Smart City Platform Based on Citizen Reporting Services

George Suciu, Lucian-Alexandru Necula, Vladimir Jelea, Dragos-Sebastian Cristea, Carmen-Catalina Rusu, Luigi-Renato Mistodie, and Marius-Petrut Ivanov

1 Introduction

The smart city concept integrates different types of Internet of Things (IoT) devices for collecting data and using it to manage resources efficiently and improve the quality of life for the citizens [1]. Usually, collected data are analysed in order to improve traffic and transportation systems, utilities infrastructure, waste disposal, crime detection, community services and other services within the city [2]. The main factors that generated interest in the Smart City domain are environmental protection, ageing population, increase of urban population and economic restructuring [3]. The inhabitants of a city are increasingly looking for a friendly city, a smart city where people enjoy the services offered and the connections with the other inhabitants. By designing intelligent systems and connecting the existing ones, urban services address various needs and enhance the visibility of the inhabitants' problems to the authorities [4].

To address the main challenges of the Smart City domain, the CitiSim platform [5] is defined by its services, protocols and instruments for the development of smart services, 3D visualization and control of the Smart City ecosystem, and

G. Suciu (✉) · L.-A. Necula · V. Jelea
Beia Consult International, Bucharest, Romania
e-mail: george@beia.ro; lucian.necula@beia.ro; vladimir.jelea@beia.ro

D.-S. Cristea · C.-C. Rusu · L.-R. Mistodie
"Dunarea de Jos" University of Galati, Galati, Romania

Altfactor, Galati, Romania
e-mail: carmen.rusu@ugal.ro; luigi.mistodie@ugal.ro

M.-P. Ivanov
Altfactor, Galati, Romania
e-mail: marius.ivanov@altfactor.ro

D. Cagáňová et al. (eds.), *Advances in Industrial Internet of Things, Engineering and Management*, EAI/Springer Innovations in Communication and Computing,
https://doi.org/10.1007/978-3-030-69705-1_5

simulation for substantiation and implementation of strategic decisions within urban environments. CitiSim focuses on various domains of the city including mobility, health, comfort, security, emergencies, energy and citizen reporting.

In the context of the CitiSim project, the current paper presents a Citizen Reporting smart service meant to enhance the relationship between citizens and authorities and to solve problems with a higher efficiency within the Smart City. The rest of the article is structured as follows: Sect. 2 presents Smart City solutions and focuses on citizen reporting services, Sect. 3 depicts the CitiSim concept, Sect. 4 proposes a Citizen Incident Reporting smart service developed within the CitiSim project, while Sect. 5 concludes the paper.

2 Related Work

The current section presents various Smart City solutions that provide various functionalities for enhancing the living conditions of citizens. Solutions that aim to address various aspects of the Smart City ecosystem are oriented to provide custom tools for the city managers on request or to provide generic services that can be implemented in any city.

2.1 Smart City

The current sub-section presents solutions created to provide Smart City services to the citizens and society, thus improving aspects related to comfort, environment, health, traffic, utilities and economy.

The CitySDK [6] project provides a development environment for the creation of Smart City services using APIs (Application Program Interfaces). The solution has been tested in eight European cities, namely Amsterdam, Barcelona, Helsinki, Istanbul, Lamia, Lisbon, Manchester and Rome.

IBM Intelligent Operation Center [7] represents a platform provided by IBM which offers various Smart City services customizable on-demand. The challenges of the Smart City are addressed through data visualization and analytics which are the basis for optimizing operational efficiency. KPIs (Key Performance Indicators) facilitate the enhancing of city services, personnel and Smart City applications (traffic control, emergency management, incident reporting, etc.).

Sentilo [8] is a Smart City open-source platform with a modular architecture that facilitates its expansion without modifying the core system. The data visualization and management rely on a REST interface. Through the catalogue and administration console, the user can manage connected devices and associated users. At its origin, the solution was oriented towards the development of Barcelona in the Smart City domain, but the concept extended to cities as Terrassa and Reus.

Huawei Smart City [9] is a platform for real-time data reporting and analysis based on technologies as Cloud Computing, Internet of Things (IoT), Big Data

and Artificial Intelligence (AI). It can integrate applications and devices in order to monitor the land planning, economy, transportation, population and ecological environment and manage specific operations related to emergencies, surveillance, utilities, traffic and parking, public illumination, urban agriculture, etc.

SmartCity Budapest Transport [10] is a mobile application for public transport information in Budapest. The application is free and can be used offline. This solution offers a public transport route planner, the full schedule of all the public transport lines of Budapest and a vector-based map with address search.

Smart City Traveler [11] is a solution that improves the experience of a person who likes to travel the city and wanted to explore the city by specifying the time in hours. Based on a questionnaire, the system analyses and creates a user program based on the time specified by the user for a trip.

SMART CITY Inspector [12] analyses RGB data, DSM, DTM or thermal data from drones and aircraft captured images. The application offers various solutions for smart data analysis, water management and smart planning for the future of cities. This solution is recommended for spatial planners, city builders, environmentalists, etc.

2.2 Citizen Incident Reporting

Citizen incident reporting applications allow citizens to effectively participate in the local governance by documenting their concerns and sending a report to the government order management services. The current sub-section presents solutions that aim to facilitate the communication between citizens and Smart City stakeholders through reporting of various events that may affect the ecosystem.

CitySourced [13] is a citizen reporting solution that allows the user to take a picture using the mobile phone camera, classify it in a category of interest and submit the report using a mobile application to municipalities or other stakeholders. Due to the usage of GPS to associate the report to a certain location, the need to add the address in the mobile application interface is not necessary.

Citizen Problem Reporter [14] represents a reporting application that allows the user to submit problems not addressing emergencies in their community using a mobile device or a personal computer. The report is used by the local government or other stakeholders to enhance the quality of citizen services. Thus, after analysing the requests, the local government can plan specific actions and send the request further to responsible parties for resolution.

MyTown Smart City [15] is an application used to report a problem, for example, a pothole, a street light outage, parking concerns or sensitive information anonymously via the HotLine tool. This application allows citizens to easily connect with local governments.

FixMyStreet [16] is an application made to be used online and offline. This application is used by citizens to report street issues. In this way, problems can be solved more quickly by the authorities.

At Romanian level, various Smart City reporting solutions are available for the citizens to report events. e-Alba Iulia [17] is a proximity mobile application that guides the user in exploring landmarks and to participate in events and provides the option to report issues that impact the city to local authorities. My Cluj [18] is an application provided by the Cluj-Napoca City Hall that provides a mobile service for reporting events associated with the public domain. Based on the user's location, images and the event information, the report is sent to the responsible public institutions for evaluation and intervention. A similar solution, Cluj Now [19] focuses on reports related to infrastructure work that affects urban traffic. The application also provides information on events affecting urban traffic for the public. Târnăveni Smart City [20] is another solution for reporting infrastructure problems (leakage of gas or water, dangerous driving conditions, etc.) to the municipality, thus lowering the intervention time of intervention for public authorities. The mobile application also provides information regarding such events and news related to infrastructure enhancements. With the Smart City Giurgiu application [21], the user can report various problems or irregularities that are encountered in Giurgiu, such as: asphalt pits, damaged benches in parks, public lighting issues, sewerage, etc. The reported problems are sent automatically to the Giurgiu City Hall, which will notify the competent authority. The user is notified by email about the status of the reported problem.

3 CitiSim Concept

In the last two decades, the proliferation of ICT technologies has led the evolution towards a new digital era that facilitates the sharing of information between citizens and environments at a global scale. With a continuous increase of urban population, cities are facing various challenges that can be managed using technology innovations [22]. In this context, a considerable number of research projects and pilots have been deployed as an attempt to study and manage resource consumption, environmental quality and urban mobility. However, due to a wide variety of technologies which pose various limitations in terms of scalability and integration, the proposed solutions imply a considerable effort for their administration and are not viable from an economic perspective.

Currently, the absence of a common platform that supports the implementation and integration of smart city services represents a blocking factor in the deployment of sustainable solutions. To address this challenge, the CitiSim ecosystem provides powerful monitoring and management solutions that enable city planners to substantiate viable decisions both on tactical and strategic levels based on the data collected from various sources. For a natural interaction with the Smart City ecosystem within the digital world, CitiSim provides 3D visualization instruments, facilitating the exploration of various augmented and virtual reality scenarios.

CitiSim provides a framework for a facile development and deployment of Smart City services, addressing various market verticals, such as energy management,

environmental monitoring, urban mobility and emergency management. The main CitiSim instruments are:

- A platform consisting of different software blocks and data transmission protocols for Smart City services implementation;
- A 3D visualization tool for digital interactions with the Smart City ecosystem;
- A simulation framework for decision-making, successfully demonstrated in emergency management and energy efficiency scenarios as part of the CitiSim project.

Since smart services applications are moving from laboratories to the real city, there exists a growing need for advanced tools to manage and promote the smart city ecosystem. For the development of the so-called smart city services, aspects as advanced platforms (e.g. middleware, standards, protocols, interfaces, etc.), data visualization, and a safe software environment where testing new applications become capital issues. Consider an SME that is in charge of developing an application for a smart city. This SME currently finds several barriers: firstly, the access to the city information, such as the layout of pedestrian routes or people mobility patterns, that has to be elaborated by them. Secondly, the SME developer team has to deal with a variety of protocols, heterogeneous data format and data sources; and thirdly, there is a lack of environments for testing smart city applications. These barriers impact on time-to-market of feasible solutions and make very complicated to develop applications for smart cities and, in turn, the realization of smart cities.

The problem with the current state-of-the-art technologies is the lack of a holistic platform that helps developers to implement applications and to provide citizens with a powerful tool to translate data into meaningful information. Until today most of the products of the market, and research and innovation projects were focused mainly on developing specific applications or standardizing interfaces in the case of middleware. Simulation of different processes involved in the day-to-day of a smart city represents a challenge to be addressed in order to support tactical and strategic decisions about mobility, city layout design, emergency situations, etc. The CitiSim project aims to fill this gap and proposes an e-infrastructure that enables fast design and development, a safe test environment and the deployment of advanced applications for smart cities. This e-infrastructure is a key element in the smart city development path, which will provide to different agents (e.g. city councils, SMEs, and citizens) with a catalogue of advanced services built from up-to-date data that represents the state of the city.

Therefore, the final goal of CitiSim is providing a platform integrating multiple smart services that offer structured information collected from the urban environment, and whose knowledge is valuable for a wide range of stakeholders (see Fig. 1): firstly, citizens may take advantage of up-to-date, rich information on dimensions not explored before; SMEs may interact with CitiSim platform for developing pioneer, added-value services that help them to position them as leaders in relation to their competitors; large companies act both providing technology (e.g. hardware devices, network providers) and as developers of services and applications (e.g. data

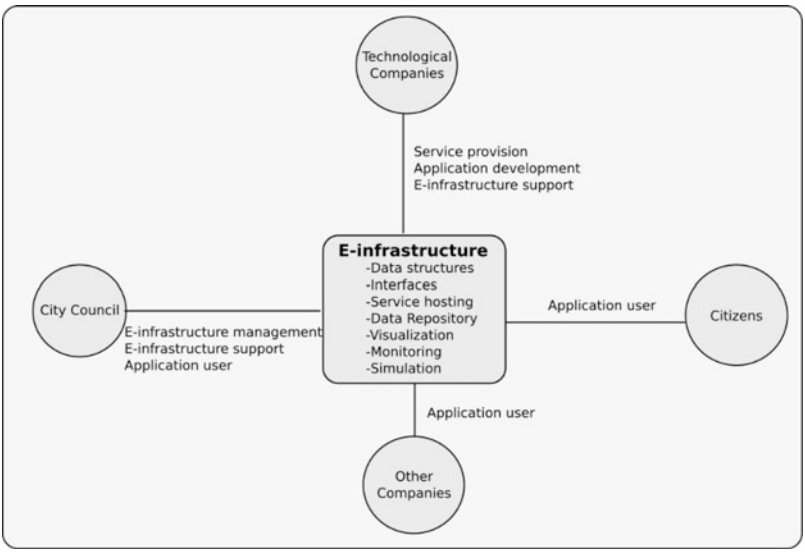

Fig. 1 Stakeholders of the market value chain for CitiSim

analysis, 3D models, algorithms) for the final users and, city councils hold most part of the CitiSim infrastructure, participate in its definition through regulations, contribute with their information systems, and act also as managers, obtaining strategical information from the city and from citizens.

This novel approach allows us focusing on the problem and to identify market-specific and common services with great potential of reusability. Two are the markets to which these uses cases are oriented, such as environmental friendly mobility and energy efficiency.

Figure 2 identifies seven steps involved in the production of smart services and their delivery to the end-users of the four markets cited above as well as their actors and enablers:

- Monitoring devices: The CitiSim infrastructure will be populated by a large set of heterogeneous devices for the monitoring of variables of interest for each particular use case. We are getting in touch with different hardware manufacturers (sensors, actuators, RFIDs) that may provide the most adequate devices.
- Smart things: Due to the interest showed by several city councils around the Europe (e.g. Rivas VaciaMadrid), the consortium will offer possibilities of collaboration to those organisms. To this purpose, they will provide requirements. This fact demonstrates that the CitiSim project already has an access market.
- Network integrator: Development and integration of networked devices that use different communication technologies.

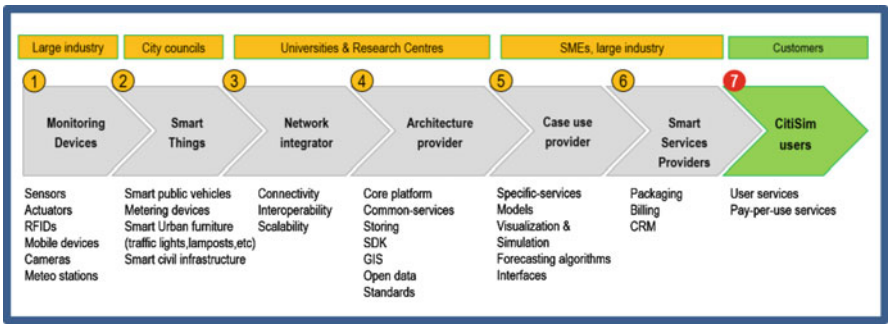

Fig. 2 Market value chain for CitiSim project

- Technology provider: Universities and research centres in collaboration with industrial partners in the CitiSim consortium will define the reference architecture for CitiSim based on the study of the state-of-the-art and their expertise.
- Use case providers: CitiSim partners grouped in a country-basis will propose at the beginning of CitiSim project the definition of a use case to be deployed on CitiSim architecture, and with relevance and potential impact on the citizens.
- Smart services providers: Smart models go beyond the urban models based on LUTI, cellular automates and agents found in the current state-of-the-art. The analysis of data by means of Big Data analytics about the city will allow defining smart services with added value for citizens. Advanced visualization techniques (augmented virtuality and augmented reality) need 3D models about different physical infrastructures (transport, energy, water, etc.), geodata visualization, and gamification.
- Project innovations and technology value chain.

The technological value chain is composed by a set of components where different technologies are involved and where partners of CitiSim accumulate proved experience:

- The monitoring and simulation smart city platform covers functional requirements described above and operational issues like security, scalability, Big Data software solutions, etc.
- Smart city low-level infrastructure: data proceed from different sources as heterogeneous multi-platform devices (sensors and actuators, GPSs, RFIDs, city infrastructure, smartphones) and social networks must be extracted, stored in a robust, scalable middleware and clouds, combined together, analysed and integrated.
- Smart urban models about different physical infrastructures and interest dimensions of the city (transport, energy, etc.) that are continuously and dynamically acquiring data from the things of the city, recomputing the outputs and forecasting behaviours in a mid-term predictive context. Smart models go beyond the urban models based on LUTI, cellular automates and agents found in the current

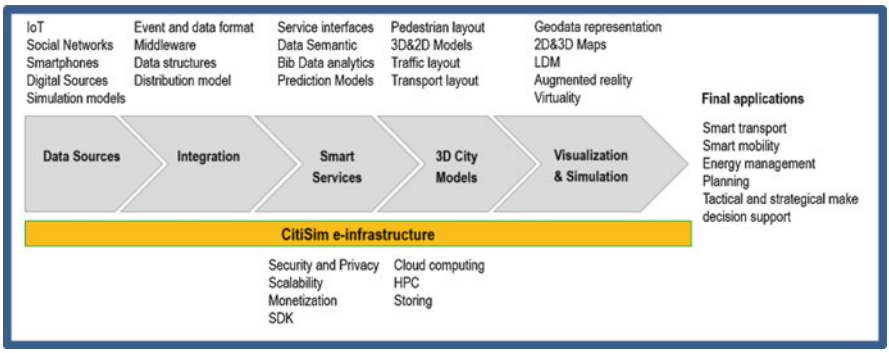

Fig. 3 Technology value chain for CitiSim project

state-of-the-art. The analysis of data by means of Big Data analytics about the city will allow defining smart services with added value for citizens.

- 3D visualization and simulation: advanced visualization techniques (augmented virtuality and augmented reality) need 3D models about different physical infrastructures (transport, energy, etc.), geodata visualization and gamification.

The technological value chain of CitiSim project is shown in Fig. 3.

The core of CitiSim is the development of a smart city ecosystem that provides both functional and non-functional issues and makes smart services available to citizens. The CitiSim reference architecture is presented in Fig. 4, and it is organized on five horizontal layers from bottom to up.

The five horizontal layers are presented within the following paragraphs.

- Cognitive Monitoring Layer: This layer is responsible for collecting data through the smart things of the CitiSim ecosystem. It is also more ambitious than the monitoring solutions found in the current state-of-the-art since it includes pre-processing modules for extracting cognitive data in addition to the monitoring itself of the smart city. The format of the data should be compliant with a standardized and open-data format, e.g. SensorML. This layer provides events to the rest of the layers of the e-infrastructure related to what and where is happening on the city.
- Simulation Layer: Simulation models are designed to use both the data of the Persistence Layer (synthetic data and data provided directly by the monitoring devices). According to the use-cases defined, CitiSim is going to put focus (without preventing the use of other models) on the following simulation models: people mobility model, traffic mobility model, mass transit model and business location model. This layer can provide to the service layer with raw events on the same way that of Cognitive Monitoring Layer. According to the desired configuration, a service/application can receive information from the simulation layer exactly on the same way that from the monitoring layer.

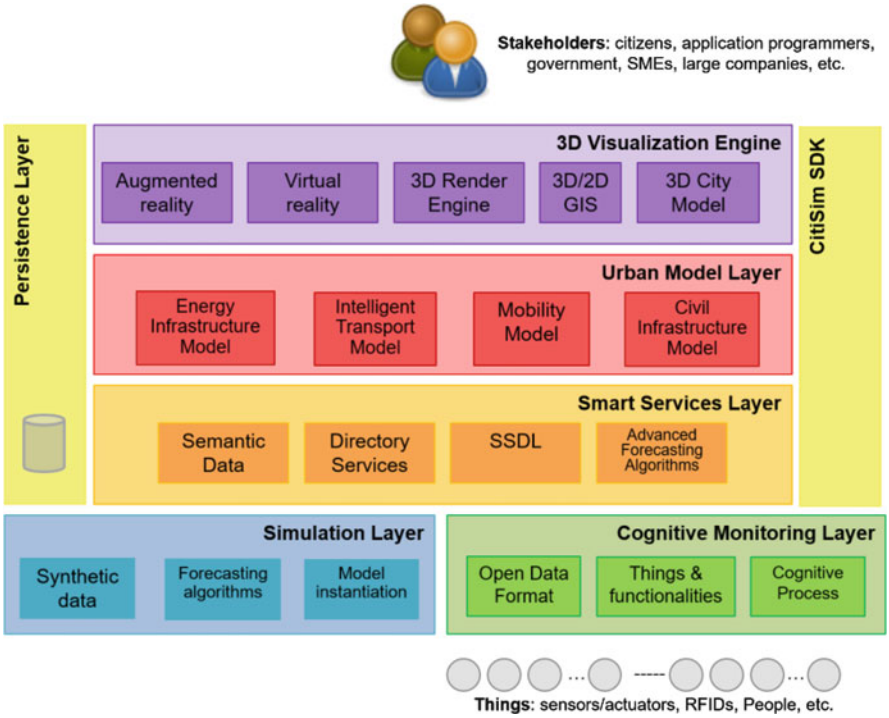

Fig. 4 Detailed reference architecture of CitiSim platform

- Smart Services Layer: This layer is the core of the e-infrastructure. Common services for several use cases can be reused by overlaying applications, such as directory services, services to provide semantic to data, and services description (Smart Services Definition Language, SSDL). From a developer point of view, these services provide with a well-known interface useful functionality like subscription mechanism to specific type of data related with, for example, people mobility, traffic mobility, etc. Specific middleware-related services (e.g. event distribution service or service composition service) are also included on this layer.
- Urban Model Layer: This layer provides all type of city layout urban models as a service. The models can be contributed by companies and citizens on a collaborative effort done by the smart city community.
- 3D Visualization Engine Layer: This layer uses the underlying layers for representing the city and geo-positioning the information of the city. Attending to the purpose of the final application, the data can be represented on a 3D virtual world, a 2D map, or on an augmented reality app, over a variety of devices. In the case of mayor console application, i.e. a holistic decision support system for municipalities, the application enables to control and monitor all parameters of

the city at real time on augmented reality world, that is, a 3D virtual world where real information is added.

CitiSim SDK Layer and Persistence Layer are vertical layers that enable the access to the services and information for development purposes. The former follows a sandbox approach, i.e. the developers will use a local CitiSim platform where they develop and test new services and applications and then they upload such services to the global CitiSim platform. The second one is intended to be storing and recovering of raw data, semantic data, and results of simulation through interfaces that can be accessed by the rest of the layers in CitiSim architecture.

4 CitiSim Citizen Incident Reporting

As cities got bigger, problems started to increase in number and become more difficult to spot by authorities, such as environmental monitoring [23]. CitiSim Citizen Incident Reporting is a smart service available through a mobile application, compatible with Android and iOS mobile devices, which provides a better communication between citizens which spot problems and authorities responsible for their resolution. When using the reporting application, the user can take a photo and provide additional information regarding the event. The photo is analysed using AI (Artificial Intelligence) and metadata describing the object is generated (building, road, car, tree). After the report is submitted, the event data are processed, stored in the database and displayed on a heatmap. In addition, based on the data provided by the user, the report is sent to the authorities responsible for managing that specific issue. Based on the location, the user can be informed regarding various events happening in an area of interest (construction work on the road, water leakage on the sidewalk, car blocking public transportation, etc.).

The CitiSim Citizen Incident Reporting application uses an API to send and receive JSON objects containing account-resource, report-resource and user-resource data. The map is implemented using Google's Maps SDK over which a heatmap is generated to show places with different densities of reports using different gradients.

The application uses an API consisting of three main parts:

- Account Resource
- Report Resource
- User JWT Controller

Using the Account Resource package, the user can register, login, post and get personal data like first name, last name, username, user id, latitude and longitude. The Report Resource package is used for managing reports. It requests report data such as the report title, image, latitude, longitude, time and assign it to the user that sends it.

The user can view the submitted reports as a list containing all the necessary data. In the same way, authorities or other stakeholders can view the received reports as a list and filter their content based on the metadata and urgency. For example, a report containing metadata such as “dangerous leak” will be treated as an emergency and investigated immediately by the responsible authorities. When the reported problem is acknowledged, addressed or solved, the user is notified through the application interface or by email.

The application communicates with the API using JSON Objects, these are data structures written in key/value pairs surrounded by curly braces. The keys and values are separated by a column and each key/value pair is separated by a comma. These objects are created by transferring all the necessary data for the API in a HashMap and then send it to the Cloud using the Volley library. HashMap is a collection type in java, it is used in this context for its efficiency when working with large data sets because elements are being searched using their HashCode. A JSON Object Request contains a request method (GET/POST), an URL (where the data is being sent), the data and a header containing the authentication token. The AI agent analyses the photo submitted by the user, generates metadata associated with the identified objects or events and sends the data to the database. The CitiSim Citizen Incident Reporting service architecture is presented in Fig. 5.

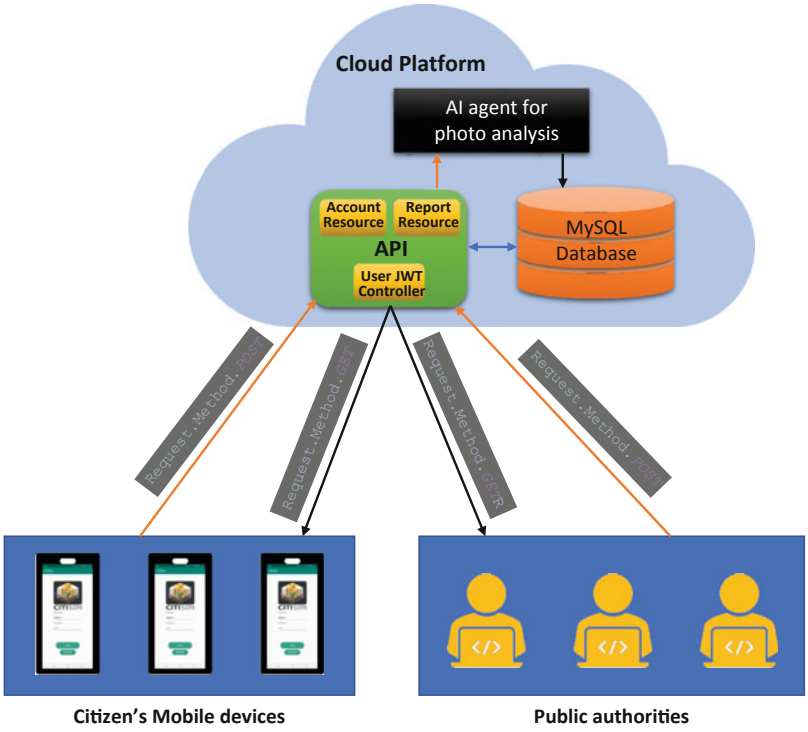

Fig. 5 CitiSim Citizen Incident Reporting service

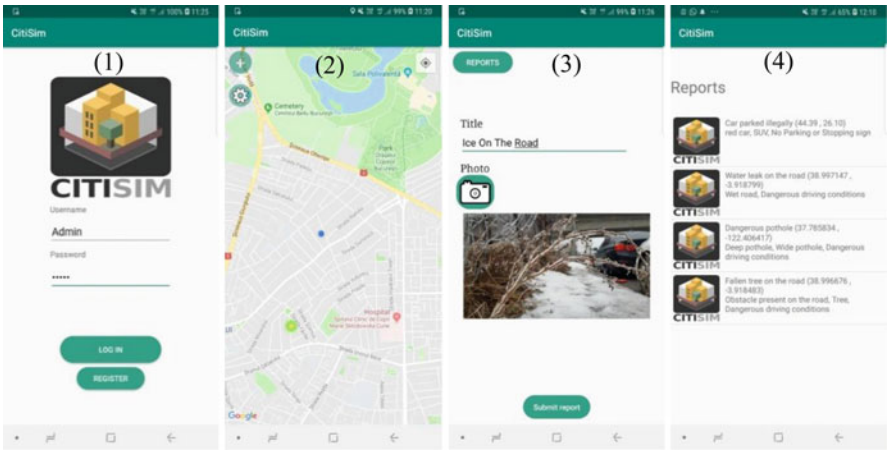

Fig. 6 Citizen incident reporting mobile application GUI

The Citizen Incident Reporting application provides the following functionalities:

- Log in activity: in the Log in screen the user is able to register to the platform or log in using an existing account, as presented in Fig. 6(1).
- Map activity: in the map activity, the reports are illustrated as a heatmap, as presented in Fig. 6(2). Thus, other citizens can be aware of the events in an area of interest. It is an overlay on the Google maps SDK.
- Event reporting: as illustrated in Fig. 6(3), in the New Report activity the user can load an image from a mobile device, add a title and send it to the server where it will be processed, displayed on the map and sent to the authorities responsible for the investigation and resolution of the event.
- Reports history: as presented in Fig. 6(4), in the Reports list activity the reports are being presented in a vertical list together with the title and latitude and longitude coordinates, and keywords identified by the AI agent after image analysis. The list is available both for the user and the responsible authorities.

The Citizen Incident reporting service can be integrated with other available smart services in order to enhance their functionality. For example, the reporting service can be used by Smart City solution providers to facilitate the reporting of damage/theft/malfunction of equipment deployed within the city or issues encountered when using the smart services.

5 Conclusions

The concept of Smart Cities is based on urban development by integrating systems and technologies to more easily manage the resources of a city and to improve

the livelihood of its residents. The goal of a Smart City is to promote technical innovation and to improve the efficiency of urban management.

Mobile applications may be an important part in the process of improving a city by facilitating the communication between citizens and the authorities responsible for the city administration. To address the difficulties in reporting various events within the city, the CitiSim Citizen Incident Reporting application facilitates actuation towards problem-solving by using AI to categorize the event (e.g. damage to a monument, water leakage affecting traffic, parked car affecting the tram, ice on the road), send it to responsible authorities, and inform citizen about events in an area of interest and their resolution.

With this application, the authorities can monitor all the problems in the city and can find solutions to ensure a better quality of life for the citizens. As future work, we intend to enhance the performance of the AI agent in terms of object/event recognition. Another aspect would be providing the possibility to upload specific to damage or malfunction of the CitiSim devices deployed within the Smart City or the application available for the users.

Acknowledgements This work has been supported in part by UEFISCDI Romania and MCI through projects CitiSim, ESTABLISH, PARFAIT and WINS@HI, funded in part by European Union's Horizon 2020 research and innovation program under grant agreement No. 826452 (Arrowhead Tools), No. 787002 (SAFECARE), No. 777996 (SealedGRID) and No. 813278 (A-WEAR).

References

1. P. Ta-Shma, A. Akbar, G. Gerson-Golan, G. Hadash, F. Carrez, K. Moessner, An ingestion and analytics architecture for IoT applied to smart city use cases. IEEE Internet Things J. **5**(2), 765–774 (2017)
2. A.K. Singh, D. Kumar, V. Prakash, Importance and needs of IoT in developing smart cities (2019)
3. S. Myeong, Y. Jung, E. Lee, A study on determinant factors in smart city development: An analytic hierarchy process analysis. Sustainability **10**(8), 2606 (2018)
4. F. Bhatti, M.A. Shah, C. Maple, S.U. Islam, A novel internet of things-enabled accident detection and reporting system for smart city environments. Sensors **19**(9), 2071 (2019)
5. CitiSim Homepage, http://citisim.org. Last accessed 15 May 2019
6. CitySDK Homepage, http://citysdk.waag.org. Last accessed 14 May 2019
7. IBM Intelligent Operation Center Homepage, https://www.ibm.com/ro-en/marketplace/city-insights. Last accessed 14 May 2019
8. Sentilo Homepage, http://www.sentilo.io/wordpress/. Last accessed 19 Mar 2019
9. Huawei Smart City, https://e.huawei.com/en/solutions/industries/smart-city. Last accessed 19 Mar 2019
10. SmartCity Budapest Transport on Google Play, https://play.google.com/store/apps/details?id=hu.ponte.mobile.smartcity. Last accessed 19 Mar 2019
11. Smart City Traveler on Google Play, https://play.google.com/store/apps/details?id=com.smartcitytraveler. Last accessed 14 May 2019
12. Smart City Inspector on Google Play, https://play.google.com/store/apps/details?id=com.smart_city_inspector. Last accessed 14 May 2019

13. CitySourced Homepage, https://www.esri.com/news/ArcUser/0111/files/citysourced.pdf. Last accessed 15 Apr 2019
14. Citizen Problem Reporter Homepage, https://solutions.arcgis.com/local-government/help/citizen-problem-reporter/. Last accessed 15 Apr 2019
15. MyTown Smart City on Google Play, https://play.google.com/store/apps/details?id=com.mytown.realtermenergy. Last accessed 15 Apr 2019
16. FixMyStreet Homepage, https://play.google.com/store/apps/details?id=org.mysociety.FixMyStreet. Last accessed 15 Apr 2019
17. e-Alba Iulia on Google Play, https://play.google.com/store/apps/details?id=ro.gebs.discover.albaiulia. Last accessed 6 Mar 2019
18. My Cluj on Google Play, https://play.google.com/store/apps/details?id=com.indsoft.mycluj&hl=en. Last accessed 6 Mar 2019
19. Cluj Now, https://play.google.com/store/apps/details?id=ro.lifeishard.clujnow. Last accessed 6 Mar 2019
20. Târnăveni Smart City on Google Play, https://play.google.com/store/apps/details?id=unserver.tarnaveni. Last accessed 6 Mar 2019
21. Smart City Giurgiu on Google Play, https://play.google.com/store/apps/details?id=ro.itom.smartcitygiurgiu. Last accessed 6 Mar 2019
22. Á. Carrera, E. Merino, P. Aznar, G. Fernández, C.A. Iglesias, An agent-based simulation model for emergency egress, in *International Symposium on Distributed Computing and Artificial Intelligence* (2018), pp. 140–148
23. G. Suciu, M.A. Sachian, A. Pasat, LoRa architecture for air quality monitoring, in *Advanced Topics in Optoelectronics, Microelectronics, and Nanotechnologies IX*, vol. 10977, (International Society for Optics and Photonics, Bellingham, WA, 2019), p. 109770T