Automation in Construction 124 (2021) 103562

Contents lists available at ScienceDirect

Automation in Construction

journal homepage: www.elsevier.com/locate/autcon

Building applications for smart and safe construction with the DECENTER Fog Computing and Brokerage Platform

Petar Kochovski [a], Vlado Stankovski [a,b,*]

[a] University of Ljubljana, Faculty of Computer and Information Science, Ljubljana, Slovenia
[b] University of Ljubljana, Faculty of Civil and Geodetic Engineering, Ljubljana, Slovenia

ARTICLE INFO

Keywords:
Smart construction
Internet of things
Cloud-to-edge computing
Fog computing
Blockchain
Artificial intelligence

ABSTRACT

Various smart applications are needed to address complex problems in construction falling under the broad categories of safety at work, construction site management, management of resources, waste and assets and construction progress monitoring. Fog computing emerges as a new computing paradigm for Edge-to-Cloud computing that integrates Internet of Things (IoT), Artificial Intelligence (AI), and Blockchain technologies to facilitate the development and operation of smart applications. However, a comprehensive methodology that applies Fog computing to construction projects is currently missing. In our work, we use the novel DECENTER Fog Computing and Brokerage Platform to address requirements for flexible use of AI methods in construction projects and develop a relevant methodology. Evaluation is performed through all application development phases at a real construction site in Ljubljana, Slovenia. Testing results show that the use of Fog computing contributes to high response rates, privacy and security when processing sensitive worker and company data.

1. Introduction

A number of complex problems and issues falling under the broad categories of safety at work [1–3], construction-site management, management of resources, waste and assets [4], construction progress monitoring [5], early disaster warning [6], infrastructure monitoring [7,8], and similar have to be addressed in the course of every construction project. Our initial review of the state of the art revealed various parts of the construction process where the development of new smart applications could contribute to specific improvements [9,10]. Different studies have used the Internet of Things (IoT), Artificial Intelligence (AI), Cloud-to-Edge computing, Blockchain and Digital-Twin technologies to implement applications for smart and safe construction. Improvements have been demonstrated in areas such as safety at work, intruder detection, real-time equipment (assets) positioning, access-routes control, collision detection, waste mapping, construction progress monitoring, alignment of the construction process with the Building Information Model (BIM), construction progress tracking and similar [11].

The present study investigates problems related to the development, deployment and operation of AI-based applications that are specific to the construction domain. Due to the great diversity of construction processes, construction projects usually differ because of their specific requirements. First, is the need for the flexible use of AI methods within smart applications. This requirement can be addressed by developing suitable AI-method repositories with complementary Graphical User Interfaces (GUIs) that will make it possible to search, use and combine the input sensor streams, including video streams, and to set up AI methods to process the input data. Second, different AI methods have varying network and computer requirements, due to which their response times can vary a great deal. However, the fast response times of smart applications could be particularly important in a dynamic environment such as a construction site. For this reason it is necessary to employ specific algorithms that help to achieve a high Quality of Service (QoS) when the AI methods are orchestrated across the Edge-to-Cloud computing continuum. Third, the handling of data is a particularly sensitive topic in every industrial process, and construction is no exception. It is necessary to achieve an end-to-end transparency and the ability to trace the whole process, which can contribute to building trust when smart applications are used to process personal and industrial data. Fourth, the operational costs of every smart application can be significant due to the need to set up and maintain both the necessary computing infrastructures and the applications.

The state-of-the-art DECENTER Fog Computing and Brokerage

* Corresponding author at: University of Ljubljana, Faculty of Computer and Information Science, Ljubljana, Slovenia.
E-mail addresses: petar.kochovski@fri.uni-lj.si (P. Kochovski), vlado.stankovski@fri.uni-lj.si (V. Stankovski).

https://doi.org/10.1016/j.autcon.2021.103562
Received 10 August 2020; Received in revised form 30 December 2020; Accepted 18 January 2021
Available online 26 January 2021

Platform [12], which is the result of a European Union and South Korean, Horizon 2020 research and innovation project, aims to support the design and implementation of smart applications in a variety of sectors, including construction.

In particular, DECENTER delivers an advanced Fog Computing Platform that allows resource providers to share resources and be automatically rewarded through the collaborative establishment of Smart Contracts for the seamless execution of applications across multiple, geographically distributed administrative domains, each with their own data governance, security, legal and business policies. Compared to other existing systems [13–15], DECENTER creates a much more flexible infrastructure, achieving a substantially larger scope for the orchestration and data- and application-aware allocation of resources, thus enabling cooperative and parallel computation between the IoT devices at the edge and among the different tiers of the computing infrastructure, resulting in smooth and dynamic business flows.

In this context, the goal of this study is to present a positive outcome from integrating IoT, AI, Cloud-to-Edge computing and Blockchain in construction-related smart-application scenarios, on the one hand, and to undergo the design-and-implementation process with all its technical and non-technical intricacies. The goal of each smart-application scenario is to facilitate: (1) QoS-aware orchestration of resources, (2) effective and timely computation with improved network and computational performance, (3) seamless selection from a variety of AI methods, (4) trustworthy and secure access to AI methods and support to privacy-preservation regulations. Therefore, in this study we present a novel platform, application and methodology that allow construction sites to be smoothly automated into smart environments by benefiting from a plethora of AI methods and models.

Each construction project is unique. This includes the actual construction site, the collaborating organisations as well as the actual building. It is difficult to imagine that a single smart application could apply to all building projects. Rather, it would be necessary to plan smart applications along with the overall building-planning activities. Moreover, our general aims are to investigate the possibilities for information integration based on IoT. We have worked towards a new methodology that can be used to turn a specific construction site into a smart and safe construction site by including a specific number of cameras and sensors on the ground, on the actors, such as construction workers and visitors, and on objects, such as building equipment, waste, materials and similar. These data and the information can then be processed by AI methods using the novel DECENTER platform, and fed back to both the construction-site managers, workers, visitors and similar, via various signalisation and notification mechanisms. In order to achieve this, we worked closely with an actual building project, which remains ongoing in the city of Ljubljana, Slovenia. Our designed scenarios and the application and its implementation are elaborated in the following sections.

The rest of the paper proceeds as follows. Section 2 presents the state of the art and identifies the gap that is addressed in this study. Section 3 describes the mechanisms that can provide intelligence during the construction process and can improve it overall. Section 4 presents the DECENTER Fog Computing and Brokerage Platform and its importance for building smart applications. Section 5 presents the DECENTER-based smart application for smart construction sites. Section 6 concludes the paper.

2. Related works

This study is focused on the design and implementation of smart applications in the construction sector. To the best of our knowledge, this is the first study that explores in actual implementation terms the overall methodology that should be applied in the context of building smart construction sites. The basis for our work is the state-of-the-art DECENTER Fog Computing and Brokerage Platform and the variety of documented use cases for smart and safe construction in the context of IoT, AI, Cloud computing and Blockchain.

Various studies have already shown potential benefits when using IoT technologies for construction [16,17]. In relation to AI and Cloud computing there are numerous authors that provide solutions for AI processing [18,19] in centralised clouds [20–23]. However, processing in centralised clouds is now notorious for introducing large latency due to poor network connections from the Edge of the network towards the Cloud, which reduces the utility of such applications. Implementing time-critical applications is very challenging, and it has not been sufficiently well addressed in existing studies. Today's good practices recommend that the data arriving from field sensors, such as the data from video surveillance cameras, should first be processed and aggregated at the Edge of the network, geographically close to the actual construction site. The use of Fog computing, which is generally understood by us as computing across the whole computing continuum, from the Edge of the network to the Cloud, with specific infrastructure planning algorithms can significantly improve the network's service quality measurements, such as bandwidth, latency, and packet loss [24]. Moreover, the implementation of container virtualisation technologies, such as Docker [25], would facilitate the use and management of various AI methods closer to the sources of data. This will lower the strict network-performance requirements.

Another practice is the implementation of Blockchain to address the privacy, security and traceability requirements required for smart building environments to operate. In particular, the transaction protocols, such as Smart Contracts that the Blockchain offers, can be used to automatically execute, control or document relevant actions according to the conditions defined in the contract [26,27]. For instance, the Smart Contracts can be used as business process management [28], ownership transfer for construction materials, project data between entities [29], supply-chain traceability [30] and similar.

The review of the existing state of the art related to the implementation of IoT, AI, Cloud-to-Edge and Blockchain technologies in the construction domain revealed a gap. Although the IoT, Cloud and Blockchain technologies are already converging at a relatively high technology-readiness level, the level of integration of AI methods in real-world applications is still not satisfactory, particularly in industrial domains such as construction.

Our related works analysis revealed that there were no existing solutions that merge the above-mentioned technologies into a unified solution. Hence, the contributions of this study are the following:

- A methodology for the component-based development, configuration and deployment of an AI-based smart application for different construction-site scenarios;
- A QoS-aware resource orchestration for smart-construction-site applications that allows the (re)deployment of smart applications to satisfy the high performance requirements in the Edge-to-Cloud computing continuum;
- A repository of AI methods with pre-trained AI models that can be implemented in different construction-site scenarios;
- A leveraging blockchain technology for the transparent and secure operations over sensor data and AI methods with specially designed Smart Contracts.

This lays the ground for our Methodology section.

3. Methodology

Transforming constructions sites into smart and safe environments is a challenging process that requires careful information integration for various construction-process-related problems. In particular, this process can include activities such as: setup of a specific number of surveillance cameras and sensors in the field, specific objects in the field, building equipment, materials, or even include wearable sensors that can be attached to workers, site managers and visitors. The DECENTER project and the solutions it provides address these challenges by facilitating the use of various AI methods on video streams and sensor data in order to detect and identify specific details and use the information to send notifications. For instance, such notifications can be sent to construction-site engineers and managers that will allow them to react appropriately to certain situations.

3.1. Use-case scenarios

We explored mechanisms for information gathering, fusion and enrichment that can provide intelligence during the construction process and help to improve various aspects of the work that must be performed. The collection of information related to the ongoing construction process can be useful for both time-critical operations, such as collision detection and early-disaster warning, and longer-term logistic and other operations, such as ordering material, documenting the process, and similar. In the scope of our work we considered four scenarios to be implemented on the premises of the construction site Šumi, Slovenia, as depicted in Fig. 1. The scenarios are described in detail in the following:

- *Scenario 1: Improve safety at work* by issuing notifications to the construction-site manager. The goal of this scenario is to: (1) identify workers at the construction site, (2) detect whether the worker is wearing a helmet, work clothes or a safety vest and (3) locating workers' positions at the construction site. In the case of a safety concern, the supervisor is notified. This scenario demonstrates DECENTER's capability to provide a high QoS and a rapid response time for smart applications.
- *Scenario 2: Construction-site surveillance* for vehicles that enter or leave the construction site. This facilitates vehicle detection by type, colour and number on the license plate. In addition, any person that appears at the entrance (i.e., entering or exiting) of the construction site will be identified as a worker or a visitor. This scenario exploits several capabilities of the DECENTER platform, such as: (1) selection of AI models/methods, which is optimised for specific computational resources, from a repository; (2) utilising Smart Contracts for access management to the AI models/methods in order to satisfy the security and privacy standards for data-movement and processing.
- *Scenario 3: Management of resources, waste and assets* is a scenario that requires continuous construction-site monitoring that will allow the identification of various objects and facilitates the means for their tracking. In the case of changes to the resource quantities, a notification will be issued to the construction-site manager. Like with other scenarios, this scenario exploits DECENTER's capability to integrate various AI methods/models, in order to significantly increase the performance when monitoring resources, machinery, inventories and material consumption.
- *Scenario 4: Working conditions* is a scenario that involves monitoring the environmental conditions at the construction site, such as weather, noise and a comparison between the optimum, minimum and current working conditions. This scenario is designed to maintain the optimum working conditions and improve environmental protection. This use-case scenario exploits the capability of the DECENTER platform to use various IoT sensors along with the camera-based video streams. This is possible because the SensiNact IoT platform [31] has been containerized and embedded in the DECENTER platform.

This work further elaborates one use-case scenario that combines more elements of all the above-mentioned scenarios and was selected for an initial implementation. That required the positioning of cameras at the construction site, setting up Kubernetes-based computing clusters, the implementation of an application by using the DECENTER computing platform, and its testing and evaluation.

3.2. Actors and roles

A smart construction site can be defined as one that is equipped with cameras and sensors and, potentially, with leased or owned computational resources, such as Edge nodes that can be used to generate data and perform AI processing closer to the data source [24].

The above scenarios for smart and safe construction can involve several actors and roles with different prior-knowledge of smart applications and services. The implemented AI-based applications can issue construction-process-specific messages either via onsite signalisation or notifications to mobile phones. The following actors could be involved:

- Construction investor/client, supervisor that could benefit from

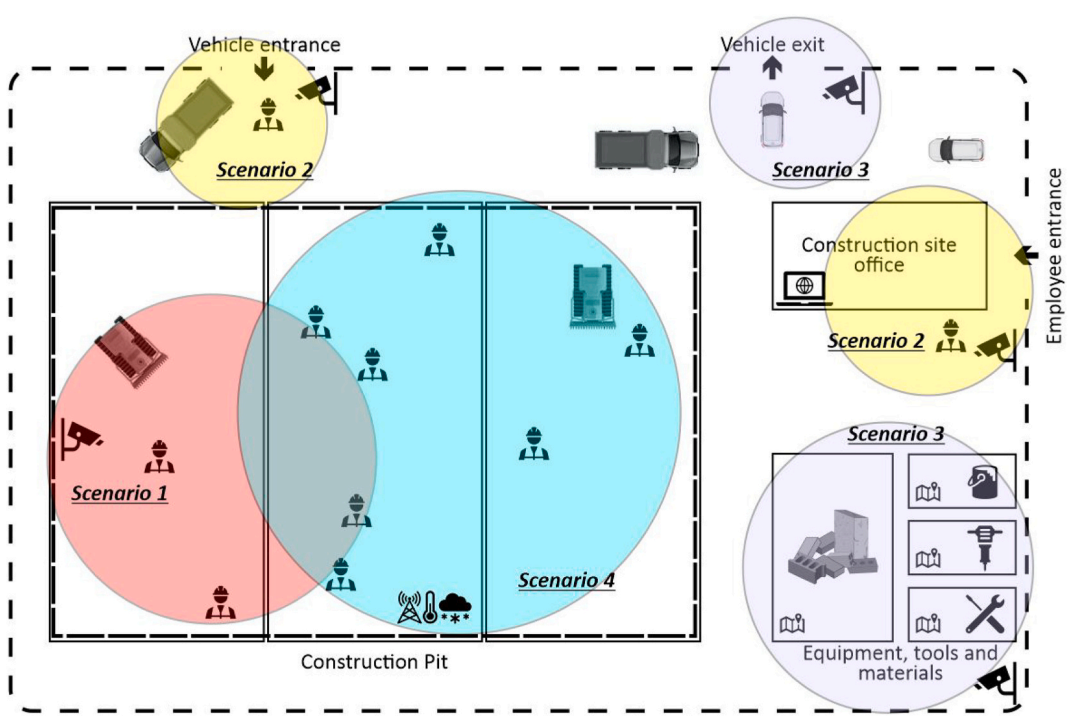


Fig. 1. Use-case scenarios for implementation at the Šumi construction site in Ljubljana, Slovenia.

construction-progress tracking and receives timely notifications of any safety breaches or risks;

- Construction company, in order to reduce operational costs and provide a safe working environment;
- Construction-site manager, who is employed by the company to coordinate the work at the site;
- Worker(s) that can be more productive when working in optimum conditions and can benefit from applications for safety at work;
- Construction equipment rental/lease providers support the construction site with equipment;
- Objects: hard hats and protective vests represent equipment (i.e., resources) that should be monitored
- AI methods, software components to detect and identify people and objects, also trigger events that issue specific notifications based on video streams and moving objects;
- Data sources: cameras, e.g., IP or USB cameras, and sensors that are used to collect raw data;
- Any required computing infrastructure that can be used for the reliable AI processing of data.

From the analysis that we have conducted so far, it is obvious that the actual smart-construction-site setup is a highly non-trivial task due to the unique requirements within each construction project. However, DECENTER allows the seamless integration of various cameras and other IoT sensors due to its integration with the SensiNact platform, which simplified the overall setup process.

3.3. Requirements

The following is a summary of the key requirements that must be addressed in order to realise our individual use cases for smart and safe construction. The requirements are listed in Table 1 and highlight in detail the complexities involved in realising our use-case scenarios.

In the following sections we present the DECENTER Fog Computing Platform that is specifically designed to address the requirements of such use-case scenarios.

4. The DECENTER Fog Computing and Brokerage Platform

The DECENTER Fog Computing and Brokerage Platform unites the quadrumvirate technologies, i.e., IoT, AI, Cloud computing and Blockchain technologies, that allow the seamless development and orchestration of microservices-based smart applications. It supports the design and creation of federated Cloud-to-Edge computing environments. In particular, DECENTER facilitates the development of AI-empowered smart applications that will perform the AI processing of data gathered from IoT resources in the Cloud-to-Edge computing continuum. With these properties, DECENTER is one of the most advanced, state-of-the-art Fog Computing platforms.

Table 1
Requirements for the considered smart and safe construction use cases.

Functional Requirements (FRs)	Non-Functional Requirements (NFRs)	System Requirements (SRs)
Access and use existing pre-trained AI database models. Train and additionally customize existing AI models (transfer learning). Receive and process data from a video camera. Place bounding boxes at specific (interesting) images parts (object detection). Trigger notifications for construction-site engineer.	The smart application will be able to use more or less video cameras and will be reused in different layouts with respect to different construction sites. Keep private the information processed on each construction site. Provide a processing time of object detection in less than 30 s. Have the possibility to operate even if a specific Fog Node fails to respond in time. Perform correctly in different temperature/ illumination conditions	Have sufficient computing resources necessary to run the application. Have enough HD capacity to store the data of at least the monthly operation of the site. Use a specific number of cameras. Use GPU to run AI functionalities. Provide data access, which will be controlled Have a stable internet connection.

DECENTER delivers the following key innovations:

- QoS-aware orchestration of AI applications onto Cloud-to-Edge computing resources;
- Blockchain-based framework for the data management and brokerage of resources across multiple clouds;
- Smarter IoT fabric that takes advantage of AI algorithms to extract context information from sensor data;
- Decentralised AI models' exploitation through an AI model repository from which various AI methods and models can be used flexibly within applications.

Fig. 2 presents a high-level overview of the DECENTER architecture and its three main layers: Infrastructure, Platform and Application. These are further elaborated in the following sub-sections.

4.1. Infrastructure Layer

The Infrastructure Layer consists of different types of hardware (e.g., sensors, computing, network, storage and various field smart devices). This hardware is deployed in the Cloud-to-Edge continuum, thus covering the complete AI data pipeline.

AI applications for smart environments have to rapidly process large amounts of data, thus they are required to satisfy specific QoS requirements, such as: low network latency, high network bandwidth or fast computations. As a result, DECENTER's Infrastructure Layer is composed of three computing tiers (i.e., Edge-Fog-Cloud) that primarily differentiate between properties such as: geolocation, cost, computing performance, network performance and many more.

The closest computing tier to the smart construction site is the Edge computing tier. This is a highly distributed environment that consists of

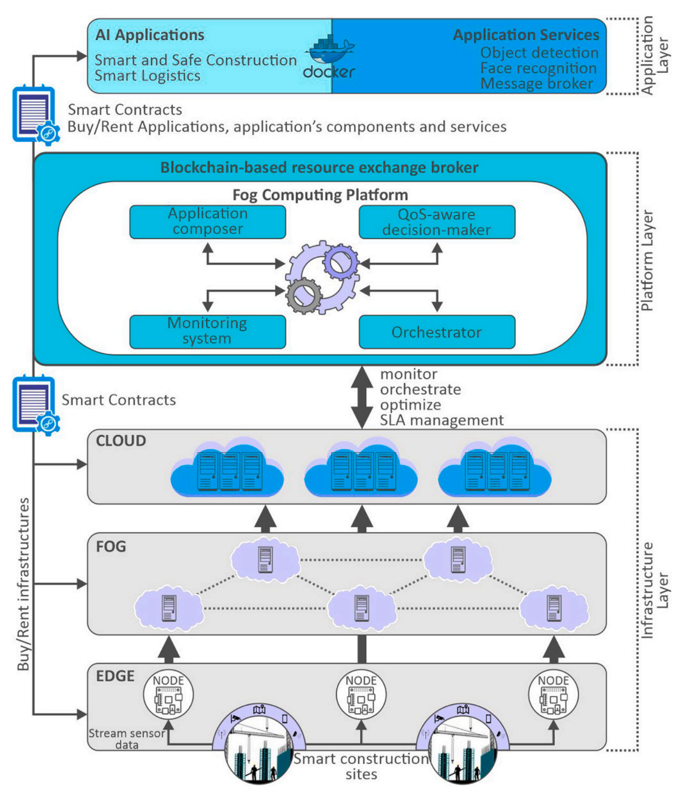


Fig. 2. Key components of the DECENTER architecture used to realise the use-case scenarios for smart and safe construction.

low-power computing devices (e.g., Raspberry Pi) that are able to perform a simple computational task in close proximity to the physical devices (i.e., cameras, sensors). Because the computing devices are in close proximity to the sources of data, this tier guarantees better network performance than the Fog or the Cloud. Next, are the computing resources in the Fog tier, which are perceived as computing resources that exist in the middle between the Cloud tier and the Edge tier [32]. These resources offer better network performance than the resources in the Cloud tier, whilst achieving better computing performance than the Edge tier. Finally, the Cloud tier is reserved for tasks that require very high computing power, large storage capacities, but lower network performance. The tasks that require the characteristics of this tier can be run on private or public cloud services.

The DECENTER Platform is designed to support scenarios where infrastructure providers can interact with each other and federate their resources in order to provide services to the users. DECENTER not only brings advances to the Infrastructure Layer; it leverages on existing hardware to deliver AI processing capabilities with a high QoS.

4.2. Platform Layer

The Platform Layer is placed between the Infrastructure Layer and the Application Layer. It is composed of logical components that allow the discovery, brokerage and orchestration of resources across the Cloud-to-Edge continuum.

This layer offers DECENTER four baseline functionalities: (1) Setup and management of highly distributed and heterogeneous computing environments, (2) composition of cloud applications from containerized microservices and a definition of QoS requirements, (3) deployment and orchestration of applications, (4) brokerage and negotiation of resources that belong to different administrative domains. To achieve the necessary platform functionalities, the platform layer is composed of two sublayers:

- The Blockchain-based resource-exchange broker is a mechanism that is responsible for management of the federation of Fog Computing Platforms across different administrative domains. This mechanism provides Smart Contracts that facilitate trusted interactions between different stakeholders that are included in the system. It allows service providers to register resources (e.g., AI applications, application services, computing infrastructures) on the Blockchain. On the other hand, service consumers can utilise another set of Smart Contracts to rent/buy a service that will satisfy their QoS requirements.

More details about the methodology and implementation of the Smart Contracts in the Blockchain-based resource-exchange broker are described in detail in our previous studies [33,34].

- The Fog Computing Platform is responsible for application composition, resource allocation, monitoring and orchestration throughout the complete Edge-to-Cloud continuum. The Application composer describes the applications in a formal TOSCA [35] specification and forwards it to the Orchestrator. The Orchestrator, which is based on Kubernetes [36], is integrated with the Monitoring server (e.g., Prometheus [37]) and the QoS-aware decision making. In order to deploy an application, the Orchestrator considers the current status of the available computing infrastructures, triggers the QoS-aware decision maker and through a custom-designed orchestration controller, deploys the application on the selected infrastructure.

For the implementation purposes of this study, the QoS-aware decision maker utilises a stochastic decision-making algorithm that is based on the theory of the Markov Decision Process [38].

4.3. Application Layer

The Application Layer is used to facilitate the seamless development of AI applications by exploiting a variety of AI methods and models.

It offers preset Applications and Application Services. Applications that exploit AI methods are designed by application developers and can be easily implemented in various smart environments to execute well-defined business tasks. Application Services can be seen as generic-purpose microservices that can be implemented in different applications. For instance, object detection can be an Application Service that will enable the detection of a set of different objects from video streams. Another example could be a message-broker microservice, which can handle real-time data feeds. These services can be very useful, because by using them the application developers can easily implement the applications' business logic, without the need to develop the core functionalities from zero.

5. Smart application design and implementation

This section describes the details of a DECENTER-based smart application that is the main outcome of our work. The application was developed to address the use-case-scenario requirements for Ljubljana, Slovenia at a construction site of the company Šumi. In particular, the application is designed to perform AI processing of video-stream data from on-field surveillance cameras, while the application satisfies high QoS requirements. It exploits the DECENTER Platform and the DECENTER Pool of Infrastructures, and application-specific components, particularly the application GUI and the message broker.

5.1. Application architecture

Fig. 3 shows the design of the implemented two-tier smart application that exploits AI methods in order to process the video surveillance data. The application offers two main functionalities for the user, as follows: (1) registration and use of new AI models on the Blockchain, and (2) orchestration of the AI models onto trusted computing nodes.

The first functionality allows users to register their services (i.e., applications, application services, computing infrastructures) on the Blockchain. This will allow the system to operate only with trusted services, where the service providers can be traced and the transactions between the service consumers and providers can be executed in a transparent way. To register an AI model on the Blockchain, the service provider uses the GUI that integrates the Metamask wallet [39]. Once the service provider inputs all the necessary metadata about the service (e.g., model type, cost, location, access URL, etc.), through Metamask, it executes a Smart Contract. When the Smart Contract is successfully executed, the service will be registered on the Blockchain and made available on the platform. The registration status of the service can be verified on the Blockchain at any time.

The second functionality consists of 10 consecutive use steps, which can be followed in Fig. 3. (1) The user (i.e., the construction-site manager) sets the QoS requirements, such as network throughput, network latency, packet-loss and minimum video fps for the deployment infrastructure, chooses a suitable AI model to rent and selects a public wallet address. This information is forwarded to the QoS-aware decision maker. (2) The decision maker receives the request and communicates with the Blockchain service to execute the Smart Contract and gain access to the requested AI model. (3) If the Smart Contract is successfully executed, it will trigger the deployment operation, after which the orchestration algorithm retrieves the monitoring metrics from the Monitoring system (4) and forwards the deployment decision in the form of YAML instructions to the Orchestrator, which is a Kubernetes cluster (5). When the application components are deployed on the optimum deployment options (6), they start receiving video-surveillance-stream data from the surveillance cameras at the construction site (7). The video-surveillance data is then constantly being processed for object detection and person identification. If the AI methods detect some kind of violation on the video (e.g., a vehicle or a person in a restricted area or identify an unknown person on the construction site), it forwards the context data to a Message broker (8) that forwards the notification to the subscribed user in real-time (9). When the service consumer spends its prepaid access to the AI models, the application will request additional

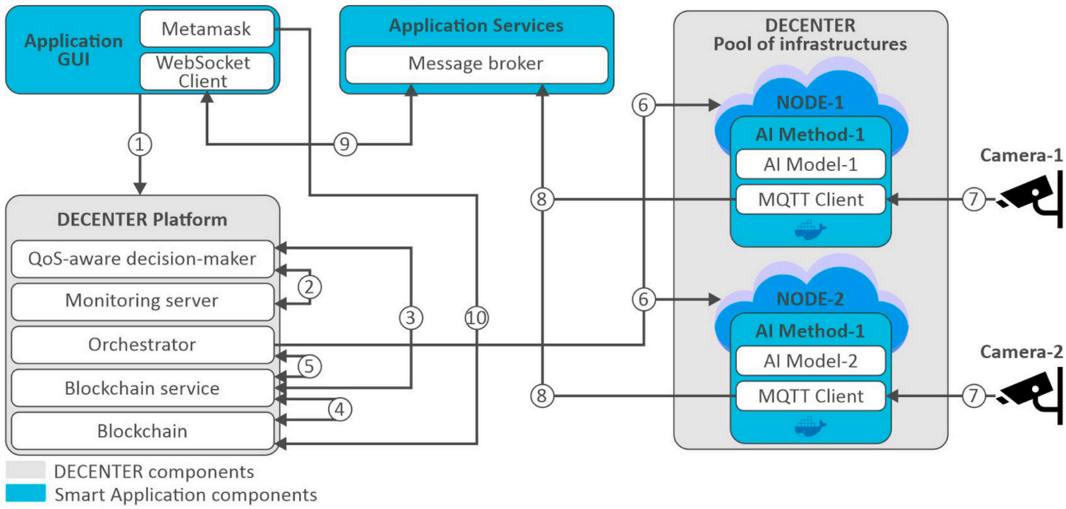


Fig. 3. Application design for smart construction.

funds. (10) Unless the service consumer pays for further use of the AI models, the Smart Contract will terminate the service.

5.2. Smart-application testing and evaluation

The application GUI that the service consumer uses to operate the implemented application is shown in Fig. 4. The application's main menu allows the user to navigate to the main application's screens, which are:

- Home - this screen displays basic information for the Smart Applications and offers access to the rest of the functionalities.
- Dashboard - this is the most important screen, because it delivers the main functionality. It allows the user to search for a specific transaction on the Blockchain, see currently available computing nodes in the cluster, monitor the current work status of the nodes that host the smart application's microservices, manage containers by triggering Smart Contract functions and execute new contracts on the Blockchain. In the case that the smart application offers a specific output (e.g., a video stream), it will also be shown on the Dashboard.
- Notifications - this screen shows the list of notifications that are sent to the construction-site manager from the running smart application.
- Services - this screen provides a description of the available services that can be used for the smart applications to the construction-site manager.
- Help Center and Settings - these screens are to provide help to the user of the application and allow configuration of the system parameters.

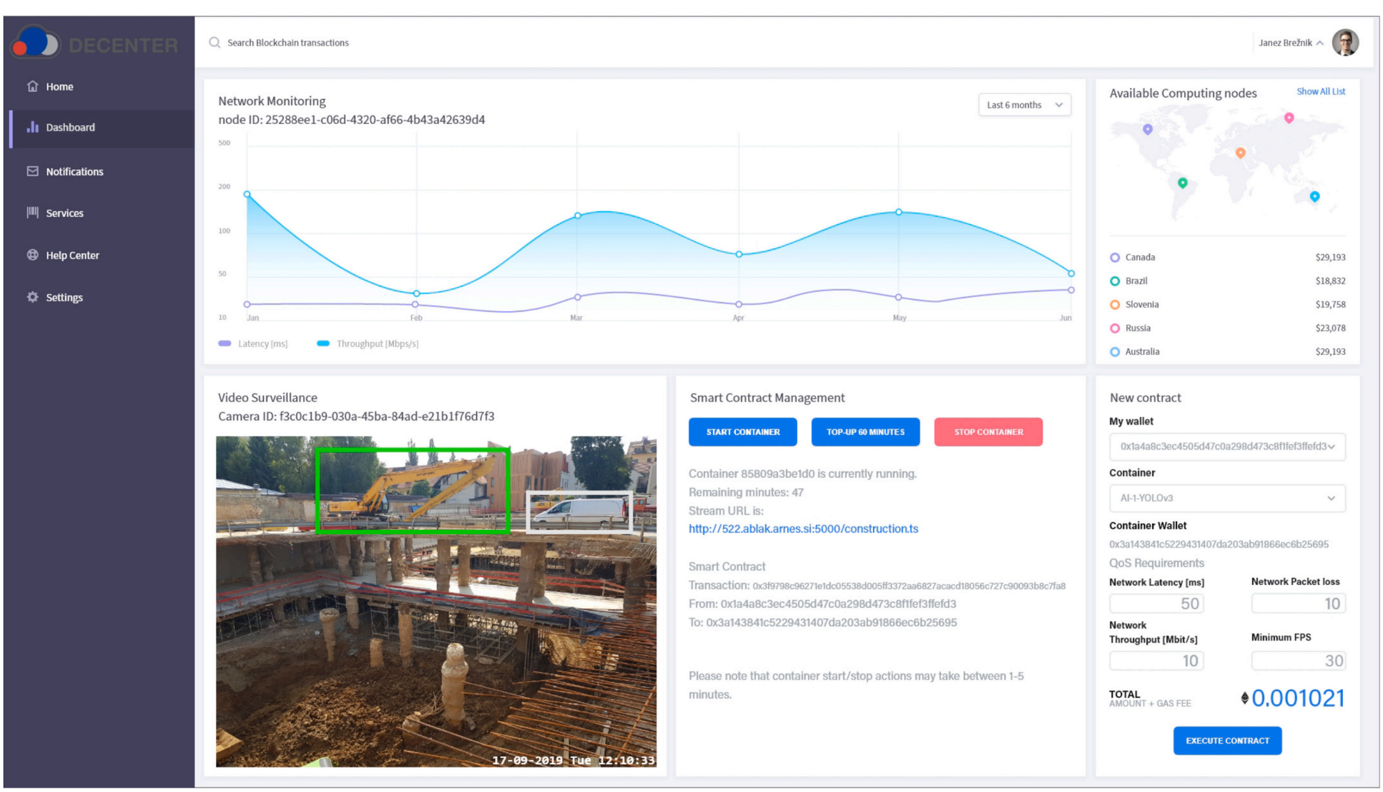


Fig. 4. Graphical User Interface for AI application management.

In order to evaluate our application, we performed multiple evaluation and testing activities.

- Evaluation of the QoS-aware orchestration to show that DECENTER Fog Computing and Brokerage Platform, particularly its (re) deployment algorithms, which can be used to maintain a high QoS at all times. Once the AI application was deployed, it was exposed under a heavy workload where the number of incoming requests slowly increased from 100 to 2000. Such a workload pattern significantly reduced the network performance (i.e., latency) and computation performance (i.e., CPU utilisation and memory utilisation), hence significantly reducing the overall QoS and triggering a redeployment action. Fig. 5a depicts the three stages, which are: (1) deployment on optimum computing infrastructure, (2) significant workload and (3) redeployment of the application to another optimum infrastructure. In the same context, Fig. 5b and Fig. 5c depict the difference in CPU and memory usage before and after the redeployment took place during the evaluation. A detailed explanation of the technology behind the (re)deployment algorithms, alongside their thorough evaluation, is described in our previous studies [38,40].

(a) Network latency between the sources of data and the AI application.

(b) Computing infrastructures' CPU usage.

(c) Computing infrastructures' memory usage.

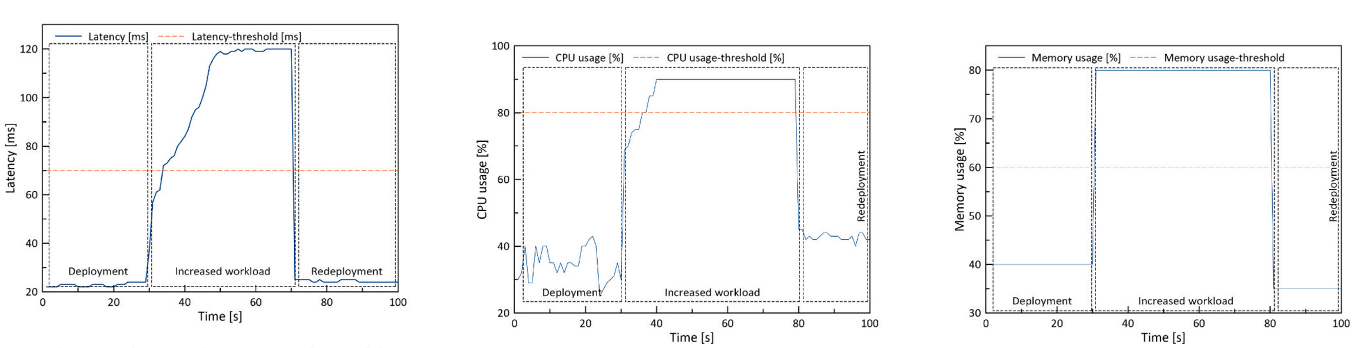
- Inspection of the system log files with input and output time stamps to estimate the time needed to generate and issue a notification. To perform a more precise estimation of the time required between an event taking place and the notification being received, the application was tested and optimised on multiple stages. The first stage is an estimation of the time required between the event happening and it being detected by the AI method. This mostly depended on the AI model being used; however, AI models based on YOLO [41] that could process more than 30 frames per second could detect a violation almost in real-time. The next stage was estimating the time required by the application's backend to receive the output from the AI method and decide whether a notification should be generated. The third stage was the time required for the generated notification to travel between the application's backend and the frontend that the user has access to. Due to the high-performance network and the rapid response time of the AI methods, a notification can be received in less than 5 s.
- Economic estimation of the operational cost reduction in infrastructures: cost of ownership vs. cost of temporary leasing. In the context of the evaluation, a comparison between the smart application that was dynamically orchestrated and allowed to run while there were activities on the construction site and an application that ran non stop on infrastructure owned by the construction company. After a month of testing it was concluded that the DECENTER Fog and Brokerage platform outperforms the cost of ownership for the infrastructures by reducing the costs by up to 60%, while offering infrastructures with high computing and network performance.
- Counting the available AI models and the AI models that are employed. The AI repository that is part of the DECENTER Fog and Brokerage platform offers a large variety of AI models and methods that can be easily implemented at any time. Currently, the repository counts twenty highly optimised AI models and methods that can be used in a plethora of scenarios. However, the repository offers users the option to upload new or update the existing models, thus the number of AI models and their performance is expected to rise in the future.
- Apply cross-border data-management technology to control the data utilisation through the Smart Contract. In order to protect the privacy of the involved personnel, each participant at the construction site was offered a public wallet through which was executed a Smart Contract that gave the person's consent for their data to be processed at the construction site. As a result, the AI method could be deployed and used only upon verifying that all the personnel had given consent. Moreover, the immutability of the Blockchain made it possible to check all the transactions at anytime, thus verifying that the methods were running only with the consent of the parties involved.

Following the testing and evaluation of the implemented smart application we can make several conclusions about its capabilities: (1) detection and alerting with respect to safety violations at the construction site based on the AI models used for the DECENTER AI Model repository; (2) use of Smart Contracts for the management of resources and to orchestrate the services across the Cloud-to-Edge computing continuum; (3) offers digital representation of the AI by placing binding boxes on the video-surveillance stream, the currently used AI application and infrastructure status information; and (4) help with achieving AI objectives, such as object detection and identification, and use of various AI models for object recognition, people identification and prediction.

Having the application fully functional and in production, it can be gradually extended to incorporate different AI Methods and Models. The backend part is capable of integrating the information and based on already-identified elements on the video stream(s) it can launch new AI-based microservices for further information processing. For this reason the orchestration process relies largely on the actual information required to address the specific scenario.

6. Discussion and conclusions

This study reveals the benefits for construction sites of implementing the DECENTER Fog and Brokerage Platform. A traditional construction site was transformed into a smart construction site that allowed the flexible use of AI methods, while achieving a high QoS and secure data management. Following the successful pilot, the users (i.e., construction engineers and managers) left positive feedback and highlighted the following benefits:



(a) Network latency between the sources of data and the AI application

(b) Computing infrastructures' CPU usage

(c) Computing infrastructures' memory usage

Fig. 5. Monitoring data comparison before and after the (re)deployment process controlled by the DECENTER Fog Computing and Brokerage Platform. When the platform detects QoS threshold violations, it chooses a new deployment option in a timely manner from the pool of available resources.

- Anomaly-detection performance. The time from the event to issuing or receiving a notification by the manager is considerably improved with the Fog Computing approach.
- Temporary use of external infrastructures. Our estimates show that the operational costs will be reduced.
- Improve the access to AI methods and models. This is a significant improvement because with our approach it is possible to significantly improve the ability to reuse various AI methods and models.
- Improve privacy in the industrial setting. This is achieved by using specially designed Smart Contracts.

Although construction sites differ and their transformation into smart environments might not be a trivial operation, the DECENTER project and its solutions significantly simplified the process. By following interoperability standards (e.g., MQTT communication protocol), each AI application could be started in a matter of seconds for each of the scenarios elaborated earlier in this study. Therefore, the AI applications could be seamlessly replicated at other construction sites, as well as in other industry domains, such as: smart-city safety crossing, robotics logistics or even providing intelligence for offices.

A short response time is another functionality that is guaranteed by DECENTER's QoS algorithms. DECENTER's QoS algorithms are implemented along with a Kubernetes controller that employs an advance MDP algorithm for ranking cloud options, orchestration of resources, horizontal scalability, formal assurances and verification [38].

The ability to quickly switch between the AI methods that operate on top of a specific video stream, for example, after detecting a vehicle that enters the construction site, another AI method that detects whether the driver is wearing a safety vest and the colour of the vest. This is achieved by the DECENTER's technology for the brokerage of AI models via its repository and orchestration, i.e., exchanging the running services.

Although this study addresses important challenges for building smart and safe construction sites, there are still many challenges to be tackled in the future. For instance, the ability to use biometric AI (biometric is an AI model that can be used to identify a person) at the construction site might demand, in the near future, the application of European and Korean legislation that includes the certification of the processing devices or regulatory alignment for the processing of personal data. For this purpose, specially designed Smart Contracts that will properly translate the legislation and laws to a standardised code, understandable by the Blockchain, will be necessary [42]. Moreover, to improve interoperability in the context of Blockchain within smart construction sites requires the execution of smart contracts between different ledgers (i.e., intrachain operations) [43]. These challenges are going to be further researched and developed in the scope of the DECENTER cross-border data and AI model management technology and will be elaborated in our future investigations.

Declaration of Competing Interest

The review process should not be managed by an editor affiliated with the University of Ljubljana.

Acknowledgement

The DECENTER project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 815141. The authors would like to express very great appreciation to Mr. Janez Brežnik for his valuable and constructive suggestions during the planning and development of the smart-application scenarios, and to the Šumi construction site for access during the implementation of the scenario.

References

[1] J. Teizer, T. Cheng, Proximity hazard indicator for workers-on-foot near miss interactions with construction equipment and geo-referenced hazard areas, Autom. Constr. 60 (2015) 58–73, https://doi.org/10.1016/j.autcon.2015.09.003.
[2] W. Yi, A.P. Chan, X. Wang, J. Wang, Development of an early-warning system for site work in hot and humid environments: a case study, Autom. Constr. 62 (2016) 101–113, https://doi.org/10.1016/j.autcon.2015.11.003.
[3] C. Zhou, L. Ding, Safety barrier warning system for underground construction sites using internet-of-things technologies, Autom. Constr. 83 (2017) 372–389, https://doi.org/10.1016/j.autcon.2017.07.005.
[4] Y. Wu, Y. Wang, A study of smart construction and information management models of aec projects in China, International Journal of Simulation: Systems, Science and Technology 17 (21, 2016) 1–2, https://doi.org/10.5013/IJSSST.a.17.21.02.
[5] A. Braun, S. Tuttas, A. Borrmann, U. Stilla, A concept for automated construction progress monitoring using bim-based geometric constraints and photogrammetric point clouds, Journal of Information Technology in Construction 20 (8) (2015) 68–79. https://www.scopus.com/inward/record.uri?eid=2-s2.0-84921690694&partnerID=40&md5=d0539a28858985c06486586cd1132c4f.
[6] W. Ren, Z. Wu, Real-time anticollision system for mobile cranes during lift operations, J. Comput. Civ. Eng. 29 (6) (2015), 04014100, https://doi.org/10.1061/(ASCE)CP.1943-5487.0000438.
[7] D. Liu, Y. Wu, S. Li, Y. Sun, A real-time monitoring system for lift-thickness control in highway construction, Autom. Constr. 63 (2016) 27–36, https://doi.org/10.1016/j.autcon.2015.12.004.
[8] K.M. Lundeen, S. Dong, N. Fredricks, M. Akula, J. Seo, V.R. Kamat, Optical marker-based end effector pose estimation for articulated excavators, Autom. Constr. 65 (2016) 51–64, https://doi.org/10.1016/j.autcon.2016.02.003.
[9] A. Zanella, N. Bui, A. Castellani, L. Vangelista, M. Zorzi, Internet of things for smart cities, IEEE Internet Things J. 1 (1) (2014) 22–32, https://doi.org/10.1109/JIOT.2014.2306328.
[10] A. Al-Fuqaha, M. Guizani, M. Mohammadi, M. Aledhari, M. Ayyash, Internet of things: a survey on enabling technologies, protocols, and applications, IEEE communications surveys & tutorials 17 (4) (2015) 2347–2376, https://doi.org/10.1109/COMST.2015.2444095.
[11] M. Štefanič, V. Stankovski, A review of technologies and applications for smart construction, in: Proceedings of the Institution of Civil Engineers-Civil Engineering 172, Thomas Telford Ltd, 2018, pp. 83–87, https://doi.org/10.1680/jcien.17.00050.
[12] Decenter - decentralised technologies for orchestrated cloud-to-edge intelligence. https://www.decenter-project.eu/ [Online; accessed 04-August-2020].
[13] G.S. Ramachandran, B. Krishnamachari, Real-Time Internet of Things for Smart Environments, Springer Singapore, Singapore, 2020, pp. 1–25. URL, https://doi.org/10.1007/978-981-4585-87-3_47-1.
[14] D. Korzun, E. Balandina, A. Kashevnik, S. Balandin, F. Viola, Ambient Intelligence Services in IoT Environments: Emerging Research and Opportunities, 2019, https://doi.org/10.4018/978-1-5225-8973-0.
[15] D.G. Korzun, I.V. Galov, A.A. Lomov, Smart space deployment in wireless and mobile settings of the internet of things, in: 2016 3rd International Symposium on Wireless Systems within the Conferences on Intelligent Data Acquisition and Advanced Computing Systems (IDAACS-SWS), 2016, pp. 86–91, https://doi.org/10.1109/IDAACS-SWS.2016.7805793.
[16] D. Pasini, S.M. Ventura, S. Rinaldi, P. Bellagente, A. Flammini, A.L.C. Ciribini, Exploiting internet of things and building information modeling framework for management of cognitive buildings, in: 2016 IEEE International Smart Cities Conference (ISC2), IEEE, 2016, pp. 1–6, https://doi.org/10.1109/ISC2.2016.7580817.
[17] B. Dave, S. Kubler, K. Främling, L. Koskela, Opportunities for enhanced lean construction management using internet of things standards, Autom. Constr. 61 (2016) 86–97, https://doi.org/10.1016/j.autcon.2015.10.009.
[18] J.K. Chow, Z. Su, J. Wu, Z. Li, P.S. Tan, K.-f. Liu, X. Mao, Y.-H. Wang, Artificial intelligence-empowered pipeline for image-based inspection of concrete structures, Autom. Constr. 120 (2020) 103372, https://doi.org/10.1016/j.autcon.2020.103372.
[19] J.L. Blanco, S. Fuchs, M. Parsons, M.J. Ribeirinho, et al., Artificial intelligence: construction technology's next frontier, building economist, The 2018 (Sep 2018) 7.
[20] H.-Y. Chong, J.S. Wong, X. Wang, An explanatory case study on cloud computing applications in the built environment, Autom. Constr. 44 (2014) 152–162, https://doi.org/10.1016/j.autcon.2014.04.010.
[21] H.-M. Chen, K.-C. Chang, T.-H. Lin, A cloud-based system framework for performing online viewing, storage, and analysis on big data of massive bims, Autom. Constr. 71 (2016) 34–48, https://doi.org/10.1016/j.autcon.2016.03.002.
[22] H.S. Ko, M. Azambuja, H.F. Lee, Cloud-based materials tracking system prototype integrated with radio frequency identification tagging technology, Autom. Constr. 63 (2016) 144–154, https://doi.org/10.1016/j.autcon.2015.12.011.
[23] G. Xu, M. Li, C.-H. Chen, Y. Wei, Cloud asset-enabled integrated iot platform for lean prefabricated construction, Autom. Constr. 93 (2018) 123–134, https://doi.org/10.1016/j.autcon.2018.05.012.
[24] P. Kochovski, V. Stankovski, Supporting smart construction with dependable edge computing infrastructures and applications, Autom. Constr. 85 (2018) 182–192, https://doi.org/10.1016/j.autcon.2017.10.008.
[25] D. Merkel, Docker: lightweight linux containers for consistent development and deployment, Linux journal 239 (2) (2014), https://doi.org/10.5555/2600239.2600241.

[26] V. Buterin, et al., Ethereum white paper: a next generation smart contract & decentralized application platform, https://cryptorating.eu/whitepapers/Ethereum/Ethereum_white_paper.pdf, [Online; accessed 04-August-2020] (2014).

[27] Z. Zheng, S. Xie, H.-N. Dai, W. Chen, X. Chen, J. Weng, M. Imran, An overview on smart contracts: challenges, advances and platforms, Futur. Gener. Comput. Syst. 105 (2020) 475–491.

[28] R. Yang, R. Wakefield, S. Lyu, S. Jayasuriya, F. Han, X. Yi, X. Yang, G. Amarasinghe, S. Chen, Public and private blockchain in construction business process and information integration, Autom. Constr. 118 (2020) 103276, https://doi.org/10.1016/j.autcon.2020.103276.

[29] M. Das, H. Luo, J.C. Cheng, Securing interim payments in construction projects through a blockchain-based framework, Autom. Constr. 118 (2020) 103284, https://doi.org/10.1016/j.autcon.2020.103284.

[30] Z. Wang, T. Wang, H. Hu, J. Gong, X. Ren, Q. Xiao, Blockchain-based framework for improving supply chain traceability and information sharing in precast construction, Autom. Constr. 111 (2020) 103063, https://doi.org/10.1016/j.autcon.2019.103063.

[31] L. Gürgen, C. Munilla, R. Druilhe, E. Gandrille, J. Botelho do Nascimento, sensinact iot platform as a service, Enablers for Smart Cities (2016) 127–147, https://doi.org/10.1002/9781119329954.ch6.

[32] F. Bonomi, R. Milito, J. Zhu, S. Addepalli, Fog computing and its role in the internet of things, in: Proceedings of the first edition of the MCC workshop on Mobile cloud computing, 2012, pp. 13–16, https://doi.org/10.1145/2342509.2342513.

[33] P. Kochovski, S. Gec, V. Stankovski, M. Bajec, P.D. Drobintsev, Trust management in a blockchain based fog computing platform with trustless smart oracles, Futur. Gener. Comput. Syst. 101 (2019) 747–759, https://doi.org/10.1016/j.future.2019.07.030.

[34] S. Gec, D. Lavbič, M. Bajec, V. Stankovski, Smart contracts for container based video conferencing services: Architecture and implementation, in: International Conference on the Economics of Grids, Clouds, Systems, and Services, Springer, 2018, pp. 219–233, https://doi.org/10.1007/978-3-030-13342-9_19.

[35] T. Binz, U. Breitenbücher, O. Kopp, F. Leymann, Tosca: portable automated deployment and management of cloud applications, in: Advanced Web Services, Springer, 2014, pp. 527–549, https://doi.org/10.1007/978-1-4614-7535-4_22.

[36] Kubernetes documentation. https://kubernetes.io/docs/home/ [Online; accessed 04-August-2020].

[37] Prometheus documentation. https://prometheus.io/docs/introduction/overview/ [Online; accessed 04-August-2020].

[38] P. Kochovski, P.D. Drobintsev, V. Stankovski, Formal quality of service assurances, ranking and verification of cloud deployment options with a probabilistic model checking method, Inf. Softw. Technol. 109 (2019) 14–25, https://doi.org/10.1016/j.infsof.2019.01.003.

[39] Metamask docs. https://docs.metamask.io/guide/ [Online; accessed 04-August-2020].

[40] P. Kochovski, V. Stankovski, S. Gec, F. Faticanti, M. Savi, D. Siracusa, S. Kum, Smart contracts for service-level agreements in edge-to-cloud computing, Journal of Grid Computing (2020) 1–18, https://doi.org/10.1007/s10723-020-09534-y.

[41] J. Redmon, A. Farhadi, Yolov3: An incremental improvement, https://arxiv.org/pdf/1804.02767.pdf, [Online; accessed 04-August-2020] (2018).

[42] J.B. Bernabe, J.L. Canovas, J.L. Hernandez-Ramos, R.T. Moreno, A. Skarmeta, Privacy-preserving solutions for blockchain: review and challenges, IEEE Access 7 (2019) 164908–164940, https://doi.org/10.1109/ACCESS.2019.2950872.

[43] F. Casino, T.K. Dasaklis, C. Patsakis, A systematic literature review of blockchain-based applications: current status, classification and open issues, Telematics Inform. 36 (2019) 55–81, https://doi.org/10.1016/j.tele.2018.11.006.