kubernetes/latest/connection\\_pooling/](https://cloudnative-pg.io/documentation/1.19/postgres_for_kubernetes/latest/connection_pooling/)
- [72] Contributors, T. C.: CloudNativePG. [visited 2023-02-17].  
URL [https://cloudnative-pg.io/documentation/1.19/postgres\\_for\\_kubernetes/latest/postgresql\\_conf/](https://cloudnative-pg.io/documentation/1.19/postgres_for_kubernetes/latest/postgresql_conf/)
- [73] Stölting, S. J.: PostgreSQL On Kubernetes Experiences. [visited 2023-02-20].  
URL <https://proopensource.it/blog/postgresql-on-k8s-experiences>
- [74] Contributors, T. C.: Release notes for CloudNativePG 1.19. [visited 2023-04-15].  
URL [https://cloudnative-pg.io/documentation/1.19/release\\_notes/v1.19/](https://cloudnative-pg.io/documentation/1.19/release_notes/v1.19/)
- [75] Inc., O.: OnGres Inc. / StackGres. [visited 2023-02-20].  
URL <https://gitlab.com/ongresinc/stackgres>
- [76] Inc., O.: About. [visited 2023-02-20].  
URL <https://www.ongres.com/about-us/>
- [77] Inc., O.: SGDbOps. [visited 2023-02-20].  
URL <https://stackgres.io/doc/latest/reference/crd/sgdbops/#major-version-upgrade>
- [78] Inc., O.: SGPostgresConfig. [visited 2023-02-20].  
URL <https://stackgres.io/doc/latest/reference/crd/sgpgconfig/>

- [79] Inc., O.: Architecture. [visited 2023-02-20].  
URL <https://stackgres.io/doc/latest/intro/architecture/>
- [80] Inc., O.: CHANGELOG.md · main · OnGres Inc. / StackGres. [visited 2023-02-20].  
URL <https://gitlab.com/ongresinc/stackgres/-/blob/main/CHANGELOG.md>
- [81] Inc., O.: Licensing. [visited 2023-02-20].  
URL <https://stackgres.io/doc/latest/intro/license/>
- [82] OperatorHub.io: OperatorHub.io | The registry for Kubernetes Operators. [visited 2023-02-14].  
URL <https://operatorhub.io/operator/stackgres>
- [83] LLC, P.: About Percona - Percona. [visited 2023-02-14].  
URL <https://www.percona.com/about>
- [84] Pronin, S.: Run PostgreSQL in Kubernetes: Solutions, Pros and Cons. [visited 2023-02-20].  
URL <https://www.percona.com/blog/run-postgresql-in-kubernetes-solutions-pros-and-cons>
- [85] LLC, P.: Update Percona Operator for PostgreSQL. [visited 2023-02-21].  
URL <https://docs.percona.com/percona-operator-for-postgresql/update.html>
- [86] LLC, P.: Comparison with other solutions. [visited 2023-02-20].  
URL <https://docs.percona.com/percona-operator-for-postgresql/compare.html>
- [87] LLC, P.: Providing Backups. [visited 2023-02-21].  
URL <https://docs.percona.com/percona-operator-for-postgresql/backups.html>
- [88] LLC, P.: Monitor with Percona Monitoring and Management (PMM). [visited 2023-02-20].  
URL <https://docs.percona.com/percona-operator-for-postgresql/monitoring.html>
- [89] LLC, P.: Percona Operator for PostgreSQL. [visited 2023-02-21].  
URL <https://docs.percona.com/percona-operator-for-postgresql/2.0/index.html>

- [90] OperatorHub.io: OperatorHub.io | The registry for Kubernetes Operators. [visited 2023-02-14].  
URL <https://operatorhub.io/operator/percona-postgresql-operator>
- [91] Gilb, T.; Finzi, S.; et al.: *Principles of software engineering management*, volume 11. Addison-wesley Reading, MA, 1988.
- [92] Graham, D.; Black, R.; van Veenendaal, E.: *Foundations of software testing*. Australia: Cengage, 4th edition, 2020, ISBN 978-147-3764-798.
- [93] ISO/IEC/IEEE International Standard - Software and systems engineering —Software testing —Part 2:Test processes. *ISO/IEC/IEEE 29119-2:2013(E)*, 2013: pp. 1–68, doi:10.1109/IEEEESTD.2013.6588543.

## LIST OF ABBREVIATIONS

ACID	Atomicity, Consistency, Isolation, Durability
API	Application Programming Interface
CNPGO	CloudNativePG
CR	Custom Resource
CRD	Custom Resource Definition
EDBO	EDB Postgres for Kubernetes Operator
K8s	Kubernetes
ORDBMS	Object-relational Database Management System
PGO	Crunchy Postgres for Kubernetes
PPO	Percona Operator for PostgreSQL
RBAC	Role-Based Access Control
SPGO	StackGres Operator
WAL	Write Ahead Log

**LIST OF FIGURES**

Fig. 1.1.	Postgres Architecture [6] .....	13
Fig. 1.2.	The components of a Kubernetes cluster [18].....	17
Fig. 1.3.	Kubernetes controller [35] .....	20
Fig. 1.4.	Application Life Cycle [37] .....	21
Fig. 1.5.	Definition of Kubernetes Operator [38] .....	22
Fig. 1.6.	Operator pattern [35] .....	23
Fig. 1.7.	Operator maturity levels described by Operator Framework [41] .....	23
Fig. 4.1.	PGO's architecture [58] .....	30
Fig. 4.2.	CNPGO's architecture [71] .....	33
Fig. 4.3.	SPGO's architecture [79].....	34
Fig. 6.1.	Test management process relationships [93] .....	42
Fig. 6.2.	Test plan creation activities [93] .....	43
Fig. 6.3.	Test completion process [93] .....	44
Fig. 6.4.	Dynamic test processes [93] .....	45
Fig. 6.5.	Test design and implementation [93] .....	46
Fig. 6.6.	Test execution process [93] .....	46
Fig. 7.1.	Test process .....	48
Fig. 8.1.	SPGO's user interface.....	56
Fig. 8.2.	Kubernetes performance setup.....	59
Fig. 8.3.	GKE nodes details .....	60

**LIST OF TABLES**

Tab. 4.1.	Summary of selected Operators .....	36
Tab. 4.2.	Key differences between selected Operators .....	36
Tab. 8.1.	Popularity of Operators .....	49
Tab. 8.2.	Operators issues.....	50
Tab. 8.3.	Operators maturity .....	50
Tab. 8.4.	Operators renewal .....	51
Tab. 8.5.	Training needed .....	52
Tab. 8.6.	Documentation examples .....	52
Tab. 8.7.	Learnability of Operators.....	53
Tab. 8.8.	Vulnerability analysis .....	54
Tab. 8.9.	Operability.....	54
Tab. 8.10.	Ease of use.....	57
Tab. 8.11.	Monitoring .....	58
Tab. 8.12.	Performance analysis .....	60
Tab. 8.13.	Usability .....	61
Tab. 9.1.	Overall quality of Operators .....	62
Tab. 2.1.	Test plan No. 1 .....	82
Tab. 3.1.	Test plan No. 2 .....	83
Tab. 4.1.	Test plan No. 3 .....	88
Tab. 5.1.	Test plan No. 4 .....	89
Tab. 5.2.	Use case No. 1.....	90
Tab. 5.3.	Use case No. 2.....	90
Tab. 5.4.	Use case No. 3.....	91
Tab. 5.5.	Use case No. 4.....	91
Tab. 5.6.	Use case No. 5.....	92
Tab. 5.7.	Use case No. 6.....	92
Tab. 5.8.	Use case No. 7.....	93
Tab. 5.9.	Use case No. 8.....	93
Tab. 5.10.	Use case No. 9.....	94
Tab. 5.11.	Use case No. 10.....	94
Tab. 5.12.	Use case No. 11.....	95
Tab. 5.13.	Use case No. 12 .....	95
Tab. 5.14.	Use case No. 13 .....	96
Tab. 5.15.	Use case No. 14 .....	96
Tab. 5.16.	Use case No. 15 .....	97
Tab. 5.17.	Use case No. 16 .....	97

Tab. 6.1. Test plan No. 5 .....	98
---------------------------------	----

## LIST OF APPENDICES

- A I. General test plan
- A II. Test Plan No. 1
- A III. Test Plan No. 2
- A IV. Test Plan No. 3
- A V. Test Plan No. 4
- A VI. Test Plan No. 5

## APPENDIX A I. GENERAL TEST PLAN

- Test plan ID: TP0
- Context of testing:
  - Project: Bachelor's thesis.
  - Test levels: Acceptance testing.
  - Test types: Static and dynamic.
  - Test items:
    - \* Crunchy Postgres for Kubernetes Operator v5.3.1.
    - \* CloudNativePG Operator v1.20.0.
    - \* StackGres Operator v1.4.3.
    - \* Percona Operator for Postgres 1.4.0.
  - Test scope: Operator, Operator's documentation, Operator's repository.
  - Test basis: Defined criteria.
- Risk register:
  - Limited staff and time might prevent thorough testing of all features and functionalities of the software during acceptance testing.
  - Inadequately trained staff might struggle to design effective test cases, which could result in missed defects and lower overall testing effectiveness.
  - Due to the lack of expertise among staff members, the software's readiness for production might be inaccurately assessed, leading to incorrect conclusions about its quality and suitability for release
- Test strategy:
  - General: The purpose of testing is to evaluate the ability of Operators to fulfill the desired criterias, and to provide information for making informed decisions on which Operator to select in last chapter. Non-functional requirements will be tested with static and dynamic test techniques.
  - Test levels: Acceptance testing
  - Test deliverables: Test plans, test model specification, test procedure specification, incident reports.
  - Test design techniques: Exploratory Testing, Use cases, Walkthroughs.
  - Entry criteria: Created environments.

- Exit criteria: Decision metrics were collected.
- Test competition criteria: All criteria covered by at least one test case.
- Degree of independence: No connection between tested Operators and tester. Tester is fully independent.
- Metrics to be collected:
  - \* Static testing: Vulnerability analysis (number of vulnerabilities and their severity), Repository review (sum of issues, sum of repaired issues, sum of stars, sum of commits), Documentation review (examples, training needed),
  - \* Dynamic testing: Sum of passed, ignored and failed tests. Performance described by transactions per second.
- Test data requirements:
  - \* Crunchy Postgres for Kubernetes Operator v5.3.1
    - PGO: <https://github.com/CrunchyData/postgres-operator-examples>
    - PGODOC: <https://access.crunchydata.com/documentation/postgres-operator/v5/>
    - PGOREPO: <https://github.com/CrunchyData/postgres-operator>
  - \* CloudNativePG Operator version 1.20.0
    - CNPGO: <https://raw.githubusercontent.com/cloudnative-pg/cloudnative-pg/release-1.20/releases/cnpg-1.20.0.yaml>
    - CNPGODOC: <https://cloudnative-pg.io/documentation/1.20/>
    - CNPGOREPO: <https://github.com/cloudnative-pg/cloudnative-pg>
  - \* StackGres Operator version 1.4.3
    - SPGO: <https://stackgres.io/downloads/stackgres-k8s/stackgres/helm/>
    - SPGODOC: <https://stackgres.io/doc/1.4/>
    - SPGOREPO: <https://gitlab.com/ongresinc/stackgres>
  - \* Percona Operator for PostgreSQL version 1.4.0
    - PPOO: <https://raw.githubusercontent.com/percona/percona-postgresql-operator/v1.4.0/deploy/operator.yaml>
    - PPODOC: <https://docs.percona.com/percona-operator-for-postgresql/index.html>
    - PPOREPO: <https://github.com/percona/percona-postgresql-operator>

- Test environment requirements:
  - \* Kind Kubernetes cluster with two worker nodes for all dynamic test except performance tests, installed on Unix/Linux compatible machine.
  - \* Google Kubernetes Engine with two worker nodes.
  - \* Terraform
  - \* Trivy security scanner.
  - \* Kubectl kubernetes controll tool.
  - \* EXCEL.
- Retesting: Retesting is not needed.
- Regression testing: Regression testing is not needed.
- Testing activities and estimates:
  - \* Environment setup – 30m.
  - \* Repository walkthrough – 2h/Operator.
  - \* Documentation walkthrough – 2h/Operator.
  - \* Deployment and configuration – 4h/Operator.
  - \* Performance – 4h/Operator.
  - \* Operability and documentation – 8h/Operator.
  - \* Test completion report – 1h/testing day.
- Staffing (roles and responsibilities)
  - \* Roles: Test architect, test manager, test designer, test automator, tester and test analyst
  - \* Staff: Miroslav Širina.
- Training needed
  - \* Test management.
  - \* Test design.
  - \* Test analyst.
  - \* Trivy and results interpretation skills.
- Test priorities
  - \* Static tests have higher priority to dynamic.
  - \* Critical features have higher priority.
- Schedule
  - \* May 1st repositories and documentations walkthroughs.
  - \* May 2nd vulnerability analysis.

- \* May 3rd - 8th operability testing.
- \* May 9th performance testing.
- \* May 10th – 11th Testing closure.

## APPENDIX A II. TEST PLAN NO. 1

Table 2.1 Test plan No. 1

Test plan ID	tp1
Revision	1
Introduction	Repositories walkthrough
Test items	Operator's repositories
Covered criteria	C2, C4
Test type	Static
Test approach	Repositories walkthrough
Exit criteria	All metrics gathered
Deliverables	Sum of commits, sum of stars, sum of issues, sum of fixed issues.
Duration	2 h for each Operator
Reviewer	Miroslav Šířina
Start	May 1st
Schedule	May 1st repositories walkthrough and test report.

### Test completion report

Testing performed: Repositories walkthrough, repositories cloning, Percona Jira walkthrough

Deviations from planned testing: Percona is using Jira for tracking issues. To get issues Jira walkthrough was necessary. To count number of commits and get the date of first commit the repository cloning was necessary.

Test completion evaluation: The testing process was successful in gathering key data about the system despite deviations from the initial plan. The flexibility in testing procedures resulted in a more comprehensive evaluation and provided valuable insights into the system.

Factors that blocked progress: repository cloning, Jira walkthrough

Test Result Analysis: The tests provided valuable data about the state and history of repositories, as well as key insights into issue tracking.

Lessons Learned: The necessity to deviate from the initial test plan underlines the importance of flexibility in testing procedures. An adaptive approach can lead to a more thorough evaluation and better data collection.

## APPENDIX A III. TEST PLAN NO. 2

Table 3.1 Test plan No. 2

Test plan ID	tp2
Revision	1
Introduction	Checklist-based documentations walkthrough
Test items	Operator's documentations
Covered criteria	C3
Test type	Static
Test approach	Checklist-based Testing
Exit criteria	All checklists completed
Deliverables	List of examples and checklist
Duration	2 h for each Operator
Reviewer	Miroslav Šířina
Start	May 1st
Schedule	May 1st documentations walkthrough and test report.

### Checklist

- Installation
- Minor upgrade to new version
- Major upgrade to new version
- Backup
- Restore
- Monitoring
- Vertical scaling
- Horizontal scaling
- Configuration Update
- Uninstall
- Training needed

## Test results

PGO Documentation <https://access.crunchydata.com/documentation/postgres-operator/v5/>

Cluster creation  
<https://access.crunchydata.com/documentation/postgres-operator/v5/tutorial/create-cluster/>

Minor upgrade to new version  
<https://access.crunchydata.com/documentation/postgres-operator/5.3.1/tutorial/update-cluster/>

Major upgrade to new version  
<https://access.crunchydata.com/documentation/postgres-operator/5.3.1/guides/major-postgres-version-upgrade/>

Backup  
<https://access.crunchydata.com/documentation/postgres-operator/v5/tutorial/backup-management/>

Restore  
<https://access.crunchydata.com/documentation/postgres-operator/5.3.1/tutorial/disaster-recovery/>

Monitoring  
<https://access.crunchydata.com/documentation/postgres-operator/5.3.1/tutorial/monitoring/>

Vertical scaling  
<https://access.crunchydata.com/documentation/postgres-operator/5.3.1/tutorial/resize-cluster/>

Horizontal scaling  
<https://access.crunchydata.com/documentation/postgres-operator/5.3.1/tutorial/resize-cluster/>

Configuration Update  
<https://access.crunchydata.com/documentation/postgres-operator/5.3.1/tutorial/customize-cluster/>

Uninstall  
<https://access.crunchydata.com/documentation/postgres-operator/5.3.1/tutorial/delete-cluster/>

Notes: PGO use kustomize for customization of yaml manifests.

CNPGO

Documentation  
<https://cloudnative-pg.io/documentation/1.19/>

Cluster creation

<https://cloudnative-pg.io/documentation/1.19/quickstart/#part-3-deploy-a-postgresql-cluster>  
Minor upgrade to new version  
[https://cloudnative-pg.io/documentation/1.19/rolling\\_update/#scheduled-backups](https://cloudnative-pg.io/documentation/1.19/rolling_update/#scheduled-backups)  
Major upgrade to new version Not found  
Backup  
[https://cloudnative-pg.io/documentation/1.19/backup\\_recovery/#scheduled-backups](https://cloudnative-pg.io/documentation/1.19/backup_recovery/#scheduled-backups)  
Restore  
[https://cloudnative-pg.io/documentation/1.19/backup\\_recovery/#scheduled-backups](https://cloudnative-pg.io/documentation/1.19/backup_recovery/#scheduled-backups)  
Monitoring  
<https://cloudnative-pg.io/documentation/1.19/monitoring/#resource-management>  
Vertical scaling  
[https://cloudnative-pg.io/documentation/1.19/resource\\_management/#resource-management](https://cloudnative-pg.io/documentation/1.19/resource_management/#resource-management)  
Horizontal scaling  
[https://cloudnative-pg.io/documentation/1.19/resource\\_management/#resource-management](https://cloudnative-pg.io/documentation/1.19/resource_management/#resource-management)  
Configuration Update  
[https://cloudnative-pg.io/documentation/1.19/postgresql\\_conf/#postgresql-configuration](https://cloudnative-pg.io/documentation/1.19/postgresql_conf/#postgresql-configuration)  
Uninstall  
<https://cloudnative-pg.io/documentation/1.19/cnpg-plugin/#destroy>  
Notes: Uninstall example use cnpg plugin  
SPGO Documentation  
<https://stackgres.io/doc/1.4/>  
Cluster creation  
[#major-version-upgrade](https://stackgres.io/doc/1.4/demo/quickstart)  
Minor upgrade to new version – It is mentioned in documentation but without example  
<https://stackgres.io/doc/1.4/reference/crd/sgdbops/#minor-version-upgrade>  
Major upgrade to new version - It is mentioned in documentation but without example  
<https://stackgres.io/doc/1.4/reference/crd/sgdbops/#minor-version-upgrade>  
Backup  
<https://stackgres.io/doc/1.4/tutorial/complete-cluster/backup-configuration/>

Restore

<https://stackgres.io/doc/1.4/runbooks/restore-backup/>

Monitoring

<https://stackgres.io/doc/1.4/install/prerequisites/monitoring/>

Vertical scaling

<https://stackgres.io/doc/1.4/tutorial/complete-cluster/instance-profile/>

Horizontal scaling

<https://stackgres.io/doc/1.4/tutorial/complete-cluster/create-cluster/>  
Configuration Update

<https://stackgres.io/doc/1.4/tutorial/complete-cluster/postgres-config/>  
Uninstall

<https://stackgres.io/doc/1.4/administration/uninstall/>

Notes: helm is needed to install monitoring

POD Documentation

<https://docs.percona.com/percona-operator-for-postgresql/index.html>

Cluster creation

<https://docs.percona.com/percona-operator-for-postgresql/gke.html#installing-the-operator>

Minor upgrade to new version

<https://docs.percona.com/percona-operator-for-postgresql/update.html?h=postgres+update#semi-automatic-upgrade>

Major upgrade to new version

<https://docs.percona.com/percona-operator-for-postgresql/update.html?h=postgres+update#semi-automatic-upgrade>

Backup

<https://docs.percona.com/percona-operator-for-postgresql/backups.html?h=backup#use-google-cloud-storage-for-backups>

Restore

<https://docs.percona.com/percona-operator-for-postgresql/backups.html?h=backup#use-google-cloud-storage-for-backups>

Monitoring

<https://docs.percona.com/percona-operator-for-postgresql/monitoring.html?h=version#installing-the-pmm-client>

Vertical scaling Not found

Horizontal scaling

<https://docs.percona.com/percona-operator-for-postgresql/scaling.html?h=scale>

Configuration Update

<https://docs.percona.com/percona-operator-for-postgresql/options.html#creating-a-cluster-with-custom-options>

Uninstall Not found

### **Test completion report**

Testing performed: Checklist-based Testing

Deviations from planned testing: None

Test completion evaluation: The testing process was successful.

Factors that blocked progress: None

Test Result Analysis: The tests provided valuable data about the state of documentations, as well as key insights into Operators operation.

Lessons Learned: Future projects should be prepared for a high level of diversity in documentations. This might involve allocating more time for research or including personnel with a broader range of expertise.

## **APPENDIX A IV. TEST PLAN NO. 3**

Table 4.1 Test plan No. 3

Test plan ID	tp3
Revision	1
Introduction	Vulnerability analysis of operators
Test items	Operator deployed in the cluster
Covered criteria	C5
Test type	Static
Test approach	Vulnerability analysis
Exit criteria	Completed analysis
Tools	Trivy security scanner
Deliverables	Vulnerability reports
Duration	4 h for each Operator
Reviewer	Miroslav Šířina
Start	May 2nd
Schedule	May 2nd analysis and test report.

### **Test completion report**

Testing performed: Vulnerability analysis

Deviations from planned testing: None

Test completion evaluation: The testing process was successful.

Factors that blocked progress: None

Test Result Analysis: The tests provided valuable data about vulnerabilities in Operators.

## APPENDIX A V. TEST PLAN NO. 4

Table 5.1 Test plan No. 4

Test plan ID	tp4
Revision	1
Introduction	This test should test the Operators usability and quality of their monitoring.
Test items	Operator deployed in the cluster
Covered criteria	C3
Test type	Dynamic
Test approach	Use case based Blackbox testing
Exit criteria	Each use case covered with atleast one test case
Tools	Kind cluster, kubectl, helm, kustomize
Deliverables	Number of commands needed to perform required operation. List of covered monitoring topics. Print screens of monitoring.
Duration	8 h for each Operator
Tester	Miroslav Šířina
Start	May 3rd
End	May 8th
Schedule	May 3rd Use cases creation May 4th PGO May 5th CNPGO May 6th SPGO May 7th PPO

Actors:

K - Kubernetes cluster

U - User

O - Operator

Table 5.2 Use case No. 1

Use case name	Operator installation	
Use case ID	UCA1	
Traceability	C3	
Precondition	Prepared Kubernetes cluster	
Scenario		
Step No.	Actor	Description
1	U	Use case starts with prepared kubernetes cluster.
2	U	The user initiates the installation of the Operator.
3	K	Kubernetes installs the Operator.
4	U	Use case ends.

Table 5.3 Use case No. 2

Use case name	Basic cluster creation	
Use case ID	UCA2	
Traceability	C3	
Precondition	Installed Operator	
Scenario		
Step No.	Actor	Description
1	U	Use case starts with the Operator installed.
2	U	The user initiates basic cluster install.
3	O	The Operator installs the cluster.
4	U	Use case ends.

Table 5.4 Use case No. 3

Use case name	Monitoring installation	
Use case ID	UCC1	
Traceability	C3	
Precondition	Installed Operator and created cluster	
Scenario		
Step No.	Actor	Description
1	U	Use case starts with created cluster.
2	U	The user initiates monitoring installation.
3	O	The Operator installs cluster monitoring.
4	U	Use case ends.

Table 5.5 Use case No. 4

Use case name	Vertical scaling	
Use case ID	UCD1	
Traceability	C3	
Precondition	Installed Operator and created cluster	
Scenario		
Step No.	Actor	Description
1	U	Use case starts with created cluster.
2	U	The user initiates vertical scaling.
3	O	The Operator scales the cluster.
4	U	Use case ends.

Table 5.6 Use case No. 5

Use case name	Horizontal scaling	
Use case ID	UCE1	
Traceability	C3	
Precondition	Installed Operator and created cluster	
Scenario		
Step No.	Actor	Description
1	U	Use case starts with created cluster.
2	U	The user initiates horizontal scaling.
3	O	The Operator scales the cluster.
4	U	Use case ends.

Table 5.7 Use case No. 6

Use case name	Connection pooling	
Use case ID	UCF1	
Traceability	C3	
Precondition	Installed Operator and created cluster	
Scenario		
Step No.	Actor	Description
1	U	Use case starts with created cluster.
2	U	The user initiates connection pooling installation.
3	O	The Operator installs connection pooler.
4	U	Use case ends.

Table 5.8 Use case No. 7

Use case name	Configuration update - extension installation	
Use case ID	UCG1	
Traceability	C3	
Precondition	Installed Operator and created cluster	
Scenario		
Step No.	Actor	Description
1	U	Use case starts with created cluster.
2	U	The user initiates Postgis extension installation.
3	O	The Operator installs Postgis extension.
4	U	Use case ends.

Table 5.9 Use case No. 8

Use case name	Configuration update - connections increase	
Use case ID	UCG2	
Traceability	C3	
Precondition	Installed Operator, created cluster, installed pooler	
Scenario		
Step No.	Actor	Description
1	U	Use case starts with created cluster and installed pooler.
2	U	The user increase connection pooler connections.
3	O	The Operator updates connection pooler configuration.
4	U	Use case ends.

Table 5.10 Use case No. 9

Use case name	Configuration update - max wal size	
Use case ID	UCG3	
Traceability	C3	
Precondition	Installed Operator and created cluster	
Scenario		
Step No.	Actor	Description
1	U	Use case starts with created cluster.
2	U	The user initiates max_wal_size parameter update.
3	O	The Operator updates max_wal_size parameter.
4	U	Use case ends.

Table 5.11 Use case No. 10

Use case name	Cluster scheduled backup	
Use case ID	UCH1	
Traceability	C3	
Precondition	Installed Operator and created cluster	
Scenario		
Step No.	Actor	Description
1	U	Use case starts with created cluster.
2	U	The user creates cluster backup schedule.
3	O	The Operator applies the cluster backup schedule.
4	O	The Operator creates cluster backup.
5	U	Use case ends.

Table 5.12 Use case No. 11

Use case name	Cluster ad-hoc backup	
Use case ID	UCH2	
Traceability	C3	
Precondition	Installed Operator and created cluster	
Scenario		
Step No.	Actor	Description
1	U	Use case starts with created cluster.
2	U	The user initiates ad-hoc backup.
3	O	The Operator creates cluster backup.
4	U	Use case ends.

Table 5.13 Use case No. 12

Use case name	Cluster restore	
Use case ID	UCI1	
Traceability	C3	
Precondition	Installed Operator and created backup	
Scenario		
Step No.	Actor	Description
1	U	Use case starts with created backup.
2	U	The user initiates cluster restore.
3	O	The Operator restores the cluster.
4	U	Use case ends.

Table 5.14 Use case No. 13

Use case name	Minor upgrade	
Use case ID	UCJ1	
Traceability	C3	
Precondition	Installed Operator and created lower minor version cluster.	
Scenario		
Step No.	Actor	Description
1	U	The use case with the Operator installed and lower minor version cluster created.
2	U	The user initiates minor version upgrade.
3	O	The Operator performs minor version upgrade.
4	U	Use case ends.

Table 5.15 Use case No. 14

Use case name	Major upgrade	
Use case ID	UCK1	
Traceability	C3	
Precondition	Installed Operator and created lower major version cluster.	
Scenario		
Step No.	Actor	Description
1	U	The use case with the Operator installed and lower major version cluster created.
2	U	The user initiates major version upgrade.
3	O	The Operator performs major version upgrade.
4	U	Use case ends.

Table 5.16 Use case No. 15

Use case name	Operator uninstallation	
Use case ID	UCL1	
Traceability	C3	
Precondition	Installed Operator and created cluster	
Scenario		
Step No.	Actor	Description
1	U	Use case starts with created cluster.
2	U	The user initiates Operator uninstallation.
3	O	Operator uninstalls but keep the cluster
4	U	Use case ends.

Table 5.17 Use case No. 16

Use case name	Cluster uninstallation	
Use case ID	UCM1	
Traceability	C3	
Precondition	Installed Operator and created cluster	
Scenario		
Step No.	Actor	Description
1	U	Use case starts with created cluster.
2	U	The user initiates cluster uninstallation.
3	O	Operator uninstalls cluster.
4	U	Use case ends.

## APPENDIX A VI. TEST PLAN NO. 5

Table 6.1 Test plan No. 5

Test plan ID	tp5
Revision	1
Introduction	Performance analysis
Test items	Operator deployed GKE in the cluster
Covered criteria	C1
Test type	Dynamic
Test approach	Performance analysis
Exit criteria	Completed analysis
Tools	PgBench Postgres benchmark tool
Deliverables	Performance reports
Duration	4 h for each Operator
Tester	Miroslav Šířina
Start	May 9th
Schedule	May 9th analysis and test report.

### Test completion report

Testing performed: Performance analysis

Deviations from planned testing: SPGO analysis too

Test completion evaluation: None

Factors that blocked progress: Deploying SPGO proved challenging due to the fact that SPGO requires a cluster profile to deploy the cluster, which will specify the allocated processor and memory. With the correct settings of these values, the cluster was unable to find suitable resources for SPGO. By gradually reducing these values, available resources were eventually found.

Test Result Analysis: The tests provided valuable data about performance of Postgres deployed by Operators.

### Test results

PGO

pgbench (15.2)

starting vacuum...end.

transaction type: <builtin: TPC-B (sort of)>

scaling factor: 1

query mode: simple

number of clients: 25  
number of threads: 10  
maximum number of tries: 1  
number of transactions per client: 10000  
number of transactions actually processed: 250000/250000  
number of failed transactions: 0 (0.000%)  
latency average = 45.879 ms  
initial connection time = 745.406 ms  
tps = 544.913924 (without initial connection time)  
pgbench (15.2)  
starting vacuum...end.  
transaction type: <builtin: TPC-B (sort of)>  
scaling factor: 1  
query mode: simple  
number of clients: 25  
number of threads: 10  
maximum number of tries: 1  
number of transactions per client: 10000  
number of transactions actually processed: 250000/250000  
number of failed transactions: 0 (0.000%)  
latency average = 46.016 ms  
initial connection time = 688.436 ms  
tps = 543.289895 (without initial connection time)  
pgbench (15.2)  
starting vacuum...end.  
transaction type: <builtin: TPC-B (sort of)>  
scaling factor: 1  
query mode: simple  
number of clients: 25  
number of threads: 10  
maximum number of tries: 1  
number of transactions per client: 10000  
number of transactions actually processed: 250000/250000  
number of failed transactions: 0 (0.000%)  
latency average = 46.424 ms  
initial connection time = 750.453 ms  
tps = 538.511794 (without initial connection time)

CNPG

pgbench (15.2)  
starting vacuum...end.  
pgbench: error: client 6 script 0 aborted in command 4 query 0: FATAL: query wait  
timeout  
SSL connection has been closed unexpectedly  
transaction type: <builtin: TPC-B (sort of)>  
scaling factor: 1  
query mode: simple  
number of clients: 25  
number of threads: 10  
maximum number of tries: 1  
number of transactions per client: 10000  
number of transactions actually processed: 240000/250000  
number of failed transactions: 0 (0.000%)  
latency average = 61.927 ms  
initial connection time = 729.483 ms  
tps = 403.698126 (without initial connection time)  
pgbench: error: Run was aborted; the above results are incomplete.  
command terminated with exit code 2

pgbench (15.2)  
starting vacuum...end.  
pgbench: error: client 21 script 0 aborted in command 4 query 0: FATAL: query wait  
timeout  
SSL connection has been closed unexpectedly  
transaction type: <builtin: TPC-B (sort of)>  
scaling factor: 1  
query mode: simple  
number of clients: 25  
number of threads: 10  
maximum number of tries: 1  
number of transactions per client: 10000  
number of transactions actually processed: 240000/250000  
number of failed transactions: 0 (0.000%)  
latency average = 62.105 ms  
initial connection time = 710.013 ms  
tps = 402.544415 (without initial connection time)  
pgbench: error: Run was aborted; the above results are incomplete.  
command terminated with exit code 2

pgbench (15.2)  
starting vacuum...end.  
pgbench: error: client 1 script 0 aborted in command 4 query 0: FATAL: query wait timeout  
SSL connection has been closed unexpectedly  
transaction type: <builtin: TPC-B (sort of)>  
scaling factor: 1  
query mode: simple  
number of clients: 25  
number of threads: 10  
maximum number of tries: 1  
number of transactions per client: 10000  
number of transactions actually processed: 240000/250000  
number of failed transactions: 0 (0.000%)  
latency average = 63.673 ms  
initial connection time = 706.203 ms  
tps = 392.629101 (without initial connection time)  
pgbench: error: Run was aborted; the above results are incomplete.  
command terminated with exit code 2  
PPO  
pgbench (15.2, server 14.7 - Percona Distribution)  
starting vacuum...end.  
transaction type: <builtin: TPC-B (sort of)>  
scaling factor: 1  
query mode: simple  
number of clients: 25  
number of threads: 10  
maximum number of tries: 1  
number of transactions per client: 10000  
number of transactions actually processed: 250000/250000  
number of failed transactions: 0 (0.000%)  
latency average = 62.272 ms  
initial connection time = 707.856 ms  
tps = 401.464378 (without initial connection time)  
pgbench (15.2, server 14.7 - Percona Distribution)  
starting vacuum...end.  
transaction type: <builtin: TPC-B (sort of)>  
scaling factor: 1

query mode: simple  
number of clients: 25  
number of threads: 10  
maximum number of tries: 1  
number of transactions per client: 10000  
number of transactions actually processed: 250000/250000  
number of failed transactions: 0 (0.000%)  
latency average = 63.769 ms  
initial connection time = 690.586 ms  
tps = 392.039997 (without initial connection time)  
pgbench (15.2, server 14.7 - Percona Distribution)  
starting vacuum...end.  
transaction type: <builtin: TPC-B (sort of)>  
scaling factor: 1  
query mode: simple  
number of clients: 25  
number of threads: 10  
maximum number of tries: 1  
number of transactions per client: 10000  
number of transactions actually processed: 250000/250000  
number of failed transactions: 0 (0.000%)  
latency average = 64.467 ms  
initial connection time = 574.644 ms  
tps = 387.793393 (without initial connection time)  
SPGO  
pgbench (15.2, server 15.1 (OnGres 15.1-build-6.18))  
starting vacuum...end.  
transaction type: <builtin: TPC-B (sort of)>  
scaling factor: 1  
query mode: simple  
number of clients: 25  
number of threads: 10  
maximum number of tries: 1  
number of transactions per client: 10000  
number of transactions actually processed: 250000/250000  
number of failed transactions: 0 (0.000%)  
latency average = 87.906 ms  
initial connection time = 60.527 ms

tps = 284.394442 (without initial connection time)  
pgbench (15.2, server 15.1 (OnGres 15.1-build-6.18))  
starting vacuum...end.  
transaction type: <builtin: TPC-B (sort of)>  
scaling factor: 1  
query mode: simple  
number of clients: 25  
number of threads: 10  
maximum number of tries: 1  
number of transactions per client: 10000  
number of transactions actually processed: 250000/250000  
number of failed transactions: 0 (0.000%)  
latency average = 89.321 ms  
initial connection time = 67.533 ms  
tps = 279.890815 (without initial connection time)  
pgbench (15.2, server 15.1 (OnGres 15.1-build-6.18))  
starting vacuum...end.  
transaction type: <builtin: TPC-B (sort of)>  
scaling factor: 1  
query mode: simple  
number of clients: 25  
number of threads: 10  
maximum number of tries: 1  
number of transactions per client: 10000  
number of transactions actually processed: 250000/250000  
number of failed transactions: 0 (0.000%)  
latency average = 80.863 ms  
initial connection time = 74.577 ms  
tps = 309.164610 (without initial connection time)  
pgbench (15.2, server 15.1 (OnGres 15.1-build-6.18))