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CITIMAN: Sustainable Polymer-Driven Smart City Design to Monitor, Manage, and Mitigate

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Abstract

The exponential growth of urbanization leads to a rise in the complexity of the city's infrastructure, resources, and needs, thereby overshooting the boundaries of governance. Thus, the necessity of time is to find a smart solution to such problems and one such potential candidate is the smart city management system. Ideally, in the context of smart cities, the development of a complete system includes all city services which provide modular as well as scalable solutions that are standardized to solve the problems of the above complexities. In this paper, a prototype has been postulated that provides an intelligent solution for smart city services viz. Mobility, People, Waste Management, Environment, Security, and Energy. With it, we aim to demonstrate a possible approach towards the development of such systems providing a modular and functional prototype to the above city services. CitiMan intends to provide a complete solution to monitor, manage, and mitigate the ongoing progress, planning, and development of the city services. In the context of smart city design, polymer materials directly support the ability to monitor, manage, and mitigate everyday urban challenges. Each smart city service is divided into three parts viz. Services for providing the features and functionalities, Help Desk for mitigating the problems, and Infographics for monitoring and analyzing the data. CitiMan proposes to help in bridging the gaps by providing distinct features and functionalities for the city services to the already existing solutions.

Keywords: Smart city, smart city management system, smart city services, polymer, renewable, waste management, security, energy

INTRODUCTION

Renewable polymer synthesis—especially when guided by sustainable production and green chemistry offers essential material solutions for the cities of the future. By relying on renewable feedstocks and environmentally responsible synthesis pathways, these polymers help lower urban environmental impacts while providing durable, adaptable materials. When applied to energy systems, such as flexible solar materials, advanced batteries, or lightweight storage components, renewable polymers strengthen the technological backbone needed for efficient and resilient urban infrastructures [1].

In the context of smart city design, these materials directly support the ability to monitor, manage, and mitigate everyday urban challenges [2]. Polymer-based sensors enable continuous monitoring of pollution levels, building conditions, and energy use. High-performance polymer materials in energy devices help cities better manage distributed energy flows, improve storage capacity, and maintain system stability [9–11]. At the same time, recyclable and long-lasting polymer systems aid in mitigation efforts by reducing waste

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and promoting circular resource use. Altogether, renewable polymer innovation and its technological applications form a vital foundation for smart cities that aim to operate intelligently, sustainably, and proactively [12, 13].

The infrastructure layer, sustainable polymer composites and smart polymer coatings are integrated into buildings, roads, and public utilities. These materials enhance durability, corrosion resistance, and energy efficiency while embedding sensing functionality directly into urban structures. Shape-memory polymers and self-healing polymer coatings further support mitigation by enabling adaptive responses to environmental stress [3], material degradation, and load variations.

Overall, the CITIMAN framework leverages polymer-driven sensing and infrastructure integration to create a scalable, energy-efficient, and environmentally sustainable smart city ecosystem capable of monitoring, managing, and mitigating urban challenges in real time.

In the CITIMAN framework, polymer-based sensor outputs, including conductivity, impedance, and strain-responsive electrical signals, are analyzed using machine learning models. Random forest and support vector machines enable environmental state prediction, while gradient boosting supports resource optimization. LSTM networks model temporal behavior in polymer sensor data, and autoencoders and isolation forest algorithms detect anomalies by identifying deviations in sensor response patterns, facilitating early detection of pollution and infrastructure faults.

At present, cities contribute 80% to the global GDP, and it is estimated that by 2050 the urban population will grow up to 68% (United Nations, 2018). With this evident impact of cities on the global

economy, it becomes imperative to meet the sustainable growth and smart utilization of limited resources in these cities to accomplish the global agenda of development as per the international standards. This can only be ensured if planning, development, and management are aligned with the present growth trajectories of these cities. In one way, this alignment can be achieved by using smart city management software. This software provides a systematic and analytical solution of management for the development and growth of a city that provides meaningful interpretation to the measurement of developing projects, services, and facilities that will assist in smart and meaningful governance, thus, improving the sustainable and efficient usage of resources and manpower. A smart city management software should provide two salient functions: one, administrating the cities by doing real-time analysis of data of current smart city parameters as defined in the ISO 37120 standards (ISO Standard, 2018), and two, managing the smart devices in the city, for example, the Internet of Things (IoT) devices. For the first-mentioned, the analysis of smart city parameters is important to evaluate the performance of the city at regular intervals and the data required to do this can be collected from various direct and indirect sources. For the second- mentioned, a smart city consists of many smart devices that are installed or deployed for various activities like managing the traffic through red lights and surveillance cameras, smart dustbins for waste management, smart lights for visibility, air purifiers, and sensors for monitoring the weather, etc. All these smart devices can be configured, controlled, monitored, and managed under a single console of smart city management software. The main objective of building a smart city management prototype like CitiMan is to propose a single centralized platform that can deliver the above-mentioned functions for smart city services which are aimed towards governance.

Additionally, it is suggested that such platforms should also focus on implementing an integrated Help and Support center for each city service. CitiMan provides the following important features:

- *Unified management solution:* It is a single management software that will act as a unified solution for all the matters of smart city services to all the people. This centralized approach differs from the conventional way of implementing isolated services, facilities, and infrastructure such as maintaining a separate website or platform for each public work department of transportation, water, and electricity supply, etc., which are running under the legal framework.

- *Multi-user accessibility:* It provides accessibility and usage for both the citizens as well as authorities. Each type of user has different privileges on how they can use and access the various functionalities of the CitiMan.
- *Modular structure:* The structural design of CitiMan is modular in its implementation that provides independent and isolated modules for different city services, enabling easier maintenance and usability.

The CITIMAN framework utilizes bio-based and recyclable polymer and polymer–composite materials to support sustainable smart city systems. Bio-based polymers such as polylactic acid (PLA) and cellulose-based composites are employed for sensor substrates and housings, while recyclable polymers including PET and thermoplastic polyurethane (TPU) are used for durable encapsulation and infrastructure components. Material performance is validated using ASTM and ISO standard protocols, including ASTM D638 for tensile properties, ASTM D4060 for wear resistance, and ISO 4892 for UV aging, ensuring reliable operation under urban environmental conditions [20].

The paper is outlined as follows: in section 2, we considered the related works in which we performed and summarized a comparative analysis of various popular smart city applications and dashboards based on a few performance parameters and features. In section 3, the focus is translated from related works to the abstract design that can be used to build a prototype like CitiMan, in which the core principle emphasizes the generic steps of the Software Development Life Cycle (SDLC) and selecting an appropriate technology stack that should be used to build it. Finally, we concluded the paper by presenting some rational views on the above approach with a possible future scope in section 4.

LITERATURE REVIEW

Before designing the novelty of the CitiMan prototype, it becomes crucial to analyze the previous attempts that have been done concerning the work which approaches the above problem of management with similar solutions. We have parameterized a few smart city services namely Education, Energy, Environment, Safety, Solid Waste, Transportation, etc. Its major benefit in the above context of comparing various related platforms is that there will be a uniformity in the accessibility of the features and functionalities of various smart city services which are implemented on these platforms. By categorizing them under their respective smart city service, the data and analytics are organized in their domain and hence it helps in increasing the overall ease of usability.

The classification of previous works based on the city services requires a clear understanding of these parameters from the perspective of technology and innovation. In context to this paper and based on the above analogy, the definition of smart city services are as follows:

- *Mobility:* It refers to optimizing the existing ecosystem of the city's transportation system and related services for the people to increase their ease of daily movement, safety, environmental sustainability, etc. The analysis of the city's performance in this domain can be done through the city indicators such as road density, vehicle density, the number of vehicles per capita in transportation, etc.
- *People:* It refers to the sustainable, inclusive, and holistic development of the human resources in a city by improving the existing ecosystems related to their socio-economic factors such as education, income, health, demographics, etc. The analysis of the city's performance in this domain can be done through the city indicators such as enrollment ratio in education, employment ratio in the economy, per capita earning and expenditure in the income, property prices, and average monthly rental prices in housing, etc.
- *Waste management:* It refers to the sustainable management of any kind of waste from the generation to its treatment and disposal. Generally, the major form of waste generated in a city is solid. The analysis of the city's performance in this domain can be done through the city indicators such as the portion of a city's population that have regular waste collection facilities, solid waste generated per capita, etc.

- *Environment:* It refers to the development of an ecosystem that consists of a network of smart devices, sensors, etc., to monitor the natural environment of a city for the betterment of its people. This can include managing environmental pollution like air, soil, noise, water, etc. The analysis of the city's performance in this domain can be done through the city indicators such as particulate matter concentration in air, soil profile and slaking in the soil, city's noise levels, pH scale and turbidity of the water, etc.
- *Security:* It refers to integrating new technologies to improve the cyber-security and public safety of the city. This can include developing a network of security solutions with the help of smart devices and improving the existing public safety services such as the police station, fire station, etc. The analysis of the city's performance in this domain can be done through the city indicators such as the global cybersecurity index (ITU, 2020) [4] and crime rate in public safety, etc.
- *Energy:* It refers to the management of the energy resources, optimal and sustainable utilization of active sources of energy in the city by developing energy-efficient management systems, infrastructure, and related services. The analysis of the city's performance in this domain can be done through the city indicators such as electricity consumption per capita, the total power generated, and total energy supplied in the city, etc.

In Table 1 and Table 2, we have discussed and summarized the features and functionalities of the existing related platforms. Additionally, some extra services of the platforms that do not fall under the analogy of smart city services have been considered in the "Others" category.

In Table 1 and Table 2, some notable observations and outcomes of the comparative analysis are as follows: Most of the completely accessible platforms are primarily dashboards that provide analytics for the city parameters of their respective smart city services.

Table 1. Comparative analysis of related platforms for mobility and people services.

Name of the platforms	**Smart City Services**	
	Mobility	***People***
Dublin Dashboard (2021) [8]	Data analysis of public transport usage, Dublin bikes, and traffic counters	*Housing:* Data Analysis of house prices, property price index, etc. *Economy:* Data analysis of employment, gross value added per capita, passengers' arrival numbers at Dublin airport. *Education:* Data analysis of Pupil's number at the primary and secondary level. *Demographics:* Data analysis of population and households based on their socio-economic characteristics.
HK Smart City Blueprint (2021) [5]	Data analysis of daily commute and travel to different locations, and traffic.	*Living:* Data analysis of life expectancy, population, health, and popular public service venues. *Human Resource:* Data analysis of education, research and development. *Economy:* Data analysis of employment, payment and related services, taxation, and gross domestic product
London City Dashboard (2021) [6]	Implemented features like traffic camera in different locations.	Implemented a feature related to public sentiments (mood). Update of financial stocks. Updates on timing schedules, the status of the tube line, and availability of public transportation services like buses, bicycles, trains, etc.
Singapore Data Repository (Data.gov.sg) (2021) [7]	Data analysis of automobiles, and traffic police cameras	*Economy:* Data analysis of business expectations, domestic exports, government operating revenue, and total expenditure. *Education:* Data analysis of education enrollment and completion, and government expenditure on it. *Health:* Data analysis of health services, infrastructure, and related parameters. *Infrastructure:* Data analysis of real estate and land area. *Society:* Data analysis of population, and related parameters.

Table 2. Comparative analysis of related platforms for waste management, environment and security.

Name of the platforms	SMART CITY SERVICES				
	Waste Management	***Environment***	***Security***	***Energy***	***Others***
Dublin Dashboard (2021)	N/A	Data analysis of noise levels across Dublin.	N/A	N/A	N/A
HK Smart City Blueprint (2021)	N/A	Data analysis of atmosphere which includes weather, UV radiation, and air quality.	N/A	N/A	*Government:* Data analysis of public WiFi hotspots and government expenditure on related services
London City Dashboard (2021)	N/A	Data analysis of weather and air quality.	Implemented a feature like Traffic cameras for public safety	Update of electricity demand.	Updates of news, Twitter trends, and open street maps of London
Singapore Data Repository (Data.gov.s g) (2021)	Data analysis of waste disposed and recycled.	Data analysis of sunlight, and rainfall.	N/A	Data analysis of energy consumption.	*Technology:* Data analysis of patents, industrial revenue, mobile services, research and development.

These platforms offer assistance in monitoring and mitigating the growth trajectory of the city through the visualized representation of smart city indicators. Even in the data visualization, the analytics on the cities do not represent uniform standardization in the context of the analogy used in ISO 37120 standards (ISO Standard, 2018) for evaluating the smart city performance.

Recent research shows growing interest in improving natural fiber–reinforced composites for sustainable applications. Studies in *Molecules* and *Journal of Composites Science* highlight how optimizing fabrication and machining parameters can significantly enhance mechanical performance [15]. Work published in the *Journal of Reinforced Plastics and Composites* [18] and *BioResources* demonstrates the value of incorporating waste materials and natural fillers to improve strength while supporting sustainability [19]. Additionally, findings related to Pineapple fibers [16] and Natural fibers [17] emphasize how fiber treatments can strengthen fiber–matrix bonding. Together, these studies reflect practical efforts toward developing stronger, eco-friendly composite materials [18].

Architecture of CitiMan

The abstract implementation of CitiMan's architecture is based on the Model – View - Controller (MVC) pattern.

There are many generic yet logical reasons to suggest an MVC architecture for a web application such as a CitiMan, which are as follows:

- Modern and popular web application frameworks like ASP.Net, Ruby on Rails, and many more, are built to use the MVC architecture pattern.
- A design pattern like MVC helps us to separate the view and model (data) by building controller classes that are designed in modern programming frameworks. This practice makes the development of complex web applications easier yet more powerful.

The CitiMan's architecture is divided into 3 components where each controls a specific functionality of the CitiMan prototype, and it is as follows:

1. *Model:* In general, it represents the logical schema of the database tables that will be stored in a database. Any data that is visible to the user was stored in the database in a structure defined by the model in any web application framework. For instance, a user can be treated as an object that

can be stored with the attributes like username, email address, Figure 1. CitiMan's Architecture. and so on, which are defined in a user model. In Figure 1, CitiMan's Model represents the model of the MVC pattern. The smart city services which are discussed in section 2, will have their distinct models so that the data is separated and maintained easily. Each model in the CitiMan is communicating with its controller. The data is queried by the controller to the model. On processing the query, it is sent to the controller to do the further task as per the request of the user from the view.

2. *View:* It is the presentation layer of CitiMan. It is the only component that is visible to the user. In Figure 1, CitiMan's Dashboard represents the view. Each smart city service has its view on CitiMan's dashboard. Whenever there is a request by the user through some input action on the view, a Hypertext Transfer Protocol (HTTP) request is routed to the particular controller of that view. After getting a response to the above request the state of the view is changed accordingly. A view is typically a markup language document designed for web applications like Hypertext Markup Language (HTML) and Extensible Markup Language (XML).
3. *Controller:* It represents the controller classes that are designed and built in a specific programming language compatible with the chosen web application framework, which is responsible for controlling the view and model of an entity in the CitiMan. In Figure 1, CitiMan's Controller represents the controller of the MVC architecture. As mentioned above, each smart city service has its controller and associated methods which are in charge of handling a particular smart city service. Without a controller, the view and model cannot function on their own.

Abstract Design of Smart City Services

In Figure 1, CitiMan's Dashboard contains the corresponding view objects that characterize the black-box view of the above smart city services. The abstract design for these views is depicted in Figure 2. The view of smart city service is divided into 3 parts based upon its functionality, which is as follows.

1. *Services:* This section is designed to contain all the features and functionalities that CitiMan is providing under a particular smart city service. The type of features and functionalities under one smart city service is subjected to the availability of smart infrastructure deployed in the city which includes smart sensors, IoT devices, and other relevant systems that can capture real-time city parameters under the corresponding smart city service.
2. *HelpDesk:* This section is designed to address all the relevant complaints and grievances of the people living in the city under a single platform. It involves integrating all the existing Figure 2. Design of Smart City Services. complaint and grievance centers of the public departments of the city which are governing the corresponding city service.
3. *Infographics:* This section is designed to monitor and analyze the smart city parameters and other related data that are generated from various sources like smart sensors, public reports, surveys, etc. These data are related to the smart city parameters that fall under the category of the respective smart city service. The data is visualized in the form of graphs, histograms, charts, etc., which can make its understanding easier and simple.

Proposed Smart City Services

To gain more clarity for the design given in Figure 2, the views of each smart city service which are discussed in section 2, have been designed separately. Each smart city service contains the most relevant city parameters and related terms as per the ISO 37120 standards (ISO Standard, 2018). These city parameters which have been captured are not the only parameters that one can include in a smart city management prototype like CitiMan.

The selection of city parameters differs from one city to another. Each city has its own environmental and geographical challenges, so it depends upon the discretion of the governing body of the city on which challenges it emphasizes more. For instance, in a smart city service like the environment, the air pollution of the city is a critical parameter that should be considered through smart infrastructure and central management platforms. The details of these designs are summarized below.

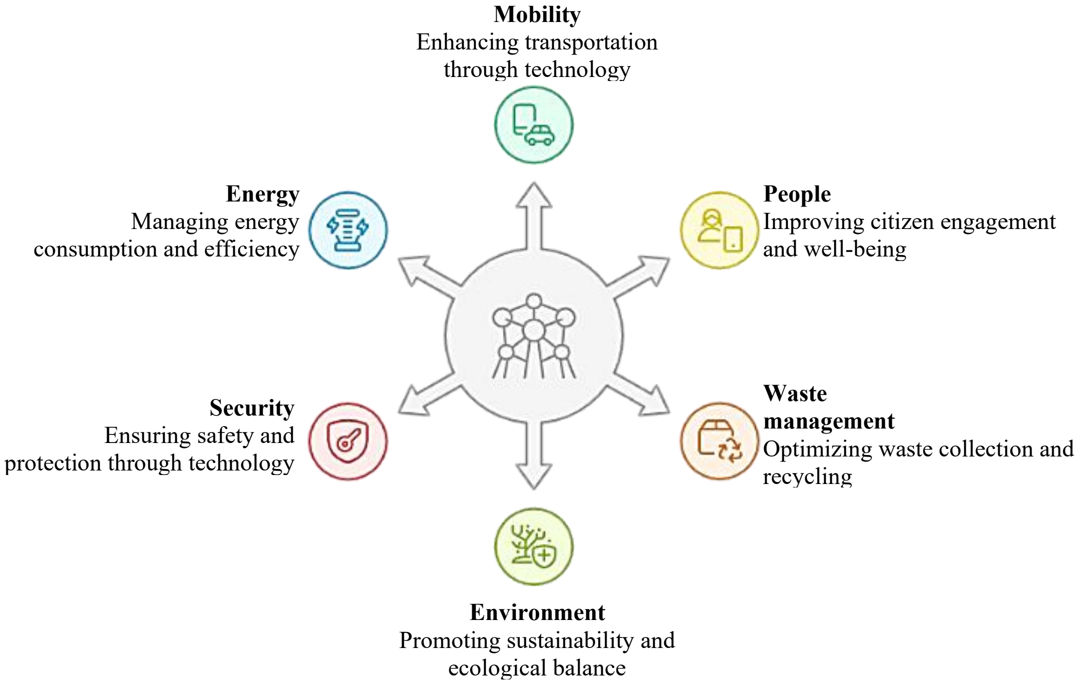

Figure 1. Citiman's architecture.

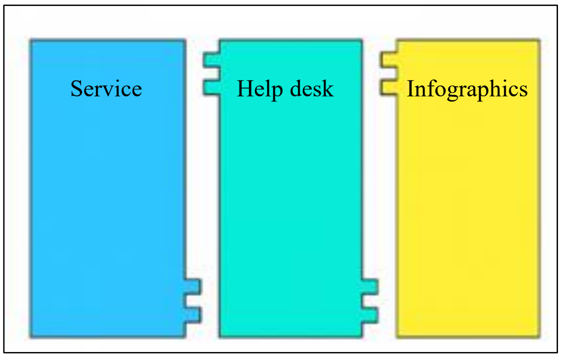

Figure 2. Design of Smart City services.

Mobility

As discussed in section 2, while the necessary infrastructure for transportation is built on the ground, its related facilities and services can be given to the people through platforms like CitiMan with the help of smart infrastructure. Most of the critical city parameters related to the mobility of people in the urban cities are related to the daily movement of people in public transportation systems and personal vehicles. CitiMan's iMobility Services aims to monitor and analyze smart mobility parameters through realtime iMobility analyzer, and real-time iMobility monitor and management. The complaint and grievances related to the transportation of the city can be integrated into CitiMan's iMobility Help Desk, which involves the integration of existing complaints and grievances services governed by the city's public transportation departments to the CitiMan to provide a central platform to the people. The analytics and information related to transportation and services can be accessed through CitiMan's iMobility infographics. Figure 3 describes the design of mobility as a smart city service.

People

People or Human resources of the city is a very important factor that turns an ordinary city into a smart city. CitiMan's iPeople Dashboard, focuses on analyzing the data related to the socio-economic parameters of the people that live in a particular city. These parameters are considered in the iPeople Infographics.

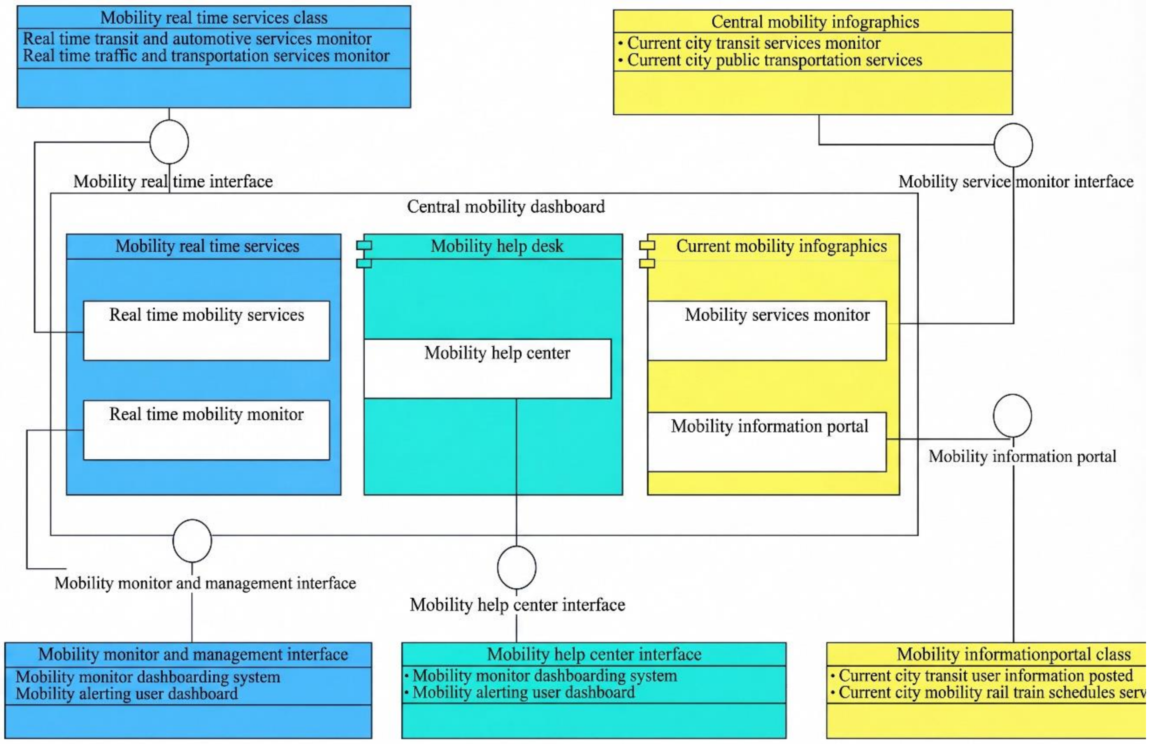

Figure 3. Design of mobility as a smart city service.

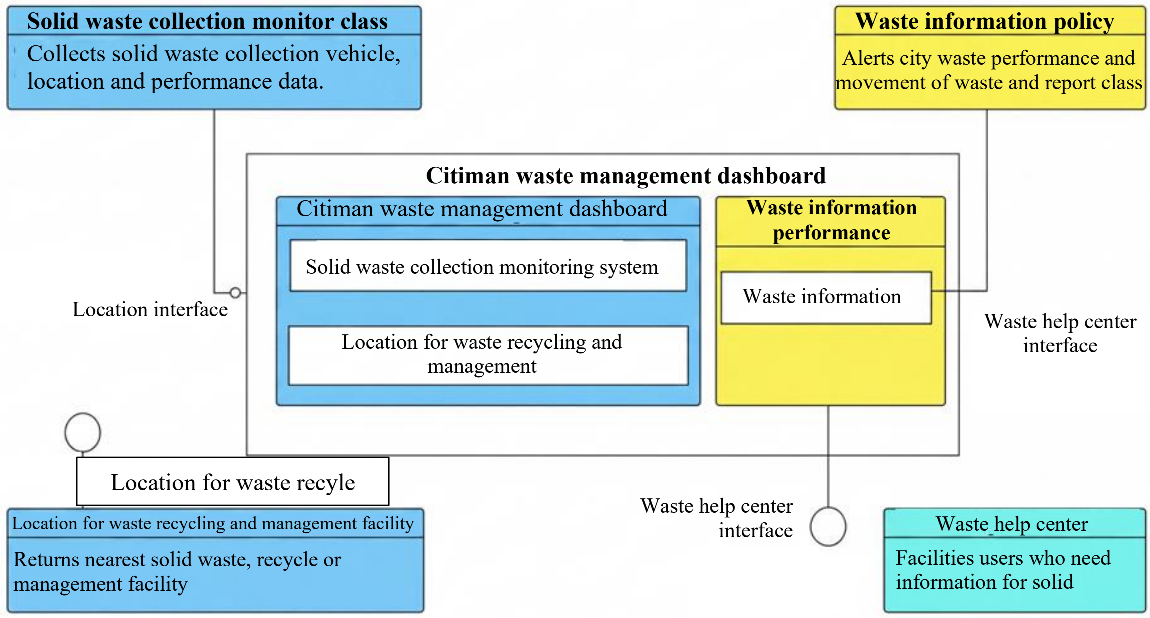

Figure 4. Design of waste management service.

Waste Management

As the population of the city increases, handling the waste becomes a huge problem. Waste Management becomes critical for maintaining health and hygiene in the city which is the collective responsibility of the citizen and local municipal authorities. But the services provided by the local municipal authorities are decentralized which often raises challenges for the people to contribute to the smooth handling of domestic and industrial waste. To make this process centralized and easy to monitor, we propose a CitiMan's iWaste management Dashboard, as shown in Figure 4. It will be responsible for monitoring the daily collection of waste by local garbage collectors in the city by analyzing the city parameters related to waste management. Through the iLocator service, people will be able to track the live location of the garbage collectors and nearby waste recycling plants. The complaint and grievances related to the daily waste management are handled by the iWaste Help Desk, which is essentially an integrated platform linked to the existing services and platforms of local municipal authorities to resolve the issues of the people. In the iWaste Infographics, information related to waste management and services can be analyzed.

Environment

As mentioned in section 2, smart environment service is all about building a complete ecosystem of smart devices that monitors the weather and environment of the city. This involves developing the infrastructure and setting up monitoring systems across the city. As shown in Figure 5, CitiMan's iEnvi Dashboard aims to provide a real-time weather forecast and air quality monitoring system under its services. These services can be extended to cover more aspects of a smart city's environment. The related complaint and grievances can be handled through the integrated platform of CitiMan's iEnvi Help Desk. While the environment-related information and statistics can be analyzed in the iEnvi Infographics.

Security

In CitiMan, for integrating the smart security devices deployed in the city with a controller application, we have proposed CitiMan's iSecure Dashboard, as shown in Figure 6. It includes services like the iSecure Monitoring System which can be used to monitor the live feed of the surveillance cameras deployed in the cities, smart alarms systems, etc. While the iSecure Management system is responsible for the configuration, installation, and maintenance of these smart devices that will be linked to the CitiMan. The iSecure Help Desk is also critical as it handles the security of smart secure devices and people.

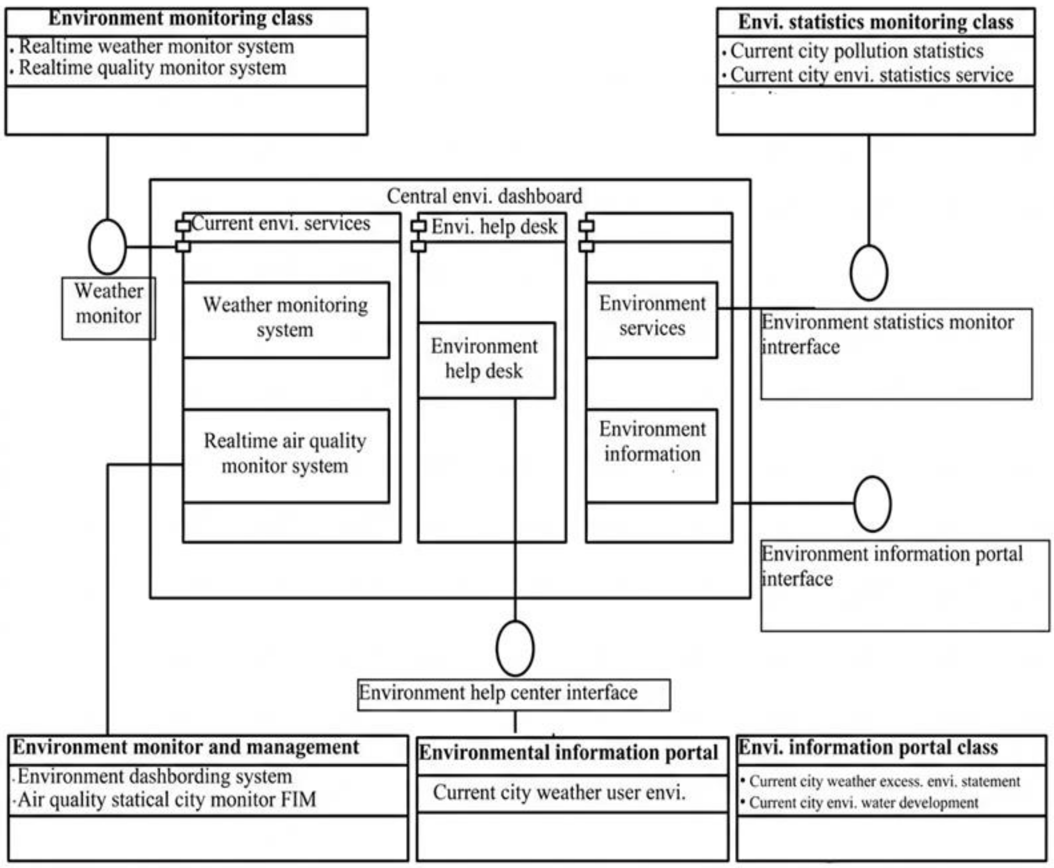

Figure 5. Design of environment service.

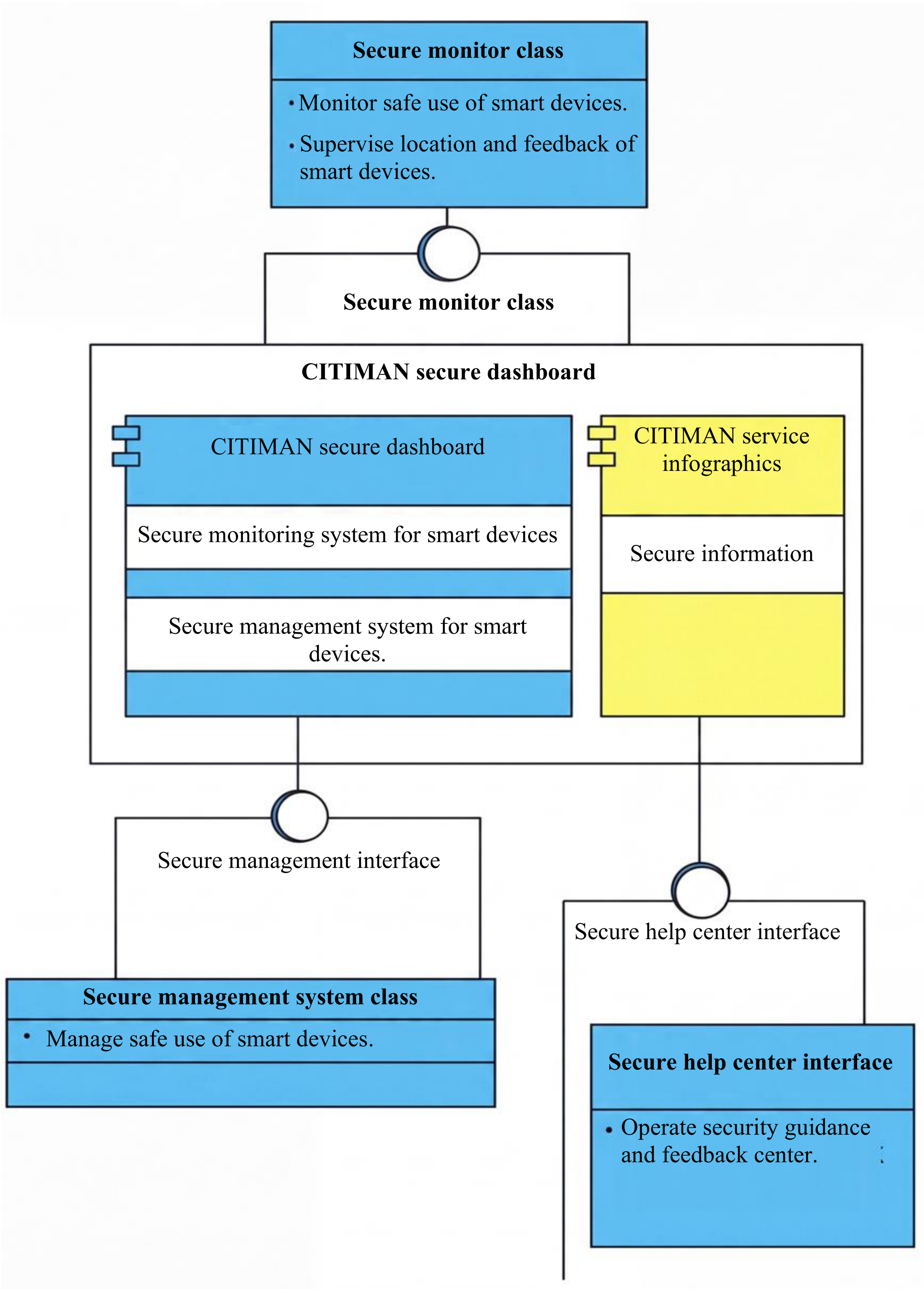

Figure 6. Design of security as a smart city service.

This platform is responsible for connecting all the departments related to public safety in the city such as police, fire safety, disaster management, and many more. Developing a common platform where people can register their complaints and grievances related to cyber frauds, theft, criminal incidents, etc., can be helpful in a variety of ways for protecting the smart security infrastructure as well as the people. The information related to the public and cyber safety in the city can be analyzed through the iSecure Infographics.

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Energy

For a smart city, analyzing and keeping the track of energy consumption and other related parameters becomes crucial as the energy sources of the city are limited. CitiMan as a platform aims to provide analytics related to the energy generation and consumption of a city through its iEnergy service. This service is responsible for providing data analytics related to energy. To monitor the quantities of current stocks of fossil fuels such as coal, petroleum, and other fuels in the city, is handled by the iEnergy monitoring system, while the smart energy devices in the city like smart lights can be managed through the iEnergy Management system.

The complaints and grievances related to the city's energy corporation can be registered and resolved on the iEnergy Help desk. All the further information and services related to the generation of energy in the city can be accessed through the iEnergy infographics, as shown in Figure 7.

Control Flow of CitiMan

After getting familiar with the abstract design of the smart city services of the CitiMan, it becomes imperative to design the logical flow of the control, when someone uses the CitiMan.

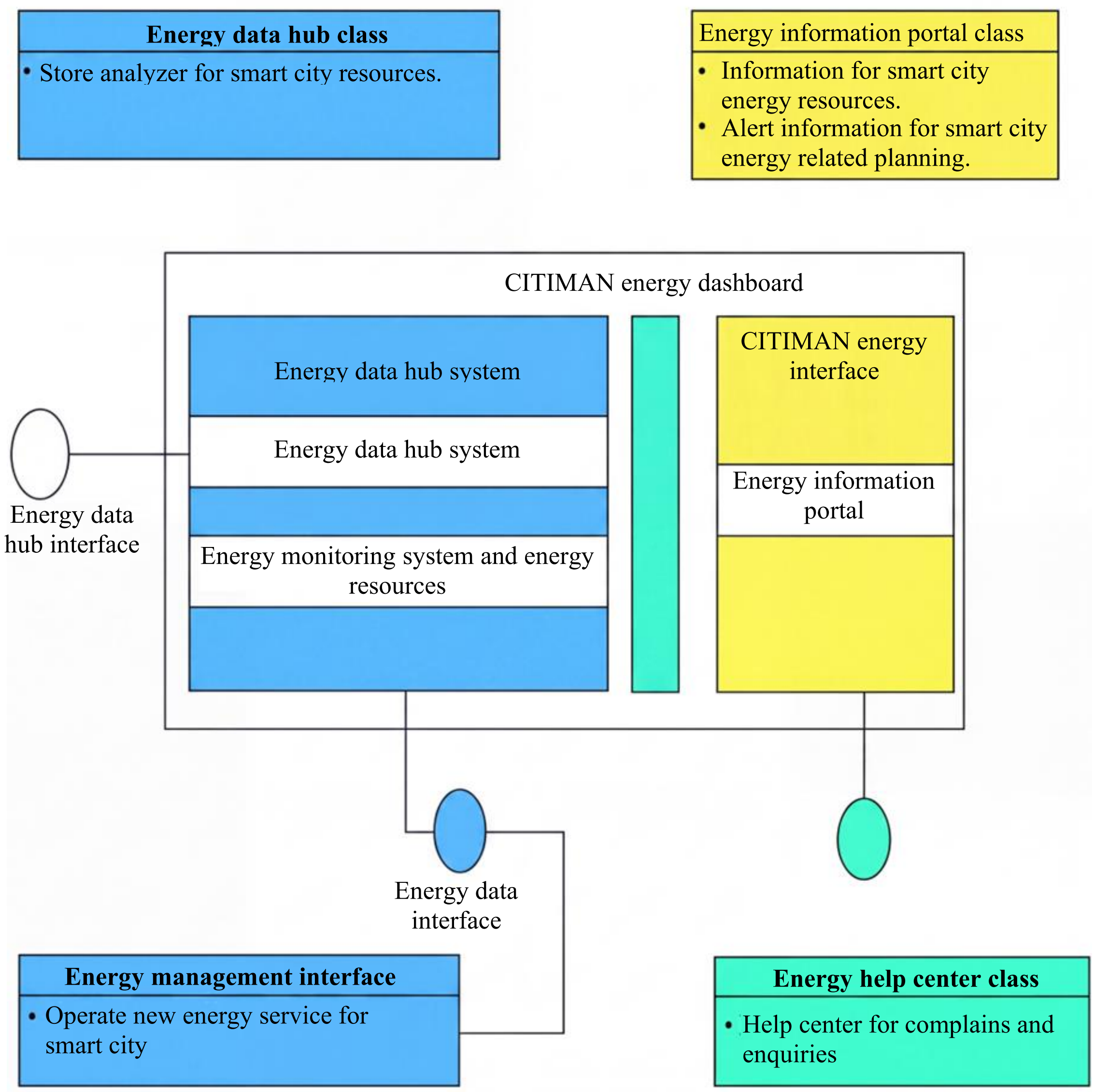

Figure 7. Design of energy as a smart city service.

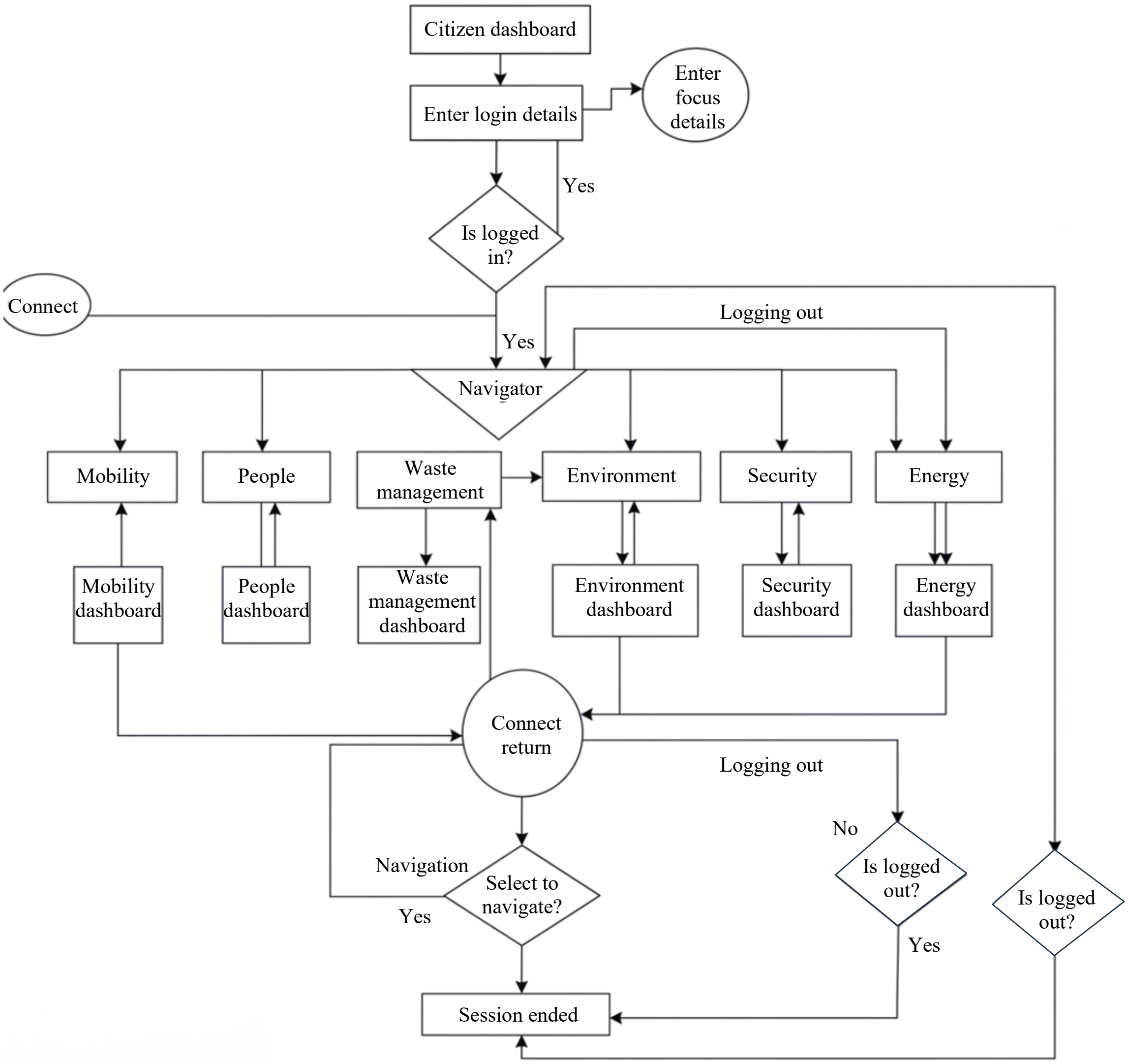

Figure 8. Control flow of CitiMan.

In Figure 8, the control flowchart of the CitiMan is depicted. Design of Energy as a smart city service. is the analogy of the user-navigation on a website which is as follows:

1. A user visits the homepage of CitiMan where he will enter his logging credentials if he is a registered user. If the user is not registered then he will have to register himself before he retries.
2. After a user enters their correct logging credentials, a user session is created. Each logged-in user has an individual private session that is logically isolated from other logged users. If the logging credentials entered by the current registered user are not valid then he will be redirected to the login view of CitiMan.
3. A logged-in user is navigated to the CitiMan's Navigator, where based upon its preferences he can select any of the smart city services he wants to use.
4. Each smart city service as discussed in section 2, has its distinct features and functionalities. A
5. logged-in user can use them under the selected service.
6. A user also has the option to navigate to the other smart city services provided by CitiMan using its navigator which is globally available to all the views of the CitiMan.
7. If the current user wants to exit CitiMan from any of the smart city services, he can simply log out of the CitiMan platform using the Logout option.
8. After the user is logged out, his user session is ended in the CitiMan.

CONCLUSION

Overall, the integration of renewable polymer synthesis with smart city strategies highlights how sustainable materials can meaningfully support future urban development. By relying on green, resource-efficient production pathways, renewable polymers reduce environmental strain while offering advanced capabilities for energy generation and storage. When these materials are incorporated into smart city systems, they enhance the city's ability to monitor environmental conditions, manage energy demand more effectively, and mitigate long-term sustainability challenges. Together, these innovations demonstrate how material science and smart city design can work hand in hand to create urban spaces that are cleaner, more resilient, and better equipped to meet the needs of a rapidly changing world. As the modern cities across the globe are becoming larger with the growing population, there is a significant risk of depleting the limited resources of these cities. If a sustainable plan and solution for managing these resources are not devised, then the city and its people will find it difficult to face the present and future challenges with growing demand and consumption for these resources. The centralized smart city management solution is one way to manage and monitor the growth of a city under a single platform. These platforms can help the people and governing authorities of the city to track, evaluate and monitor their sustainable goals of development on a real- time basis if the smart infrastructure and a management platform are developed in sync.

This paper is an attempt to study the prerequisites for designing such a smart city management prototype which is named as CitiMan. The crucial part of building such a platform is the availability of the smart infrastructure and its related services that can be integrated into the platform like CitiMan. The implementation is a more exhaustive process that involves the feasibility study of smart city services that can be provided on the platforms like CitiMan. In future, machine learning techniques can be implemented for this citiman for crowdfunding success evaluation and security enforcement [14].

Declaration of Interest

The authors declare that there is no conflict of interest regarding thepublication of this manuscript.

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