

HOBBIT: A Platform for Benchmarking Big Linked Data

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Abstract. An increasing number of solutions aim to support the steady increase of the number of requirements and requests for Linked Data at scale. This plethora of solutions leads to a growing need for objective means that facilitate the selection of adequate solutions for particular use cases. We hence present HOBBIT, a distributed benchmarking platform designed for the unified execution of benchmarks for Linked Data solutions. The HOBBIT benchmarking platform is based on the FAIR principles and is the first benchmarking platform able to scale up to benchmarking real-world scenarios for Big Linked Data solutions. Our online instance of the platform has more than 300 registered users and more than 13000 experiments were executed. It has also been used in eleven benchmarking challenges. We give an overview of the results achieved during 2 of these challenges and point to some of the novel insights that were gained from the results of the platform. HOBBIT is open-source and available at <http://github.com/hobbit-project>.

Keywords: Benchmarking, Big Linked Data

1. Introduction

While the adoption of Linked Data (LD) is increasing steadily, the selection of the right frameworks for a given application driven by this paradigm remains elusive. This is partly due to the lack of (1) large-scale benchmarks for most steps of the LD life cycle [1] and (2) scalable benchmarking platforms able to generate uniform comparable evaluation results for the technologies which deal with this type of data [2]. The usefulness of benchmarks for characterising the performance of families of solutions has been clearly demonstrated by the varied benchmarks made available over recent decades [2–5]. For example, the TPC family of benchmarks is widely regarded as having provided the foundation for the development of efficient relational databases [3]. Modern examples of benchmarks that have achieved similar effects include the QALD [4] and BioASQ [5] benchmarks, which have successfully contributed to enhancing the performance of question answering systems over LD and in the bio-medical domain respectively. Modern benchmarking platforms have also contributed to the comparability of measurements used to evaluate the performance of systems. For example, benchmarking platforms such as BAT [6], GERBIL [2] and IGUANA [7] provide implementations and corresponding theoretical frameworks to benchmark different aspects of the LD life cycle in a consistent manner. Still, none of these benchmarking platforms can scale up to the requirements of modern applications.

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The main contribution of this paper is the HOBBIT (Holistic Benchmarking of Big Linked Data) platform. HOBBIT was designed to accommodate the benchmarking of Big LD applications, i.e., applications driven by LD that exhibit Big Data requirements as to the volume, velocity and variety of data they process [8]. The platform was designed with extensibility in mind. Thus, its architecture is modular and allows the benchmarking of any step of the LD life cycle.¹ The comparability of results was the second main design pillar. Consequently, HOBBIT abides by the FAIR principles [9]. The practical usability of the platform was ensured by its use in 11 challenges between 2016 and 2019 (e.g., [10–19]). HOBBIT is open-source and can be installed deployed locally, on a local cluster and on computing services such as Amazon Web Services (AWS). Additionally, we offer an online instance of the platform deployed on a cluster and available for experimentation.² In this paper, we focus on the architecture of the platform and summarise the results of the evaluation campaigns carried out with the platform.

The rest of this paper is structured as follows: We begin by giving an overview of the state of the art in benchmarking LD. Thereafter, we present requirements to the benchmarking platform that were gathered from 68 experts in an open survey. We used these requirements to derive the architecture for the platform. We demonstrate the use of the platform by showing how it can be applied to benchmark a knowledge extraction framework along the axes of accuracy and scalability—a dimension that was not considered in previous benchmarking efforts. Finally, further experimental results gathered through the platform are summarised.

2. Related Work

The work presented herein is mostly related to benchmarking platforms for Linked Data/RDF-based systems. Several benchmarks have been developed in the area of linking RDF datasets [20]. A recent detailed comparison of instance matching benchmarks can be found in [21]. The authors show that there are several benchmarks using either real or synthetically generated datasets. SEALS³ is the best-known platform for benchmarking link discovery frameworks. It offers the flexible addition of datasets and measures for benchmarking link discovery. However, the platform was not designed to scale and can thus not deal with datasets which demand distributed processing.

For a large proportion of existing benchmarks and benchmark generators (e.g., LUBM [22], BSBM [23], DBSBM [24] and FEASIBLE [25]), the focus has commonly been on creating frameworks able to generate data and query loads [22–25] able to stress triple stores. IGUANA [7] is the first benchmarking framework for the unified execution of these data and query loads. However, like the platforms aforementioned, IGUANA does not scale up to distributed processing and can thus not be used to benchmark distributed solutions at scale.

Knowledge Extraction—especially Named Entity Recognition and Linking—has also seen the rise of a large number of benchmarks [2]. Several conferences and workshops aiming at the comparison of information extraction systems (including the Message Understanding Conference [26] and the Conference on Computational Natural Language Learning [27]) have created benchmarks for this task. In 2014, Carmel et al. [28] introduced one of the first Web-based evaluation systems for Named Entity Recognition and Linking. The BAT benchmarking framework [6] was also designed to facilitate benchmarking based on these datasets by combining seven Wikipedia-based systems and five datasets. The GERBIL

¹Code and dataset generators available at <http://github.com/hobbit-project>. Project homepage at <https://project-hobbit.eu/>.

²<http://master.project-hobbit.eu>

³<http://www.seals-project.eu/>

framework [2] extended this idea by being knowledge-base-agnostic and addressing the NIL error problem in the formal model behind the BAT framework. While these systems all allow for benchmarking knowledge extraction solutions, they do not scale up to the requirements of distributed systems.

In the area of Question Answering using Linked Data, challenges such as BioASQ [5], and the Question Answering over Linked Data (QALD) [29] have aimed to provide benchmarks for retrieving answers to human-generated questions. The GERBIL-QA platform [30] is the first open benchmarking platform for question answering which abides by the FAIR principles. However, like its knowledge extraction companion, it is not designed to scale up to large data and task loads.

A few frameworks have aimed to tackle benchmarking in a generic fashion. For example, the Peel framework⁴ supports the automation of experiments on Big Data infrastructure. However, the framework only supports systems that can be executed on one of the supported Big Data solutions like Flink or Spark.⁵ Moreover, it does not support a large portion of the specific requirements for benchmarking Big LD described in Section 3. A major drawback is that the results generated by the platform are not transparent as the execution of systems and benchmarks is hidden from the users. This makes a comparison of the resources used by benchmarked systems impossible. Similar observations hold for Plug and Play Bench [31], which was designed to evaluate different hardware settings. Also relevant according to the literature are novel Big Data benchmarks for benchmarking relational databases (e.g., BigBench [32] and [33]). However, these benchmarks are limited to one step of the data life cycle and are not benchmarking platforms.

Table 1
Comparison of benchmarking frameworks

	Year	Extraction	Storage	Manual Revision	Linking	Enrichment	Quality Analysis	Evolution	Exploration	Scalable Data	Scalable Tasks	Fair Benchmarking
BAT	2013	✓	—	—	—	—	—	—	—	—	—	—
GERBIL	2014	✓	—	—	—	—	—	—	—	—	—	✓
IGUANA	2017	—	✓	—	—	—	—	—	—	✓	✓	—
OLTP Bench	2013	—	—	—	—	—	—	—	—	✓	✓	—
HOBBIT	2017	✓	✓	—	✓	✓	(✓)	✓	✓	✓	✓	✓

The HOBBIT platform is the first benchmarking framework which supports all steps of the LD life cycle which can be benchmarked automatically (see Table 1).⁶ In addition, it is the first benchmarking platform for Linked Data which scales up to the requirements of Big Data platforms through horizontal scaling. The comparability of HOBBIT's benchmarking results are ensured by the cluster underlying the open instantiation of the platform.⁷

⁴<http://peel-framework.org>

⁵The complete list can be found at <https://github.com/peelframework/peel#supported-systems>.

⁶We are not aware of the existence of an automatic benchmark for the quality analysis step. However, the platform itself would support such a benchmark.

⁷See <http://master.project-hobbit.eu>.

1 3. Requirements 1

2 We adopted a user-driven approach to develop our platform. The core requirements were mainly de-
 3 rived from the survey in [34], which had 68 expert participants. To distinguish them from the FAIR
 4 principles, we will abbreviate these user requirements with **Ux**.
 5

6 3.1. Functional requirements 6

- 8 **U1** The main functionality of the platform is the execution of benchmarks.
 9
- 10 **U2** Benchmark results should be presented in human- and machine-readable form.
 11
- 12 **U3** It should be possible to add new benchmarks and new systems.
 13
- 14 **U4** The platform should offer repeatable experiments and analysis of results.
 15
- 16 **U5** The key performance indicators (KPIs) should include the effectiveness, e.g., the accuracy, and
 17 the efficiency, e.g., runtime of systems.
 18
- 19 **U6** The platform should be able to measure the scalability of solutions, i.e., the scalable generation
 20 of data the evaluation is based on as well as tasks a system must execute.
 21
- 22 **U7** The platform should support the benchmarking of distributed systems.
 23
- 24 **U8** It should support the execution of challenges.
 25

26 These functional requirements predefined the corner stones for the platforms architecture. In Section 4,
 27 it will be shown how the platform fulfils each of them.
 28

29 3.2. Qualitative requirements 29

- 30 **U9** The benchmarks should be easy to use and interfaces provided should be as simple as possible.
 31
- 32 **U10** The platform should support different programming languages.
 33
- 34 **U11** The results should be archived safely for later reference.
 35
- 36 **U12** The platform needs to be robust regarding faulty benchmarks or systems.
 37

38 We derived the degree of modularity and the error handling of the platform from these requirements
 39 (**U1**, **U3–U12**). The result analysis component and interfaces were designed to accommodate **U2** and
 40 **U9–U12**. Details are provided in Section 4.
 41

42 3.3. FAIR principles 32

- 43 From the beginning on, the platform was build to support the FAIR principles [9].⁸
 44
- 45 **F1** (Meta)data are assigned a globally unique and persistent identifier.
 46
 - 47 **F2** Data are described with rich metadata (defined by R1 below).
 48
 - 49 **F3** Metadata clearly and explicitly include the identifier of the data they describe
 50
 - 51 **F4** (Meta)data are registered or indexed in a searchable resource.
 52
 - 53 **A1** (Meta)data are retrievable by their identifier using a standardised communications protocol.
 54
 - 55 **A1.1** The protocol is open, free, and universally implementable.
 56
 - 57 **A1.2** The protocol allows for an authentication and authorisation procedure, where necessary.
 58
 - 59 **A2** Metadata are accessible, even when the data are no longer available.
 60

46 ⁸<https://www.go-fair.org/fair-principles/>

I1 (Meta)data use a formal, accessible, shared, and broadly applicable language for knowledge representation.

I2 (Meta)data use vocabularies that follow FAIR principles.

I3 (Meta)data include qualified references to other (meta)data.

R1 Meta(data) are richly described with a plurality of accurate and relevant attributes.

R1.1 (Meta)data are released with a clear and accessible data usage license.

R1.2 (Meta)data are associated with detailed provenance.

R1.3 (Meta)data meet domain-relevant community standards.

The FAIR principles are focusing on data management. Thus, not all of them can be solely realised by the implementation of the platform. There are principles—e.g., **R1.1**—which are at least partly in the responsibility of the organisation hosting the platform. However, the following section shows the design of the HOBBIT platform and how it supports the FAIR principles.

4. Platform Architecture

4.1. Overview

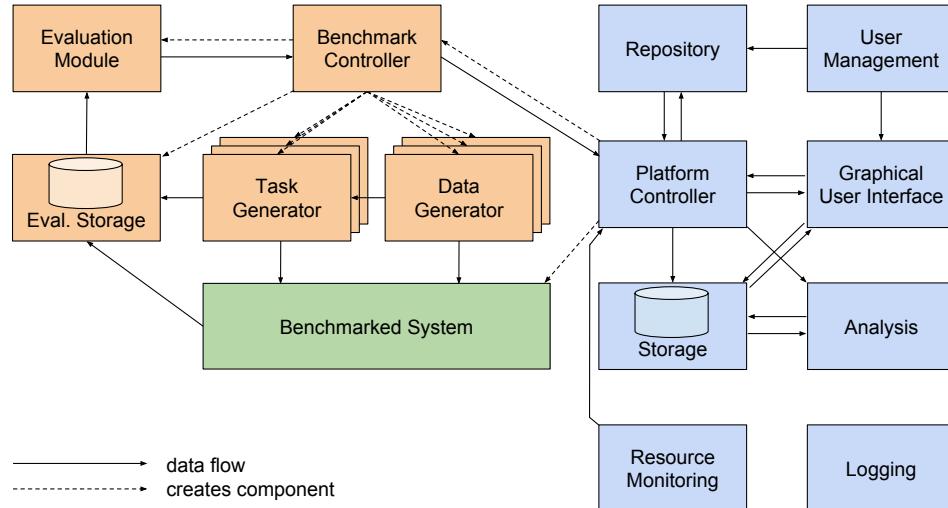


Fig. 1. Architecture of the HOBBIT platform

Figure 1 gives an overview of the architecture of the HOBBIT platform. The platform is based on a container architecture, i.e., the components are implemented as independent containers. This eases the adding of new benchmarks and systems (**U3**) which can be implemented using different languages (**U10**). Additionally, it eases the development and maintenance of the platform itself and adds a separation between the platform, benchmark and system containers, thus limiting the influence of faulty program code to its container instead of decreasing the stability of the whole platform (**U11**, **U12**). Using containers for benchmark and system components also gives the possibility of scaling both by offering the deployment of additional containers across multiple machines (**U6**, **U7**). The communication

between these components is ensured by means of a message bus. Choosing this established communication method eases the implementation of benchmarks and systems based on different programming languages (**U9, U10**).

4.2. Platform Components

The platform has several components (see blue elements in Figure 1). They offer the main functionality of the platform.

4.2.1. Platform Controller

The platform controller is the central component of the HOBBIT platform. Its main role is to coordinate the interaction of other components as needed. This mainly includes handling requests that come from the user interface component, starting and stopping of experiments, observing the health of the cluster and triggering the analysis component. In addition, the controller manages a priority queue that contains user-configured experiments that are to be executed in the future. The execution order of experiment configurations is determined using (1) the time at which they have been configured by the user (following the first-in-first-out principle) and (2) the priority of experiments, which is derived from whether the said experiment is part of a scheduled challenge (higher priority) or not (**U8**). The internal status of the platform controller is stored in a database. This enables restarting the controller without losing its current status, e.g., the content of the experiment queue.

The platform controller uses features of Docker Swarm to observe the status of the cluster that is used to execute the experiments. E.g., if one of the nodes drops out of the cluster, the comparability between single experiments might not be given (**U4**). Thus, the platform controller needs to be aware of the number of working nodes that are available for the experiment. If there is no running experiment and the queue is not empty, the platform controller initiates the execution of an experiment and observes its state. If the experiment takes more time than a configured maximum, the platform controller terminates the benchmark components and the system that belongs to the experiment. By these means, it also ensures that faulty benchmarks or systems cannot block the platform (**U12**).

4.2.2. Storage

The storage component contains the experiment results and configured challenges. It comprises two containers—a triple store that uses the HOBBIT ontology to describe results and a handler for the communication between the message bus and the triple store. The storage component offers a public SPARQL endpoint with read-only access which can be queried via HTTP/HTTPS (**U2, F4, A1**).⁹ The write access is limited to the platform controller, the user interface and the analysis component. The controller stores experiment results and manages running challenges. The user interface presents the available data to the user and enables the configuration of new challenges as well as the registration of systems for taking part in a challenge (**U8**). The analysis component requests experiment results from the storage and stores results of the analysis.

4.2.3. Ontology

The experiment results, the metadata of experiments and challenges as well as the results of the analysis component are stored as RDF triples [35] (**I1**). Where possible, we used established RDF vocabularies

⁹Our endpoint can be found at <https://db.project-hobbit.eu/sparql>.

(I2, R1.3).¹⁰ However, for describing the experiments and challenges in detail we created the HOBBIT ontology.¹¹

The ontology offers classes and properties to define the metadata for the single benchmarks and benchmarked systems. For each benchmark or system a user would like to use within the platform, a metadata file has to be provided containing some general information. This includes the definition of a URI for each benchmark and system (F1), a name, a description and a URI of the API offered by the benchmark and implemented a system. Based on the API URI the platform can map the available systems to the benchmarks to make sure that the system is applicable for a given benchmark.

Additionally, a benchmarks metadata include parameters and KPIs. The parameter can be defined to be configurable through the user interface when starting an experiment and whether the parameter should be used as feature in the analysis component.

A systems metadata offers the definition of several system instances with different parameterisations. The analysis method can make use of the different parameter values of the instances to measure the impact of the parameters on the KPIs.

Experiments are described with triples regarding (1) provenance, (2) the experiment results, (3) the benchmark configuration and (4) benchmark as well as (5) system metadata (F2, F3, I3, R1, R1.2). The provenance information covers the start and end time of the experiment as well as details about the hardware on which the experiment has been executed. The experiment results are generated by the implementation of the benchmark and typically contain results for the single KPIs which are defined in the benchmarks metadata. Together with the metadata of the benchmark and system, the description of the KPIs and their description are used by the analysis component (U4). The platform controller assigns a URI to the experiment (F1) and copies the configuration of the benchmark as well as the metadata of the benchmark and system into the experiments metadata. Note that this makes sure that even if a user removes a benchmark or system from the platform after executing an experiment their metadata is still available (A2).

Challenges which are carried out on the platform are modelled by separating them into single tasks. Each task has a benchmark with a certain parameterisation and users can register their systems for the single tasks to take part in the challenge. A challenge and its tasks have a generated URI (F1) and come with a label as well as a description. Additionally, the creator of the challenge can define the execution date and the publication date of the challenge as well as a link to a web page giving further information about the challenge. The first date defines the point in time at which the execution of the single experiments of the challenge should start while the latter defines the day at which the results should be made public. The experiments that are part of a challenge, point to the challenge task for which they have been executed (I3).

Essentially, the ontology offers classes and properties to store the configuration and the results of an experiment. URIs are assigned to benchmarks, benchmarked software systems, and KPIs. Moreover, benchmark configurations as well as benchmark and system features, e.g., a certain parameterization, can be described. In addition to experiments, the ontology allows for the description of challenges, tasks in challenges and benchmarks associated with these tasks.

4.2.4. Analysis

This component is triggered after an experiment has been carried out successfully. Its task is to enhance the benchmark results by combining them with the features of the benchmarked system(s) and

¹⁰Namely, RDF [36], PROV-O [37], Data Cube [38] and XSD [39].

¹¹The formal specification of the ontology can be found at <https://github.com/hobbit-project/ontology>.

the data or task generators. This combination can lead to additional insights, e.g., strengths and weaknesses of a certain system (**U4**). While the component uses the results of benchmarks, it is modelled independently from any benchmark implementation.

4.2.5. Graphical User Interface

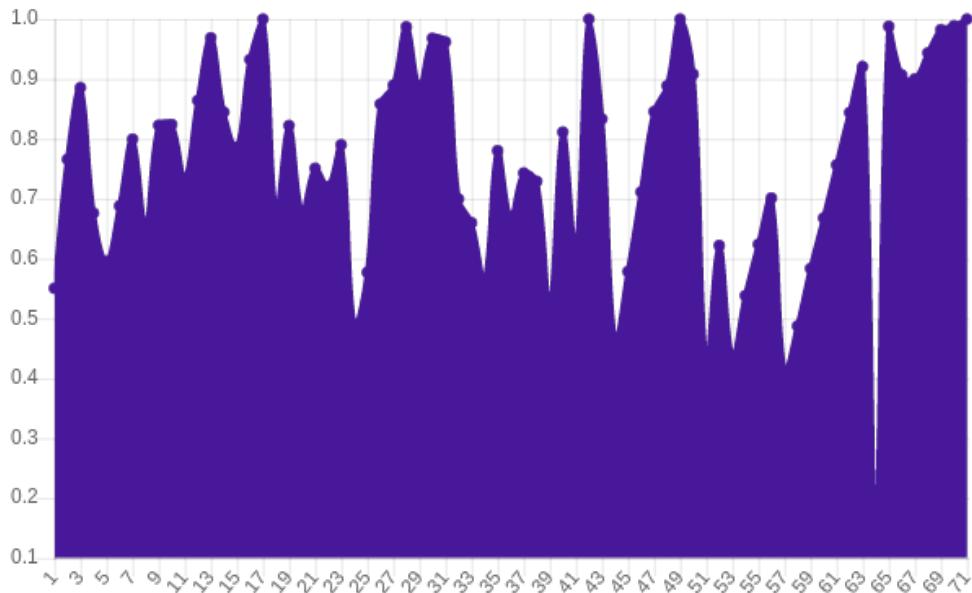


Fig. 2. An example of a plot generated for a KPI. It shows the F1-measure the Jena Fuseki triple store achieved for 71 consecutive select queries during a run of the Odin benchmark [11].

The graphical user interface component handles the interaction with the user via HTTP/HTTPS (**A1**). It retrieves information from the user management that allows different roles enabling the user interface to offer functionality for authenticated users as well as a guest role for unauthenticated users. For example, a guest is only allowed to read the results of experiments and analysis (**U2**). Since the number of experiments is steadily increasing, the user interface offers a filter and sorting mechanism to increase the findability (**F4**). Experiments are currently visualized as table containing their metadata, the parameter values and the KPI values. This table view can also be used to compare several experiments with each other. Additionally, plots as shown in Figure 2 are generated where applicable.¹²

Authenticated users have additional rights ranging from starting experiments to organising challenges, i.e., define experiments with a certain date at which they will be executed (**U1, U8**).

Additionally, experiments and challenges have dereferencable URIs assigned, i.e., a user can copy the URI of an experiment or a challenge into the browsers URL bar and the server shows the details of this resource (**F1, A1**). For our online instance, we offer w3id URIs to enable static URLs that can be redirected.¹³

For each benchmark, a report can be generated. This comprises (1) a brief overview over the results of the last experiments carried out with the benchmark, (2) scatter plots that compare values of features

¹²The example is part of the experiment <https://w3id.org/hobbit/experiments#1540829047982>.

¹³See <https://w3id.org/>.

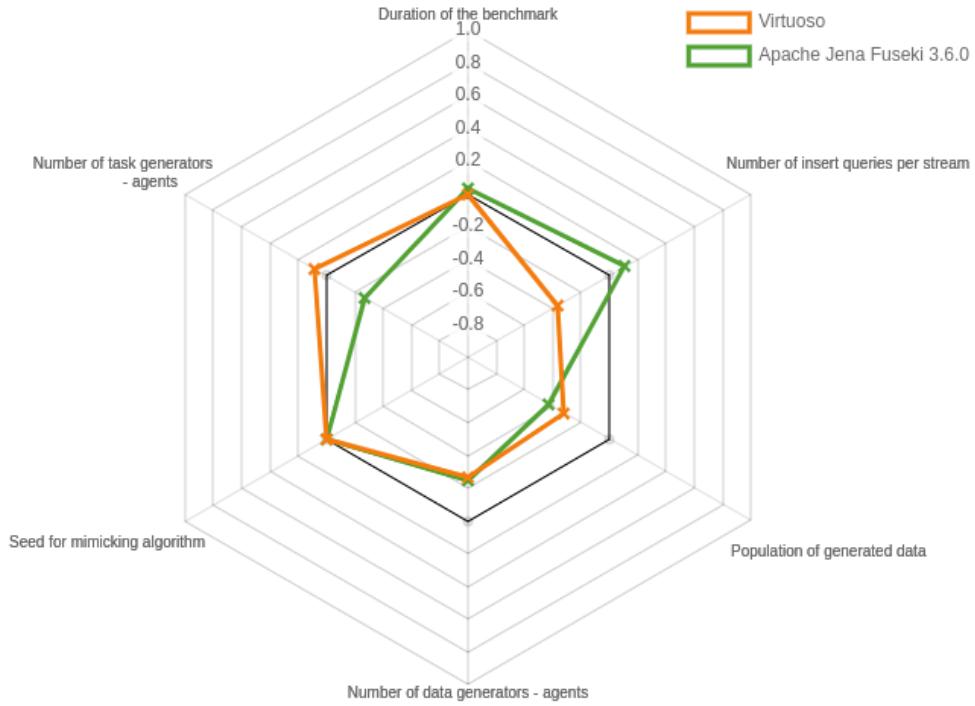


Fig. 3. An example of a diagram showing the Pearson correlations between the different parameters of the Odin benchmark [11] and the micro F1-measure achieved by the two triples stores Virtuoso and Jena Fuseki.

and KPIs as well as (3) plots showing the correlation between benchmark features and the performance achieved by the single systems. Such a plot is shown in Figure 3.

If the license of the data has been configured in the triple store, the information is shown in the user interface (**R1,1**). The data of our online instance is licensed under the Creative Commons Attribution 4.0 International Public License¹⁴.

4.2.6. Message Bus

This component contains the message bus system. Three different communication patterns are used. Firstly, labelled data queues simply forward data, e.g., the data generated by the mimicking algorithm is transferred from several data generators to several task generators. The second pattern works like remote procedure calls. The queue has one single receiving consumer that executes a command, e.g., a SPARQL query, and sends a response containing the result. Thirdly, a central broadcasting queue is used (`hobbit.command`). Every component connected to this queue receives all messages sent by one of the other connected components. This queue is used to connect the loosely coupled components and orchestrate their activities.

4.2.7. User Management

The user management relies on Keycloak.¹⁵ It allows the upload of private systems which can not be seen by other users. Additionally, the platform makes use of different user roles to enable single users to

¹⁴License: <https://creativecommons.org/licenses/by/4.0/legalcode>. The license statement of our online instance can be found at <https://master.project-hobbit.eu/home>

¹⁵<https://www.keycloak.org/>

create challenges. Note that the user management offers a guest role that enables unregistered users to see the publicly available experiment results.

4.2.8. Repository

The repository contains all available benchmarks and systems. For our online instance, the repository is a Gitlab¹⁶ instance which can be used by registered users to upload Docker images and define the metadata of their benchmarks and systems (U3, R1.3). Note that the user can define the visibility of his system, i.e., the platform supports publicly accessible systems and benchmarks that can be used by every other registered user as well as private systems. However, the experiment results (including the systems metadata) will always be made public.

4.2.9. Resource Monitoring

The resource monitoring component uses Prometheus¹⁷ to collect information about the hardware resources used by the benchmarked system. The benchmark can request this information to include it into its evaluation. At the moment, the CPU time, the disk space and the amount of RAM used by the system can be monitored. Based on the architecture of Prometheus, this list of metrics can be further extended.

4.2.10. Logging

The logging comprises three components—Logstash¹⁸, Elasticsearch¹⁹ and Kibana.²⁰ While Logstash collects the log messages from the single components, Elasticsearch is used to store them inside a fulltext index. Kibana offers the user interface for accessing this index. The logs are kept private. However, owners of systems or benchmarks can download the logs of their components from the user interface.

4.3. Benchmark Components

These components are part of given benchmarks and have been colored orange in Figure 1. Hence, they are instantiated for a particular experiment and are destroyed when the experiment ends. A benchmark execution has three phases—an initialisation phase, a benchmarking phase and an evaluation phase. The phases are described in more detail in section 4.5. It should be noted that the components described in this section represent our suggestion for the structure of a benchmark. However, the HOBBIT platform supports a wide range of possible benchmark structures as long as a benchmark implements the necessary API to communicate with the platform controller.

4.3.1. Benchmark Controller

The benchmark controller is the central component of a benchmark. It communicates with the platform controller and it creates and controls the data generators, task generators, evaluation-storage and evaluation-module.

4.3.2. Data generator

Data generators encapsulate algorithms able to generate the data needed for given benchmarks. Importantly, data generators can be run in a distributed fashion to ensure that the platform can create the necessary data volumes or data velocity. Typically, data generators are created by the benchmark

¹⁶<https://about.gitlab.com/>

¹⁷<https://prometheus.io/>

¹⁸<https://www.elastic.co/de/products/logstash>

¹⁹<https://www.elastic.co/de/products/elasticsearch>

²⁰<https://www.elastic.co/de/products/kibana>

1 controller and configured using benchmark-specific parameters. They generate data based on the given
 2 parameters and send said data to the task generators as well as to the system adapter and terminate when
 3 the required data has been created.

4 4.3.3. Task generator

5 Task generators get data from data generators, generate tasks that can be identified with an ID and
 6 send these IDs to the system adapter. Each task represents a single problem that has to be solved by the
 7 benchmarked system (e.g., a SPARQL query). The expected response for the generated task is sent to
 8 the evaluation storage. Like data generators, task generators can be scaled to run in a distributed fashion.

9 4.3.4. Evaluation storage

10 This component stores the gold standard results as well as the responses of the benchmarked system
 11 during the benchmarking phase. During the evaluation phase it sends this data to the evaluation module.
 12 Internally, the output of a benchmark is stored as a set of key-value pairs. Task IDs are used as key. Each
 13 value comprises (1) the expected result, (2) the result calculated by the benchmarked system as well as
 14 (3) the timestamp at which the task was sent to the system by a task generator and (4) the timestamp at
 15 which the response was received by the evaluation storage.

16 4.3.5. Evaluation Module

17 The evaluation module is created by the benchmark controller at the beginning of the evaluation phase
 18 and requests results from the evaluation storage. It evaluates them by computation the KPIs associated
 19 with the benchmark, summarizes the evaluation results and sends them to the benchmark controller
 20 before it terminates.

21 4.4. Benchmarked System Components

22 Each system to be benchmarked using the HOBBIT platform has to implement the API of the bench-
 23 mark to be used and the API of the platform. Since systems are typically not developed for the mere sake
 24 of being benchmarked with our platform, each system is usually connected to the platform by means of
 25 a system adapter container. The system adapter serves as a proxy translating messages from the HOBBIT
 26 platform to the system to be benchmarked and vice versa. The system adapter of each of the systems to
 27 benchmark is instantiated by the platform controller when an experiment is started. Adapters can create
 28 additional containers that might contain components of the benchmarked system. Thereafter, they send
 29 a ready signal to the platform controller to indicate that they are ready to be benchmarked. They receive
 30 incoming data and tasks, forward them to the system and send its responses to the evaluation storage.
 31 Adapters stop the benchmark system and terminate after they receive a command indicating that all tasks
 32 have been completed.

33 4.5. Benchmark Workflow

34 Since the platform was designed for executing benchmarks (**U1**), we defined a typical workflow of
 35 benchmarking a Big LD system. The workflow is abstracted to make sure that it can be used for bench-
 36 marking all steps of the LD life cycle steps. Figure 4 shows a sequence diagram containing the steps
 37 as well as the type of communication that is used. Note that the orchestration of the single benchmark
 38 components is part of the benchmark and can be different across different benchmark implementations.

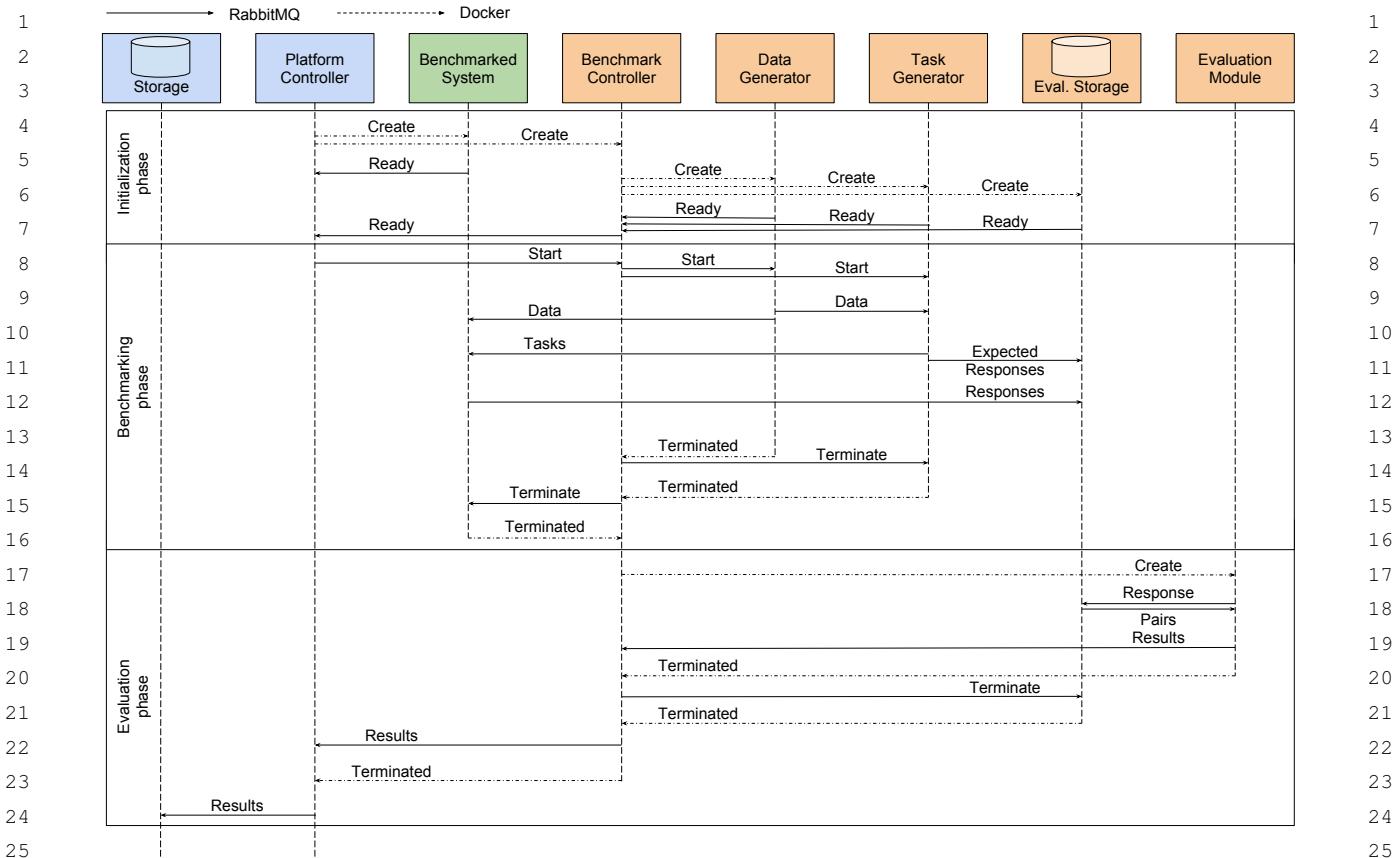


Fig. 4. Simplified overview of the general benchmarking workflow. The system as well as the user interface are left out and the benchmark controller creates other containers directly, without sending requests to the platform controller.

4.5.1. Initialisation Phase

At the beginning of the benchmarking process, the platform controller makes sure that a benchmark can be started. This includes a check to make sure that all hardware nodes of the cluster are available. The platform controller then instantiates the system adapter. The said adapter first initializes, then starts the system to be benchmarked and makes sure that it is working properly. Finally, the adapter sends a message to the platform controller to indicate that it is ready. Once the system adapter has been started, the platform controller generates the benchmark controller. The task of the benchmark controller is to ensure that the data and tasks for a given benchmark are generated and dispatched according to a given specification. To achieve this goal, the controller instantiates the data and task generators as well as the evaluation storage. It then sends a message to the platform controller to indicate that it is ready.

4.5.2. Benchmarking Phase

The platform controller waits until both the system adapter and the benchmark controller are ready before starting the benchmarking phase by sending a start signal to the benchmark controller which starts the data generators. The data generators start the data generation algorithms to create the data that will underlie the benchmark. The data is sent to the system adapter and to the task generators. The task generators generate the tasks and send them to the system adapter, which triggers the required processing

of the data in the system. The system response is forwarded to the evaluation storage by the system adapter. The task generators store the corresponding expected result in the evaluation storage. After the data and task generators finish their work, the benchmarking phase ends and both the generators and the system adapter terminate.

4.5.3. Evaluation Phase

During the evaluation phase, the benchmark controller creates the evaluation module. The evaluation module loads the results from the evaluation storage. This is done by requesting the results pairs, i.e., the expected result and the result received from the system for a single task, from the storage. The evaluation module uses these pairs to evaluate the system's performance and to calculate the KPIs. The results of this evaluation are returned to the benchmark controller before the evaluation module and storage terminate. The benchmark controller adds information for repeating the experiment, e.g., its parameters, to the evaluation results, sends them to the platform controller and terminates. Note that this makes sure that all the data is still available, although the benchmark or the benchmarked system are deleted from the servers (**A2**). After the benchmark controller has finished its work, the platform controller can add additional information to the result, e.g., the configuration of the hardware, and store the result. Following this, a new evaluation can be started. The platform controller sends the URI of the new experiment result to the analysis component. The analysis component reads the evaluation results from the storage, processes them and stores additional information in the storage.

Importantly, the platform allows for other orchestration schemes. For example, it is possible to generate all the data in a first step before the task generators start to generate their tasks based on the complete data. In another variation, the task generators can also be enabled to generate a task, wait for the response of the system and then send the subsequent task.

5. Evaluation

The HOBBIT platform has already been used successfully in a large number of challenges (see Section 6). Still, we evaluated our architecture in two different respects. First, we simulated benchmarking triple stores using HOBBIT. These experiments had two goals. First, we wanted to prove that the HOBBIT platform can be used on single, lightweight hardware (e.g., for development purposes or for benchmarks where the scalability and runtime are not of importance) as well as in a distributed environment. Second, we wanted to evaluate the throughput of storage benchmarks. In addition, we benchmarked several knowledge extraction tools and studied the runtime performance of these systems for the first time.

5.1. Triple store benchmark

To configure our simulation, we derived message characteristics from real data using the Linked SPARQL Queries Dataset [40]—a collection of SPARQL query logs. This collection of real query logs suggests that (1) the average length of a SPARQL query has a length of 545.45 characters and (2) the average result set comprises 122.45 bindings. We assumed that the average size of a single result is 100 characters leading to a result set size of approximately 12,200 characters which is created for every request by our triple store simulation.

Table 2
Platform benchmark results on a single machine (1 – 3) and a cluster (4, 5).

Experiments	Exp. 1	Exp. 2	Exp. 3	Exp. 4	Exp. 5
Data generators	2	2	2	1	3
Task generators	1	1	1	1	1
Queries	1,000	2,000	5,000	100,000	300,000
Avg. query runtime (in ms)	7,058	17,309	33,561	38,810	59,828
Query runtime std. dev.	686	4,493	3,636	22,517	24,540
Overall runtime (in s)	11.2	32.4	51.5	2,086	2,536
Queries per second (avg.)	44.9	31.0	48.6	865.1	774.2

The platform was deployed on a small machine²¹ and on a server cluster.²² The single benchmark runs are shown in Table 2. We executed the benchmark with three different numbers of queries on the smaller machine and two larger numbers of queries on the cluster. Our results show that the platform can run even on the minimalistic single machine chosen for our evaluation. Hence, the HOBBIT platform can be used locally for smoke tests and development tests. In addition, our results also clearly indicate the need for a platform such as HOBBIT by pointing to the necessity to deploy benchmarking platforms in a large-scale environment to test some of the Big LD systems. Experiments with 5000 queries run on the small machine clearly show an increase in the average runtime per query and the standard deviation of the query runtimes due to a traffic jam in the message bus queues. In contrast, our results on the cluster show that we are able to scale up easily and run 20 times more queries per second than on the single machine.

5.2. Knowledge Extraction benchmark use case

For our second evaluation, we used Task 1B of the Open Knowledge Extraction challenge 2017 [12] as use case. This task comprises the problem of spotting named entities from a given text and linking them to a given knowledge base. All experiments were run on our cluster. We benchmarked the following named entity recognition tools: (1) FOX [41], (2) the Ottawa Baseline Information Extraction (Balie) [42], (3) the Illinois Named Entity Tagger (Illinois) [43], (5) the Apache OpenNLP Name Finder (OpenNLP) [44], (5) the Stanford Named Entity Recognizer (Stanford) [45], and (6) DBpedia Spotlight (Spotlight) [46]. The entities that were found in the text by any of the tools are linked to a given knowledge base using AGDISTIS [47]. In our experiment, we used DBpedia 2015²³ as the reference knowledge base.

The aim of the benchmark was to measure the scalability and the accuracy of these systems under increasing load, an experiment which was not possible with existing benchmarking solutions. We used a gold standard made up of 10,000 documents generated using the BENGAL generator²⁴ included in the HOBBIT platform. The evaluation module was based on the evaluation used in [12] and measured

²¹Dual Intel Core i5 , 2.5 GHz, 2 GB RAM

²²1 master server (1xE5-2630v4 10-cores, 2.2GHz, 128GB RAM) hosting platform components (including RabbitMQ message broker), 1 data server (1xE5-2630v3 8-cores, 2.4GHz, 64GB RAM) hosting storages, 6 nodes (2xE5-2630v3 8-cores, 2.4GHz, 256GB RAM) divided into two groups hosting either components of the benchmark or the benchmarked system.

²³<http://dbpedia.org>

²⁴<http://github.com/dice-group/bengal>

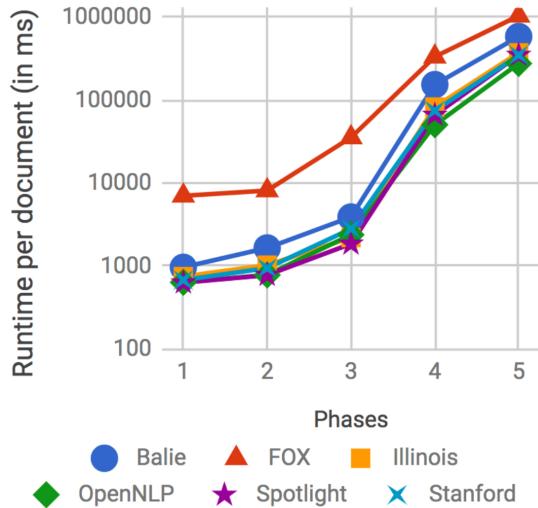


Fig. 5. Average runtime per document achieved by systems during the different phases.

the runtime for single documents as well as the result quality in terms of micro-precision, recall and F1-measure. We used 1 data and 1 task generator for our benchmark. The data generator was configured to run through 5 velocity phases (2000 documents/phase) with differing delays between single documents in each phase. The delays between the documents were set to $\{1s, \frac{1}{2}s, \frac{1}{4}s, \frac{1}{8}s, 0s\}$ leading to an increasing workload of $\{1, 2, 4, 8, \approx 800\}$ documents per second.

The results show that all approaches scale well when provided with enough hardware. As expected, FOX is the slowest solution as it relies on calling 5 underlying fully-fledged entity recognition tools and merging their results. Our results also indicate that a better load balancing could lead to even better runtimes. In particular, the runtime per documents starts to increase as soon as the tool cannot handle the incoming amount of documents in time and the documents start to be queued (see Phase 2 to 4).

6. Application

The HOBBIT platform is now being used by more than 300 registered users that already have executed more than 13000 experiments.²⁵ The HOBBIT platform was also used to carry out eleven benchmarking challenges for Big Data applications. It was used for the Grand Challenge of the 11th and 12th ACM International Conference on Distributed and Event-Based Systems (DEBS 2017 and 2018) [14, 15]. The 2017 challenge was aimed at event-based systems for real-time analytics. Overall, more than 20 participating systems had to identify anomalies from a stream of sensor data.

The Open Knowledge Extraction Challenges 2017 and 2018 used the platform for benchmarking Named Entity Recognition, Entity Linking and Relation Extraction approaches [12, 13]. For one of the challenge tasks a setup similar to our evaluation in Section 5.2 was used. This evaluation revealed that the scalability of some systems decreases drastically under realistic loads. While some of the benchmarked solutions were able to answer single requests efficiently, they became slower than competing systems when challenged with a large amount of requests [12].

²⁵See <http://master.project-hobbit.eu/experiments>.

Table 3 The effectiveness of the systems (Micro measures).

System	Precision	Recall	F1-measure
Balie	0.321	0.293	0.306
FOX	0.505	0.543	0.523
Illinois	0.524	0.614	0.565
OpenNLP	0.351	0.233	0.280
Spotlight	0.513	0.411	0.456
Stanford	0.548	0.662	0.600

The Mighty Storage Challenges 2017 and 2018 focused on benchmarking triple stores [10, 11]. Their RDF data ingestion tasks showed that most triple stores are unable to consume and retrieve triples (e.g., sensor or event data) efficiently. This insight suggests that current triple stores need to significantly improve in their scalability before they can be used for Big Data applications out of the box. The derivation of this insight was made possible by HOBBIT’s support of distributed systems and its distributed implementation that allows the generation of enough data and queries to overload the triple stores.

7. Conclusion

This paper presents the architecture of the HOBBIT benchmarking platform, which is based on real requirements collected from 68 experts from across the world. The platform is designed to be modular and easy to scale up. HOBBIT is hence the first benchmarking platform that can be used for benchmarking Big LD systems. The platform has already been used in several challenges and was shown to address the requirements of large-scale benchmarking for storage, predictive maintenance, knowledge acquisition and question answering. These challenges showed clearly that HOBBIT can be used to measure both the scalability and accuracy of Big Data platforms. As the platform is not limited to a particular step of the Linked Data life cycle and can be configured to use virtually any data generator and task generator, it is well suited for benchmarking any step of the Big LD life cycle. A fully fledged implementation of the platform is available as an open-source solution and has started to attract the developer community. While writing this paper, the platform is planned to be used for the Semantic Web Challenge 2019 as well as the OAEI Challenge 2019.²⁶ It will also serve as one of the key stones of the Innovative Training Network (ITN) KnowGraphs during the next years. We hence aim to extend it so as to build the reference point for benchmarking Big LD applications.

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Add number for RAKI

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