

Politehnica University Timișoara

Faculty of Automation and Computers

**Department of Computers and Information Technology**

**Benchmark Evaluation of Scale-Up and Scale-Out Techniques on a Functional Programming Based Microservice**

Master Thesis

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# Introduction

When data grows too large, the tendency is to either scale-out, by adding nodes to the system or to scale-up, by adding resources to a single node. It is well known that these techniques come with different complexities and bottlenecks, changing significantly the architecture, the API and the business logic of the whole application. This study proposes to capture how these scaling methods perform under different loads, and to define a common boundary between the mentioned scaling practices. It is important to establish whether or not these techniques should be applied separately or altogether, in which for the last case is essential to elaborate a concrete configuration on how the scaling entities should be managed and how the resource allocation should be done. Therefore, this work relies on a microservice architecture, where one service is taken and it is being deployed under different scaling contexts in an isolated environment. Therefore, the resulting measurements and comparisons can give us a valuable insight on how future microservices should be designed and deployed from the very beginning. A service is valuable for the client until the requirements are met, scalability being one of its essential capabilities in the cloud-computing era.

## Context

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## Problem statement

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## Motivation

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# State of the art

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# Technical background

In this section we mention the technologies and important concepts with which the project implementation and testing was realized. Therefore, it is important to understand the reason behind each component and functionality in order to interpret the final results. Shortly, the programming language in which the microservice was written is Scala, providing support for functional programming. As build tool, sbt was preferred, since it comes with a lot of features and helpers for the Scala ecosystem. Play2 was used for the RESTful API, while Akka for the scale-up technique implemented with the actor model. Cats is a library which provides abstractions for functional programming. For the realization of the business logic, Google OR-Tools represented the most efficient choice, which is a fast and portable software suite for solving combinatorial optimization problems. Docker enabled to deploy the application in containers and last but not least, Gatling allowed to perform load testing on various scaling scenarios of the planning app.

## Scala

The name Scala stands for “scalable language”. The language is so named since it was designed to grow with the demand of its users. It is general-purpose programming language, which gives the ability to its users to write small scripts or to build large systems. Its strength as a language are relieved when designing large systems and frameworks of reusable components [3.1].

Scala is a pure object-oriented language in the sense that every value is an object. Types and behaviors of objects are described by classes and traits. Classes can be extended by subclassing, and by using a flexible mixin-based composition mechanism as a clean replacement for multiple inheritance [3.1].

Scala is also a functional language in the sense that every function is a value. Scala provides a lightweight syntax for defining anonymous functions, it supports higher-order functions, it allows functions to be nested, and it supports currying. Scala’s case classes and its built-in support for pattern matching provide the functionality of algebraic types, which are used in many functional languages [3.1]. Singleton objects provide a convenient way to group functions that aren’t members of a class. Furthermore, Scala’s notion of pattern matching naturally extends to the processing of XML data with the help of right-ignoring sequence patterns, by way of general extension via extractor objects. In this context, for comprehensions are useful for formulating queries. These features make Scala ideal for developing applications like web services [3.2].

Scala’s expressive type system enforces, at compile-time, that abstractions are used in a safe and coherent manner. In particular, the type system supports [3.2]:

* Generic classes;
* Variance annotations;
* Upper and lower type bounds;
* Inner classes and abstract type members as object members;
* Compound types;
* Explicitly typed self-references;
* Implicit parameters and conversions;
* Polymorphic methods;

Type inference means the user is not required to annotate code with redundant type information. In combination, these features provide a powerful basis for the safe reuse of programming abstractions and for the type-safe extension of software [3.2].

Scala is designed to interoperate well with the popular Java Runtime Environment (JRE). In particular, the interaction with the mainstream object-oriented Java programming language is as seamless as possible. Newer Java features like SAMs, lambdas, annotations, and generics have direct analogues in Scala. Those Scala features without Java analogues, such as default and named parameters, compile as closely to Java as reasonably possible. Scala has the same compilation model as Java and allows access to thousands of existing high-quality libraries [3.2].

## sbt

The simple build tool (sbt) is used for building Java and Scala projects. Its purpose is to allow users to skillfully perform the basics of building and packaging an application. It gives the developer the freedom to customize as need demands. sbt, at its core, provides a parallel execution engine and configuration system that allow its users to design an efficient and robust script to build the desired software. sbt aims to be consistent in the basic concepts in order to facilitate the creative process. sbt is a highly interactive tool, meant to be used during all stages of the development. It provides interactive help and autocomplete for most services and promotes a type of auto-discovery for builds [3.3]. Its main features are [3.4]:

* Little or no configuration required for simple projects;
* Scala-based build definition that can use the full flexibility of Scala code;
* Accurate incremental recompilation using information extracted from the compiler;
* Continuous compilation and testing with triggered execution;
* Packages and publishes jars;
* Generates documentation with scaladoc;
* Supports mixed Scala/Java projects;
* Supports testing with ScalaCheck, specs, and ScalaTest. JUnit is supported by a plugin;
* Starts the Scala REPL with project classes and dependencies on the classpath;
* Modularization supported with sub-projects;
* External project support;
* Parallel task execution, including parallel test execution;
* Library management support that include inline declarations, external Ivy or Maven configuration files, or manual management;

## Play2

Play is a high-productivity framework for building a wide range of different types of web applications. These are applications that receive requests for data and functionality over HTTP(s). Play aims to make the construction of such applications simple, flexible and intuitive. It incorporates an integrated HTTP Server. It also incorporates a templating framework for the creation of websites and a RESTful web service API for the creation of microservices. It exploits the facilities within the Scala ecosystem, such as Akka, to ensure that the applications developed are scalable and perform well [3.5].

## Akka

Akka is a Scala-based toolkit that simplifies developing concurrent distributed applications. Perfect for high-volume applications that need to scale rapidly, Akka is an efficient foundation for event-driven systems that want to scale elastically up and out on demand, both on multi-core processors and across server nodes. The framework has at its roots the actor model concept in order to raise the abstraction level that decouples the business logic from the low-level constructs of threads, locks and non-blocking I/O. The framework provides the following features [3.6]:

* Concurrency;
* Scalability;
* Fault tolerance;
* Event-driven architecture;
* Transaction support;
* Location transparency;
* Scala/Java APIs;

## Cats

Cats is a library which provides abstractions for functional programming in the Scala programming language. The name is a playful shortening of the word category. Scala supports both object-oriented and functional programming, and this is reflected in the hybrid approach of the standard library. Cats strives to provide functional programming abstractions that are core, binary compatible, modular, approachable and efficient. A broader goal of the mentioned library is to provide a foundation for an ecosystem of pure and typeful libraries [3.7].

## OR-Tools

Google's Operations Research tools is an open source software for combinatorial optimization, which seeks to find the best solution to a problem out of a very large set of possible solutions. OR-Tools includes solvers for [3.8]:

* Constraint programming: a set of techniques for finding feasible solutions to a problem expressed as constraints;
* Linear and mixed-integer programming: the Glop linear optimizer finds the optimal value of a linear objective function, given a set of linear inequalities as constraints;
* Vehicle routing: a specialized library for identifying the best vehicle routes given in constraints;
* Graph algorithms: code for finding shortest paths in graphs, min and max cost flows, and linear sum assignments;

In most cases, problems like these have a vast number of possible solutions, too many for a computer to search them all. In order to overcome this, OR-Tools uses state-of-the-art algorithms to narrow down the variance domain of the problem, in order to find optimal or close to optimal solutions [3.8].

## Docker

Docker is a software platform for building applications based on containers. Containers are small and lightweight execution environments that make shared use of the operating system kernel, but otherwise run in isolation from one another. While containers as a concept have been around for some time, Docker is an open source project launched in 2013. It helped to popularize the technology and drove the trend towards containerization and microservices in software development, that has come to be known as cloud-native development [3.9].

Docker brings the following advantages [3.9]:

* Portability: once a containerized application tested, it can be deployed to any other system where Docker is running;
* Performance: virtual machines are an alternative to containers. The fact that containers do not contain an operating system, whereas virtual machines do, means that containers have much smaller footprints than virtual machines. As a result, containers are faster to create, and quicker to start;
* Agility: the portability and performance benefits offered by containers can help its users to make the development process more agile and responsive;
* Isolation: a container that contains an application also includes the relevant versions of any supporting software that the application requires. If other containers contain applications that require different versions of the same supporting software, that isn't a problem because the different containers are totally independent of one other;
* Scalability: when using multiple containers there are a range of management options for achieving horizontal scaling;

## Gatling

Gatling is a highly capable load testing tool. It is designed for ease of use, maintainability and high performance. It takes advantage of its asynchronous architecture, which allows it to implement virtual users as messages instead of dedicated threads, making running numerous simultaneous virtual users less resource heavy than other solutions. Gatling tests are called simulations. They are written in Scala-files and each class represents its own load simulation. We can assign properties such as the URL, parameters and headers that are needed for the HTTP requests into variables using Gatling HTTP protocol builder [3.10].

# Implementation

In the first part of this section the business logic is presented with the request and response API of the microservice. These are accompanied by the validation tests that also serve as examples. Further on the architecture of the microservice is detailed. The project structure explains each package and their scope. Next the build with sbt and the deployment with Docker are discussed, tearing down the whole process into small steps. Right after the scaling techniques are pointed out. These come accompanied by some resource limitation measures, since they are key to achieve an isolated environment, making each test execution encapsulated. Finally, the load test requests and scenarios are described. The proposed scenarios are benchmarked with different parameters, generating the final results. For that, the reports obtained by the Gatling framework are explained as well.

## Business logic

The implemented microservice serves as the solver module of a planning application. Mainly a general planning application is composed by the following parts:

* An input module, which allows the user to input its preferences. This is usually embedded in the frontend;
* A data loader or fetcher, which gathers all the relevant data to construct the search context from one database or more;
* A solver that is responsible for solving the search context guided by the given user preferences;
* An aggregator that communicates and orchestrates the data loader and the solver, performing the necessary transformations and conversions of data;
* An output module, which is embedded alongside with the input module, displaying the final results to the user;

These modules were identified as a result of the separation of concerns principle and as of need of scaling. Figure x1 helps for a better visualization of the described architecture. As it can be seen each service performs on its own a specific task, being independent from one another. This provides flexibility to the whole application, since individual parts can be scaled horizontally as the demand requires. Obtaining such separation also brings the benefit of not needing to scale the entire infrastructure if one element fails to cope with an increased load.

Further on the solver service is getting detailed as a matter of its functionality. From the data flow perspective, the solver receives data that is already transformed, converted and processed by a higher level microservice, meaning that the only step that it’s left is to solve the given search context. The search context naming is given by the fact that the data is composed of the user’s preferences and the relevant information loaded from the database, forming a so-called context of the search. The communication between the microservices is done via a RESTful API. The solver module accepts a POST operation on the route ‘/solve’ having as an input a Problems json and as an output a Solutions json. Figure x2 and Figure 3x shows the Problems, respective the Solutions API at the end of this subsection. On the right of each field there is a comment, that specifies if the field whether or not is optional. The solver engine supports an input with the lack of constraints and costs, solving a general planification problem. The searchInterval field helps to normalize the solutions costs when performing various scaling scenarios. For example, when a user wants to distribute some operations over one or ten days, then the solutions cost will vary in function of the distribution interval. The horizontal and vertical scaling methods must output the same results for the performance tests, whether the results are returned as a whole or aggregated from parts. Nonetheless this field has no essential role in the internal logic of the distribution engine, being introduced when the scaling methodologies were designed.

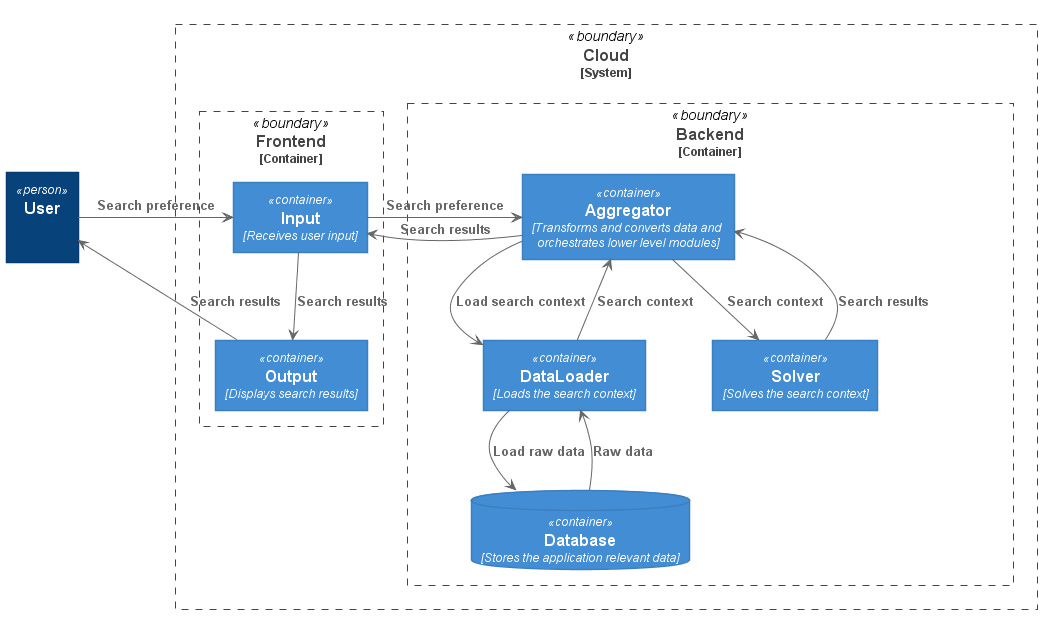


Figure 1: Planning application architecture

From a high-level perspective, the goal of the solver is to solve one or more problems. A problem consists of distributing operations on a given time interval respecting some constraints. The returned solution must ensure an optimum combination of the variance domain, fact that is guided by the search criteria during the evaluation process. The solution contains the operations distributed in time and performed by an eligible resource, and an appreciation factor called cost. The cost reflects how well did the solution perform taking into consideration the specified criteria. The next paragraphs present in detail the input and output of the solver.

The Problems API contains 3 fields from a top down approach: a problem that describes a general problem independent of the duration timeline, an array of dayFrames that place the given problem in specific time intervals, and the mentioned searchInterval. The problem is composed of a key as tracing data of the request, an array of operations, an array of resources susceptible to perform these operations, and two optional fields, constraints, respective costs. An operation is defined by a unique key, a name, a fixed duration and some resource keys that might perform it. A resource has a unique key and a name. The solver supports three kind of costs and these are:

* asSoonAsPossible – seeks to provide a solution that starts as soon as possible relative to the search start time;
* asTightAsPossible – the solution with the minimum total duration is preferred, distributing the operations as tight as possible to each other;
* preferredTimeInterval - favorizes a solution that has its operations between a given time interval that is calculated for each day, since days might differ in length when in UTC distribution;

If no costs are defined by the user, then the search engine will declare the first valid variation of the search domain as the best solution, having a cost of zero. In terms of constraints, the solver implements six and these are:

* operationGrid – operations start and an hour in minutes must be divisible by the grid value;
* sameResource – two or more operations must be performed by the same resource;
* enforcedTimeInterval – all the operations must be in the given time interval, calculated for each day, as same as the preferredTimeInterval cost;
* operationsRelation – a relation must be respected between two operations. The relations can be the following: ends after end, ends after start, ends at end, ends at start, starts after end, starts after start, starts at end, starts after end;
* program – respect the working program of the day in which the solution is;
* disjunctive – the blocked intervals of a resource must be disjunctive with the solution interval of that resource, if chosen;

The last two constraints are enforced by default on the solvers model, while the other four are exposed as optional constraints on the API. The difference between a cost and a constraint is that if a constraint is not respected, then the solution is dropped, while for a cost the solution is just depreciated. A dayFrame contains the start and stop values, the program and the blocked intervals for all the resources of a day. Each dayFrame places the generic problem in different time contexts.

The outputted Solutions API can contain some or none solutions. A solution will contain a cost, a total duration of all the operations in minutes, a day and interval in minutes to specify on which day and in which time interval are the operations distributed and finally an array of operations, each having its time interval and resource defined.

The solver contains a basic model which is capable of distributing operations in time for one day only, providing the best solution by the defined criteria. It is an exemplative model, having a lot of limitations when considering on what time interval can the distribution extend. The solver model and business logic correctness are assured by 33 validation tests. They cover sufficient input cases to approve the fairness of the model. The tests are divided into two groups, input validation tests and solver tests. The first group is focused on the Problems validator, which checks for erroneous and incorrect fields of the input, while the second group tests each cost and constraint of the model separately, assuming that when they are combined the outputted solutions are conform the expectations. These tests can be also taken as examples for elaborating more complicated requests.



Figure 2: Problems API



Figure 3: Solutions API

## Architecture

The project is named planr and is composed of three subprojects: planr-api, planr-core and planr-gatling. The architecture of the solver microservice includes only the first two, the api and the core, while the last module contains the performance test definitions. The api contains the so-called case classes which are the input and output messages of the solver described in the previous subsection, and the main and test service interfaces that are bound to the main controller to expose the ‘/solve’ and the ‘/test’ routes. As a request is captured by the controller, the implementations of the mentioned interfaces are invoked. While the TestService returns a plain ‘OK!’ message to the requester, the SolverService hands over the execution flow to the SolverActor, moment in which a context shift happens from the initial REST thread pool to the solver thread pool. This separation of dispatchers is when the vertical scale intervenes, allowing the developer to configure how much resources should be allocated to the segment in which the heavy computations are done. On the actor side first the solver model is built, creating the variance domain of the search space, the constraints and the cost criteria. Then the model is solved and the available solutions are extracted. The actor then responds to its sender with the best obtained result. The responses from all the actor instances are collected and served back to the initial requester as the final response. The architecture is depicted in Figure x.4.

One reason why the Scala programming language was picked is due to the design too. The shift of execution contexts raises difficulties when working in an environment with mutable states and impure functions. Functional programming guards against bad practices that might occur when concurrency is involved. As a result, vertical scaling can be achieved in a safe and simple manner.

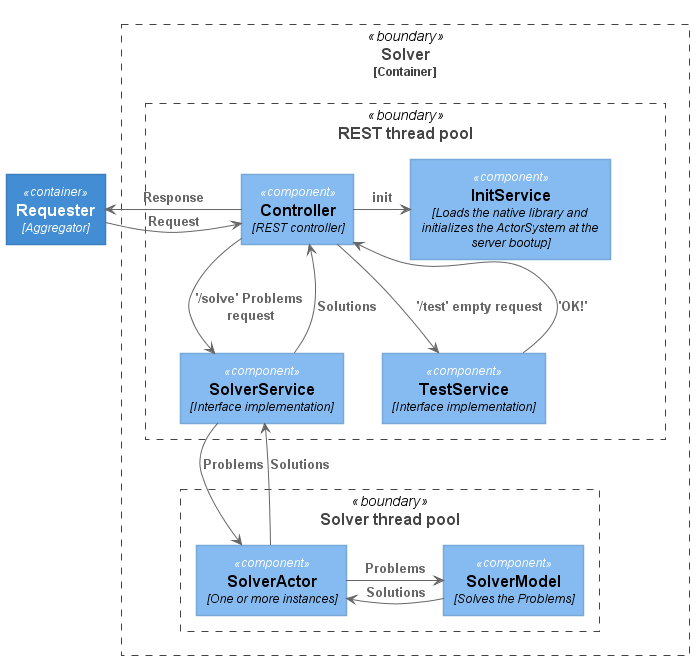
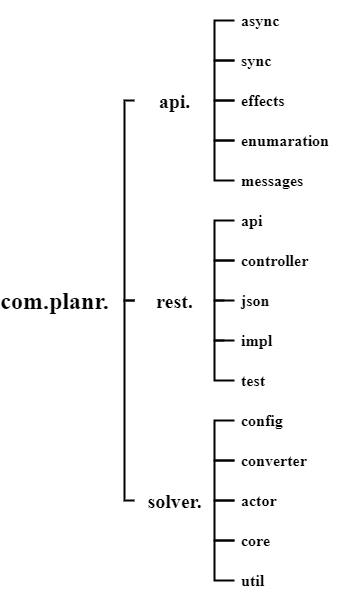


Figure 4: Solver architecture

## Project structure

From a structure perspective, the project ends up having 15 different packages. The files containing classes, objects and enumerations are separated after their responsibilities and by their scopes. It is important to mention that the configurations of the Play2 HTTP server can be found in the conf folder alongside with the logback preferences and the routes definition. The application.conf holds all the necessary properties for the server to bootup, like the scaling parameters for the actors, the published modules for the dependency injection framework and the timeouts. The rest of the files and folders are build and deployment related that is detailed in the upcoming subsection. Figure x.5 represents a tree diagram of the package hierarchy of the project, each node containing the following entities:

- interfaces that are executed asynchronously: the TestService and the SolverService;

- interfaces that are executed synchronously: the InitService;

- type definitions, functional primitives and monad transformers;

- enumeration definitions that are used in the messages package;

- the Error, Problems and Solutions API alongside with the ErrorCodes and the input validation rules;

- the REST API and helpers;

- the controllers such as the TestController and the SolverController;

- serialization primitives and helper functions;

- the async and sync service implementations;

- validation tests;

- the solver model and the cost criteria configurations;

- the SolutionConverter that transforms the data obtained from the model into the Solutions API;

- the SolverActor;

- the definition of the variance domain and the solver model;

- the NativeLibLoader that is meant to load the OR-Tools native library;

Figure 5: Project package structure

## Build and deployment

The build definition can be found in the build.sbt file. This consists of three subprojects, build dependencies, the build and the deployment tasks. This in turn uses settings and config files from the project folder and these are:

* build.properties – specifies the sbt version;
* CompilerSettings.scala – defines the Scala and the Java version of the project, and a list of custom compiler flags and plugins that are meant to avoid bad coding practices;
* plugins.sbt – a list of plugins for the jar assembly, jar unpackaging, Docker deployment, Scala formatting, Play2 server bootup and for the Gatling tests execution;
* PublishingSettings.scala – the developer credentials for publishing the project as a jar on Ivy or Maven;
* RuntimeConfig.scala – the JVM runtime configurations in development mode for debugging, memory limitation, error options and garbage collection policy;
* Settings.scala – general information about the project;
* version.sbt – project release version;

A script file called build.sh contains all the instructions necessary to obtain a planr application packaged in a Docker image. This executes the following commands:

* sbt build – cleans, compiles and test compiles the project. At the end unpacks the OR-Tools native library, that is packaged into a jar and deployed on the local maven repository;
* sbt docker – runs all the validation tests, merges the dependency tree of the planr-api and planr-core subprojects, and assemblies the final runnable jar. Afterwards creates a Docker image file and deploys it to the local Docker. The image creation process involves copying the native library and the runnable jar, and configuring the entry point of the container and the JVM runtime options of the application;

With the Docker plugin, sbt successfully embeds the build in the deployment, making it concise and simple to follow, having only three tasks defined for the whole process.

## Scaling and resource limitation

Planr is designed to support both horizontal and vertical scaling. The first is achieved in the deployment process, while the second by the microservice architecture.

Horizontal scaling is done by declaring four planr instances, placing a load balancer in front of them called Nginx. Nginx intercepts the requests, listening on port 9000 and forwards each of them to one of the available microservice instances, distributing the traffic equally. From a Docker perspective, Nginx is exposed under port 9000, while the planr instances are hidden and accessible only by the load balancer. All the setup can be found in the nginx.conf and the docker-compose.yml config files.

Vertical scaling is achieved by the actor model. The InitService is initialized during the microservice bootup, since it’s published as an eager singleton in the dependency injection framework. During the initialization, the SolverActor gets created, specifying the number of instances and the dimension of the thread pool on which the actor is placed. The SolverActor is published under the actor system that is defined by the Play2 web service API. This actor system follows the application life-cycle and restarts automatically when the application restarts. If the SolverActor from a matter of reasons crashes, it is automatically restarted by the actor system. The actor system is fault-tolerant and successfully implements the ‘Let it crash’ model. The deployment for the vertical scaling is almost the same, declaring only one instance of the microservice. In the end it resumes that the two techniques are achieved by varying the number of instances, actors and allocated resources. The request and actor message distribution are handled by the same Round-robin fashion. While the horizontal scaling contains four planr instances, each having one actor, the vertical scaling contains only one instance and four actors. The allocated resources are the same for both, the distribution being done only in different stages of the build and deployment process. Figure x.6 and x.7 shows the difference between the two deployments each embedding its specific scaling technique.

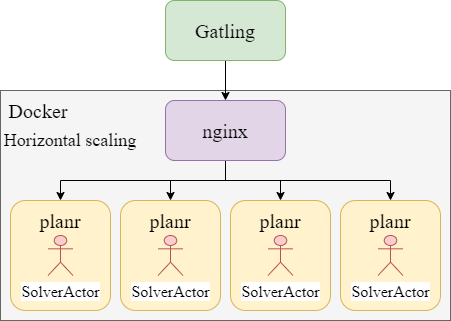


Figure 6: Horizontal scaling

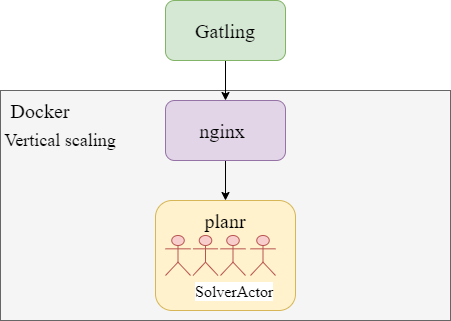


Figure 7: Vertical scaling

+ TODO resource limitation by docker, container and jvm;

## Test scenarios

+ scenario diagram and requests description, gatling report

# Results

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## Initial outcomes

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## Further improvements

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# Conclusions

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## Achievements

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## State of the art comparison

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## Future work

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# Appendix

# A – …

# B – …