CRANFIELD UNIVERSITY

YIRUI JIANG

Development of Efficient Data Management and Analytics Tools for Intelligent Sanitation Network Design

Centre for Design Engineering
PhD in Design

PhD
Academic Year: 2020 - 2023

Supervisor: Dr Trung Hieu Tran
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This thesis is submitted in partial fulfilment of the requirements for the degree of PhD
(NB. This section can be removed if the award of the degree is based solely on examination of the thesis)

ABSTRACT

According to the World Health Organisation, billions of people lack access to basic sanitation facilities and services, resulting in estimated 2.9 million cases of diseases and 95,000 deaths each year. This is because poor planning, design, maintenance, and access in traditional sanitation networks. Nowadays, intelligent sanitation systems leveraging the Internet of Things (IoT) technology can provide efficient and sustainable services, incorporating sensors, hardware, software, and wireless communication. Furthermore, advanced data analytics tools combined with the intelligent sanitation systems can provide a deeper insight into operations, make informed decisions, and enhance user experience, thereby improving sanitation services.

The thesis provides a comprehensive review of literature on intelligent sanitation systems from both academic and industrial perspectives, with the objective of identifying recent advances, research gaps, opportunities, and challenges. Existing solutions for intelligent sanitation are fragmented and immature due to a lack of a unified framework and tool. To address these issues, the thesis introduces a generalised Sanitation-IoT (San-IoT) framework to manage sanitation facilities and a standardised Sanitation-IoT-Data Analytics (San-IoT-DA) tool to analyse sanitation data. The framework and tool can serve as a foundation for future research and development in intelligent sanitation systems. The San-IoT framework can enhance the connectivity, operability, and management of IoT-based sanitation networks. The San-IoT-DA tool is designed to standardise the collection, analysis, and management of sanitation data for providing efficient data processing and improving decision making. The feasibility of the proposed framework and tool was evaluated on a case study of the Cranfield intelligent toilet. The San-IoT framework has the potential to enable system monitoring and control, user health monitoring, user behaviour analysis, improve water usage efficiency, reduce energy consumption, and facilitate decision-making among global stakeholders. The San-IoT-DA tool can detect patterns, identify trends, predict outcomes, and detect anomalies. The thesis offers valuable insights to practitioners, academics, engineers, policymakers, and other stakeholders on leveraging IoT and data analytics to improve the efficiency, accessibility, and sustainability of the sanitation industry.

Keywords:
Data analytics; Intelligent sanitation; Internet of Things; Reinvented toilets; Smart sanitation; Sustainable sanitation.

Figure 0 Y.Jiang in Lab Conducting Early-Stage Lab and Field Testing, 2022

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I would like to express my deepest gratitude to my supervisors, Dr. Trung Hieu Tran and Prof. Leon Williams, for their unwavering support, guidance, and encouragement. I am extremely grateful for their in-depth knowledge, invaluable insights, and critical feedback, which have been instrumental in helping me get through the various stages of my research. I would also like to thank all team members of Cranfield Circular Toilet for their invaluable advice and support throughout my research. I am grateful to the Bill & Melinda Gates Foundation who provided me with the opportunity and sponsorship to perform this research. In addition, I would like to thank my family, friends, animals, and plants for their unconditional love and support. Finally, I am deeply grateful to my colleagues at the Centre for Design Engineering, who provided me with a stimulating and supportive environment. I am truly thankful and appreciative of everyone who has helped me during the journey and thank them for their kind support and guidance.

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LIST OF ABBREVIATIONS

ACM	Association for Computing Machinery
AI	Artificial Intelligence
AMQP	Advanced Message Queuing Protocol
ANN	Artificial Neural Networks
ARIMA	Autoregressive Integrated Moving Average
ASK-GEN1	The First Generation of Analytical Sensor Kit
ASK-GEN2	The Second Generation of Analytical Sensor Kit
AWS	Amazon Web Services
BLE	Bluetooth Low Energy
BMGF	Bill & Melinda Gates Foundation
CARP	Channel-Aware Routing Protocol
CNN	Convolutional Neural Networks
CoAP	Constrained Application Protocol
CRISP-DM	Cross Industry Standard Process for Data Mining
CTP	Collection Tree Protocol
DA	Data Analytics
DCCP	Datagram Congestion Control Protocol
DDS	Data Distribution Service
DL	Deep Learning
DTLS	Datagram Transport Layer Security
EU	European Union

GLAAS	Global Analysis and Assessment of Sanitation and Drinking-Water
HTTP	Hyper Text Transfer Protocol
HTTPS	Hypertext Transfer Protocol Secure
ICT	Information and Communications Technology
IEEE	Institute of Electrical and Electronics Engineers
IoT	Internet of Things
IP	Internet Protocol
IPv4	Internet Protocol version 4
IPv6	Internet Protocol Version 6
IT	Information Technology
ITU	International Telecommunication Union
JSON	JavaScript Object Notation
KNN	K-Nearest Neighbor
LAN	Local Area Network
LLC	Logical Link Control
LoRaWAN	Long Range Wide-Area-Networks
LPWAN	Low Power Wide-Area-Networks
LSTM	Long Short-Term Memory
MAC	Media Access Control
MD	Membrane Distillation
MDGs	Millennium Development Goals

MQTT	Message Queuing Telemetry Transport
MRO	Maintenance, Repair, and Overhaul
NB-IoT	Narrowband Internet of Things
NFC	Near-Field Communication
NGOs	Non-Governmental Organisations
PCA	Principal Component Analysis
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
QR	Quick Response
REST	Representational State Transfer Protocol
RF	Random Forest
RFID	Radio Frequency Identification
RNN	Recurrent Neural Networks
RPL	Routing Protocol for Low-Power and Lossy Network
RTTC	Reinventing the Toilet Challenge
San-IoT	Sanitation-IoT
San-IoT-DA	Sanitation-IoT Data Analytics
SCTP	Stream Control Transmission Protocol
SDGs	Sustainable Development Goals
SDG6	Sustainable Development Goal 6 (Ensure availability and sustainable management of water and sanitation for all)
SMEs	Small and Medium Enterprises
SVM	Support Vector Machine

TCP	Transmission Control Protocol
TLS	Transport Layer Security
U.S.	United States
UDP	User Datagram Protocol
UN	United Nations
WAN	Wide Area Network
WASH	Water, Sanitation, and Hygiene
WHO	World Health Organisation
Wi-Fi HaLow	Low Power Wi-Fi
XML	Extensible Markup Language
XMPP	Extensible Messaging and Presence Protocol
1G	The First Generation
2G	The Second Generation
3G	The Third Generation
4G	The Fourth Generation
5G	The Fifth Generation
6LoWPAN	IPv6 Low-Power Wireless Personal Area Network

1 Chapter 1: Introduction

The chapter introduces a research background of the studying problem. In particular, the current state of the global sanitation industry, as well as the failure of traditional sanitation facilities are presented and discussed. Advanced Internet of Things (IoT) applications and services, and the efficient use of data analytics for critical decision making are described. The problems of the sanitation industry lagging in IoT research, and the underutilisation of sanitation data, are provided. From that, the aim and objectives of the research are highlighted. The contribution and thesis structure are articulated.

1.1 Research Background

Global sanitation is a critical issue that has far-reaching effects on communities globally. The World Health Organisation (WHO) recognises the importance of providing access to safe, clean, and proper sanitation facilities to promote human health and well-being (World Health Organisation, 2020). The 2030 Agenda for Sustainable Development also acknowledges the need for the availability and sustainability of sanitation services (Walsh et al., 2022). Sanitation services are designed to manage human excreta safely and effectively through a chain of processes, including segregation, emptying, transportation, treatment, disposal, and/or reuse (World Health Organisation, 2022a). The global sanitation challenge requires the collaboration of governments, international bodies, and non-governmental organisations to provide sanitation infrastructure such as wastewater systems, clean water supplies, and waste management (World Health Organisation, 2021). Poor sanitation is a major public health issue, with 3.6 billion people lacking access to safe sanitation and 1.7 billion missing out on basic sanitation services (The World Bank, 2022). This leads to a plethora of issues, from malnutrition and stunted growth to water-borne and vector-borne diseases, which cause estimated 2.9 million cases of diseases and 95,000 deaths each year (World Health Organisation, 2022b). Unsafe water, sanitation, and hygiene (WASH) practices can have devastating consequences, and yet, 580 million households still share limited sanitation facilities, 700 million people have missed out on the sanitation revolution, and eight percent of the population still practises open defecation (World Health Organisation, 2018; The World Bank, 2023).

Sanitation in human society is continuously evolving (World Health Organisation, 2021). The current sanitation challenges necessitate the development of advanced technologies and infrastructure. Non-sewered sanitation is an innovative and viable solution, which is more feasible, practical, and cost-effective than traditional sewer-based approaches. Non-sewered sanitation is also more compatible with environmental protection, closing the loop, and reusing resources. It is well-planned, safe, sustainable, and accountable (Michalak et al., 2023). The Reinvent the Toilet Challenge (RTTC) was sponsored by the Bill & Melinda Gates Foundation (BMGF) to provide safe, practical, affordable, and hygienic non-sewered sanitation solutions for the 2.6 billion people living without access to proper sanitation (Kone, 2012). RTTC toilets capture and contain waste in a manner that prevents the spread of disease and use waterless technologies to ensure that water is used efficiently. The RTTC is committed to developing low-cost solutions for those living in poverty, encouraging the development of sustainable sanitation and health solutions.

Adopting advanced sanitation systems based on IoT and data analytics technologies can help address the drawbacks of traditional sanitation systems, such as ineffectiveness in management, monitorability, labour intensity, and lack of data. These modern systems enable real-time data collection and decision making, resulting in improved facility availability, accessibility, acceptability, and accountability (Ahmed et al., 2017; Ray, 2018; Kassab et al., 2020). The advanced sanitation is instrumented, interconnected, and intelligent for holistic monitoring, analysing status, forecasting changes, and optimising troubleshooting. IoT-based sanitation solutions improve data collection and analysis, provide effective problem identification and resolution, improve user health and well-being, lower operational costs, and promote a more sustainable environment. Sensors, IoT devices, and cutting-edge hardware technologies help collect data on various sanitation aspects, while advanced analytics strategies help identify patterns, trends, correlations, and insights to make better decisions and unlock limitless potential.

The IoT is revolutionizing the way humans interact with physical objects (Sethi & Sarangi, 2017; Čolaković & Hadžialić, 2018). Using sensors, actuators, controllers, communication protocols, software, cloud computing, and interactive applications, IoT solutions are connecting facilities, equipment, machines, devices and assets to collect and exchange data in a more efficient manner (Díaz et al., 2016; Chettri & Bera, 2019). IoT allows smart assets to interact and form a network of connected physical objects, which can be monitored and managed remotely (Malik et al., 2021; Kumar et al., 2022). Industries such as manufacturing, transportation, energy, and agriculture are increasingly taking advantage of the power of IoT to meet their ever-evolving technological needs (Boyes et al., 2018; Asghari et al., 2019).

IoT systems typically comprise three main functions: system sensing, communication connection, and application service (Ray, 2018). System sensing converts analogue signals from smart objects into digital ones. Communication connections enable the exchange of data and information between devices, networks, and cloud services. The application service collects, cleans, stores, analyses, models, and visualises data. The intelligent systems can monitor performance, automate operational processes, schedule predictive maintenance, analyse user behaviour, provide personalised services, and reduce energy usage (Khan et al., 2020; Sunhare et al., 2022). However, the traditional sanitation industry is unable to fully exploit the potential of intelligent systems. Intelligent sanitation is still in its early stages, with little research, slow progress, and fragmented contributions.

Sanitation facilities are an essential part of everyday life, and they generate a wealth of valuable data. By leveraging intelligent sanitation systems, these data can be used to optimise performance, anticipate system failure, detect potential health risks, support decision-making, and inform sanitation improvements (Wang & Camilleri, 2020; Singh & Jayaram, 2022; Tasoglu, 2022). The focus of IoT development has shifted from connected devices to data analytics (Tsai et al., 2018). Due to the large volume, variety, velocity, veracity, and value of data generated by IoT, advanced analytics methods are needed to convert raw data into information and knowledge (Ge et al., 2018; Bansal et al., 2020; Fawzy et al., 2022). Traditional data management frameworks are inadequate for addressing the complexity and magnitude of sanitation data (Sasaki, 2021). The utilisation of advanced technologies makes it possible to acquire, clean, prepare, store, analyse, and visualise sanitation data more effectively. This enables practitioners to recognise patterns and trends in the sanitation industry more easily, allowing them to make decisions based on reliable insights (Adi et al., 2020; Sunhare et al., 2022). The usage of data analytics in the sanitation industry has enormous potential, yet it is still in its infancy. This is a result of a variety of causes, such as inadequate architecture design, a lack of research, limited awareness, and a lack of unified strategies, frameworks, processes and tools.

Figure 1-1 Cranfield intelligent toilet

(a-c: toilet design, d: toilet prototype, e: lab testing, f: field testing)

1.2 Aim and Objectives

The Aim of this research is to develop an IoT system for efficient sanitation management and decision making.

To achieve the aim, the thesis includes:

- Objective 1: Conducting a comprehensive literature review on intelligent sanitation to identify recent advances and research gaps.

- Objective 2: Designing a generalised framework for IoT-based sanitation networks to improve their connection, operation, and management.

- Objective 3: Developing an analytics tool for sanitation data intelligence to provide efficient data processing and improve decision making.

- Objective 4: Demonstrating the performance of the generalised IoT-based sanitation framework and data analytics tool on the case study of Cranfield Circular Toilet.

Possible impact the research could have:

- Helping towards the deployment of a data-driven intelligent sanitation as a transformative solution to the global sanitation crisis, and
- Contribution to the broader discourse on sustainability, innovation, and technological advancement of sanitation services.

1.3 Research Methodology

The Double Diamond is a highly respected approach in design thinking and innovation, encompassing both divergent and convergent thinking (Council, 2007; Banathy, 2013). It serves as a valuable guide for researchers and practitioners to explore and define the problem space, generate creative solutions, and refine the best ideas. This design process model is used as a research methodology in the thesis to fosters a deeper understanding of the sanitation challenges and promotes the development of innovative intelligent sanitation solutions (see Figure 1-2).

i) In the "Discover" phase, a thorough understanding of the current sanitation systems and the challenges they encounter is obtained.
    - Conducting literature review: Conduct a review of academic papers, reports, and best practices pertaining to sanitation systems and technology adoption.

- Research existing sanitation systems: Gather and analyse data on current sanitation practices, including waste management, water usage, and infrastructure conditions.
- Engaging with stakeholders: Interact with key stakeholders to gain insights into their perspectives and concerns.

ii) In the "Define" phase, the focus is on identifying challenges and establishing clear goals and objectives for the data-driven intelligent sanitation system.

- Identifying pain points: Identify challenges and gaps in the current sanitation systems.
- Identifying technological opportunities: Explore various IoT technologies and data-driven approaches that have the potential to address the identified challenges in sanitation systems.
- Defining goals: Establish clear and well-defined objectives for the IoT-based intelligent sanitation system.

iii) In the "Develop" phase, a strong collaboration between engineers, technicians, data scientists, domain experts, project managers, and end-users is established to design and implement a robust IoT-based intelligent sanitation system. Regular testing, feedback, and continuous improvement are essential to ensure that the system meets the specific needs and requirements of the sanitation sector.

- Designing system framework: Create a detailed system architecture that outlines the integration of IoT devices, sensors, data analytics, and communication protocols.
- Hardware selection: Choose appropriate IoT devices, sensors, and communication modules that are suitable for sanitation monitoring and data collection.

- Software development: Develop the necessary software applications and algorithms for data analysis, real-time monitoring, and maintenance.
- Prototype testing: Deploy the initial prototype in a controlled environment.
- User feedback: Gather feedback from sanitation operators, maintenance personnel, and end-users to understand their experiences and suggestions for system enhancements.
- Iterative development: Based on the feedback and testing results, make necessary improvements and optimisations to the system.

iv) In the " Deliver" phase, the focus is on finalising and implementing the IoT-based intelligent sanitation system.

- Integration and testing: Integrate all the components of the system to ensure seamless communication and data flow.
- Customisation and adaptation: Tailor the system to the specific needs and requirements of the target area or community where it will be deployed.
- Compliance and regulation: Ensure that the IoT-based intelligent sanitation system complies with all relevant regulations and standards related to sanitation and data privacy.
- Pilot projects: Implement the IoT-based intelligent sanitation system in small-scale pilot projects in selected areas.
- Feedback and iteration: Gather feedback from users, sanitation authorities, and other stakeholders involved in the pilot projects.
- Scaling up: Once the pilot projects demonstrate the effectiveness and benefits of the system, plan for scaling up its implementation to cover larger areas or multiple locations.

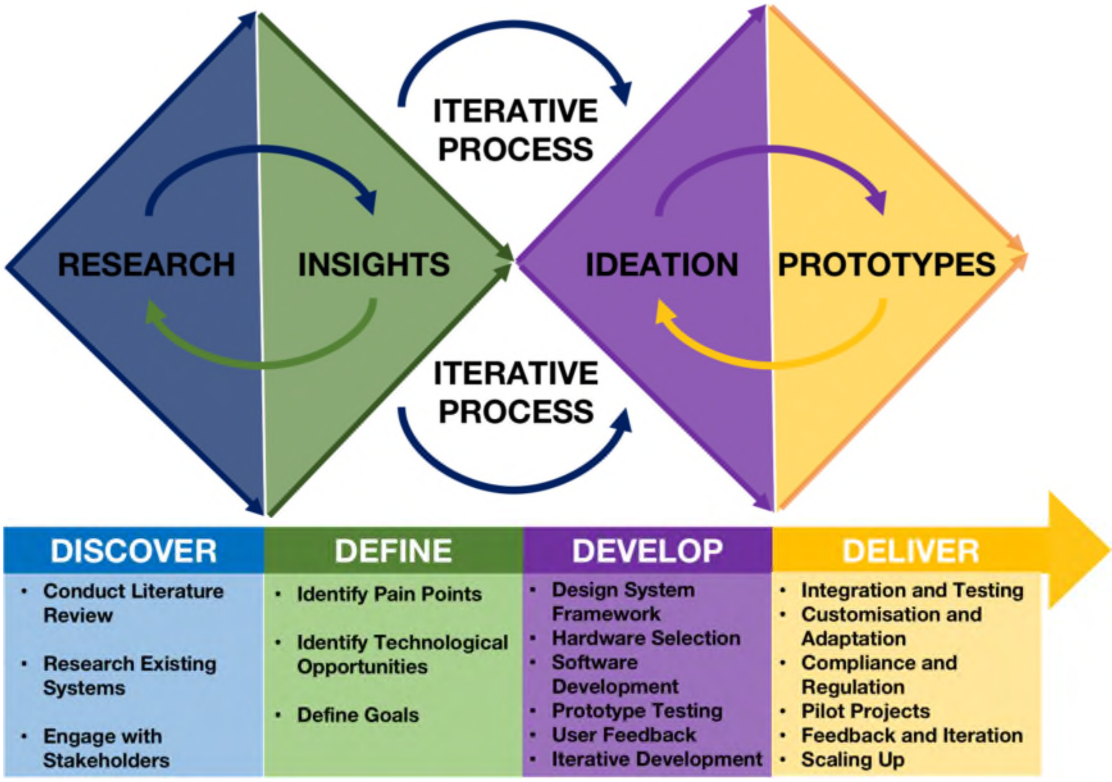

Figure 1-2 The research methodology of adapted Double Diamond

1.4 Contributions

- Theoretical value: The research reviews the literature on intelligent sanitation published between 2000 and 2022 to fill gaps in the research topic. The review provides a comprehensive overview of intelligent sanitation, including system detection, health monitoring, artificial intelligence integration, sustainability, opportunities, and challenges. The San-IoT concept is proposed as the foundation for future intelligent sanitation research. A generalised framework for IoT-based sanitation networks (San-IoT) is proposed to address the backward status of intelligent sanitation caused by the lack of a unified framework. Furthermore, a generalised data analytics tool (San-IoT-DA) for intelligent sanitation is proposed to improve understanding of sanitation data and provide a comprehensive analytics process for other participants. The Cranfield Circular Toilet is used as a case study to demonstrate the applicability of the proposed San-IoT framework and San-

IoT-DA tool, which are part of the global reinvent the toilet project in the sanitation industry.

- Industrial value: The proposed generalised San-IoT framework can be used to establish the foundation for the future development of sanitation industrial IoT-based solutions. The proposed standardised San-IoT-DA tool can be used to assist industry practitioners in collecting, transmitting, storing, analysing, and managing sanitation data, thereby improving transparency and visibility of sanitation facilities status, and effectively sharing information among global stakeholders. The case study of Cranfield Circular Toilet provides industry practitioners with valuable insight into intelligent sanitation solution development. Intelligent sanitation can bring a variety of industrial benefits, such as providing data on sanitation facility usage and maintenance, allowing quick respond to potential issues, improving user experience, and measuring environmental impact. The proposed framework and tool can help the sanitation industry to increase efficiency, reduce costs, and offer better services.

- Societal value: Intelligent sanitation solutions provide several benefits to both public and private sectors. These solutions can improve public health and safety by helping to prevent the spread of disease through the proper collection, transportation, treatment, and disposal of waste. Additionally, access to adequate sanitation is a basic human right, and intelligent sanitation can contribute to the goal of universal access to basic sanitation and hygiene. Intelligent sanitation can assist governments, academic institutions, local organisations, non-governmental organisations (NGOs), and private businesses in collaborating to ensure that everyone has access to clean and safe sanitation services. The utilisation of IoT-based intelligent sanitation has the potential to make a valuable contribution to United Nations Sustainable Development Goal 6 (SDG6) which targets to provide universal access to clean water and sanitation. The implementation of intelligent sanitation solutions can enhance the efficiency and effectiveness of sanitation systems, leading to improved access to sanitation facilities for underprivileged communities. Furthermore, these innovative solutions can help in decreasing water wastage and pollution, thus supporting the achievement of other SDGs concerning environmental sustainability.

- Environmental value: The use of intelligent sanitation systems can provide a solution to the issues caused by traditional sanitation facilities, such as open defecation and the lack of WASH. These systems utilise IoT-based sensors and devices to collect and analyse real-time data, resulting in improved resource and waste management, greater visibility, and insights into the state of sanitation facilities, and more efficient use of water and energy. In addition, intelligent sanitation systems can reduce the risk of water contamination and the spread of disease-causing organisms. The case study of Cranfield Circular Toilet provides industry practitioners with a better understanding of how innovative non-sewer sanitation systems can be more sustainable than traditional methods, using less water and causing less environmental impact.

- Economic value: Traditional sanitation systems cause significant economic losses and millions of avoidable deaths each year. Improving traditional in-house piped water systems and sewer connections necessitates a significant investment that is unreliable, unsustainable, and impractical. With intelligent sanitation, traditional, costly, and inaccessible sanitation systems can be replaced with more efficient and less expensive solutions. Intelligent sanitation can significantly reduce sanitation costs by automating processes, improving data collection and analytics, enhancing user experience, and improving public health and safety. Better sanitation can help with economic development. Improved sanitation can reduce disease burdens on populations, lower health-care costs as well as the costs of treating water and wastewater. The Cranfield Circular Toilet case study provides an example of how innovative solutions can make sanitation facilities available to the poorest people, making use of global stakeholder involvement, cross-sectoral, and cross-border collaboration.

1.5 Thesis Structure

The thesis follows the "thesis by publication" format, with each chapter published or under peer review with a journal. It is organised as follows (see Figure 1-3).

- In Chapter 1, the research topic is introduced, along with its background, aim, objectives, contribution, structure and publications. The chapter also examines the current landscape of the sanitation industry, advanced IoT systems, data analytics solutions, and the lack of intelligent sanitation solutions.

- In Chapter 2, a thorough review of the literature related to intelligent sanitation is presented. It is a comprehensive review in almost two decades, exploring its development history, system detection, health monitoring, artificial intelligence integration, sustainability, opportunities, and challenges. Existing research studies on intelligent sanitation are detailed, potential knowledge gaps are highlighted, and the limitations and prospects of sustainable intelligent sanitation are discussed. Additionally, the novel concept of San-IoT is introduced, which could be a base for future research in the field. The state-of-the-art IoT architecture, applications and services are examined, in order to determine the opportunities and challenges of the intelligent sanitation solutions. The chapter provides a valuable foundation for the remainder of the research.

- In Chapter 3, a generalised San-IoT framework for intelligent sanitation networks is presented, with an exploration of system architecture, high-level network topologies, communication protocols, data processing, and system deployment. The characteristics, benefits, and drawbacks of various IoT technologies are presented, analysed and discussed. The Cranfield Circular Toilet serves as a case study to demonstrate the applicability and feasibility of the proposed framework for the sanitation sector.

- In Chapter 4, a standardised data analytics tool (San-IoT-DA) is introduced for the intelligent sanitation industry, which includes the different phases of business understanding, data understanding, data acquisition, data cleaning and preparation, data storage, data analysis, data visualisation, modelling, evaluation, and deployment. The tool enables the access, management, and analysis of sanitation data, so as to enhance facility performance, encourage healthier lifestyles, and create more sustainable communities. The Cranfield Circular Toilet is used to demonstrate the efficacy of the proposed data analytics tool in the sanitation industry.

- In Chapter 5, the key findings, research implications, and potential limitations of the research are discussed. The research implications include the theoretical, industrial, societal, environmental, and economic contributions of the research. The chapter examines the limitations that may impact the validity of the findings, such as insufficient data quantity and quality, as well as generalisability issues. By exploring these potential research biases, the researcher can gain a better understanding of the research context.

- In Chapter 6, the thesis is concluded by summarising the key points, methodology, case study, and contribution to knowledge. Further research works are recommended.

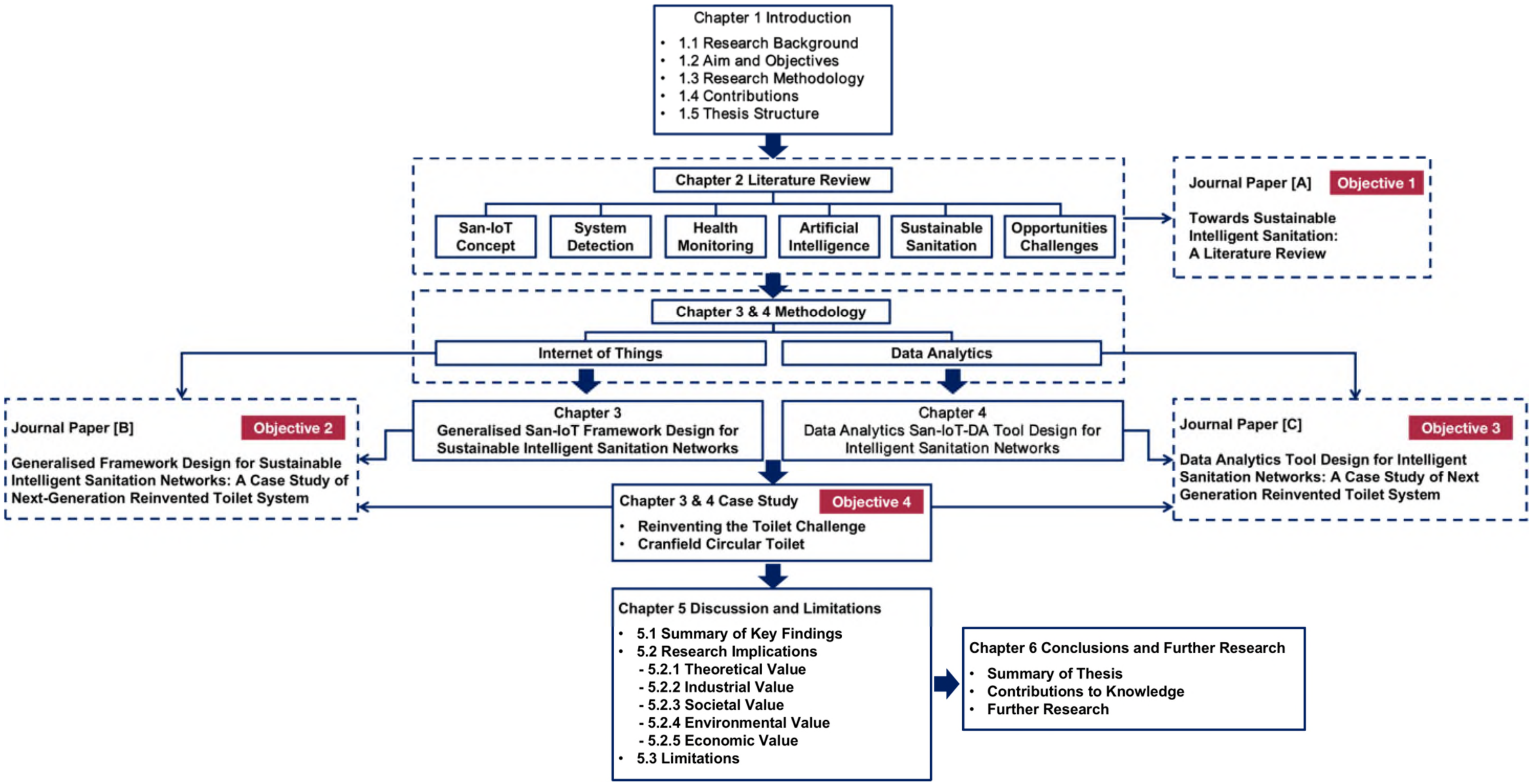

Figure 1-3 Thesis structure

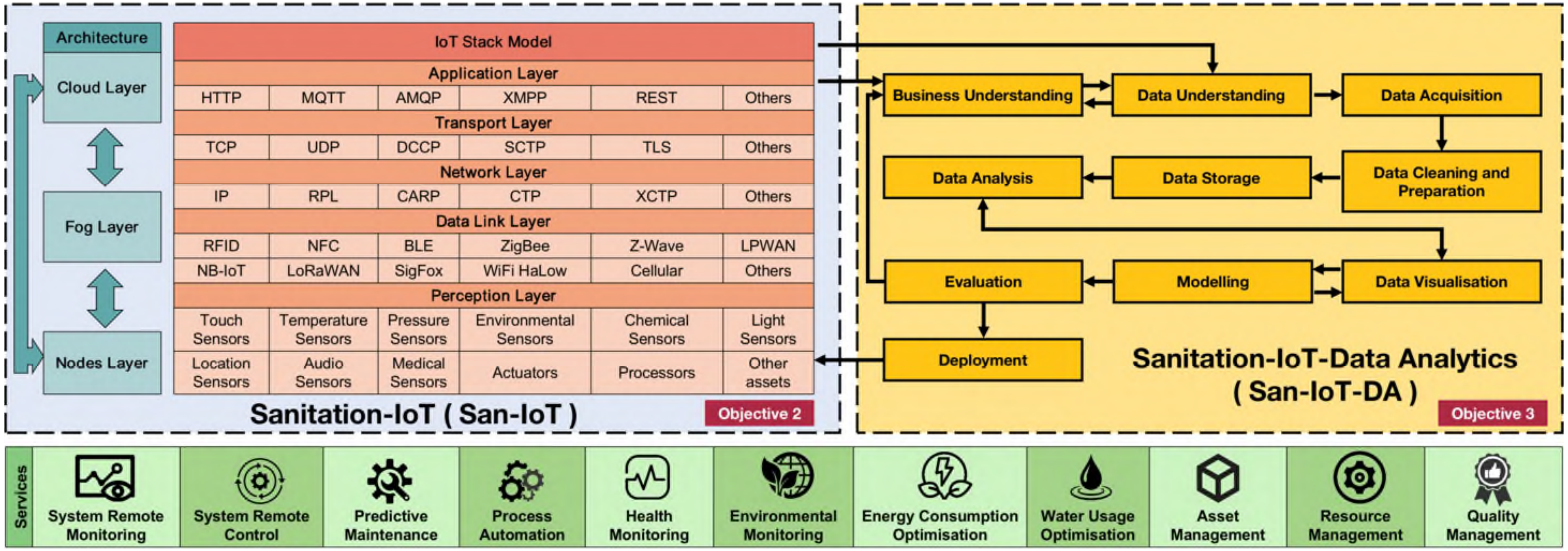

Figure 1-4 An overview of the framework

1.5.1 Papers for Publication

Three papers were written as part of the thesis. Yirui Jiang is responsible for the comprehensive literature review, framework and tool design, software development, data collection, data analysis, case study, and writing of all sections. Dr Trung Hieu Tran and Prof Leon Williams contributed as academic supervisors and provided significant support regarding editing, suggestions, and feedback. The papers are as follows:

Paper One

Jiang, Y., Tran, T. H., & Williams, L. (n.d.). Towards Sustainable Intelligent Sanitation with San-IoT: A Literature Review.

Paper Two

Jiang, Y., Tran, T. H., Williams, L., Noaman, W., & Collins, M. (n.d.). Generalised Framework Design for Sustainable Intelligent Sanitation Networks: A Case Study of Next-Generation Reinvented Toilet System.

Paper Three

Jiang, Y., Tran, T. H., Williams, L., Noaman, W., & Fox, H. (n.d.). Data Analytics Tool Design for Intelligent Sanitation Networks: A Case Study of Next Generation Reinvented Toilet System.

Table 1-1 A summary of Chapters

Chapter	Objective	Paper	Summary
Chapter 2	Objective 1	Paper One	- Comprehensive review of intelligent sanitation history, system detection, health monitoring, artificial intelligence integration, sustainability, opportunities, and challenges. - Propose the San-IoT concept as a foundation for future intelligent sanitation research.
Chapter 3	Objective 2 & Objective 4	Paper Two	- Introduce a generalised framework for IoT-based sanitation networks (San-IoT), which includes a system architecture, high-level network topologies, communication protocols, data processing, and system deployment, to improve sanitation network connection, operation, and management. - A Cranfield Circular Toilet case study is used to demonstrate the capability of proposed framework.

Chapter 4	Objective 3 & Objective 4	Paper Three	- Introduce a standardised data analytics tool for intelligent sanitation (San-IoT-DA), which includes business understanding, data understanding, data acquisition, data cleaning and preparation, data storage, data analysis, data visualisation, modelling, evaluation, and deployment phases, to improve decision making and provide industry insights. - A Cranfield Circular Toilet case study is used to demonstrate the capability of proposed analytics tool.

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2 Chapter 2: Towards Sustainable Intelligent Sanitation with San-IoT: A Literature Review

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ABSTRACT

The sanitation industry generates a significant amount of high volume, velocity, and variety data. The Internet of Things enables the sanitation industry to analyse and act on data to provide better user experiences, innovative services, cost-effective operations, efficient processes, and sustainable decision-making. However, the traditional sanitation is unable to take full advantage of the intelligent IoT revolution. Literature on intelligent sanitation is fragmented and immature. The chapter is a comprehensive review of intelligent sanitation in nearly two decades, including the development history, system detection, health monitoring, artificial intelligence integration, sustainability, opportunities, and challenges. The chapter examines sanitation-related papers published from both academic and industrial perspectives. More than 141 intelligent sanitation and sustainable sanitation papers have been deeply reviewed. Prior research on intelligent sanitation are summarised, knowledge gaps are identified, the limitations and prospects of intelligent sanitation are discussed. The chapter proposes the concept of San-IoT, which can serve as a foundation for future intelligent sanitation research. State-of-the-art IoT architecture, applications, and services are explored and drawn on to determine the opportunities and challenges of the intelligent sanitation industry.

Keywords: Artificial intelligence; health monitoring; intelligent sanitation; Internet of Things; literature review; San-IoT; sustainable sanitation; system detection; toilet design.

2.1 Introduction

Since the implementation of the Millennium Development Goals (MDGs), significant progress has been made in global sanitation, but it is still behind schedule. Globally 3.6 billion people lack access to safely managed sanitation supports, 1.7 billion people lack basic sanitation services, 580 million households share limited sanitation facilities with others, eight percent of the population practice open defecation, and 700 million people miss the sanitation revolution (The World Bank, 2022). Every year, 2.9 million cases of diseases and 95,000 deaths are caused by a missing or inaccessible safe water, sanitation, and hygiene (WASH) (World Health Organisation, 2022).

People use toilets multiple times per day, generating vast volumes of data. Access, management, and analysis sanitation data can accelerate the globalisation of WASH. With the growth on the Internet of Things (IoT), various industries such as manufacturing, transport, energy and agriculture are all reaping the potential. In IoT, facilities, equipment, machines, assets, and devices are all connected. Remote monitoring, predictive maintenance, facility management, process control, and insight discovery are performed by IoT. Data is collected and analysed for fewer wasted resources, lower costs, increased operational efficiency, better user experience and more diverse potential opportunities. However, the traditional sanitation industry is unable to take full advantage of the large, fast and complex data. Intelligent sanitation is still in its early stages, with little research, slow progress, and fragmented contributions.

To consolidate the fragmented research work, the chapter thoroughly reviews more than 141 sanitation and toilet-related papers from 2000 to 2022. The intelligent and sustainable sanitation solutions have been reviewed from development history, system detection, health monitoring, artificial intelligence (AI) integration, and sustainability standpoints. The concept of San-IoT is introduced as a foundation for future intelligent sanitation research. The opportunities and challenges of intelligent sanitation systems are discussed. In summary, the chapter makes the following contributions:

i. Reviewing sanitation and toilet-related papers between 2000 and 2022;

ii. Analysing and summarising 141 papers on intelligent sanitation;

iii. Introducing the concept of San-IoT as the foundation of future intelligent sanitation research;

iv. Researching the history and current state of intelligent sanitation systems;

v. Studying cutting-edge intelligent sanitation solutions for system detection;

vi. Outlining the most recent intelligent sanitation solutions for health monitoring;

vii. Studying intelligent sanitation solutions that are sustainable, AI-powered, cost-effective, and scalable, as well as their potential impact;

viii. Investigating advanced IoT application methods and techniques to promote future intelligent sanitation opportunities and challenges.

The remainder of the chapter is organised as follows: The remaining introduction explains the review methodology, and introduces the San-IoT concept for intelligent sanitation. Section 2.2 presents the history of intelligent sanitation as well as the most recent advances. Section 2.3 summarises the architecture, processes, techniques, and applications used by intelligent sanitation for system detection. Section 2.4 discusses the most recent methods, technologies, and applications for using intelligent sanitation for health monitoring. Section 2.5 demonstrates various machine learning integrated intelligent sanitation solutions for improved operational efficiency and better user experience. Intelligent sanitation for sustainable, efficient, and environmentally friendly solutions is covered in Section 2.6. Section 2.7 draws on insights from advanced IoT industrial applications to investigate future opportunities and challenges for sanitation industry. Finally, conclusion is presented in Section 2.8.

2.1.1 Review Method

A comprehensive literature review is conducted using the inclusion and exclusion criteria from Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) (Liberati et al., 2009). To identify high-impact intelligent sanitation research findings, the PRISMA collects materials in journals, papers, articles, studies, reports and proceedings from both academic and industrial perspectives. The PRISMA flow diagram illustrates the different phases of materials being identified, screened, analysed, included, and excluded (see Figure 2-1).

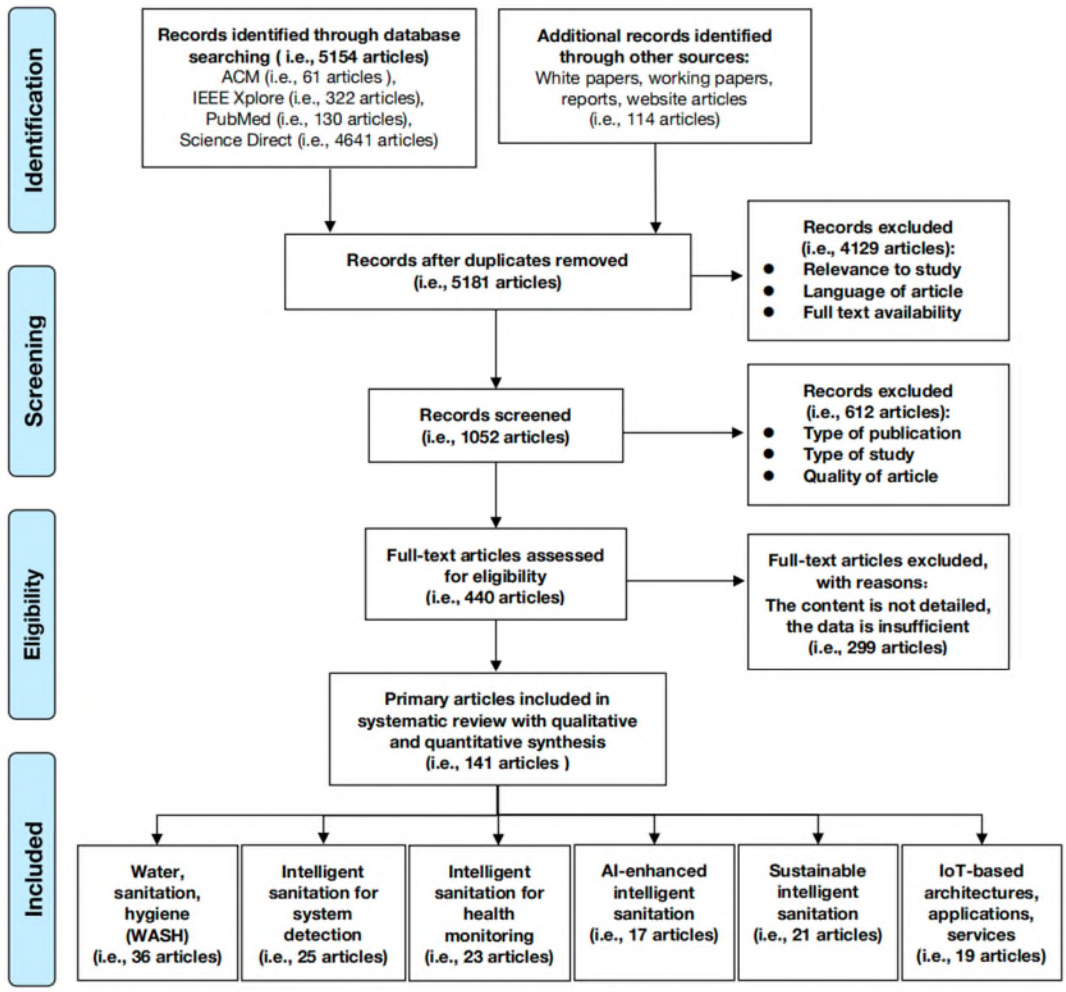


Figure 2-1 The PRISMA flowchart

2.1.1.1 Inclusion and Exclusion Criteria

The concept of the IoT was first introduced in the late 20th century. The term "Internet of Things" was coined in 1999 to describe the idea of connecting physical objects to the internet, allowing them to communicate with each other and other devices (Ashton, 2009). The actual development and implementation of IoT technologies gained momentum in the early 2000s, driven by advancements in wireless communication technologies, sensor networks, and the increasing availability of internet connectivity. Since then, IoT technology has continuously evolved and expanded, playing a significant role in various industries and becoming an integral part of our daily lives. The literature review encompasses research on intelligent sanitation published in English between 2000 and 2022. The focus on recent and up-to-date research ensures the relevance and accuracy of the information presented.

The peer-reviewed literature, grey literature, reputable articles, and authoritative reports are included. Textbooks, industrial documentation, schematics, patents and low-quality material are excluded. The literature on intelligent sanitation for system operation detection, industrial control, integrated biosensors, user health monitoring, user behaviour analysis, user experience improvement, special service support, environmental monitoring, ecological management, integrated artificial intelligence, and sustainability is included. The literature that does not incorporate advanced electronic techniques and sensor improvements in sanitation facilities and toilets is excluded.

The criteria for literature evaluation play a crucial role in ensuring rigorous and dependable research. These criteria help researchers gauge the credibility, relevance, and validity of publications. Key considerations for evaluating high-quality literature include:

- Relevance: Verify that the literature directly addresses the research topic and aligns with the research questions.

- Credibility of sources: Assess the credibility of the authors and their affiliations.

- Currency: Examine the publication date to ensure the literature is up-to-date and includes the latest findings and developments.

- Peer review: Consider whether the literature has undergone a peer review process, indicating evaluation by experts for accuracy and validity.

- Research design: Evaluate the research design and methodologies used in the literature to determine the strength of the evidence presented.

- Data analysis: Scrutinize the data analysis methods to ensure they are appropriate for answering research questions and drawing valid conclusions.

- Contribution to the field: Assess how the literature contributes to existing knowledge and whether it offers new insights or perspectives.

- Citations: Analyse the number and quality of citations the literature has received, which can indicate its influence and impact on the field.

2.1.1.2 Data Sources, Search Terms and Screening for Inclusion

The systematic literature search is conducted in databases and publishers, such as ACM, IEEE Xplore, PubMed, and Science Direct. The keywords *"sanitation" OR "toilet" AND ("intelligent" OR "smart" OR "IoT" OR "Internet of Things" OR "sensor")* are used in searches.

The following categories apply to literature: i) terms related to WASH, such as sanitation, hygiene, toilet, sewage; ii) terms related to intelligent sanitation for system detection, such as IoT, sensor, IoT-based sanitation, IoT-based toilet, smart sanitation, smart toilet, system detection, operation monitoring, environmental monitoring, system maintenance, facility management; iii) terms related to intelligent sanitation for health monitoring, such as diagnostic, public health, global health, health monitoring, patient, disabled, user behaviour, health sensor, biosensor, excreta, urine, faeces; iv) terms related to AI-enhanced intelligent sanitation, such as artificial intelligence, machine learning, deep learning, computer vision, decision making, cloud computing, predictive maintenance; v) terms related to sustainable intelligent sanitation, such as sustainability, sustainable development goals, sanitation revolution, toilet revolution, ecological sanitation, eco-sanitation, eco-toilet, environmentally friendly sanitation, water conservation, energy conservation, water consumption, energy consumption, recyclable, reusable, sewage management, sanitation services. The initial review process screens the titles and abstracts of the retrieved literature and eliminates those that clearly do not match.

2.1.1.3 Information Extraction and Quality Assessment

The relevance of the study, type of publication, availability of full text, quality and language of materials are considered when evaluating literature. High-quality, high-cited journals and articles, reputable reports published by organisations and governments, as well as inspiring and innovative material are included. Unpublished papers, industrial documents, non-peer reviewed material, generic and uninnovative articles, non-English written papers, low-quality and low-citation articles are excluded.

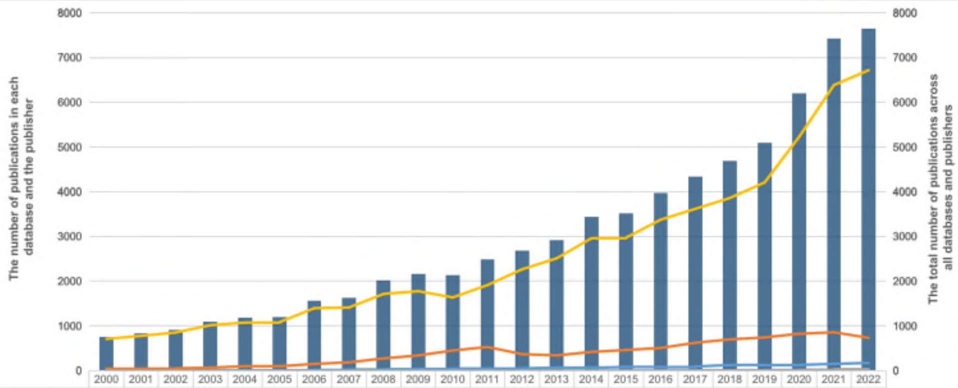
2.1.2 Review Result Analysis

The number of papers published on intelligent sanitation has increased significantly over the last two decades. From 2000 to 2005, there were few publications on the topic of intelligent sanitation. Intelligent sanitation received gradual attention from 2005 to 2015, and the amount of relevant publication began to increase gradually and steadily. From 2015 to 2020, as advanced IoT architecture, applications, and services were developed, the number of intelligent sanitation studies increased at a faster rate each year, implying that more researchers were involved. Since 2022, the benefits of intelligent sanitation have been revealed, resulting in a massive amount of research work and many excellent contributions (see Figure 2-2).

The selected keywords are searched in the entire field of publications to reveal the attention paid to the sanitation industry and intelligent sanitation topics from 2000 to 2022 (see Figure 2-2_a). From 2000 to 2005, the topic of sanitation was studied in general databases such as Science Direct, but it received little attention and did not focus on intelligent sanitation. From 2005, the electronics integrated sanitation system began to gain traction in computer science, electrical engineering, and electronics-related databases such as ACM and IEEE Xplore, and it received even more attention after 2010. There were few studies on intelligent sanitation for health monitoring in life sciences and biomedical-related databases such as PubMed from 2000 to 2015, and more researchers gradually joined the topic after 2015.

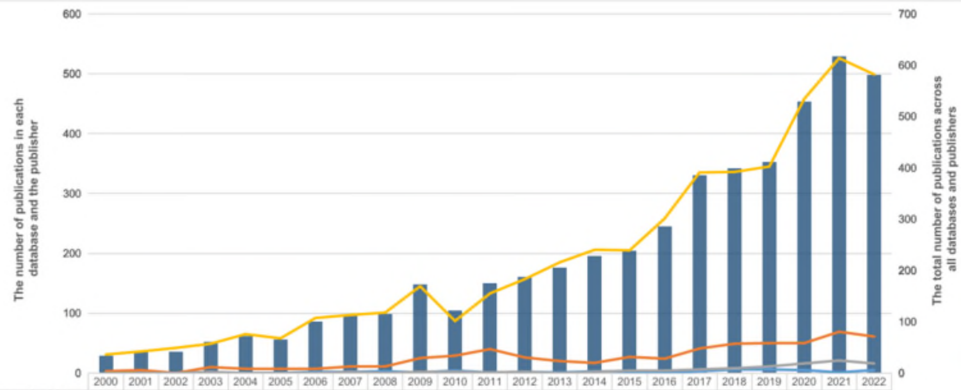
From 2000 to 2022, research on intelligent sanitation received increasing attention and had a significant impact in the recent past. The keywords are searched in the abstracts of publications, revealing trends in specific intelligent sanitation research from 2000 to 2022 (see Figure 2-2_b). Intelligent sanitation began to gain popularity at a rapid pace from 2010 onward. The frequency of keywords in publication titles reflects the increasing popularity of intelligent sanitation over time (see Figure 2-2_c).

From 2000 to 2005, the publications centred on the broad topic of sanitation. From 2004 to 2018, the number of publications on intelligent sanitation increased steadily each year, but only a few research groups contributed. More diverse teams are participating in intelligent sanitation research and research contribution has increased dramatically between 2019 and 2022 as advanced IoT technologies and smart home applications become more popular. Even though intelligent sanitation is receiving increasing attention as of 2022, it is still extremely underdeveloped in comparison to other IoT-based industrial applications.



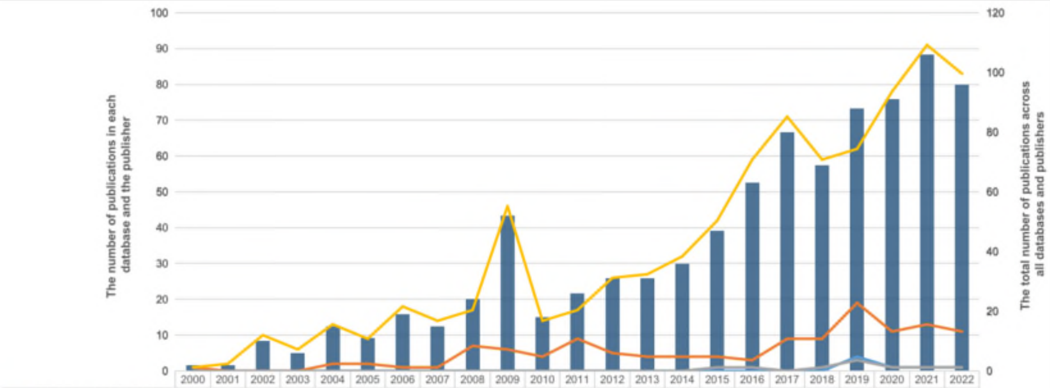
	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
All databases and publishers	754	827	913	1094	1184	1192	1563	1625	2024	2156	2139	2491	2689	2919	3445	3521	3969	4341	4696	5089	6204	7426	7651
ACM	2	3	7	9	9	8	15	25	33	37	47	45	51	65	63	82	79	92	127	124	128	151	173
IEEE Xplore	42	45	52	67	100	98	151	186	274	340	451	529	369	340	419	462	508	623	699	743	825	858	733
PubMed	0	1	0	2	0	0	0	2	1	2	3	3	2	1	2	4	6	8	9	14	20	33	28
Science Direct	710	778	854	1016	1075	1086	1397	1412	1716	1777	1638	1914	2267	2513	2961	2973	3376	3618	3861	4208	5231	6384	6717

Figure 2-2_a Annual publications (full-fields) in intelligent sanitation from various databases and publishers from 2000 to 2022



	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
All databases and publishers	34	41	42	61	72	65	101	112	115	173	122	175	187	206	228	238	286	385	399	412	529	617	581
ACM	0	0	0	0	0	0	2	2	3	1	4	1	2	1	3	2	0	3	6	6	5	1	5
IEEE Xplore	3	5	0	10	7	7	7	11	11	25	29	40	26	20	17	27	24	41	49	50	50	69	61
PubMed	0	0	0	2	0	0	0	2	0	2	2	1	2	0	2	4	4	6	8	11	16	21	16
Science Direct	31	36	42	49	65	58	92	97	101	145	87	133	157	185	206	205	258	335	336	345	458	526	499

Figure 2-2_b Annual publications (abstract) in intelligent sanitation from various databases and publishers from 2000 to 2022



	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
All databases and publishers	2	2	10	6	15	11	19	15	24	52	18	26	31	31	36	47	63	80	69	88	91	106	96
ACM	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	1	1	1
IEEE Xplore	1	0	0	0	2	2	1	1	7	6	4	9	5	4	4	4	3	9	9	19	11	13	11
PubMed	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	1	3	1	1	1
Science Direct	1	2	10	6	13	9	18	14	17	46	14	17	26	27	32	42	59	71	59	62	78	91	83

Figure 2-2_c Annual publications (title) in intelligent sanitation from various databases and publishers from 2000 to 2022

Figure 2-2 Annual intelligent sanitation literature review

2.1.3 Definition of the San-IoT Concept

The results of the literature review show that current publications on intelligent sanitation are fragmented and unsystematic. The chapter proposes the concept of Sanitation-IoT (San-IoT), which stands for computer science, electrical engineering, electronics, and IoT integrated intelligent sanitation systems. San-IoT integrates multiple technologies into sanitation facilities, including sensors, hardware, software, automation, embedded system, control systems, wireless communication, and data analytics. San-IoT enables system monitoring and control, user health monitoring, user behaviour analysis, and secure data storage, retrieval, sharing, and use. Advanced AI technologies bring great potential for San-IoT. For sustainable sanitation, San-IoT makes efficient decisions, improves water usage efficiency, and reduces energy consumption and operating costs.

The definition of intelligent sanitation is broader than San-IoT. San-IoT places more emphasis on the use of IoT technologies in sanitation industry than general intelligent sanitation systems. Some early intelligent sanitation systems relied on simple centralised control systems or gathered underutilised data, resulting in untapped potential. San-IoT is committed to enabling the sanitation industry to provide self-service using IoT technologies by emphasising interactivity, communication, and collaboration between sanitation facilities and users.

2.2 History of Intelligent Sanitation

Intelligent sanitation, also known as smart sanitation, intelligent toilets, smart toilets, electronic toilets. The first intelligent sanitation system was invented in 1964 (Gong et al., 2020). Intelligent sanitation systems use advanced electromechanical components, programmed controls, and automation technologies to improve the efficiency, effectiveness, and sustainability of traditional sanitation facilities. During the 1980s and 1990s, intelligent sanitation systems were improved, upgraded, and popularised with new washing, drying, seat heating, and buttock washing features. Intelligent sanitation has been thriving since the 1990s, with improved system performance and user experience (Gong et al., 2020). The IoT concept first appeared in the 1990s and has since transformed the way human interact with the world (Ashton, 2009). The early days of the IoT-based intelligent sanitation (i.e., San-IoT) were characterized by a lack of standardisation and interoperability, as different researchers and organisations developed their own proprietary technologies and systems. With the evolution of technology such as ubiquitous computing, commodity sensors, embedded systems, wireless networks, and machine learning, San-IoT has gained greater recognition and adoption. San-IoT can improve operational efficiency, monitor user health, and recycle waste in an eco-friendly manner, making life easier, less stressful, and more efficient (Singh & Jayaram, 2022). The chapter classifies San-IoT applications for services into system detection, health monitoring, AI enhancement, and sustainability (see Figure 2-3), as well as exploring future opportunities and challenges.

Intelligent sanitation research from 2000 to 2022 is shown in Table 1. Intelligent sanitation was initially used for health monitoring; however, as technology advances, solutions for system detection and environmental monitoring are gradually proposed. Intelligent sanitation was initially based solely on mechanical mechanisms. The system's potential was increased by advanced sensor techniques, user privacy (user identification), and AI. Intelligent sanitation solutions are effective in both the public and private sectors. In the research topic, user experience, special group needs, and sustainability are becoming increasingly important. Innovative ideas and concepts are identified in Table 2-1.

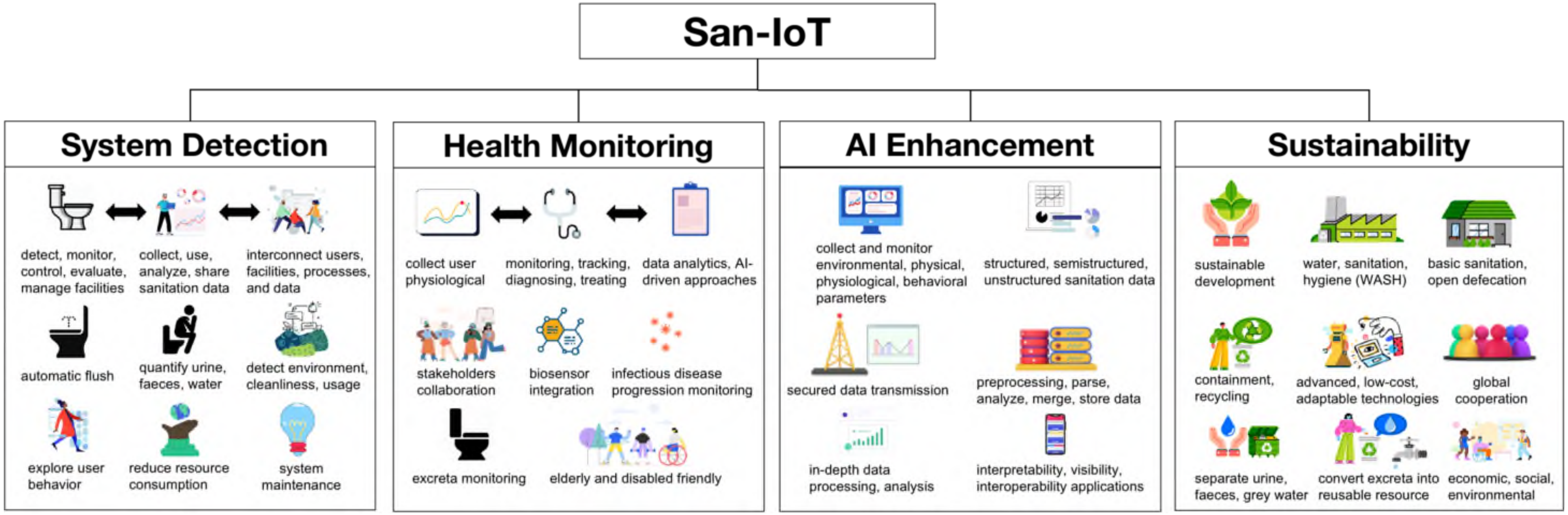


Figure 2-3 San-IoT applications and services

Table 2-1 Summary of intelligent sanitation literature

Reference	System Purpose			Adopted Advanced Technology				Sanitation Type		Interdisciplinary Extension			Innovative Concept
	Sys.	Hea.	Env.	Mac.	Sen.	User.	AI-.	Pub.	Hou.	Exp.	Spe.	Sus.	
Panek et al. (2005)				✓				✓	✓	✓	✓		✓
Kim et al. (2006)		✓			✓				✓				
Tanaka et al. (2006)		✓			✓				✓				
Biplob et al. (2011)				✓				✓	✓	✓		✓	✓
Magnusson et al. (2011)					✓			✓	✓	✓	✓		
Molenbroek & De Bruin (2011)		✓		✓	✓			✓	✓	✓	✓	✓	✓
Panek et al. (2011)		✓		✓	✓	✓			✓	✓	✓		
Schlebusch (2011)		✓			✓				✓		✓		

Table 2-1 Summary of intelligent sanitation literature (continued)

Reference	System Purpose			Adopted Advanced Technology				Sanitation Type		Interdisciplinary Extension			Innovative Concept
	Sys.	Hea.	Env.	Mac.	Sen.	User.	AI-.	Pub.	Hou.	Exp.	Spe.	Sus.	
Huang et al. (2012)		✓			✓	✓	✓	✓	✓				
Amat Azhar et al. (2013)	✓			✓	✓			✓	✓				
Atta (2013)	✓			✓	✓			✓	✓				✓
Pranger et al. (2013)								✓	✓	✓		✓	✓
Wan Mohammed et al. (2013)	✓		✓	✓	✓			✓					
Taniguchi et al. (2014)		✓			✓		✓	✓	✓		✓		✓
Dutta (2016)			✓	✓				✓					
Kim & Allen (2016)		✓			✓				✓		✓		

Table 2-1 Summary of intelligent sanitation literature (continued)

Reference	System Purpose			Adopted Advanced Technology				Sanitation Type		Interdisciplinary Extension			Innovative Concept
	Sys.	Hea.	Env.	Mac.	Sen.	User.	AI-.	Pub.	Hou.	Exp.	Spe.	Sus.	
Kodali & Ramakrishna (2017)	√		√		√			√				√	√
Pilissy et al. (2017)	√			√	√			√	√	√	√		√
Zakaria et al. (2017)	√		√	√	√			√	√	√			
Bae & Lee (2018)		√			√				√	√			√
Boonyakan et al. (2018)	√			√	√			√	√			√	
Cheng et al. (2018)								√		√		√	√
Namekar & Karthikeyan (2018)	√		√		√			√					

Table 2-1 Summary of intelligent sanitation literature (continued)

Reference	System Purpose			Adopted Advanced Technology				Sanitation Type		Interdisciplinary Extension			Innovative Concept
	Sys.	Hea.	Env.	Mac.	Sen.	User.	AI-.	Pub.	Hou.	Exp.	Spe.	Sus.	
Ramasamy et al. (2018)	✓		✓		✓			✓					✓
Yoon et al. (2018)				✓			✓	✓	✓	✓	✓		✓
Zakaria et al. (2018)	✓				✓			✓		✓		✓	
Balaceanu et al. (2019)	✓	✓	✓	✓	✓			✓	✓	✓	✓		
Cai et al. (2019)	✓		✓		✓			✓		✓			
Mannopantar et al. (2019)		✓							✓				
Mohanty & Mohanty (2019)				✓					✓	✓	✓		✓

Table 2-1 Summary of intelligent sanitation literature (continued)

Reference	System Purpose			Adopted Advanced Technology				Sanitation Type		Interdisciplinary Extension			Innovative Concept
	Sys.	Hea.	Env.	Mac.	Sen.	User.	AI-.	Pub.	Hou.	Exp.	Spe.	Sus.	
Shaikh et al. (2019)	√		√	√	√			√		√			√
Shinganwade et al. (2019)	√		√		√			√		√			√
Tsuchiyama & Kajiwara (2019)		√			√		√		√		√		
Wu & Sun (2019)		√			√				√	√	√		√
Cid et al. (2020)	√				√			√					
Deshmukh et al. (2020)	√		√		√		√	√		√			
Liang (2020)				√	√				√				

Table 2-1 Summary of intelligent sanitation literature (continued)

Reference	System Purpose			Adopted Advanced Technology				Sanitation Type		Interdisciplinary Extension			Innovative Concept
	Sys.	Hea.	Env.	Mac.	Sen.	User.	AI-.	Pub.	Hou.	Exp.	Spe.	Sus.	
Park et al. (2020)		✓			✓	✓	✓		✓		✓		✓
Raendran et al. (2020)	✓		✓		✓			✓		✓			✓
Rary et al. (2020)		✓			✓				✓	✓			✓
Syafaah et al. (2020)		✓			✓		✓		✓		✓		
Turman-Bryant et al. (2020)	✓				✓		✓	✓					
Cotera Rivera & Bilton (2021)	✓				✓				✓			✓	
Zhang et al. (2021)		✓		✓	✓	✓	✓		✓				✓

Table 2-1 Summary of intelligent sanitation literature (continued)

Reference	System Purpose			Adopted Advanced Technology				Sanitation Type		Interdisciplinary Extension			Innovative Concept
	Sys.	Hea.	Env.	Mac.	Sen.	User.	AI-.	Pub.	Hou.	Exp.	Spe.	Sus.	
Akaho&Yoshioka (2022)		√			√		√		√		√		
Bimantara et al. (2022)	√				√			√				√	√
Ganesapillai et al. (2022)							√	√	√			√	√
Ge et al. (2022)		√			√	√		√	√		√		√
Huh et al. (2022)							√		√	√	√		√
Kumar et al. (2022)		√			√			√		√			√
Lokman et al. (2022)					√			√	√	√			√
SeeTo et al. (2022)	√				√		√	√					√

Table 2-1 Summary of intelligent sanitation literature (continued)

Reference	System Purpose			Adopted Advanced Technology				Sanitation Type		Interdisciplinary Extension			Innovative Concept
	Sys.	Hea.	Env.	Mac.	Sen.	User.	AI-.	Pub.	Hou.	Exp.	Spe.	Sus.	
Swathy et al. (2022)				✓	✓				✓	✓	✓		✓
Tasoglu (2022)		✓			✓		✓		✓	✓			✓
Wang et al. (2022)					✓		✓	✓			✓		✓
Zhang et al. (2022)	✓				✓				✓				
Zhao et al. (2022)				✓	✓		✓	✓					✓

Where sys. = system detection, hea. = health monitoring, env. = environmental monitoring (air quality, cleanliness, user number), mac. = mechanical principle, sen. = sensor integration, user. = user identification, AI-. = AI-Powered, pub. = public sanitation, hou. = household sanitation, exp. = user experience, spe. = special groups (elderly, disabled, children, pets), sus. = sustainability.

2.3 Intelligent Sanitation for System Detection

Intelligent sanitation for system detection is the process of detecting, monitoring, controlling, evaluating and managing sanitation facilities. The sanitation facilities integrate embedded hardware, sensors, and interactive software to collect and share real-time data on equipment operation with stakeholders. The data gathered reveals the function, performance, and troubleshooting of the various facility components. Users, facilities, processes, and data are all interconnected. Data-driven decisions are generated after information is shared, used, and analysed. The San-IoT promises a major paradigm shift in how humans interact with and think about sanitation, driving global access to better sanitation services. The chapter examines literature on intelligent sanitation for system detection from 2000 to 2022. According to the review, each IoT-based sanitation system applies non-uniform architectures, employs fragmented mechanisms, and develops different features, causing intelligent solution to lag. As advanced IoT technology grows, San-IoT for systems detection is providing the following functions:

- Sensor-integrated sanitation facilities, stable operating platforms, and effective equipment management tools.
- Establish consistent, stable, and efficient connections between components, devices, assets, equipment, facilities, and cloud-based platforms.
- Data collection, operational monitoring, component control, facility management, configuration settings, wireless communication, and software services are offered.

- Analyse the collected data, operating processes, and system state to generate customised reports based on business logic, providing extremely powerful insights.
- Data visualisation of sanitation data, presenting insights into system operation in an understandable manner for users and stakeholders.
- Control the sanitation system using interpreted findings to make it more efficient, cost-effective, and sustainable.
- Monitoring and detection of anomalies in the sanitation system, analysis of operational status and provision of immediate failure alerts.

The intelligent sanitation for system detection is made up various integrated sensors, wireless communication, insight analysis, and visibility tools. The various systems in terms of their purposes, components, sensors, features and applications are compared (see Table 2-2). Most of the systems are used to monitor, control, analyse, and manage sanitation facility operations. Some of the most recent research work is gaining useful insights into user behaviour patterns by further analysing the operational state with the introduction of cross-disciplinary knowledge. A toilet front end (i.e., toilet seat), a water tank, and an excreta evacuation pipe are the main components of a conventional toilet. Monitoring the operational performance of the water tank is an important part of system detection. A few studies have attempted to quantify the volume of urine, faeces, and grey water. Individual user behaviour is detected by infrared sensors and motion sensors in household toilets. Public toilets are more concerned with detecting the surrounding environment, such as air quality, cleanliness, and the number of users. Most current research use intelligent sanitation to reduce water consumption and make toilet maintenance easier. With the advancement of data visualisation techniques, interactive applications (i.e., website, mobile, tablet, computer software) are increasingly being used to provide stakeholders with operation information. Some intelligent sanitation systems are still in the concept and idea stages, while others have been tested in the field and received feedback.

2.3.1 Household San-IoT System Detection

Early household intelligent sanitation systems installed sensors that are inexpensive and easy-to-access. Atta (2013) proposed an intelligent toilet with pH sensors integrated. The pH sensors detect impurities in the toilet and activate flushing automatically, significantly reducing water consumption. Amat Azhar et al. (2013) developed a basic intelligent toilet with infrared sensors, float sensors, and a central controller installed. The infrared sensor detects user access to activate toilet operation; the float sensor detects changes in tank water volume; and the central processor regulates toilet flushing for cleanliness. Not only can the toilet flushing mechanism be automatically triggered based on detected user behaviour, but also the flushing duration. Boonyakan et al. (2018) used a microcontroller, an infrared sensor, and a solenoid valve to create an automatic flushing toilet. When the infrared sensor detects changes in user behaviour, the solenoid valve activates flushing. The system automatically adjusts the flushing time based on the cleanliness of the toilet to save water. The early household intelligent sanitation systems mentioned above integrated affordable and easily accessible sensors, leading to cost-effective implementations. The use of intelligent sensors enabled automatic flushing based on user behavior and toilet cleanliness, effectively reducing water consumption and contributing to water conservation efforts. These insights highlight the potential of IoT and sensor technologies to revolutionize sanitation practices.

Anomalies and emergencies in the sanitation system are detected by data analytics. The analysis of historical data for field testing toilets reveals facility operational performance and user behaviour. Zakaria et al. (2018) proposed an emergency sanitation system by integrating information communication technologies (ICT). When the tank is nearly full, users receive warning messages, effectively preventing the tank from overflowing. Self-monitoring is used to diagnose failures, preventing system crashes, reducing unnecessary costs, and strengthening product reputation (Cid et al., 2020). Sanitation data are used for user behaviour analysis in cross-disciplinary and user-centred design to improve system operation (Cotera Rivera and Bilton, 2021). The information on intelligent sanitation systems reveals valuable insights for the enhancement of sanitation services. The integration of IoT technologies in toilets overcomes limitations of traditional systems, providing warning messages, data tracking, and self-diagnosis features.

2.3.2 Public San-IoT System Detection

The chain of public sanitation services includes toilets, waste treatment, and disposal. Traditional facilities and methods have made slow progress toward achieving global sanitation. Sanitation facilities in public places, such as schools, airports, hospitals, communities, and parks, must be clean, sanitary, and well-maintained. San-IoT can measure, detect, monitor, and control sanitation facilities operation. Wan Mohammed et al. (2013) created a public toilet with a motion sensor, float sensor, and timer that detects user behaviour, adjusts water volume, and transforms the surroundings automatically. Keeping the public health system clean has always been critical, but a challenge. Dutta (2016) designed an intelligent toilet with automatic flushing to provide cleaner public sanitation. Namekar and Karthikeyan (2018) installed odour, humidity, and ultrasonic sensors to monitor toilet surrounding. By incorporating motion sensors, float sensors, timers, and automatic flushing capabilities, public toilets can efficiently regulate water usage, maintain cleanliness, and enhance user experiences, leading to improved resource efficiency. The synchronisation of sanitation data to a database enables real-time monitoring and visualisation, making it easier for citizens to locate clean and accessible toilets. The integration of IoT technologies into sanitation facilities empowers public authorities to effectively manage sanitation conditions, ultimately fostering better public health.

Cleaning, maintenance, and management of sanitation facilities are critical for public restrooms. Cai et al. (2019) proposed an intelligent system for tracking the use and cleanliness of public restrooms. Data collected by ultrasonic and button sensors is wirelessly transmitted to a cloud server; cleaning staff and queue users are provided with useful information in real time. San-IoT improves the comfort, convenience, and efficiency of public sanitation services by informing users about toilet congestion levels (Shinganwade et al., 2019). As smart assets evolve, more diverse types of sensors are installed on intelligent toilets, and more data analytics tools are employed. Deshmukh et al. (2020) proposed a San-IoT system with odour, ultrasonic, RFID, infrared, and light sensors to monitor the cleanliness of public restrooms. A web-based app provides cleaners, users, and managers with accurate information on the cleanliness of sanitation facilities. San-IoT enables real-time monitoring of restroom usage and cleanliness, leading to enhanced efficiency and convenience for users. The system employs diverse sensor data collection, providing comprehensive information on various sanitation aspects, thus empowering managers to make data-driven decisions.

San-IoT functionality is constantly being improved and expanded by advanced technologies. The combination of AI and IoT enhances San-IoT performance by extracting more value from exponential growth data for smarter decision making. Turman-Bryant et al. (2020) introduced a toilet equipped with machine learning capabilities, enabling it to predict waste overflow events. This predictive feature allows for dynamic scheduling of toilet operations, effectively reducing the occurrence of failures. Liang (2020) introduced a smart flushing toilet design to minimise user-toilet interaction, surface contamination, and virus transmission. The system activates flushes automatically by considering factors such as user behaviour, ambient humidity, contact friction, and motor speed. Bimantara et al. (2022) proposed an intelligent sanitation system to manage water and electricity consumption in densely populated areas. Manual measurements are being replaced by more accurate and automated water temperature adjustment mechanisms (Zhang et al., 2022). The integration of IoT and AI technologies in sanitation systems has the potential to transform traditional practices, offering data-driven, efficient, and intelligent solutions for better public health and environmental outcomes.

Table 2-2 Summary of intelligent sanitation for system detection literature

Reference	System Purpose		Detected System Parametres						Service	System Benefits		Implementation Phase	
	Sys.	Use.	Liq.	Uri.	Fec.	Gre.	Usa.	Env.	App.	Sav.	Mai.	Con.	Fie.
Amat Azhar et al. (2013)	✓		✓				✓			✓		✓	
Atta (2013)	✓		✓							✓		✓	
Wan Mohammed et al. (2013)	✓		✓				✓	✓		✓		✓	
Dutta (2016)	✓		✓										✓
Boonyakan et al. (2018)	✓		✓				✓			✓			✓
Namekar & Karthikeyan (2018)	✓		✓					✓	✓	✓		✓	
Ramasamy et al. (2018)	✓						✓	✓	✓			✓	

Table 2-2 Summary of intelligent sanitation for system detection literature (continued)

Reference	System Purpose		Detected System Parametres						Service	System Benefits		Implementation Phase	
	Sys.	Use.	Liq.	Uri.	Fec.	Gre.	Usa.	Env.	App.	Sav.	Mai.	Con.	Fie.
Zakaria et al. (2018)	✓	✓	✓	✓	✓	✓				✓	✓		✓
Cai et al. (2019)	✓		✓				✓					✓	
Shaikh et al. (2019)	✓	✓					✓	✓		✓		✓	
Shinganwade et al. (2019)	✓		✓				✓	✓	✓	✓	✓	✓	
Cid et al. (2020)	✓		✓								✓		✓
Deshmukh et al. (2020)	✓							✓	✓			✓	
Liang (2020)	✓	✓	✓				✓			✓		✓	
Raendran et al. (2020)	✓	✓	✓					✓	✓	✓		✓	✓

Table 2-2 Summary of intelligent sanitation for system detection literature (continued)

Reference	System Purpose		Detected System Parametres						Service	System Benefits		Implementation Phase	
	Sys.	Use.	Liq.	Uri.	Fec.	Gre.	Usa.	Env.	App.	Sav.	Mai.	Con.	Fie.
Turman-Bryant et al. (2020)	√		√	√	√						√		√
Cotera Rivera & Bilton (2021)	√	√	√				√	√		√			√
Bimantara et al. (2022)	√		√				√	√	√	√			√
Zhang et al. (2022)	√		√						√			√	

Where sys. = system operating status detection, use. = user behaviour pattern detection, liq. = liquid volume in the water tank, uri. = urine volume, fel. = fecal volume, gre. = grey water volume, usa. = usage detection (infrared sensor, motion sensor), env. = environmental monitoring (air quality, cleanliness, user number), app. = applications for interaction and visualisation (web, mobile, tablet, computer software), sav. = save water consumption, mai. = maintenance for sensors, components, assets, devices, equipment, facilities, con. = concepts and ideas, fie. = field testing.

2.4 Intelligent Sanitation for Health Monitoring

San-IoT has enormous potential for monitoring user health and improving medical care. With advanced IoT infrastructure, data analysis, optimisation, and visualisation technologies, users can access the most recent health information in a comfortable and easy manner, greatly increasing engagement and satisfaction. Doctors, patients, scientists, engineers, managers, and other stakeholders are collaborating to create more dynamic, open, and agile platforms through streamlined processes and optimised strategies. The intelligent health monitoring platforms encourage information sharing, improve patient safety, reduce diagnostic time, optimise resource allocation, personalise healthcare services, continuously track disease, provide faster responses, and reduce social pressure on healthcare. Smart wearables, implants, and ingestible electronics are already being used in healthcare for remote physiological monitoring. These smart devices are expensive, specialised, and complex. Human can produce a large amount of excrement, which is extremely rich in information but is not used effectively to increase its value. San-IoT integrated smart assets on toilets to provide users with contactless, low-cost, user-friendly continuous health monitoring. The workflows for San-IoT health monitoring are detailed below:

- Smart sensors collect user physiological data from intelligent sanitation facilities.
- Stable, secure, and efficient communication networks provide high quality data transfer.
- Services such as monitoring, tracking, diagnosing, alerting, and treating are available for user tracking health.

- Data analytics tools and AI-driven approaches analyse health data to gain useful insight.
- Doctors, health practitioners, patients, and other stakeholders use health data to make actionable healthcare solutions and informed decisions.
- Data visualisation and interactive software (web, mobile devices, computers, tablets) provide users with up-to-date health information, allowing them to participate in healthcare services in a more proactive, continuous, and coordinated manner.

Intelligent sanitation for health monitoring includes biosensors, communication networks, data processing, health data analysis, and insight display. San-IoT for health monitoring is still in its early stages. The chapter summarises and compares the sensors integrated, health parameters monitored, and advanced technologies used in various sanitation systems (see Table 2-3). Early research on intelligent sanitation for health monitoring concentrates on physiological data measurement techniques. As sensor technique bottlenecks are overcome and basic health information become more easily captured, more and more research work begins to place an emphasis on the user experience. Facilities are frequently outfitted with easily accessible and specialised sensors at the start of intelligent system development. Smart assets such as pressure sensors, biometric identification sensors (fingerprints), and photoplethysmogram sensors are used to monitor basic physiological and ECGs features. Cameras, infrared sensors, and ultrasonic sensors are being integrated into toilets as a result of advances in hardware, analytics, and vision technologies. The data generated by urine, faeces, and respiration gradually begin to form insights with data analysis algorithms. Central control boards are used in the basic intelligent sanitation systems to control toilet operation and collect user health data. Early smart systems keep user health information in local databases. With massive amounts of data generated, cloud databases are used to provide secure, dependable, and simple-to-use data storage services. AI algorithms lay the groundwork for quick, accurate, and efficient processing of health data. To enable cost-effective and contactless disease diagnosis, computer vision is used to analyse the colour and shape of excrement images. With the proliferation of mobile devices, increased communication availability, and the ease development of interactive applications (i.e., web, mobile, tablet, and computer software), stakeholders have access to the most recent health information efficiently.

2.4.1 Biosensors-integrated San-IoT

Installing low-cost, compact, efficient, and scalable sensors on intelligent toilets to provide users with continuous health monitoring can help improve healthcare services. Early intelligent toilets were primarily used for standard physiological parameter measurement, such as the user's weight and blood pressure. Kim et al. (2006) integrated copper-coated electrodes and a photoplethysmogram into the toilet seat to non-invasively measure the user's electrocardiogram. Tanaka et al. (2006) developed a continuous blood pressure monitoring toilet for early cardiovascular disease diagnosis and treatment. Intelligent toilets aid in the early detection and treatment of disease in the elderly. Schlebusch (2011) embedded electrocardiograms and bioimpedance spectroscopy in toilets to detect heart disease, recording ECG signals, measuring cell membranes to determine hydration status, and sending healthy data to a central database to investigate health trends. The doctor receives the health data for real-time tracking, timely treatment, accurate decisions, and comprehensive insights. Huang et al. (2012) developed an intelligent toilet to detect unconscious biosignals, with the ECG analysing cardiac performance, the bio-impedance analysing user body composition, and the pressure sensor measuring user weight. Intelligent sanitation has the potential to revolutionise healthcare by enabling early disease diagnosis, proactive monitoring, and personalised treatment. They offer a non-intrusive and convenient way to gather vital health information. The seamless integration of health monitoring technologies into toilets can lead to more accessible and proactive healthcare, improving the overall well-being and quality of life for individuals, particularly the elderly population.

2.4.2 Advanced Continuous Excreta Monitoring

Human secretions such as saliva, sweat, urine and faeces contain a wealth of health information. However, saliva is ninety-eight percent water, and the concentration of detectable substances is extremely low, making measurement difficult with simple and low-cost equipment. Sweat monitoring is non-invasive, but sample collection is time-consuming, pasted sensors cause allergic, and testing results highly dependent on the environment, resulting in inaccurate measurements. For continuous health monitoring, human excreta are a good option. Sanitation facilities are easily accessible, and urine-faeces contain a wealth of information. Urine has numerous measurable physical, chemical, and microscopic properties, including colour, odour, pH, sugars, hormones, proteins, ascorbic acid, nitrites, bacteria, yeast, and microbiota.

Early urine-based household health monitoring relied heavily on medically validated monitoring methods such as dipstick urinalysis, urine culture, urine particle flow cytometers, and mass spectrometry (Kim and Allen, 2016; Bae and Lee, 2018). Clinical medicine combined with intelligent facilities for early disease detection is prohibitively expensive and extremely complex. Intelligent sanitation assists patients with chronic diseases by remotely monitoring them, lowering healthcare costs and increasing patient health awareness (Park et al., 2020). The intelligent toilet derives powerful insights from daily excrement and provides information to aid in diagnosis. The papers highlight the importance of employing medically validated monitoring techniques for health assessment. This strategy is anticipated to offer cost-effective and user-friendly solutions, fostering heightened health consciousness among individuals with chronic illnesses. By merging clinical medicine with intelligent technology, the system can remotely monitor patients and reduce healthcare expenses. However, the papers acknowledge that while the notion of intelligent sanitation holds potential for enhancing healthcare, further research and validation are imperative to ensure their efficacy and dependability within a household environment. Moreover, addressing data privacy and security concerns is essential to safeguard user information and uphold patient confidentiality.

Machine learning has the potential to provide more efficient, helpful, and faster excreta sample analysis for healthcare. Through image recognition, detection, and identification, computer vision diagnoses real-time health status by analysing the colour and shape of excreta. Syafaah et al. (2020) installed a camera on the toilet to capture urine images and use the K-Means algorithm to diagnose diabetes based on urine colour. Machine learning for health analytics expedites doctor decision making and solutions. Artificial neural networks interconnecting complex artificial neurons are commonly used in healthcare. Zhang et al. (2021) combined a variety of toilet sensors with convolutional neural networks to analyse urine and faeces, recording dynamic changes in excrement colour and identifying types and quantities of faeces using image classification. The papers delve into the promising potential of machine learning in the domain of healthcare, with a specific focus on its application in intelligent sanitation and excreta sample analysis. The integration of machine learning in this context holds immense significance for healthcare professionals, as it can lead to more efficient, accurate, and timely diagnoses. By automating the analysis of excreta samples, doctors and medical practitioners can expedite decision-making processes, leading to more prompt treatment and solutions for patients. Advanced technology has the potential to revolutionise traditional methods of excreta sample analysis, rendering them less time-consuming and labour-intensive.

2.4.3 Infectious Disease Progression Monitoring

The failure of traditional sanitation facilities has resulted in poor public health. COVID-19 has brought this failure to public attention. Intelligent sanitation aids in the tracking of COVID-19 to improve patient satisfaction and prevent infection spread.

Users are concerned about viral infections from improperly cleaned public toilets. Kumar et al. (2022) proposed an intelligent toilet with a urine testing device installed to prevent virus transmission. Urine samples are tested for bacteria and viruses, infected people are notified, and the potential risk is displayed on the toilet LCD. The intelligent toilet transforms public sanitation from a virus distributor to a health protector. COVID-19 virus detection with a nasopharyngeal swab is expensive, complicated, and time-consuming. SARS-COV-2 RNA in human faeces also indicates a positive COVID-19 testing result. However, manually collecting patient faeces is difficult and has long-term limitations. Ge et al. (2022) proposed an intelligent toilet that automatically collects faeces samples and analyses user health status. This intelligent sanitation system can be used in both public and private restrooms. Users scan QR codes to perform anonymous COVID-19 faecal testing. The test report is sent to their mobile app after five minutes, where positive patients are notified. The intelligent toilet-based COVID-19 testing process is completely automated, from sample collection to report generation, with no interference to user behaviour and minimal user-toilet interaction. UV disinfection units are installed in the toilet to prevent cross-contamination, and temperature and photoelectric sensors measure body temperature and oxygen saturation. The intelligent toilet network communicates with one another via a centralized IoT platform.

For COVID-19 researchers, the intelligent sanitation network generates a massive amount of powerful personalized health data. The information gathered will be used to investigate the time, severity, symptoms, persistence, and potential transmission routes of the COVID-19 virus. Data science approaches are used to further process the health data to predict and prevent disease pandemics in the community. The stakeholders can use the San-IoT network to track community health and increase the efficiency of pandemic management. San-IoT can detect the COVID-19 virus as well as other faecal-oral transmission diseases in the future.

2.4.4 Friendly Intelligent Sanitation

Intelligent toilets tailored to the elderly and disabled are important. The European Union has launched the 'Friendly Rest Room (FRR)' project to improve the autonomy, independence, dignity, and safety of elderly and disabled when using sanitation facilities (Panek et al., 2004). Interactive user interfaces, touch screens, voice interaction, and central computer controller are integrated into intelligent toilets to provide friendly user experience (Panek et al., 2005). Molenbroek and De Bruin (2011) investigated simple, efficient, and friendly FRR with cross-disciplinary technologies such as advanced computer technologies, healthcare informatics, ergonomics, gerontology, sociology, ethics, and cultural perspectives. A 'design-evaluation-prototype-testing' process iterates the toilet design, resulting in more accurate, efficient, and friendly products (Magnusson et al., 2011). The intelligent toilet has been researched, designed, developed, installed, tested, and evaluated, and it combines visual, auditory, and tactile senses (Panek et al., 2011). Taniguchi et al. (2014) proposed a system with camera installed for detecting falls and measuring the distance between an elderly person and a danger zone. Another intelligent system employs ultra-wideband sensors and AI to detect fatigue, fainting, and falls (Tsuchiyama and Kajiwara, 2019). Machine learning provides unrivalled benefits in data processing and analysis, as well as personalising the user experience for the elderly. Akaho and Yoshioka (2022) proposed an intelligent toilet that uses random forest algorithm to detect strain. Signals such as sitting posture, strain, winding paper, and wiping are recorded and analysed. Time series data is used to estimate breathing times accurately and to provide accident warnings.

Inaccessible physical environments, insufficient assistive technology, negative attitudes, inadequate services, systems, and policies all pose significant barriers to disabled participating in public health services. The needs of intelligent toilets in the disabled and elderly populations were being researched (Pilissy et al., 2017). Highly adaptive, user recognition, voice interaction, and emergency contact features were demonstrated. A low-cost and stable lifting wheelchair-toilet is proposed, which uses computer vision and voice control to automatically place the user in the proper position on the toilet seat for user privacy and independence (Yoon et al., 2018). Mohanty (2019) used cognitive and fuzzy logic to create an intelligent toilet for bedridden patients by combining a hospital bed and a toilet. This toilet can be widely used in hospitals and nursing homes to help ICU patients with sanitation and body cleaning. Balaceanu et al. (2019) integrated system control, health monitoring, and environmental detection in the Toilet4me toilet for both the private and public sectors. Swathy et al. (2022) created a wheelchair-accessible eco-toilet in which natural anaerobic bacteria convert human excrement into environmentally friendly methane gas and water.

Everyone, especially children, the disabled, the elderly, and patients, deserves accessible and safe sanitation services (Giné-Garriga et al., 2017). Households, as well as public places such as schools, workplaces, and markets, should provide better sanitation services. Huh et al. (2022) developed intelligent toilets with integrated AI voice services for preschool infants. The toilet design is user-centred and visually stimulating for children. The intelligent toilet assists children in learning to use the toilet in a more intimate and natural manner. More diverse San-IoT are being designed as sanitation services evolve. Wang et al. (2022) proposed a pet sanitation system with autonomy, responsiveness, and interactivity. The system encourages pets to use civilised toilets and improves public service.

Table 2-3 Summary of intelligent sanitation for health monitoring literature

Reference	System Purpose		Integrated Sensors and Smart Assets							Monitored Health Parametres					Implemented Advanced Technologies						
	Hea.	Use.	Pho.	Pre.	Bio.	RFID	Cam.	Ult.	Inf.	ECG.	Uri.	Fae.	Res.	COV.	Bas.	Dat.	IoT	Clo.	AI	Com.	App.
Kim et al. (2006)	✓		✓							✓						✓					
Tanaka et al. (2006)	✓		✓							✓					✓						
Panek et al. (2011)	✓	✓		✓	✓	✓		✓							✓	✓	✓				✓
Schlebusch (2011)	✓			✓	✓					✓					✓	✓	✓				
Huang et al. (2012)	✓			✓	✓					✓					✓	✓	✓	✓	✓		✓
Taniguchi et al. (2014)	✓						✓								✓					✓	✓
Kim & Allen (2016)	✓										✓										
Bae & Lee (2018)	✓	✓							✓		✓					✓	✓				✓

Table 2-3 Summary of intelligent sanitation for health monitoring literature (continued)

Reference	System Purpose		Integrated Sensors and Smart Assets							Monitored Health Parametres					Implemented Advanced Technologies						
	Hea.	Use.	Pho.	Pre.	Bio.	RFID	Cam.	Ult.	Inf.	ECG.	Uri.	Fae.	Res.	COV.	Bas.	Dat.	IoT	Clo.	AI	Com.	App.
Tsuchiyama & Kajiwara (2019)	√	√						√					√		√		√				
Wu & Sun (2019)	√	√													√		√	√			√
Park et al. (2020)	√				√		√				√	√				√	√	√	√	√	
Syafaah et al. (2020)	√						√				√				√	√	√		√	√	√
Zhang et al. (2021)	√		√	√		√				√	√				√	√		√	√	√	√
Akaho & Yoshioka (2022)	√		√										√		√	√	√		√		
Ge et al. (2022)	√					√					√			√		√	√	√			√

Table 2-3 Summary of intelligent sanitation for health monitoring literature (continued)

Reference	System Purpose		Integrated Sensors and Smart Assets							Monitored Health Parametres					Implemented Advanced Technologies						
	Hea.	**Use.**	**Pho.**	**Pre.**	**Bio.**	**RFID**	**Cam.**	**Ult.**	**Inf.**	**ECG.**	**Uri.**	**Fae.**	**Res.**	**COV.**	**Bas.**	**Dat.**	**IoT**	**Clo.**	**AI**	**Com.**	**App.**
Kumar et al. (2022)	✓	✓						✓		✓					✓	✓	✓				✓

Where hea. = health monitoring, use. = user experience, pho. = photoplethysmogram, pre. = pressure sensors, bio. = biometric identification (fingerprint, anal print), RFID. = radio frequency identification, cam. = camera, ult. = ultrasonic sensors, inf. = infrared sensors, ECG. = ECG monitoring, uri. = urine monitoring, fae. = faecal monitoring, res. = respiratory monitoring, COV = COVID-19, bas. = basic control board, dat. = database, IoT = Internet of Things, clo. = cloud platform, AI = artificial intelligence, com. = computer vision, app. = applications for interaction and visualisation (web, mobile, tablet, computer software).

2.5 AI-Enhanced Intelligent Sanitation

To collect and monitor environmental, physical, physiological, and behavioural parametres, intelligent sanitation facilities are connected to many sensors. These sensors generate massive amounts of redundant, heterogeneous, and complex real-time data. Traditional data analysis techniques with limited data processing capability stymie the advancement of intelligent sanitation systems. With significant advantages in big data processing, feature extraction, and in-depth analysis, machine learning has the greatest potential for improving the San-IoT decision-making process. Machine learning algorithms include supervised algorithms such as KNN, decision trees, random forest (RF), support vector machine (SVM), naive Bayesian, logistic regression, and unsupervised algorithms such as K-Means, principal component analysis (PCA), and neural networks.

Most AI-enhanced San-IoT solutions are proposed after 2020, when machine learning, IoT, computer vision, and natural language processing are gaining popularity (see Table 2-4). The natural language processing module provides contactless language support services for San-IoT, which improves user experience and caters specific needs. Computer vision efficiently process images of excreta (i.e., urine and faeces) and features of data (i.e., colour and shape). Image processing challenges such as image classification, image detection, target detection, semantic segmentation, and instance segmentation are solved using deep learning (DL), artificial neural networks (ANN), and convolutional neural networks (CNN). To process data with significant temporal characteristics, recurrent neural networks (RNN), long short-term memory (LSTM), and autoregressive integrated moving average models (ARIMA) are used. A typical AI-enhanced San-IoT workflow is shown below:

- Device sensing: Sanitation facilities integrate efficient, low-cost, high-precision, and low-power sensors and communication modules.
- Raw data collection: Structured, semistructured, and unstructured sanitation data is collected.
- Secured data transmission: Outliers, noise, and redundancies are removed, and data is transmitted asynchronously and passively to the server. To prevent data leakage, eavesdropping, and DoS attacks, all transmitted data is encrypted.
- Data preprocessing and storage: Real-time and batch data are parsed, analysed, merged, and stored for faster computations.
- In-depth data processing and analysis: AI and machine learning are used to analyse sanitation data. Characterisation, discrimination, classification, clustering, association analysis, time series analysis, and outlier analysis are used to discover high-level patterns and relationships.
- Interpretability, visibility, and interoperability service: Historical data is properly stored for future use. Data is transformed into knowledge by mining and extracting information. Data insights are visually presented to stakeholders in an understandable manner.

2.5.1 AI-Enhanced San-IoT for Facilities

AI-enhanced San-IoT solutions can monitor system performance and alert component failures. Turman-Bryant et al. (2020) used Lasso regression, multivariate adaptive regression, and random forests algorithms to predict tank overflow risk. Machine learning was used to trade off waste collection efficiency and overflow event frequency. Intelligent sanitation provides environmental sensing to improve visibility, reduce costs and manage operations. Deshmukh et al. (2020) proposed a San-IoT system for monitoring the cleanliness of public toilets. Odour and air sensors are installed, ARIMA model analyses historical time series data to predicts future surrounding trends. More parametres are being monitored in the San-IoT solutions to provide more insights. SeeTo et al. (2022) installed environmental sensors, odour sensors, light sensors, electrical operation metres, and water capacity metres on public sanitation facilities, developed an interactive user interface for information visualisation, and used a convolutional bidirectional long short-term memory model to predict operational status. The papers discussed demonstrate the application of AI-driven technologies to enhance system performance monitoring, reduce operational costs, and provide valuable insights for efficient sanitation management.

2.5.2 AI-Enhanced San-IoT for Health Care

Intelligent sanitation in health care not only benefits patient health but also increases doctor productivity. AI and San-IoT combined solutions are transforming the way health care is delivered. Advanced computer vision algorithms analyse the colour and shape of excrement to detect diabetes status. Syafaah et al. (2020) installed camera in the toilet to collect urine images, which were then fed into a K-Means model to classify urine as diabetic or normal. Park et al. (2020) used computer vision to measure urine flow, camera-captured urine depth information and geometric averages to accurately construct the 3D urine stream, CNN to classify faeces images as constipated, normal, or diarrhoeal with an average accuracy of 64.28%. With advanced AI, the San-IoT solutions can be used in more clinical studies, such as microfluidics observation of cellular components in urine, physical, quantitative defecation analysis, and genomics and microbiomics analysis of faecal samples. San-IoT foreshadows a promising future for the development and advancement of toilet-based health monitoring systems (Wang & Camilleri, 2020). San-IoT for health care are facing new challenges in data privacy protection. Persistent data from sensors and actuators are stored on different system components. The security configuration of these assets is weak and vulnerable to attack. Attackers can steal historical system operational data and patient physiology data. Transferring health-care data from physical devices to remote servers with lax security raises the risk of data leakage. To address the security issue, some protocols employ encryption, hashing, and password checking. Zhang et al. (2021) proposed intelligent toilet identifies the user using frictional electrical sensors rather than traditional camera or RFID technology, addressing the privacy concerns and achieving a user recognition rate of over ninety percent. Urine and faeces analysis results are transmitted to a cloud system and displayed on mobile devices securely.

Table 2-4 Summary of AI-enhanced intelligent sanitation literature

Reference	System Detection	Health Monitoring		Feature		Artificial Intelligence Algorithms								
		urine	faeces	color	shape	regression	K-Means	SVM	RF	DL	CNN	RNN	LSTM	ARIMA
Deshmukh et al. (2020)	✓													✓
Park et al. (2020)		✓	✓	✓	✓					✓	✓			
Syafaah et al. (2020)		✓		✓			✓							
Turman-Bryant et al. (2020)	✓					✓			✓					
Zhang et al. (2021)		✓	✓	✓	✓			✓		✓	✓	✓	✓	
SeeTo et al. (2022)	✓					✓		✓	✓	✓	✓			

2.6 Sustainable Intelligent Sanitation

2.6.1 Early Sustainable Sanitation

From 2000 to 2022, sustainable sanitation has been in constant development (see Table 2-5). The MDGs were originally set out in the 1990s and were later compiled in as International Development Goals (The United Nations Development programme, 2022; World Health Organisation, 2022). At the Millennium Summit in 2000, all the 191 United Nations member states unanimously adopted the Millennium Declaration to accelerate global economic, social, and environmental development, as well as to combat poverty, hunger, and disease (United Nations, 2000). In the early 2000s, one-sixth of the global population did not have access to safe drinking water, and two-fifths did not have access to basic sanitation services (World Health Organisation, 2000). Every year, 2.2 million people die as a result of a lack of water, sanitation, and hygiene (Supply & Council, 2004). With global urbanisation trend, the rapid growth of urban populations has caused sanitation challenges for open defecation (Ezzati et al., 2004; World Health Organisation, 2004). Traditional sanitation facilities such as pit latrines, cesspits, and septic tanks lead to high levels of bacteria in groundwater. Sustainable sanitation systems and eco-sanitation are proposed for containment, sanitisation, and recycling, which is critical to ensuring public health (Esray, 2002; Winblad, 2004). The urine-diverting dry toilet, constructed wetlands, and composting toilets, which separate urine, faeces, and grey water, and convert human excreta into nutrients and reusable water, were the most common low-cost and adaptable technologies in early sustainable sanitation systems (Rosemarin, 2005; Crennan, 2007).

2.6.2 Environmentally Friendly Sanitation

Innovative approaches, enabled by technological advancements, offer the possibility of lower-cost, simpler, and more adaptable sanitation facilities (Rheingans et al., 2006; Khatri et al., 2008). Advanced eco-sanitation systems combine high-tech with low-tech to create a flexible framework that provides optimal and economic sanitation solutions. With a growing population and limited water resources, wastewater recycling is essential. Daily household grey water is treated and recycled with reusable quality standards for toilet flushing (Lazarova et al., 2003). The recycled toilets use less water and are more efficient than traditional toilets (Razi & Husna, 2004). Ho (2004) proposed a small-scale sustainable sanitation system with water supply modules, wastewater collection modules, and wastewater treatment modules that collects rainwater from the roof and recycles wastewater to nutrients for agricultural use. Reusable water, wastewater, and rainwater sanitation facilities are environmentally friendly in both developed and developing countries (Jha, 2005; Li et al., 2005). Ecologically and economically eco-sanitation systems are being researched for Africa, Asia, EU, and US to meet the needs of local users and the respective local conditions (Winblad, 2004; Biplob et al., 2011). Cooperation of government, the academic, local organisations, non-governmental organisations (NGOs), and private enterprises has made encouraging and positive progress in sustainable sanitation (Lane, 2004; Busari & Jackson, 2005; Pranger et al., 2013).

2.6.3 IoT-based Sustainable Sanitation with Global Cooperation

Countries have urged increased regional cooperation to share knowledge and address global sanitation issues (World Health Organisation, 2008). Poor sanitation services, as well as improper disposal of excreta, grey water, and solid waste, pose a significant threat to public health (Katukiza et al., 2012).

The goal of sustainable development is to provide adequate and equitable sanitation services to all people by 2030, as well as to eliminate open defecation. However, progress on global sanitation continues to lag expectations (Owho & Ndakara, 2022). San-IoT is a technological advancement that improves health, environment, and quality of life. Failed traditional sanitation facilities consume a large amount of water, accounting for a significant portion of household water consumption. Kodali and Ramakrishna (2017) proposed a sanitation system with sensors that monitors and controls system operation, separates urine from faeces, reuses human waste as bio-fertilizer, and is tailored to the Indian drainage system. Zakaria et al. (2018) integrated sensors and ICT in a sanitation system to save up to ninety-seven percent of water consumption. Boonyakan et al. (2018) designed automatic flushing toilets for public sanitation services based on cleanliness. Cheng et al. (2018) investigated large-scale sustainable toilet networks using multidisciplinary approaches such as facility development, process design, ergonomics, psychology, and social science. Human excreta, solid waste, and rainwater are collected, stored, transported, treated, and reused in the sanitation service chain, and sanitation facilities are operated, maintained, and upgraded in accordance with ecological principles.

The number of people without basic sanitation has decreased to 29 million, but there is still a significant gap in sanitation coverage between countries due to geographical, economic, and social factors (World Health Organisation, 2022). The implementation of sustainable water and sanitation in 123 UN member countries with low and middle incomes was investigated (Pereira and Marques, 2021; Kumar et al., 2022). Humans, industry, and the WASH sectors are interconnected in a complex network that balances and integrates economic, social, and environmental factors (ESCAP, 2017; Giné Garriga, 2018; Requejo, 2021). Government advocacy, institutional reform, financial support, social participation, technology transfer, experience exchange, and innovative research are used to improve sanitation services in each country (World Health Organisation, 2020). Researchers continue to propose novel sustainable sanitation solutions using qualitative and quantitative approaches. Solution modelling, data collection, and insight analysis are used to investigate relationships between human and sustainable sanitation (Jiang, 2022). Various stakeholders are actively involved in the dynamic transformation of sustainable sanitation, with the goal of achieving universal sanitation access by 2030 (World Health Organisation, 2022).

Table 2-5 Summary of sustainable intelligent sanitation literature

Reference	Sanitation Revolution	Type of Waste Processed		Country		Solution Target						Involved Stakeholders			
		Hum.	Was.	Ded.	Deg.	Pub.	Pri.	Env.	Eco.	Eca.	Gen.	Aca.	Soc.	Gov.	Pbi.
Lazarova et al. (2003)	✓		✓	✓				✓				✓			
Ho (2004)	✓	✓	✓	✓	✓			✓	✓			✓			
Winblad (2004)	✓			✓	✓	✓		✓	✓	✓			✓		
Biplob et al. (2011)	✓	✓	✓		✓	✓	✓	✓	✓	✓		✓		✓	
Pranger et al. (2013)	✓	✓			✓	✓	✓	✓	✓	✓		✓			
Kodali&Ramakrishna (2017)	✓	✓	✓		✓	✓		✓	✓			✓	✓		

Table 2-5 Summary of sustainable intelligent sanitation literature (continued)

Reference	Sanitation Revolution	Type of Waste Processed		Country		Solution Target						Involved Stakeholders			
		Hum.	Was.	Ded.	Deg.	Pub.	Pri.	Env.	Eco.	Eca.	Gen.	Aca.	Soc.	Gov.	Pbi.
Boonyakan et al. (2018)			✓	✓	✓			✓				✓			
Cheng et al. (2018)	✓	✓	✓		✓	✓		✓	✓	✓	✓	✓	✓	✓	✓
Zakaria et al. (2018)		✓	✓		✓	✓		✓			✓	✓	✓		
Pereira & Marques (2021)	✓			✓	✓	✓	✓	✓		✓		✓	✓	✓	

Where hum. = human waste, was. = wastewater, ded. = developed countries, deg. = developing countries, pub. = public health, pri. = private sanitation service, env. = environment protection, eco. = ecological protection, eca. = economic affordability, gen. = gender consideration, aca. = academic, soc. = society, gov. = government, pbi. = public-private partnership.

2.7 Opportunities and Challenges

The IoT-based convergence of user, assets, data, and processes is transforming the sanitation industry. Breakthroughs in smart assets, data storage, data processing, data analysis, and intelligent service are enabling San-IoT with unlimited potential. Despite all its promises and potential, San-IoT must still address issues such as coverage and communication, compatibility and interoperability, privacy and security, scalability and deployment. The section summarises the opportunities and challenges for future intelligent sanitation.

2.7.1 Opportunities

Smart assets: Smart assets are a key element of the future San-IoT and are becoming increasingly ubiquitous. Smart sanitation assets sense, measure, detect, and monitor operational, mode, temperature, pressure, speed, vital signs, and user behaviour. Embedded sensors are becoming more affordable, smaller, accurate, efficient, and accessible, enabling larger-scale deployments of intelligent sanitation facilities. With advanced network communications, low bandwidth costs, and stable data transmission, smart assets are becoming more connected and sharing data seamlessly. Smartphones, as the closest end asset and personal gateway to the San-IoT, are becoming more widely available, improving human-machine interaction. Sensor networks monitor systems, users, and environments to enable informed decisions and better resource utilisation such as industrial automation, energy efficiency, water management, and waste management. AI-enabled smart assets learn patterns from collected data, predict future events, identify potential issues, and develop efficient solutions. Smart assets improve hardware to support a wide range of innovative San-IoT solutions.

Data pre-processing: Facilities located throughout the sanitation network generate massive amounts of data. Data integration is the process of combining San-IoT data from various sources into a unified comprehensive view. Sanitation data is extracted from multiple sources, transformed into desired formats, and loaded into a destination such as data warehouses and data lakes. Data integration ensures the accuracy and consistency of sanitation data, allowing stakeholders to more easily analyse the data, identify trends, and make better decisions, thereby providing end users with timely and efficient information (Lenzerini, 2002; Sreemathy et al., 2021). Sensors collect a large amount of data, which frequently contains low-quality data, necessitating data quality management. The quality of the data directly influences the quality of the insights obtained from data analysis. Data cleaning is the process of identifying data source, verifying data accuracy and security, and removing inaccurate, incomplete, and irrelevant data. Manual data cleaning is less efficient and requires extensive knowledge of the data context. Automated tools, such as data wrangling software or batch processing via scripting, can quickly identify and eliminate errors and inconsistencies. Data cleaning replaces, modifies, and deletes dirty or coarse data, as well as organises data into meaningful formats, thereby improving the accuracy and reliability of data analysis (Chu et al., 2016; Hajjaji et al., 2021; Majeed et al., 2021).

Data storage: As the amount of data created and managed by San-IoT solutions grows, advanced technologies are shaping data storage trends. Edge computing stores sanitation data at the edge of the network, closer to the source of data generation, reducing latency, accelerating data processing, and enabling smart assets to make faster decisions. Edge computing does not send data over the Internet, which reduces the risk of data leakage and provides more control and security for data management (Shi et al., 2016; Yu et al., 2017; Chang et al., 2021). Distributed storage stores sanitation data across a network of multiple locations to provide data availability, reliability, and scalability. Sanitation data is stored redundantly across multiple nodes in a network of interconnected devices, so that if one node fails, the others can still access it normally (Chang et al., 2008; Tajeddine et al., 2018). Cloud storage is a secure and reliable way to remotely store, access, back up, and manage sanitation data over the internet. Cloud storage solutions reduce the cost of data management for SMEs by eliminating the need for expensive storage equipment and instead relying on secure and cost-effective products developed by cloud providers (Yang et al., 2020; Ren et al., 2021). Flash storage devices are a popular choice for data storage due to their small size, fast speeds, and low power consumption (Raza et al., 2016). Blockchain enables users and stakeholders to verify data integrity by providing a secure, tamper-proof method of storing and managing data (Novo, 2018; Reyna et al., 2018; Wang et al., 2020). End-to-end encryption protocols and strong authentication methods are deployed to protect data. AI is used to automate repetitive tasks to analyse and interpret data more quickly. ML-driven storage solutions offer improved data compression, deduplication, and real-time analytics capabilities (Adi et al., 2020; Hussain et al., 2020; Al-Turjman et al., 2022; Hua et al., 2022).

Data analytics: Advanced tools, technologies, and algorithms are used to process and analyse relationships, trends and correlations in San-IoT data to gain insights and make better decisions. To analyse high volume and fast-moving sanitation data, clustering analysis, cohort analysis, regression analysis, neural networks, factor analysis, data mining, text analysis, time series analysis, decision trees, and conjoint analysis are frequently used (LaValle et al., 2011; Tsai et al., 2015; Li et al., 2021). The future of data analytics in San-IoT will be focused on using AI and ML to automate analysis and decision-making, as well as to reveal patterns that humans cannot detect. Predictive analytics forecasts future trends and behaviours based on historical sanitation data. Sanitation equipment predicts failures based on previous performance to avoid damage. AI identifies sanitation facility operating patterns and trends to automate equipment calibration and maintenance, saving time, labour, and money spent on sanitation network management (Ghosh et al., 2018). The combination of data security and data analytics reduces the risk of data breaches and cyber-attacks. Data encryption, authentication protocols, and access controls ensure that data is secure and only accessible to authorised users (Mohanta et al., 2020).

Intelligent service: The San-IoT enables a wide variety of applications and services, such as remote monitoring and control, interactive visualisation, predictive maintenance, optimised resource usage, and improved healthcare. The smart asset can be accessed, managed, and monitored remotely, and the sensors and actuators installed have real-time automatic control and adjustment capabilities. Data visualisation optimises the way end-users and facilities interact by presenting insights to stakeholders in an easy-to-understand format and providing real-time notifications to increase user engagement. To improve the performance and reliability of sanitation facilities, predictive maintenance analyses data collected to detect potential issues, reduce the risk of facility failure, save time and cost, and increase user satisfaction (Dalzochio et al., 2020). San-IoT improves resource utilisation efficiency, such as water and electricity consumption, by monitoring facility real-time operations and automatically adjusting system operating mode. San-IoT provides more efficient, effective and patient-centred healthcare solutions. It tracks vital signs, monitors health status and alerts to potential illnesses. Historical medical data is securely stored and shared, allowing medical personnel to diagnose and treat patients quickly and accurately.

2.7.2 Challenges

Coverage and communication: Sanitation network has physical coverage and network communication limitations. Sanitation facility deployment environments are frequently complex, making it difficult to cover large areas of required access points with existing technologies. Collecting and transforming large amounts of data between smart assets, as well as establishing communications between them, can raise several contentious issues. Broad, dependable, low-latency connectivity is required as the number of interconnected smart assets grows. Some sanitation facilities are deployed in locations with less signal, small spaces blocked by walls and obstructions, resulting in inefficient data transmission performance. Existing wireless technologies are prone to interference and signal degradation, making it impossible to send and receive data consistently.

Compatibility and interoperability: San-IoT smart assets adhere to different standards, rendering sanitation facilities incompatible. Systems from various manufacturers struggle to share data and communicate with one another, resulting in a lack of interoperability in San-IoT. Incompatible protocols, data formats, communication speeds, and operating systems between smart sanitation facilities can cause generated data to be lost, misplaced, or incorrectly transmitted. Advanced San-IoT solutions must use common languages, protocols, and open-source standards to ensure device, platform, and technology compatibility. Integrating different types of devices and services into a unified architecture is difficult, resulting in communication gaps, difficulty exchanging information, and a lack of interoperability. Researchers develop standard protocols such as MQTT, CoAP, and AMQP to enable stable facility communication; system designers develop common open architectures to enable seamless data exchange; and developers use cloud-based solutions such as Amazon Web Services (AWS) and Microsoft Azure to enable cross-platform device connectivity and data transfer.

Privacy and ethics: The advancement of San-IoT technologies has brought forth legitimate concerns regarding privacy, security, and ethics. The integration of intelligent systems in sanitation networks requires robust protocols and methods to safeguard against potential threats and ensure data protection. Establishing secure connections between smart assets is crucial to prevent unauthorised access and potential data leaks. External and internal threats such as security breaches, malicious attacks, privacy breaches, and weak authentication protocols should be avoided. The adoption of privacy-enhancing technologies, tools, and standards can further strengthen the protection of sensitive information. San-IoT solutions can strengthen their defences against potential risks by incorporating robust security policies and ensuring compliance with relevant laws and regulations governing data privacy.

Ethical considerations pertaining to data ownership and consent hold paramount significance. Ensuring that users and stakeholders possess a comprehensive understanding of the underlying functioning of the San-IoT technology, the nature of data being collected, and the decision-making processes derived from this data is critical. Transparent disclosure of these elements fosters accountability and engenders trust in the San-IoT systems. The integration of AI algorithms in San-IoT introduces noteworthy ethical challenges, particularly regarding bias and fairness. Diligent measures must be adopted to prevent biases in data collection, algorithm design, and the decision-making procedures to preclude any potential unfair outcomes. Rigorous data management throughout the system lifecycle, coupled with strategic measures to mitigate potential negative long-term impacts on individuals or communities, is essential in upholding ethical standards and safeguarding data integrity.

Scalability and deployment: As San-IoT evolves, more facilities, devices, data, and users are connected, making scaling up the intelligent sanitation system a challenge. As the number of connected smart assets grows, advanced San-IoT solutions must become more secure against data leakage and malicious attacks. Scaling systems must be interoperable to communicate and exchange data accurately. When the volume of data packets increases rapidly, scalable solutions must be able to avoid network congestion while maintaining a good user experience. To handle the massive amounts of data generated by sanitation facilities, scalable architectures necessitate large and secure data storage. Serverless computing, edge computing, containers, message queues, and automated scaling can be used to improve the scalability of San-IoT solutions.

When deploying smart sanitation facilities on a large scale, concerns about scalability, security, privacy, and cost arise. The sanitation network architecture must be capable of handling large amounts of data and accommodating future growth. Large sanitation networks must be designed to use fewer resources such as water, energy, memory, and computing. Before they can be deployed, sanitation systems must undergo extensive testing. Open-source solutions and cloud platforms are recommended to reduce installation and maintenance costs. Following system deployment, the entire sanitation network must be regularly monitored and optimised to identify potential problems and ensure stable and efficient operation.

2.8 Conclusions

This is a comprehensive review of the literature on intelligent sanitation from 2000 to 2022, with a focus on development history, system detection, health monitoring, artificial intelligence enhancement, sustainability, future opportunities and challenges. Using the PRISMA review criteria and process, the paper provided a detailed discussion of 141 papers from solution purpose, function, architecture, technology, device, service, application, and contribution. Based on an examination of the existing fragmented and immature literature, the paper introduced San-IoT, a generalised IoT concept for the sanitation industry. The paper provided an overview of advanced intelligent sanitation solutions, identified knowledge gaps, talked about limitations, and discussed future work.

San-IoT is a growing topic that connects various physical sanitation facilities to the internet and allows them to interact and communicate with one another. San-IoT is transforming how human interact with sanitation facilities. Smart assets monitor and detect systems and their surroundings, and use data analysis to make better decisions, automate processes, and increase operating efficiency. San-IoT benefits healthcare by utilising advanced sensors, more powerful computing, and dependable connectivity. Intelligent sanitation, which includes biosensor integration, excreta analysis, continuous infectious disease monitoring, and the elderly and disabled friendly, has the potential to improve medical outcomes, improve quality of life, saved time and money, increase patient engagement, and enhance remote care. San-IoT combined with AI improves automation, decreases manual workload, increases resource utilisation, improves personalised user experience, and reduces potential risks. San-IoT assists the sanitation industry tracking and monitoring resources more effectively, improve resource utilisation in a more responsible and sustainable manner, and reduce unnecessary waste to drive SDGs. Opportunities in smart assets, data storage, data processing, data analysis, and intelligent services are investigated, as well as challenges in coverage and communication, compatibility and interoperability, privacy and ethics, scalability and deployment.

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3 Chapter 3: Generalised Framework Design for Sustainable Intelligent Sanitation Networks: A Case Study of Next-Generation Reinvented Toilet System

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ABSTRACT

The chapter introduces a generalised framework for IoT-based sanitation networks to improve their connection, operation, and management. The framework includes a system architecture, high-level network topologies, communication protocols, data processing, and system deployment. In the framework, advanced IoT strategies, processes, and tools are proposed to efficiently collect, transmit, store, analyse and manage data. A case study of the Cranfield Circular Toilet is used to demonstrate the capability of the framework. The results show that the proposed framework can enhance transparency and visibility of toilet status while effectively sharing information among global stakeholders. In addition, data analytics tools integrated into the sanitation system can assist operators make efficient decisions, improve water usage efficiency, and reduce energy consumption.

Keyword: Industry 4.0; intelligent sanitation; Internet of Things; reinvented toilets; San-IoT; smart products and services; smart sanitation; sustainable sanitation.

3.1 Introduction

According to the World Health Organisation report, 2.2 billion people globally lack access to safely managed water, 4.2 billion people live without proper sanitation services, and 3 billion people do not have basic facilities installed in their households (World Health Organisation, 2020; World Health Organisation, 2022a; World Health Organisation, 2022b). The lack of access to safe water, sanitation, and hygiene (WASH) systems is a major cause of diarrhea, respiratory infections, and malnutrition, affecting more than one billion people in 149 tropical and subtropical countries. This results in an estimated 2.9 million cases of diseases and 95,000 deaths per year (World Health Organisation, 2019a). Ensuring access to adequate and safe sanitation (e.g., toilets, waste treatment, disposal, and safe re-use) can benefit millions of individuals' health and quality of life (World Health Organisation, 2022c). The Global Analysis and Assessment of Sanitation and Drinking-Water (GLAAS) reported that most countries have plans to improve sanitation services, which will better manage water resources and reduce disease transmission (World Health Organisation, 2017). Among them, 63 percent of countries have set targets for eliminating open defecation. However, approximately three-quarters of countries continue to practice open defecation. The level of safe sanitation implementation is insufficient, particularly in vulnerable and backward developing countries (World Health Organisation, 2019b). The United Nations Sustainable Development Goals (SDGs) set an ambitious vision of achieving universal access, eliminating open defecation for one billion people, and providing easier access to water and sanitation services for all (UNICEF, 2016). While much progress has been made in closing the sanitation inequity gap in WASH in recent years, achieving universal access will require innovative solutions, practical approaches, and scalable systems.

Over the past years, intellectual assets have emerged, and industries have gained easy access to innovative, practical, and cost-effective solutions through the Internet of Things (IoT) (Boyes et al., 2018; Anosike et al., 2021; Jimeno-Morenilla et al., 2021). However, the WASH sector is lagging due to the outdated design, skills shortage, high installation costs, and time-consuming reconstruction of traditional WASH systems (Kassab and Darabkh, 2020). Intelligent WASH becomes an emerging concept in which a large quantity of data can be collected, stored, and analysed to optimise system operations, improve decision making, save maintenance costs, reveal customer behaviour, and achieve sustainable benefits (Sethi and Sarangi, 2017). Intelligent sanitation facilities are in infancy period and are ill-equipped to keep up with modern technological advancements.

WASH systems based on IoT can monitor and control infrastructure, provide insight into services, reduce costs, and improve efficiency. Koo et al. (2015) presented a networked water system schematic that connects water sources to millions of consumers and collects large amounts of data from facilities to track breaks, resources, usage, and performance. Gourbesville et al. (2018) created a WASH information system for rapidly urbanising environment, combining waste collection, water allocation, and energy forecasting into a single framework. Dogo et al. (2019) introduced real-time monitoring systems for water supply network management, including water saving, asset management, and water quality predictions. Kotzé and Coetzee (2019) reviewed the design, development, and implementation of intelligent WASH systems to support policy development and shape advanced services. Salam (2020a) developed a water analysis system that simulates ecosystems, decreases waste, detects contaminants, and advises ecological standards for sustainable WASH development.

General intelligent WASH system research demonstrates how to connect the physical and digital worlds while providing significant societal and environmental benefits. Untreated human waste is a specific sanitation challenge that threatens human and environmental health. Intelligent sanitation has emerged to address issues such as a lack of essential services and open defecation by providing an understanding of system status and individual behaviour. Huang et al. (2012) developed an intelligent toilet capable of detecting physiological parametres and managing user health. Bae and Lee (2018) investigated sensor-based toilets to monitor individual health. Bhatia et al. (2020) developed intelligent toilet framework for home-based urinary health prediction. Park et al. (2020) proposed an intelligent toilet to measure excreta in a non-invasive and reliable manner for continuous health monitoring. Syafaah et al. (2020) created an intelligent toilet that can detect diabetes based on urine colour. Kumar et al. (2022) proposed an intelligent toilet for COVID-19 testing based on excreta analysis. Shaikh et al. (2019) created an intelligent toilet equipped with odour sensors, infrared sensors, acoustic sensors, and RFID readers to control system operation and monitor the environment. Cid et al. (2020) developed an intelligent toilet with self-diagnostic capabilities. Deshmukh et al. (2020) proposed a centralised public toilet monitoring system for underserved villages and slums. Bimantara et al. (2022) proposed an intelligent public toilet system for managing water and electricity consumption in densely populated areas. Each stakeholder can gain deeper insights from intelligent sanitation. Technicians make evidence-based decisions about the availability and maintenance of sanitation facilities (Salam, 2020b). Engineers collect and analyse operational data to predict impending failures, identify minor failure chains, and prevent major failures (Compare et al., 2019).

Intelligent sanitation systems are tracked, evaluated, and managed to improve operational efficiency, reduce environmental impact, and enhance decision-making. Existing intelligent sanitation systems, however, are inefficient due to a lack of a comprehensive and unified framework. Intelligent sanitation is still in its infancy, with little research, slow progress, and fragmented contributions.

The chapter makes the following contributions:

i. Designing a generalised San-IoT framework for sustainable intelligent sanitation;

ii. Developing strategies, processes, and tools for sanitation data processing;

iii. Applying the San-IoT framework to a case study of Cranfield with good performance;

iv. Using San-IoT intelligent sanitation to reduce water and energy consumption for a sustainable environment.

The remainder of the chapter is organised as follows: Section 3.2 introduces the generalised San-IoT framework for sustainable intelligent sanitation. Section 3.3 presents a case study of the Cranfield intelligent sanitation in the Reinventing the Toilet Challenge (RTTC) programme. Section 1.1 demonstrates the water and energy consumption reduction via the application of the proposed San-IoT framework. Finally, the conclusions and future work are provided in Section 3.5.

3.2 Generalised San-IoT Framework

A comprehensive literature review is conducted based on the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) (Liberati et al., 2009) to identify high impact research findings of intelligent sanitation framework (see Figure 3-1). The systematic literature search is conducted in databases and publishers, such as ACM, IEEE Xplore, PubMed, and Science Direct. The keywords *"sanitation" OR "toilet" AND ("intelligent" OR "smart" OR "IoT" OR "Internet of Things" OR "sensor")* are used in searches. After applying the PRISMA process, over 141 relevant articles are selected to study for a generalised IoT-based framework (San-IoT) design for intelligent sanitation networks.

An overview of the generalised San-IoT framework for intelligent sanitation networks is shown in Figure 3-2. The generalised San-IoT framework includes three layers, namely nodes layer, fog layer, and cloud layer at the architecture level (see Figure 3-2-top, and detailed in Section 3.2.1); and five layers, namely perception layer, data link layer, network layer, transport layer, and application layer at the IoT-stack model level (see Figure 3-2-middle, and detailed in Section 3.2.2). The San-IoT is able to remotely monitor and control the sanitation system, gain insight from sanitation data, sustain system operation through efficient process automation, reduce environmental impact, and efficiently manage sanitation assets and services.

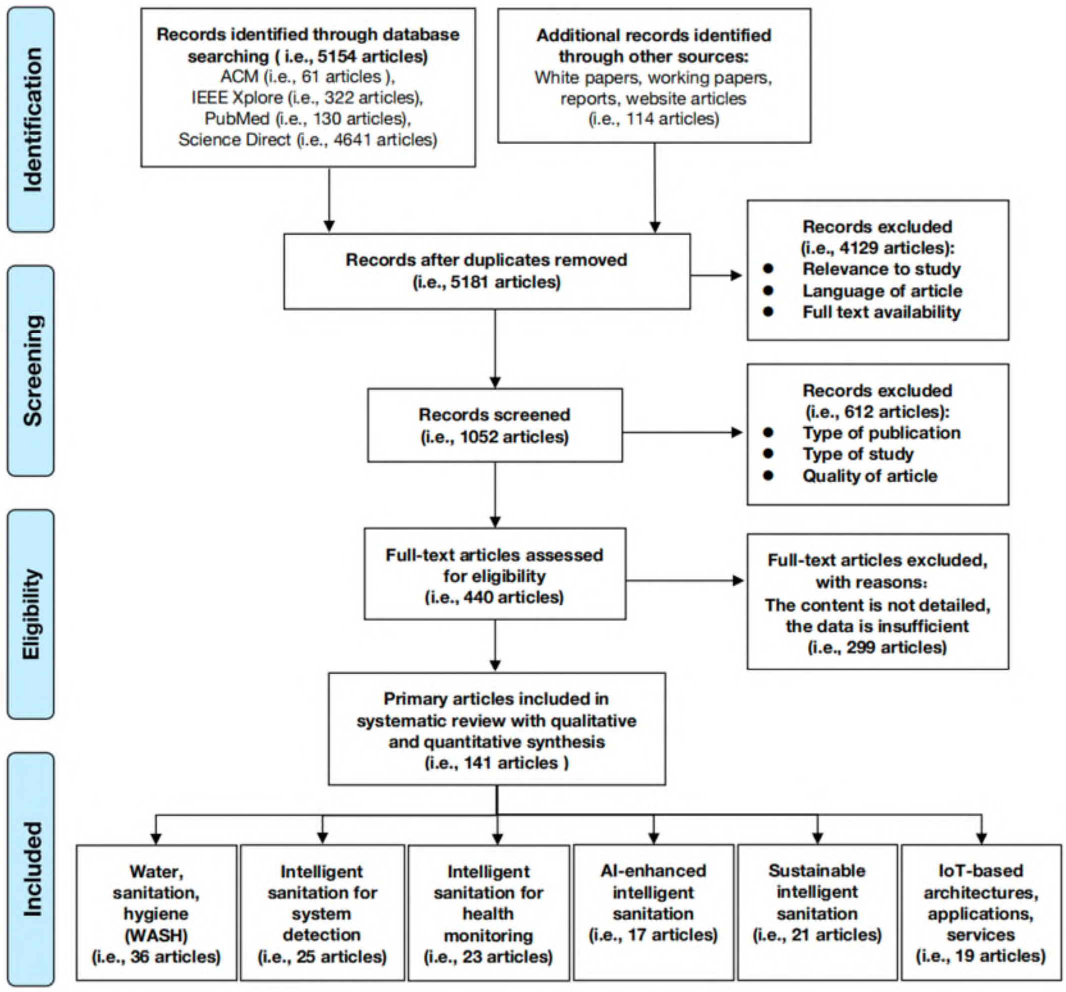

Figure 3-1 The PRISMA flowchart

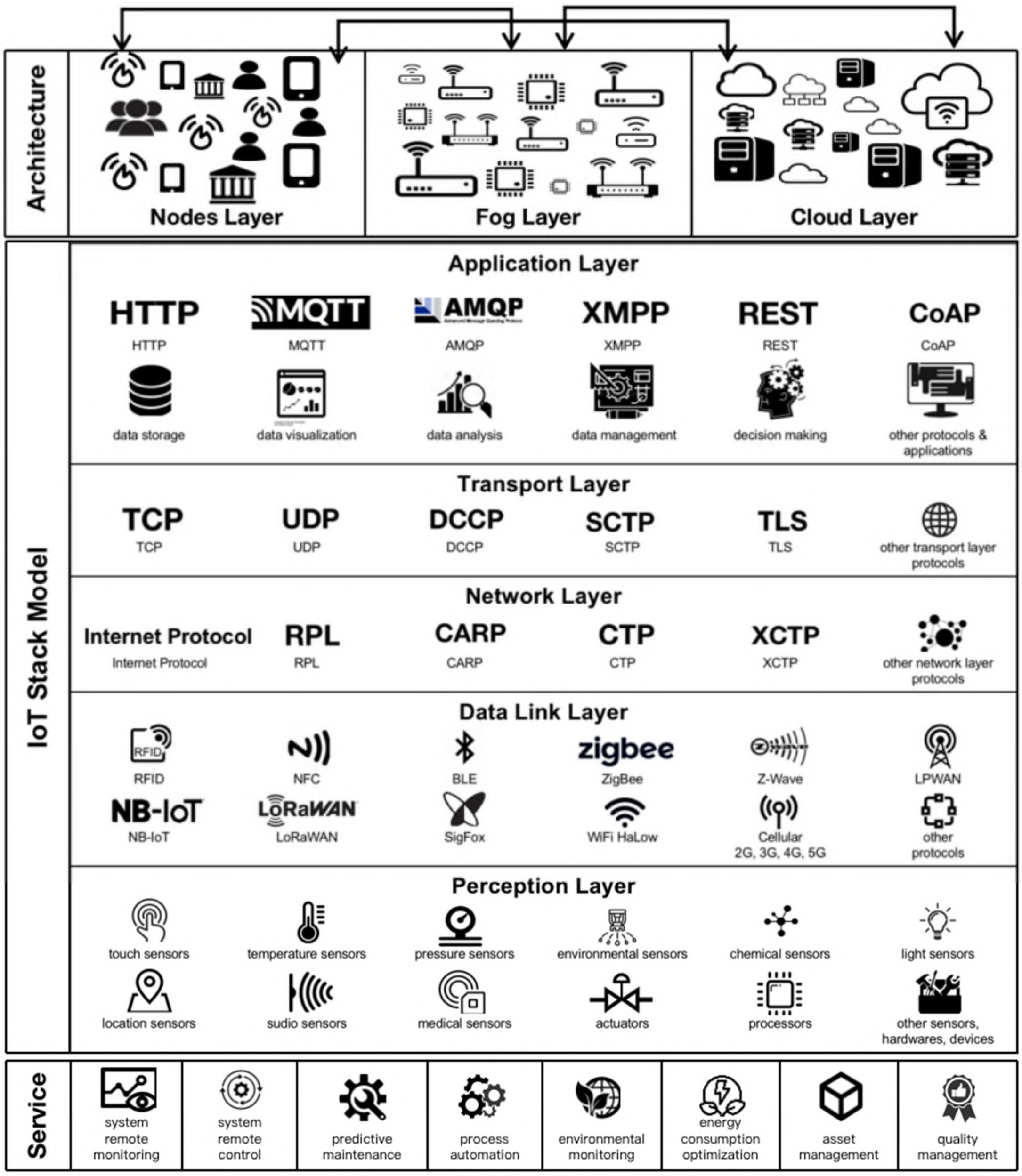

Figure 3-2 An overview of the generalised San-IoT framework

3.2.1 San-IoT Three-layer Architecture

Intelligent sanitation networks can connect millions of facilities and end-users, resulting in massive data processing and storage requirements, as well as interoperability, scalability, privacy, security, and latency challenges (Ahmed et al., 2017; Corallo et al., 2022; Teixeira et al., 2022). The traditional two-layer architecture (i.e., nodes and cloud) cannot address these issues.

Therefore, it is essential to develop a three-layer architecture including nodes, fog, and cloud layers that communicate and interact with one another (Kassab and Darabkh, 2020). In the novel architecture, the nodes layer contains all the sensors, devices, facilities, and entities of the sanitation industry. The data sensed by the node layer is directly transmitted to the fog layer, where all fog nodes are located. A fog node transmits data to another fog node or cloud layer either directly or after further pre-processing to reduce service delay. The cloud layer is made up of all distributed cloud servers and multiple processing units for storing, processing, and displaying large amounts of data.

3.2.1.1 Nodes Layer

Smart facilities and sensors, which can sense, monitor, control, and exchange data between applications, are critical functional blocks of IoT-based sanitation networks. Unlike other IoT domains, sanitation industry applications operate in a vastly distributed environment with more complex end-user placement, more diverse data collection sources, and numerous stakeholders involved. The nodes layer of intelligent sanitation network is designed to allow millions of smart objects from various manufacturers to securely join in the network and exchange sensed data without being exposed, while also including sensing, processing, storage, connection, communication, and management functions. At the node layer, each intelligent sanitation asset has a unique virtual identity, allowing them to connect and communicate with other physical entities and environments according to interoperable protocols and standards. The most distinguishable feature of the intelligent sanitation nodes layer is remote control without human intervention, which significantly improves operational efficiency and decision-making accuracy as compared to traditional methods of managing devices via physical buttons and switches.

3.2.1.2 Fog Layer

In the sanitation industry, smart facilities are geographically dispersed, with millions of objects expected to join in the network and devices often operating continuously. These characteristics make the industry generate massive amounts of new data to be processed and managed, requiring substantial computing resources and energy. Furthermore, IoT-based sanitation networks have low tolerance for delays, demand high levels of data accuracy, and are extremely eager to reduce the cost of data transfer to the cloud. However, these capabilities are not achievable with the traditional two-layer architecture (i.e., nodes and cloud). The proposed three-layer architecture (including nodes, fog, and cloud) can provide low-latency, fast-response, controllable-cost, and easily scalable services. In the architecture, the fog layer is a bridge between physical entities and cloud servers. It extends storage and computing services to the edge of the node layer to process large volumes of sensory data in real-time, rather than relying on the most expensive cloud computing services.

Outdoor scenarios are common in the sanitation industry, where cloud network connectivity is poor. It is critical to deploy fog nodes in a distributed fashion. Fog nodes provide mobility support and communicate directly with smart entities while maintaining good performance. As intelligent sanitation applications grow, and the number of end-users increase, the scaling of fog nodes is easier to achieve than cloud services. The three-layer architecture only transmits necessary pre-processing data to the cloud layer for subsequent processing instead of sending all the messy data. This architecture dramatically reduces unnecessary resources, time, and energy consumed by long-distance transmission while providing a good balance of performance and cost. The composition of the fog layer is as follows (Aazam et al., 2014):

- Monitoring layer: To monitor activities, resources, responses, services, and status of smart nodes, objects, devices, and networks.

- Pre-processing layer: To analyse and manage a large amount of disorganised data, and extract data that needs to be transmitted to the cloud for further processing.

- Temporary storage layer: To temporarily store data from the pre-processing layer.

- Security layer: To encrypt or decrypt user data during data transmission procedure to ensure security and privacy.

3.2.1.3 Cloud Layer

The third layer of the three-layer architecture, namely cloud layer, consists of all distributed cloud servers with colossal storage, computing, and communication capacity. As compared with the fog layer, the cloud layer has unparalleled advantages in storing, processing, and analysing the big data generated by smart objects. A few cloud nodes can quickly achieve results but require many fog nodes to work concurrently. There will be billions of intelligent IoT facilities, devices, and sensors; millions of fog nodes and gateways; and thousands of cloud servers, data centres, and storage stations in the sanitation industry. As the closest layer to the end-user in the San-IoT architecture, the cloud layer can provide efficient, seamless, and dependable services. This layer can directly receive a large amount of cluttered data from intelligent entities or partially processed information from the fog layer and analyse the data through embedded algorithms to make insightful decisions. At the same time, the cloud layer provides users with interactive visualisation applications to monitor and control the physical environment. Through the cloud layer, the system enables ubiquitous access, promotes the growth of IoT-based sanitation applications, and improves the utilisation of scarce resources. The composition of the cloud layer is as follows (Sethi and Sarangi, 2017):

- Base layer: To manage the identities, personalities, parametres, functions, and states of all smart entities.

- Component layer: To control the interaction and communication of all smart entities to perform intelligent services.

- Application layer: To provide interfaces and services for end-users to interact with the physical world.

3.2.2 San-IoT Five-layer IoT Stack Model

The section outlines a five-layer IoT stack model in the above-mentioned three-layer architecture, which is capable of collecting, processing, and analysing data for sanitation applications. Although researchers have proposed several different IoT solutions in the sanitation industry, no unified structure has been reached yet (Huang et al., 2012; Bae and Lee, 2018; Bhatia et al., 2020; Park et al., 2020; Syafaah et al., 2020; Bimantara et al., 2022; Kumar et al., 2022). The chapter proposes a general five-layer IoT stack model for intelligent sanitation networks based on the Open Systems Interconnection (OSI) model (Aschenbrenner, 1986). The San-IoT five-layer model includes:

- Perception layer: To utilise embedded intelligence to sense the properties of surrounding physical entities and convert sensed data into transmissible digital signals to enhance the awareness of smart object perception.

- Data link layer: To serve the network layer through different standard technologies and communication protocols (e.g., Bluetooth, Zigbee, Cellular).

- Network layer: Data is filtered, transmitted, and managed in packets through logical connections. The layer includes all network devices that exchange data via routing and communication protocols (e.g., 3G, 4G, 5G, Wi-Fi).

- Transport layer: To bidirectionally transmit and receive messages between the network layer and application layer to ensure orderliness, integrity, and reliability of data (e.g., TCP, UDP, SCTP).

- Application layer: To process and analyse the received data, provide users and developers with interfaces, platforms, and visualisation tools to apply IoT-based intelligent sanitation, and support insightful decision-making.

3.2.2.1 Perception Layer

In the San-IoT five-layer IoT stack model, the perception layer is most critical. A large number of distributed sensors are installed in sanitation facilities to monitor and control the physical environment and communicate with each other. The sanitation industry has developed slower than other industries due to the complexity of legacy systems, the dispersed distribution of end-users, the inconvenient installation of sensors, and the lack of uniformity in industry standards over the past decades. With the widespread successful adoption of IoT in other industries, an increasing number of stakeholders are eager to create intelligent sanitation networks to revolutionize and reinvent the traditional sanitation industry. However, without uniform standards, the sanitation industry is unable to mass-produce and install cheap and efficient sensors. Non-standard sensors clutter the data collection and analysis process, resulting in the collection of tens of thousands of noisy and useless data, slowing down the progress of intelligent sanitation. Smaller, more affordable, efficient, and sustainable sensors need to be deployed to sense and control the sanitation environment, which help drive the implementation and expansion of the system. As shown in Table 3-1, some typical sensors that comprise the perception layer of an intelligent sanitation system are listed (Chettri and Bera, 2019).

Table 3-1 Perception layer sensors

Sensors	Description	Merits	Demerits	Examples
Touch	Detect and record physical	Small, simple, fast	Easy to wear and	Buttons, switches, capacitive

Sensors	touches manually triggered by the user, replacing older mechanical switches.	response, low cost, low energy consumption.	tear, require close interaction.	sensors, resistive sensors.
Temperature Sensors	Measure the degree of hotness or coolness and converts it into a readable signal.	Cheap, easy to use and install.	Poor environmental adaptability.	Thermocouples, resistance temperature detectors, contact and non-contact temperature sensors.
Pressure Sensors	Measure the pressure, altitude, or water level of a gas or liquid. The technology, design, performance, applicability, and cost of pressure sensors vary widely due to different application fields.	Tiny, cheap, high durability, convenient construct.	Non-linear, insensitive, high-energy consumption, unstable signal.	Absolute, gauge, vacuum, differential, sealed pressure sensor.
Environmental Sensors	Detect and evaluate the surrounding environment.	Pollution prediction and timely response.	Low throughput, insufficient precision.	Gas, temperature, humidity, air, soil, and water detection.

Chemical Sensors	Convert physical and chemical properties, such as concentration, pressure, and particle activity, into measurable digital signals.	Small, cheap, multiple functions, linear output, low energy consumption, high resolution, accurate and repeatable.	Narrow detection range, short life, sensitivity to the environment.	Oxygen, carbon monoxide, hydrogen sulfide, toxic gases and electrochemical gas sensor.
Light Sensors	Detect the density, intensity, type, colour temperature, and reflection of light.	Non-contact detection, easy adjustment, low cost, low energy consumption, fast response, wide detection range.	Low sensitivity, poor environmental adaptability.	Infrared radiation sensors, photodiodes, photoresistance.
Location Sensors	Collect the location of the device or end user and provide 24/7 global positioning services.	Any time, any place, high precision, automation, simple operation, good anti-interference, strong confidentiality.	Deviations due to climate and ionosphere, good outdoor performance, limited indoor accuracy.	GPS, GSM.

Audio Sensors	Capture and convert sounds like noise, music, speech into digital signals.	Informative, versatile, high resolution, used in dark, not limited by temperature and humidity, high precision.	High cost, strict environmental requirements.	Microphone, ultrasonic, noise metre, water depth detection.
Medical Sensors	Provide fast, high-quality, low-cost diagnosis, remotely monitor user health, and support physicians in making informed decisions.	Early diagnosis, remote monitoring, personalized information, increased productivity.	High cost, high energy consumption, security issues.	Blood glucose, body temperature.

3.2.2.2 Data Link Layer

The data link layer is the physical layer of software closest to the hardware. This layer transmits data between network entities in a wide area network (WAN) or nodes on the same local area network (LAN) segment. Messages are filtered by the Logical Link Control Layer (LLC), and data is initially processed (i.e., data encapsulation, frame encoding, error detection and correction) by the Media Access Control (MAC) layer. The most widely used data link layer protocols in IoT-based sanitation applications are shown in Table 3-2 (Kassab and Darabkh, 2020).

Table 3-2 Data link layer protocols

Protocols	Description	Merits	Demerits	Transmission Range
Radio Frequency Identification (RFID)	Non-contact automatic identification, acquire data through radio frequency signals, and store the information in tags attached to identifiable physical objects.	Small, fast, multiple, strong anti-interference, stable, and safe.	Power supply required, long life, short distance specific reader required.	(1–10) cm Sub-GHz (1–30) m
Near-Field	Short-distance communication between	Inexpensive, low	Limited transmission	10 cm

Communication (NFC)	compatible devices. When devices are incredibly close to each other, data can be transferred in a extremely short time.	energy consumption, fast connection establishment, suitable for complex and crowded areas.	distance, low transmission rate, security concerns.	
IPv6 Low-Power Wireless Personal Area Network (6LoWPAN)	6LoWPAN is designed to enable the smallest devices to use Internet Protocol, acting as a bridge between IEEE 802.15.4 and IPv6, using lightweight IP-based communications over low data rate networks. Send and receive IPv6 packets on IEEE 802.15.4 based networks through encapsulation and header compression mechanisms. Provide automation applications for small objects and build micro-mesh networks between smart devices using an IPv6 backbone before sending data.	Commonly used in home and factory environments where device size is limited.	Information transmission capacity is limited to a transfer rate of 250 kbps.	(10–100) m
Bluetooth Low	A peer-to-peer technology driving a new era	Simple, real-time,	Short distance,	up to 100 m

Energy (BLE)	of connectivity between smart objects and smartphones, controlling short-range communication between devices, and enabling fast transmission of data packets.	low power consumption, reliable, compatible.	limited coverage, poor environmental adaptability.	
Zigbee	An extension of the IEEE 802.15.4 protocol, widely used in small or home projects, providing a scalable and flexible mesh structure that can support thousands of nodes. All nodes act as repeaters, passing data through a mesh network of intermediary devices that transmit data over long distances. The latest Zigbee 3.0 protocol is designed for data communication in noisy RF environments, ensuring point-to-multipoint structures and interoperability of up to 65,000 nodes per network.	Simple, scalable, low cost, low power, flexible, low latency, low duty cycle, long battery life.	Short distance, low transmission rate, vulnerable to security threats, channel noise, poor compatibility.	(10–100) m Sub-GHz up to 1 km
Z-Wave	A protocol designed for smart home applications, providing low-latency, small-	Easy implementation, low	Limited number of nodes, tree topology,	30 m

	packet, high-speed, and reliable communication to control up to 232 smart objects.	interference, mesh networking, interoperability.	security issues, closed systems.	
Low Power Wide-Area-Networks (LPWAN)	Low-power, low-bandwidth, and low-cost long-distance transmission protocols for industrial and civil IoT applications.	Low power consumption, network management, secure communication.	Low data rates, high latency between end-to-end nodes.	(1-50) km
Narrowband Internet of Things (NB-IoT)	A novel narrowband protocol based on Long Term Evolution (LTE) for complex IoT applications requiring more frequent communications, indoor coverage, low cost, long battery life, and high connection density.	Low power consumption, power saving mode, efficient spectrum usage, good indoor coverage	Low data speeds, need for global deployment, no redundant coverage, lack of switching support.	1 km (urban) 10 km (rural)
Long Range Wide-Area-Networks (LoRaWAN)	A secure wireless media protocol for remote equipment monitoring, water, and wastewater management, using a centralized gateway to communicate with	Global availability, wide coverage, low power consumption and simple	Low data rates, limited network size, not suitable for real-time applications.	(2–5) km (urban) 15 km (rural)

	internet-connected applications.	architecture.		
SigFox	A narrowband or ultra-narrowband protocol for power-constrained devices. Meager power consumption, up to 10 years of typical battery operation, ease of use, small messages, and interoperability.	Efficient handling of smaller messages, less energy, wide coverage, higher budget links.	Duty cycle limitation, strong interference with nearby existing broadband systems, low data rates.	(3–10) km (urban) (30–50) km (rural)
Low Power Wi-Fi (Wi-Fi HaLow)	The next-generation Wi-Fi protocol provides longer battery life and a more extended Wi-Fi network than standard Wi-Fi networks operating in the 2.4 GHz and 5 GHz bands.	Mobility friendly, convenience, free facilities.	Security issues, limited signal strength.	1 km
Cellular Communication Protocols	Protocols that provide long-range IoT services, such as 3G, 4G, and 5G. 5G is the latest cellular communication protocol that provides high-precision positioning, low-latency, and ultra-reliable communications to support the enormous growth of devices connected to the Internet.	Easy to maintain, easy to upgrade equipment, immediate connection.	Security issues, high infrastructure costs, sensitive to weather, and interference from other wireless devices.	1G: (2–20) km 2G: (35–200) km 3G: 10 km/h *t 4G: 500 km/h *t

3.2.2.3 Network Layer

The network layer of the IoT stack model consists of two sub-layers, namely the routing layer and the encapsulation layer. The network layer supports the communication between devices and routers, forms and transmits data packets, and covers the entire communication network of intelligent sanitation networks. Some network layer protocols are shown in Table 3-3 (Kassab and Darabkh, 2020).

Table 3-3 Network layer protocols

Protocols	Description	Merits	Demerits	Recent Enhancements
Internet Protocol (IP)	IP is open, lightweight, stable, and scalable. IP supports a wide range of applications in many different contexts around the world and provides for all IoT devices to communicate with each other.	Adaptability, simplicity, and operability.	Delivery timescales and reliability of packets are not guaranteed, and packets may be lost, duplicated, delayed or out of order during	Internet Protocol version 6 (IPv6) is the latest version of the IP, with a larger addressing space and improvements in device mobility, security, and configuration.

			transmission.	
Routing Protocol for Low-Power and Lossy Network (RPL)	A low-level routing protocol based on the 6LoWPAN standard, running on IEEE 802.15.4, for integrated wireless sensor networks. RPL is mainly used in unstable, low data rate, low energy consumption, and high data loss rate applications. RPL supports many-to-one, one-to-one message transfer, efficiently creates network routes, and quickly adjusts topology.	Advantageous in resource-limited environments and reduces memory consumption by switching between different storage modes.	High packet loss, high congestion, high latency, security issues.	The Cognitive Routing Protocol for Low-Power and Lossy Network (CORPL) is an extension to RPL, designed for cognitive networks. Each node keeps and updates information, and forwards packets between nodes using opportunistic.
Channel-Aware Routing Protocol (CARP)	A distributed routing protocol designed for underwater IoT applications. CARP transmits lightweight data packets and selects the message forwarding direction based on past link quality. Field tests have	Energy saving, high connection quality, buffer space.	Security issues, non-reusable data, high communication costs.	The data backtracking function is limited in CARP, which is not suitable for applications with frequent data

	been carried out in the Norwegian fjord and the Mediterranean Sea, and the performance is good.			modification. To solve this issue, the E-CARP is proposed, which can save previously received sensor data by upgrading the CARP.
Collection Tree Protocol (CTP)	A tree-based routing protocol transmits data from one / more sensors to one / more root nodes. It is specially designed for low-energy sensor networks to provide agile, efficient, and reliable data transfer. Use agile and accurate link quality estimation, data path verification, and adaptive beaconing mechanisms to overcome challenges faced by distance vector routing protocols in highly dynamic wireless networks. It has been tested on various platforms, hardware, and link layers.	Lightweight packets, high data transfer rates, and low energy consumption.	High energy and bandwidth consumption, unreliable data transmission.	The Extended Collection Tree Protocol (XCTP) is proposed as an extension to CTP, allowing bidirectional communication.

3.2.2.4 Transport Layer

The transport layer of the IoT stack model provides host-to-host communication services for intelligent sanitation applications. An end-to-end data transmission bridge is established between the network layer and the application layer, segmenting data streams, alleviating congestion, and providing reliability, flow control, and multiplexing services. The main transport layer protocols are shown in Table 3-4 (Kassab and Darabkh, 2020).

Table 3-4 Transport layer protocols

Protocols	Description	Merits	Demerits
Transmission Control Protocol (TCP)	One of the leading IoT protocols that provide reliable messaging between different devices. TCP ensures that data is not corrupted, lost, duplicated, or delivered abnormally. The original message is broken into small packets and forwarded to the IP layer rather than all at once. Packets are sent from different routes to their destination and then acknowledged, making data transfer accurate, efficient, and simple.	Support for most IoT applications, high performance, high quality, and high robustness.	Strictly sequential requirements, not real-time.
User Datagram	UDP provides an unreliable minimal message queue, unlike TCP.	High transmission	Unreliable, low

Protocol (UDP)	Since no end-to-end connection is established between communicating entities, it is mainly used for low-latency, efficient, real-time sanitation applications. However, the transmitted data is unsorted, replicated, unreliable, and losable. The latest Quick UDP Internet Connections (QUIC) protocol extends the UDP, establishes multiple connections through UDP, and provides general, secure, and multiplexing capabilities.	rates, mostly for real-time communication applications.	accuracy, high packet loss rate.
Datagram Congestion Control Protocol (DCCP)	A minimal transport layer protocol. DCCP provides an unreliable and dynamic unicast bidirectional connection, significantly reducing the overhead of packet header and end node processing. It is suitable for sanitation applications that need to transmit a large amount of data in a short time, where old messages quickly become useless, and new messages are rapidly iterated.	Low latency, congestion control and switching between multiple modes.	Unreliable and lacking receiving windows.
Stream Control Transmission Protocol (SCTP)	Inheriting most of the features of TCP, unlike byte-oriented TCP, SCTP is message-oriented. SCTP provides security features not available in TCP and UDP, with consistency, accessibility, and compatibility.	Flexible, reliable, and secure messaging.	Dynamic IP addressing issues, and network address translation issues.

Transport Layer Security (TLS)	TLS provides security for communicating entities against eavesdropping and tampering with messages, thus guaranteeing data confidentiality and integrity. The latest TLS v1.3 improves the original TLS protocol and uses a new, more robust encryption algorithm. Datagram Transport Layer Security (DTLS) extends the TLS protocol to provide security services for disordered and unreliable data.	Security against tampering and attackers.	Delayed, resource consuming and complex to configure.

3.2.2.5 Application Layer

The application layer is the highest layer in the San-IoT five-layer IoT stack model. It is the interface between the end-user and the network, providing users with specific services, such as water quality testing and remote monitoring of smart objects. According to the requirements of different applications on data delay, reliability, bandwidth, and compatibility, the most used protocols are listed in

Table 3-5 (Kassab and Darabkh, 2020). The application layer provides intelligent services for different scenarios. In intelligent sanitation, tremendous smart objects generate massive amounts of data characterized by volume, variety, and velocity, i.e., big data (Laney, 2001; Ray, 2018). The application layer of intelligent sanitation provides stakeholders insights to support better decision-making, improved services, optimised management, and future forecasting with big data. The big data-powered application layer supports the dynamic integration, processing, and analysis of sanitation networks, such as customer service, maintenance, repair, and overhaul (MRO), and remanufacturing (Zhang et al., 2017). The big data processing for intelligent sanitation includes the following four steps:

- Data acquisition and integration: To use standardised modes to capture diverse heterogeneous data throughout the lifecycle of intelligent sanitation products.
- Data processing and storage: To process and store large volumes of structured, semi-structured, and unstructured data to support further analysis of raw data.
- Data mining and knowledge discovery: To apply data analysis, data mining, and knowledge management methods to derive valuable information from intelligent sanitation products. The methods include clustering, prediction, regression, classification, and association analysis models.

- Application services: Various services are provided for different sanitation product lifecycle stages, such as system remote monitoring and control, predictive maintenance, process automation, environmental monitoring, energy optimisation, asset management, and quality management.

Table 3-5 Application layer protocols

Protocols	Description	Merits	Demerits
HyperText Transfer Protocol (HTTP)	Support a wide range of IoT services and establish connection-oriented communication between the server and the client. HTTP supports request/response RESTful functions, primarily used for IoT applications with high network resource consumption.	Persistent connection, high interpretability.	High energy, resource, and bandwidth consumption.
Message Queue Telemetry Transport (MQTT)	A lightweight protocol for exchanging messages between IoT devices and the network through publish and subscribe operations. MQTT provides unreliable connections with limited bandwidth and is suitable for smart objects with limited resources. The latest version is MQTT v5.0.	Simple, lightweight, and low bandwidth.	Security issues, no encryption.
Advanced Message Queuing Protocol (AMQP)	Support publish/subscribe architecture, like MQTT, has higher reliability and security, and is widely commercialized.	Scalable, supporting heterogeneous devices.	Not real time, high resource consumption.

Extensible Messaging and Presence Protocol (XMPP)	Pass messages between heterogeneous applications based on readable XML. XMPP is mainly used for IoT applications with low latency and small messages.	Decentralized, flexible, open standards.	No QoS support, high network overhead.
Representational State Transfer Protocol (REST)	Commonly used in machine-to-machine and machine-to-human IoT applications, compatible with XML and JSON. REST is lightweight, simple, extensible, and modifiable.	Scalability, ease of implementation, independence.	Security issues, no support for distributed environments.
Constrained Application Protocol (CoAP)	Support multicast and unicast requests based on a publish/subscribe model. CoAP is suitable for IoT applications with small data packets and limited resources.	Simple, reliable, and low overhead.	Less secure.
Data Distribution Service (DDS)	A P2P decentralized protocol based on the publish/subscribe model, with robust and efficient data transmission, is one of the critical solutions for IoT applications.	Real-time, durability, safety, operability.	High resource and bandwidth consumption.

3.2.3 Middleware

With over 21 billion IoT devices expected by 2025, the data accumulated by intelligent objects will be better collected, analysed, and managed. However, the sheer volume of smart devices and data will also pose a huge challenge to the industry. Common standards in the sanitation industry are difficult to universalise, as early proposals for different competitors' products often follow different protocols. A large number of incompatible commercial products have led to the development of middleware software to facilitate communication between smart objects. Middleware, which acts as a bridge between end applications and smart devices, hides complex technologies and provides simple development interfaces for engineers. Typical middleware solutions are summarised in Table 3-6.

Table 3-6 Middleware solutions

Solutions	Description	Examples
Service-based Solution	A heavyweight solution, not suitable for resource-constrained devices, establishes the communication between the cloud layer and the perception layer, consisting of the physical layer, the virtualized layer, and the application layer.	LinkSmart, Kaa, GSN, ThingSpeak IoT, Aura

Cloud-based Solution	Provides a simple and efficient way to connect smart objects. However, due to the limitation of cloud computing resources, the number and types of connected devices allowed by the platform are limited.	AWS IoT, Azure IoT Hub, IBM Watson IoT, Google Cloud IoT, Xively, Oracle IoT
Actor-based Solution	Lightweight solutions, mainly implemented at the edge of IoT networks.	Calvin, Node-RED, Ptolemy Accessor Host
Event-based Solution	Solutions are based on the publisher-subscribe paradigm, hiding the complexity of distributed applications, and providing developers with an easy-to-use interface.	Hermes, Gryphon, Rebeca, FiWare

3.3 A Case Study of the Cranfield Reinvented Toilet System

The section presents a case study of the Cranfield reinvented toilet system (i.e., Cranfield Circular Toilet) in the Reinventing the Toilet Challenge (RTTC) programme, which is initiated by Bill & Melinda Gates Foundation. The case study demonstrates the applicability of the proposed generalised San-IoT framework for intelligent sanitation in practice.

Traditional sanitation system costs developing countries nearly US$260 billion in economic losses and millions of avoidable deaths each year (World Health Organisation, 2021). With the pressures of urbanisation, socioeconomic inequalities, and water scarcity, providing safe, affordable sanitation has become increasingly complex. Improving traditional in-house piped water systems and sewer connections requires an annual investment of US$136.5 billion but does not ensure reliable and sustainable wastewater treatment (World Health Organisation, 2015). Therefore, solutions based on upgrading traditional sanitation facilities are impractical. In response to the global WASH challenge, the RTTC programme is launched to address the failure of traditional, expensive, and most inaccessible sanitation systems (Kone, 2012). Reinvented toilets are designed for sustainable sanitation and generating energy, reusable water, and other nutrients rather than polluting the environment. The RTTC reinvented toilet is self-contained, unlike capital-intensive and large-scale water treatment assets, making it easily adoptable by the world's poorest urban environments (Elledge and McClatchey, 2013; Demasure, 2017). Cranfield University proposed a novel sewer less nanomembrane toilet solution, namely, Cranfield Circular Toilet. The Cranfield Circular Toilet has been proposed to avoid waste and contaminated water, dispose of waste safely on-site, and keep users from defecating in the open. The system converts waste into clean water and ash without the need for sewer connections, and it is able to make the facilities accessible to the poorest people for as little as US$0.05 per user per day (Kone, 2012). The proposed system is more efficient, less expensive, and widely used in low-income households, particularly in dense urban areas (Tierney, 2017; Parker, 2014).

As the user base expands, the Cranfield Circular Toilet project will include more stakeholder involvement, cross-sectoral and cross-border collaboration, and more complex application scenarios. There is an increasing need to combine advanced technologies to link, manage, and monitor sanitation systems (Sethi and Sarangi, 2017). An analytical sensor kit is proposed as part of the Cranfield Circular Toilet solution for developing advanced, safe, independent, and manageable intelligent sanitation networks. Using the cutting-edge technologies, the analytical sensor kit can support universal sanitation continuity and foster frequent feedback among stakeholders.

The first generation of analytical sensor kit (ASK-GEN1) is a low-cost end-to-end monitoring and control IoT system. The ASK-GEN1 that was field-deployed and tested collaborating with global research partners produced excellent results (Mead et al., 2022). Sensors are integrated into the system to capture operational and environmental field test data in real-time to create a digitally enabled environment. The implementation of ASK-GEN1 can furnish data for system control and gain insights into the environment. However, its focus on environmental data, like pH and temperature, limited its analysis of machines and users, resulting in raw data capture with few intelligent data analysis capabilities to uncover concealed insights within the system. Thus, a second generation, the analytical sensor kit (ASK-GEN2), is proposed.

By utilising the San-IoT framework, the ASK-GEN2 improves and innovates over the first generation. Sensors mounted on various components collect real-time data on the operational status and user behaviour of the toilets. The data is then sent to a cloud platform for visualisation and analysis via microcontrollers and communication networks. The most recent data analytics approaches are used to monitor, control, and predict system and user performance. The framework of the ASK-GEN2 is as follows.

- System sensing: The perception layer of the generalised San-IoT intelligent sanitation system. It converts analogy signals from sensors, actuators, machines, devices, and smart objects into digital signals. Various sensors are installed in the ASK-GEN2 to monitor and control toilet performance. These sensors are all controlled by a microcontroller, which is programmed to transmit the digital signals to the cloud and change the operating mode of toilet components interactively.

- Communication connection: The data link layer, network layer, transport layer of the generalised San-IoT intelligent sanitation system, and the communication protocols in the application layer. It facilitates data transmission by establishing communication between devices, networks, and cloud services. The ASK-GEN2 chooses the most suitable communication protocols for each application scenario.

- Application service: The application layer of the generalised San-IoT intelligent sanitation system. The raw data captured by the ASK-GEN2 is accumulated, stored, and processed, including data acquisition, data cleaning, data abstraction, data analysis, and data modelling. The ASK-GEN2 also offers diverse applications such as smart toilet monitoring and control, mobile applications for user interaction, data visualisation, intelligent services, and AI-powered solutions.

Figure 3-3 depicts an overview of the ASK-GEN2 framework based on the San-IoT solution, Cranfield Circular Toilet experimental models, lab testing, and field testing.

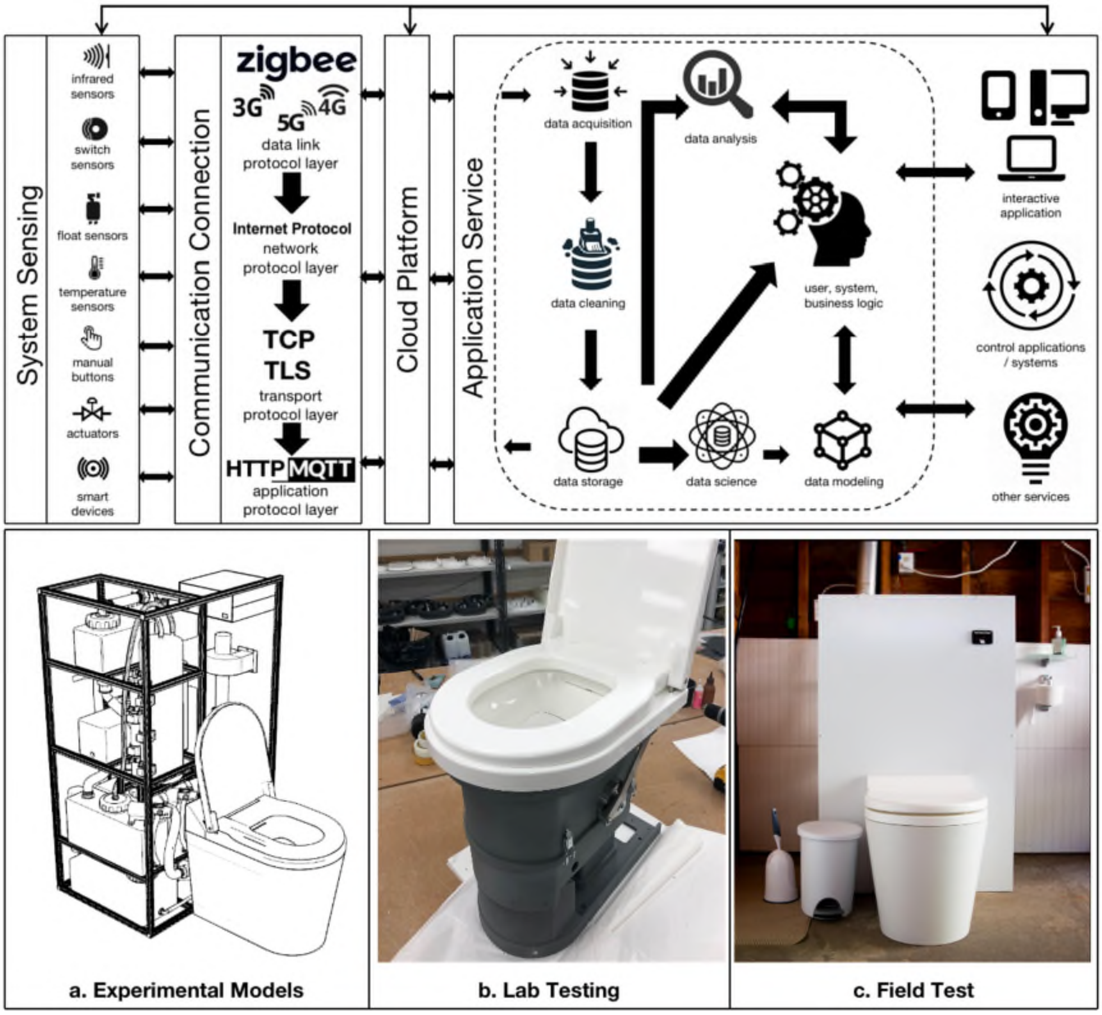

Figure 3-3 An overview of the ASK-GEN2.

3.3.1 System Sensing

The perception layer of the ASK-GEN2 hosts all smart objects and end devices, establishing communication between the physical and digital worlds. Smart objects in the intelligent sanitation systems include sensors, actuators, machines, and devices. When designing, developing, and deploying the ASK-GEN2 perception layer, all smart objects installed meet the requirements for measurement, connectivity, performance, scalability, and security. The ASK-GEN2 uses smart objects that are simple, easy to use, versatile and open-design. The intelligent device is autonomous, and the data collected is accurate and in real-time. The system converts captured analogy data into digital signals by simple operation with detailed data reporting. Sensors are easily and quickly connected to electronic prototyping platforms, such as Arduino, in a wired or wireless manner.

As compared to other industries, the application of intelligent sanitation is more environmentally adapted. The ASK-GEN2 uses stable, durable, low-maintenance, and flexible communication objects. These smart objects can be installed in large-scale public environments with unstable network signals and high interference, as well as in cramped domestic environments with limited facility space, weak network signals, and short-distance transmission. Because of the unique and complex deployment environment, the ASK-GEN2 devices are distinguished by high water resistance, strong robustness, low energy consumption, stable signal, high reliability, and ease of maintenance.

The numerous stakeholders and widely dispersed users of the Cranfield Circular Toilet project necessitate the ability to expand and handle many devices. Most of the devices in the ASK-GEN2 are inexpensive and simple to replicate on the production line. The installed sensors support small and large-scale deployments and can be connected to cloud platforms with middleware support to reduce the complexity of system development and maintenance.

Each toilet system stores a unique identity to efficiently monitor and control the sanitation network. The QR code identifies different toilets, enables physical sanitation facilities to be registered on a digital platform, and ensures a quick response to operations with identification, add, delete, and access functions. With these requirements, various sensors and actuators, such as temperature sensors, float sensors, infrared sensors, and mechanical sensors, are mounted on the Cranfield Circular Toilet in the ASK-GEN2 (see Figure 3-4).

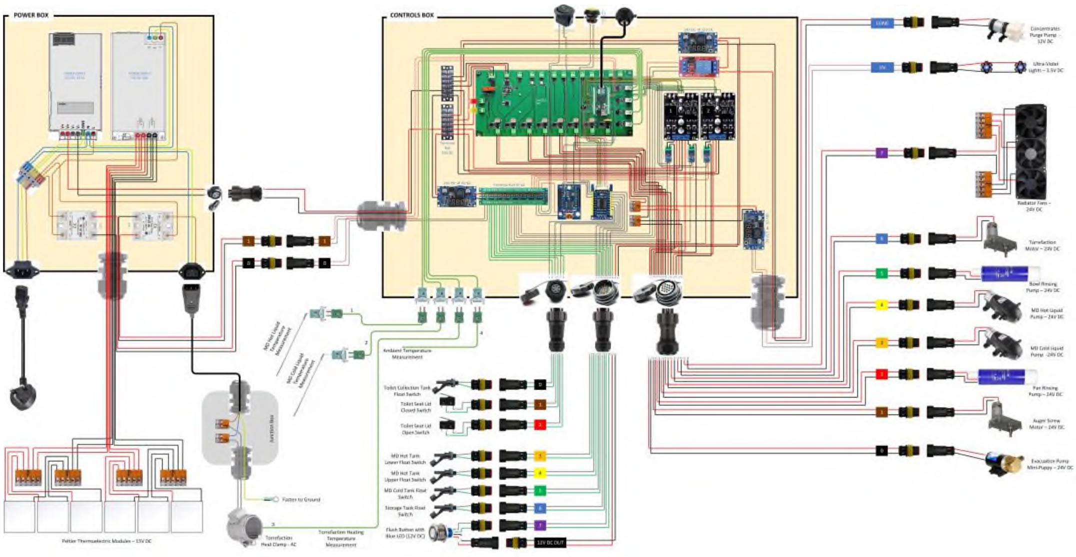

Figure 3-4 An overview of the smart objects

3.3.2 Communication Connection

The communication connection established at the data link layer, network layer and transport layer are the bridge between system sensing and application services, transmitting and receiving data for the ASK-GEN2. There is a significant infrastructure development gap between low-industrialised developing countries and high-industrialised developed countries, ensuring global communication connections for intelligent toilet is critical. Lack of connectivity may prevent toilets from taking root in developing and emerging countries, such as Africa, India, and rural China, which are among the biggest beneficiaries of intelligent sanitation but lack adequate communication facilities.

With the explosion of digitalisation and the construction of IT infrastructure around the world, the International Telecommunication Union (ITU) estimates that global internet coverage will reach 100% between 2025 and 2040, allowing for technological leapfrogging (Biggs, 2018). The Cranfield Circular Toilet is dedicated to providing safe, dependable, and efficient intelligent sanitation all over the world.

The ASK-GEN2 network structure is created with scalability, performance, and security. It bridges the connectivity gap between countries by utilising proven, low-cost, high-speed, high-capacity, and low-latency communication technologies. To make intelligent sanitation systems more widely available, ASK-GEN2 employs global, scalable, and stable communication protocols and considers the construction of base stations in various countries.

Communication is a fast-paced technology, and some developing regions may struggle to keep up with the rate of change in the face of exponentially increasing demand. Some technology providers develop generic cloud platforms and middleware to better meet the growing global demand for communications. These high-quality international products make the widespread deployment of intelligent sanitation cheaper and more efficient, while also playing an essential role in global digital transformation. However, these products are incompatible with one another. The ASK-GEN2 employs cross-platform, easy-to-migrate, and highly compatible protocols to adapt to existing services while avoiding systemic issues.

The ASK-GEN2 communication protocol enables stable and efficient device-to-device communication, is compatible with other commercial IoT platforms, meets the specific needs of the sanitation industry, and strikes a balance between performance and energy consumption. Security is essential for communication connections, and toilets transmit and receive highly confidential data directly or indirectly. The ASK-GEN2 uses high-security protocols to prevent data leakage, avoids open ports to prevent reverse engineering decoding, and applies asymmetric encryption to improve identification and access management. The protocols used by the various layers of ASK-GEN2 are detailed below.

- Data link layer protocols: Zigbee and cellular communication protocols are used. Zigbee is a low-cost, low-power, open global IoT connectivity solution that is critical to the widespread adoption of ASK-GEN2. 2.4 GHz frequency band Zigbee operates globally, allowing devices from various manufacturers to connect and communicate with one another machine-to-machine. Zigbee supports a mesh network topology in which nodes communicate with one another, improving data transmission stability and allowing the entire system to function normally even if one of the devices fails. Zigbee is a robust, well-deployed, low-risk technology that has already been used in tens of thousands of smart home applications. Zigbee has a diverse and well-established global supply chain, making it readily available for ASK-GEN2 global deployments. Around the world, different cellular systems are in use, and they operate in a variety of ways. 1G can only support voice services, and 2G can only provide basic text services. Although 5G improve mobile network speeds and efficiency, they are not widely used, particularly in developing countries with underdeveloped infrastructure. To balance data efficiency with global deployment feasibility, the ASK-GEN2 uses 3G and 4G to transfer intelligent sanitation data to the cloud. The ASK-GEN2 employs Digi XBee to provide a networking solution with robust standard device connectivity that supports both Zigbee and cellular protocols (Bell, 2020).

- Network layer protocols: IP, an open, free, cross-platform protocol, is used. It standardises how all machines and applications on an intelligent sanitation network transmit data packets. The ASK-GEN2 adopts the latest IPv6 to enhance sanitation data security, mobility, and flexibility. Furthermore, the ASK-GEN2 is extensible and easily convertible from IPv6 to IPv4.

- Transport layer protocols: TCP protocols are used. The ASK-GEN2 employs the TCP/IP protocol suite to ensure transmission reliability. TCP/IP is a widely used protocol for digital network communications that are highly scalable and versatile. Because the toilets require precise data transfer from one device to another, the low-overhead, high-real-time UDP is abandoned in favor of the more reliable TCP. TCP sends data from end to end using three handshakes to ensure data integrity and accuracy. The TCP protocol establishes a connection between two network endpoints for bidirectional data transfer, sending and receiving data simultaneously. TCP connections are widely used in public and local network services worldwide, making them ideal for ASK-GEN2 global deployments. Toilets generate a large amount of private sanitation data concerning user privacy. Data security is critical for ASK-GEN2. The ASK-GEN2 uses the TLS protocol to provide encryption between smart devices. Using certificates to prevent eavesdropping and tampering, TLS ensures user data privacy, integrity, and authenticity. The latest TLS v1.3 provides communication security for intelligent sanitation and employs data encryption, identity verification, and data integrity verification.

- Application layer protocols: HTTP, HTTPS, and MQTT are used. HTTP is the foundation of data communication. The ASK-GEN2 deploys cloud servers and develops applications for users to monitor and control toilets. HTTP serves as a distributed and collaborative request-response protocol between clients and servers during the communication. To protect the privacy of the sanitation data, the ASK-GEN2 employs a bi-directional encryption HTTPS protocol. HTTPS encrypts user and toilet data while verifying the client and server's identities, preventing private information from being read or altered during transmission. MQTT is a lightweight, publish-subscribe machine-to-machine networking protocol with limited resources, low data volumes, limited bandwidth, and different cross-platform deployment methods. Toilets generate large amounts of real-time data and will be deployed globally across various platforms where MQTT is ineffective. However, MQTT can be used as an alternative protocol to the application layer in certain intelligent sanitation scenarios where the amount of data is not too large.

3.3.3 Application Service

The application layer of the ASK-GEN2 handles data from other layers and provides complex applications. It brings value to the sanitation data and provides efficient solutions for stakeholders. The ASK-GEN2 collects, cleans, stores, models, and analyses massive amounts of toilet data. The microcontroller pre-processes the data collected by the various sensors before sending it to the server via a network connection. Pre-processed data masks sensor details and device specifications from various hardware vendors, allowing developers to focus more on the business level while improving smart device interoperability and system development efficiency. The ASK-GEN2 cleans up the captured toilet operation and application usage data to obtain high-quality data. The incorrect, corrupted, unformatted, duplicated, or incomplete data are corrected or deleted. Data cleaning ensures the accuracy, completeness, consistency, validity, and uniqueness of the stored data, which significantly reduces the operational costs of the intelligent sanitation system.

The processed toilet data is stored both locally and in the cloud with robust human-readable format. Each day, a large amount of time-stamped data is generated by the ASK-GEN2. Cold data, which is used less frequently, is analysed and modelled by algorithms to investigate toilet-user behavioural patterns. Hot data, which is used more frequently, is processed for retrieval and visualisation. The vast amount of cold data generated by sensors may be too large for local servers. The ASK-GEN2 stores all data on cloud servers to conserve resources. Some hot data is stored locally as a rolling backup to prevent accidental system error and data corruption. Data analysis, modelling, and management are critical in ASK-GEN2 because they rapidly extract insights from the physical world for the system, user, and business logic. The ASK-GEN2 measures and analyses deterioration data, warns of impending failure, and identifies a chain of small failures to prevent significant failures (Compare et al., 2019). With the expansion of Cranfield Circular Toilet project, more internet-connected devices will be deployed worldwide, resulting in massive data streams and the introduction of the internet of intelligent things (Resende et al., 2021). Real-time artificial intelligence analysis enables ASK-GEN2 to track, assess, and manage the system from day-to-day activities with greater insight to make better decisions and reduce energy consumption for sustainable sanitation. Figure 3-5 depicts some of the sanitation data collected by the Cranfield Circular Toilet.

Figure 3-5 Sanitation data examples collected by the ASK-GEN2

The ASK-GEN2 develops an application to display collected sanitation data (see Figure 3-6). The application is built with a web front-end and a Python back-end, making it simple to access the most up-to-date information on any portable device (e.g., iOS, Android, tablet, laptop, and desktop). Account and password pairing features protect personal information from being disclosed to unrelated stakeholders. When interacting with the cloud platform, the service security and quality are maintained (see Figure 3-6_a and Figure 3-6_b). The application connects smart devices, IoT platforms, and users to ensure reliable, high-speed, and secure information interoperability (see Figure 3-6_c). The application allows sanitation-centric systems to interact by displaying visual insights and controlling smart objects (see Figure 3-6_d). Through app interface interactions, users can control the toilet's operating mode in the app, allowing the system to perform commanded actions such as setting the data frequency (see Figure 3-6_e). The application displays sensor-measured toilet data such as system status, tank temperature, tank level, and motor speed, allowing customers and engineers to monitor toilet operation and user behaviour in real-time (see Figure 3-6_f). The ASK-GEN2 presents real-time data and analysis results in visually appealing charts (see Figure 3-6_g). The application processes, integrates, and analyses the collected data to gain meaningful information and insights about toilets to make better decisions. In the event of an emergency system failure, the user interface colours of the application become more visible, attracting the user attention (see Figure 3-6_h). The ASK-GEN2 application enables efficient interaction between users, toilets, and services, thereby initiating stakeholder collaboration, increasing productivity, and lowering operational costs.

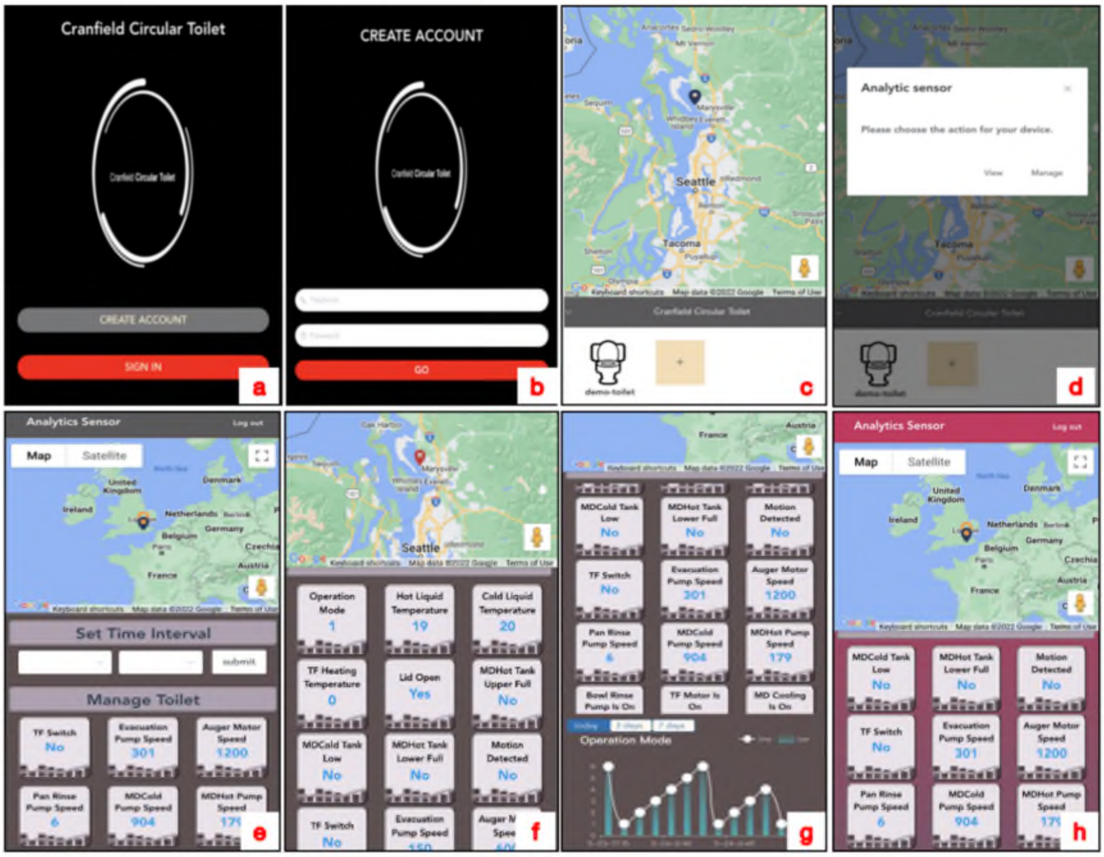

Figure 3-6 User interface of ASK-GEN2 application

3.4 Comparison of Conventional Toilets vs San-IoT Sustainable Intelligent Toilet

Through automation and insight, intelligent sanitation promotes environmental sustainability by optimising the use of natural resources, reducing waste, and achieving resource renewability. The IoT-based Cranfield Circular Toilet provides connectivity and intelligence for green and sustainable WASH solutions, using sensors and communication networks to create intelligent sanitation systems. The Cranfield Circular Toilet is made up of the sensor-controlled modules listed below.

- Ultra-low pre wetting module: An effective rotating toilet flush with minimal water pre-flush wetting and post-flush spray.

- Liquids treatment module: A high-performance membrane distillation unit for treating liquids, removing particles, and purifying liquid waste.

- Solids treatment module: A pathogen-free solid waste decomposition unit based on low-temperature pyrolysis (torrefaction).

All three main modules (see Figure 3-7) are operated by the central control board of the ASK-GEN2. With ASK-GEN2, IoT-based toilets outperform than conventional senseless toilets in terms of water efficiency, energy consumption, and operational costs.

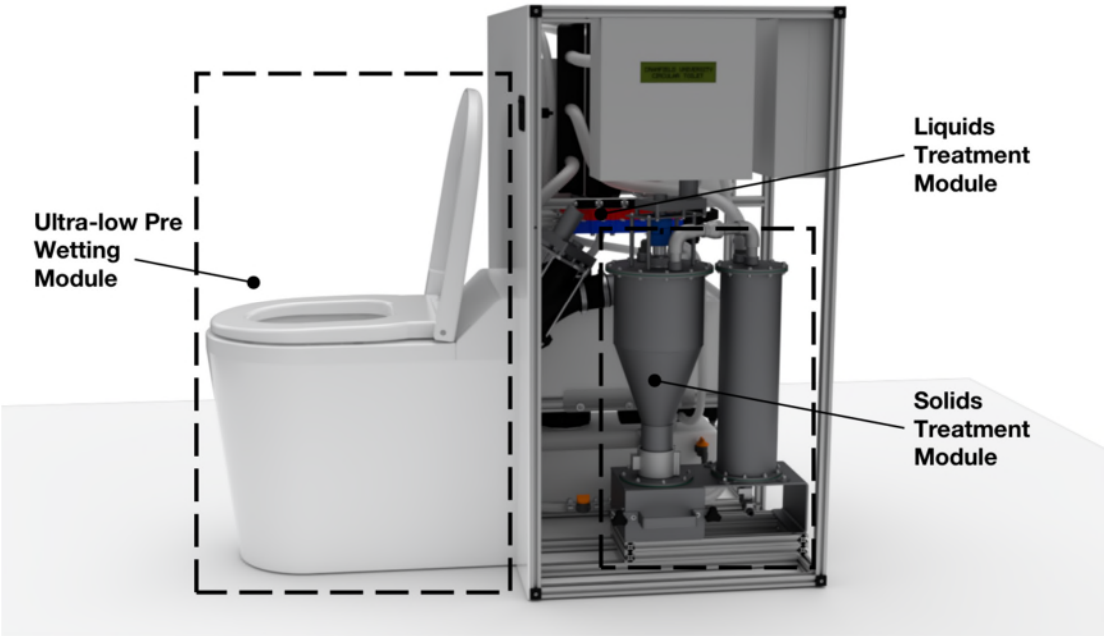

Figure 3-7 The intelligent Cranfield Circular Toilet modules

3.4.1 Water Efficiency Improvement

The Cranfield Circular Toilet use sensors to detect toilet operational status, enabling automated processes and more competent resource management to optimise water resource use. The ultra-low pre-wetting module is the most water-consuming module in the Cranfield Circular Toilet. Conventional water-saving toilets have a flush volume of 3 liters to 6 liters, while older toilets can even have a flush volume of 8 liters to 12 liters (U.S. Environmental Protection Agency, 2022). Toilet flushes account for 27% of household water use and a significant proportion of daily household water consumption (Grafton et al., 2011; U.S. Environmental Protection Agency, 2017). An ultra-low pre-wetting module for the intelligent Cranfield Circular Toilet is designed to reduce water consumption by cleaning the toilet. It is outfitted with trigger sensors (i.e., open and closed lid switches) and a redesigned rotating bowl flush component to increase water efficiency while maintaining a low manufacturing cost. When the toilet lid is opened, the central control board activates the flushing pump for pre-rinse. When the user closes the toilet lid and exits, a rotating bowl component smooth transfers the waste to the disposal module. Simultaneously, the central control board instructs the flushing pump to clean the bowl to ensure clean performance at the toilet front-end. The IoT-based mechanical sliding bowl linkage design performed well in testing, and the rational use of flushing water is a successful water conservation solution. The intelligent Cranfield Circular Toilet is a green circular system that processes the wastewater into reusable water for flushing toilets or safe discharge to environment. As a result, the water consumption of a Cranfield Circular Toilet is significantly reduced and nearly self-sufficient. Intelligent sanitation advances based on IoT improve our lifestyles and connectivity while significantly increasing water efficiency, impacting environmental sustainability.

3.4.2 Energy Consumption Reduction

The IoT is crucial in energy consumption monitoring and reduction for intelligent sanitation. Advanced technology enables smarter resource management by detecting the operational status of modules, collecting data, and using algorithms to select the best mode of operation for each component. Driving the system to make more sustainable decisions improves resource efficiency significantly. The intelligent Cranfield Circular Toilet in the case study is discussed in the section as an example of using the San-IoT to reduce energy consumption in the sanitation industry.

The liquids treatment module, which uses the most energy in the intelligent Cranfield Circular Toilet, is best suited to demonstrate how the IoT can be made more sustainable by analysing data and switching component operating states in real-time. The liquids treatment module converts waste liquid from the front end into reusable water via a series of filtration units and a membrane distillation (MD) unit. A low-cost two-stage pre-filtration unit is used to capture pulp and solids. A MD unit uses tiny hydrophobic pores to remove contaminants (such as suspended solids, micro-organisms, and pathogens) from the water. The distillation process separates the organics from the liquid stream. The final distillate can be used as front-end spray water or can be safely discharged into the environment. The MD hot tank pump, MD cold tank pump, Peltier, and radiator fans are the most energy-intensive components of the liquids treatment module. The MD hot tank holds the initial treatment waste, the MD cold tank holds the distillate, the Peltier generates a temperature difference to drive the module, and the radiator fans dissipate heat from the MD unit. The liquid treatment module is activated when the volume of wastewater in the MD hot tank reaches a certain level. The sensorless Cranfield Circular Toilet scenario lacks sensors to monitor the water level in the MD hot water tank, the liquids treatment module is triggered by a predetermined number of user visits, resulting in frequent activation of the MD unit, consuming a lot of unnecessary energy consumption. In the sensor-enhanced Cranfield Circular Toilet scenario, floating sensors in the MD hot water tank regulates the operation of the liquids treatment module. When the waste liquid in the hot tank reaches a certain level, the liquids treatment module activates, and it goes into standby mode when not needed, resulting in significant energy savings. The IoT-based intelligent toilet system can save significant amounts of energy consumption for the sanitation industry. Therefore, this is considered one of the most valuable tools towards environmental sustainability in the industry.

3.4.3 Affordable Implementation Cost

Universal access to safe excreta disposal and adequate sanitation can significantly reduce illness and death. Despite encouraging sanitation progress these years, there is still a significant gap in sanitation coverage between developing and developed countries. Developing countries lack basic facilities and safe services, and defecate in the open in fields, bushes, bodies of water, or other open spaces, endangering community health (United

Nations International Children's Emergency Fund, 2021). Construction of traditional sanitation networks and purchasing basic household facilities, such as toilets, are prohibitively expensive for low-income countries.

The innovative sanitation system makes affordable toilet facilities possible. The implementation of non-sewered sanitation systems offer a wide range of benefits, including cost-effectiveness, resource conservation, and reduced environmental impact. By treating and managing human waste locally, these systems eliminate the cost for extensive sewer networks and wastewater treatment plants, contributing to more sustainable and environmentally responsible practices. On-site sanitation plays a crucial role in reducing the overall cost of infrastructure development and minimising water usage and energy consumption. Self-circulating toilets incorporate water-saving mechanisms that enable the recycling and reuse of water within the toilet system. Sensor-based toilets adapt their operation based on usage patterns and environmental conditions. Through intelligent decision-making, these sanitation systems optimise energy usage by selecting the most suitable operating mode, such as adjusting flushing intensity, water flow, and heating. By combining these technological advancements, modern sanitation solutions can significantly improve sanitation access, reduce environmental impact, and promote more sustainable practices.

Future improvements to the intelligent RTTC can include extending the pre-industrial activities of the fully integrated toilet, reducing system complexity to lower system costs, and identifying potential value engineering opportunities. Working with commercial partners can reduce the factory gate price. By leveraging the power of the IoT, sanitation industry can now access vast amounts of data and analytics without incurring major costs. IoT-based sanitation facilities collect and transmit data in real time, allowing engineers to detect changes quickly and respond efficiently without incurring significant costs. Cloud-based services, such as analytics-as-a-service, predictive analytics, and machine learning, allow industry to quickly access and analyse large datasets without the need for expensive hardware or software. Sanitation systems based on IoT monitor machine performance, detect environmental changes, and track customer behaviour. The sanitation data gathered is used to gain insights, make decisions, improve operations, and cut costs. As demonstrated by the Cranfield Circular Toilet case study, IoT-based systems are one of the most important drivers of affordable sanitation, providing greater opportunities for environmental sustainability and assisting the global community in embracing more efficient resource management.

3.5 Conclusions and Future Work

The chapter proposed a generalised San-IoT framework for sustainable intelligent sanitation systems, including a three-layer IoT architecture (i.e., nodes layer, fog layer, and cloud layer) and a general five-layer IoT stack model (i.e., perception layer, data link layer, network layer, transport layer, and application layer). The most recent and widely used hardware, technologies, and protocols was introduced. The characteristics, benefits, and drawbacks of various technologies were presented, analysed and discussed. The generalised San-IoT intelligent sanitation framework can support other developers to select the appropriate technology for their own projects. The Cranfield Circular Toilet was used as a case study to demonstrate the applicability and feasibility of the proposed San-IoT framework. The chapter presented the installed sensors and their functions for system sensing, the various protocols used for communication connection, as well as data processing steps and user interaction interface for application services. The results shown that the intelligent Cranfield Circular Toilet has performed well in testing. The system transformed data into insight, informing global stakeholders about the status of toilet operations in real-time and responding quickly to improve sanitation. The San-IoT can advance global sanitation sustainability goals through innovative technology. The Cranfield Circular Toilet can optimise operations while saving significant amounts of water and electricity.

Although the generalised San-IoT intelligent sanitation framework has performed well in practice, further improvement is required. As intelligent sanitation services expand their global reach, the system's scalability, security, compatibility, and computability will be particularly important. For example, accommodating the growing number of smart devices, protecting the IoT architecture's security from attacks, lowering maintenance and repair costs, providing high-quality and reliable network connectivity services, standardizing device production, and so on. The numerous benefits of intelligent sanitation are being demonstrated. IoT-based sanitation systems generate a large amount of data, which AI interprets to create value for the industry. The next generation of intelligent sanitation systems will use AI to improve predictive maintenance, facility management, manufacturing efficiency, and user analytics. Unlike traditional predictive techniques, advanced AI-based predictive maintenance can extract insights from highly complex, non-linear, and untagged data. To identify anomalous trends more accurately, smart IoT architectures typically employ support vector machines (SVM), random forests (RF), neural networks, long and short-term memory (LSTM), and hybrid methods. Because data is processed faster, the damage is reported immediately, and responses are initiated quickly, the introduction of intelligent sanitation with AI allows engineers to react more quickly before system failures. Intelligent computing mines knowledge from a wide range of data streams to assess the performance of individual sanitation components, identifying patterns or similarities that can be learned to make better decisions and save energy. San-IoT will benefit greatly from advanced technology, making it easier than ever to access data, share information, and automate processes.

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4 Chapter 4: Data Analytics Tool Design for Intelligent Sanitation Networks: A Case Study of Next Generation Reinvented Toilet System

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ABSTRACT

The sanitation industry produces large quantities of data that are high in volume, velocity, and variety. However, traditional IoT approaches fail to leverage the potential of valuable sanitation data. The chapter presents a generalised data analytics tool for intelligent sanitation solutions, namely San-IoT-DA. The San-IoT-DA enhances data collection, analysis, and management and can act as a foundation for future research on intelligent sanitation. The San-IoT-DA tool includes business understanding, data understanding, data acquisition, data cleaning and preparation, data storage, data analysis, data visualisation, modelling, evaluation, and deployment phases. Within this tool, sophisticated strategies, processes, and tools are employed to gather, transmit, store, analyse, and manage data effectively. A case study of the Cranfield Circular Toilet is conducted to demonstrate the capabilities of the proposed tool. The case study shows that the San-IoT-DA tool can enhance the efficiency of toilet performance, while effectively facilitating decision-making among global stakeholders. The chapter also explores the challenges and opportunities associated with sanitation data

analytics, focusing on aspects such as availability, reliability, security, scalability, reusability, and interoperability.

Keyword: Data analytics; industrial intelligence; intelligent sanitation; Internet of Things; machine learning; reinvented toilets; San-IoT; San-IoT-DA; smart industry.

4.1 Introduction

According to the World Health Organisation report, billions of people around the world do not have access to basic sanitation facilities and services, such as toilets, waste treatment, disposal, and safe reuse (World Health Organisation, 2022a). Missing or out-of-reach safe water, sanitation, and hygiene (WASH) systems resulting in 2.9 million cases of diseases and 95,000 deaths each year (World Health Organisation, 2019). The Sustainable Development Goals (SDGs) call for WASH transformation to achieve universal access to healthy, comfortable, and safe sanitation by 2030 (World Health Organisation, 2018). Inadequate planning, outdated design, inefficient maintenance, lack of access, insufficient resources, and high costs in traditional sanitation networks not only fail to provide basic sanitation services, but can also lead to disease transmission and environmental pollution (World Health Organisation, 2021a). Traditional sanitation is significantly less effective due to the lack of monitoring and control. By introducing the Internet of Things (IoT) based intelligent sanitation solutions, it is possible to identify and track sanitation services more efficiently and effectively (World Health Organisation, 2021b). However, the intelligent sanitation solutions are relatively rare because of the large investment required, shortage of skilled workers, high installation costs, and specialised knowledge required (Saul and Gebauer, 2018; Kassab and Darabkh, 2020).

The IoT solutions connect objects, environments, and processes to the Internet, which improves productivity, increases resource utilisation, controls product lifecycles, automates maintenance operations, and facilitates industrial digitisation processes (Dey et al., 2018; Ge et al., 2018; Kassab and Darabkh, 2020; Silvestri et al., 2020). The IoT systems combine advanced technologies such as artificial intelligence, data analysis, cloud computing, and information systems, to create more flexible, efficient, and sustainable solutions (Tsai et al., 2013; Chen et al., 2015; Li et al., 2018; Zhou et al., 2021; Jamshed et al., 2022; Mishra and Tyagi, 2022).

The IoT solutions have become popular in various industries, including smart cities, smart manufacturing, smart retail, smart agriculture, smart transportation, smart healthcare, and smart energy (Misra et al., 2020; Shafiq et al., 2020; Bi et al., 2021; Jagtap et al., 2021; Majid et al., 2022; Sinha and Dhanalakshmi, 2022; Soldatos et al., 2022). However, intelligent sanitation is still lagging (Saul and Gebauer, 2018). Several intelligent sanitation solutions have been proposed, but little research has been conducted, progress has been slow, and contributions have been fragmented (Gong et al., 2020). Intelligent sanitation incorporates multiple technologies into sanitation facilities, including sensors, hardware, software, automation, embedded systems, control systems, wireless communication, and data analytics (Gong et al., 2020; Rary et al., 2020). Intelligent sanitation systems with advanced data analytics strategies can improve sanitation service by detecting sanitation facilities, monitoring daily health and disease progression, and providing user-friendly and environmentally friendly solutions (Bae and Lee, 2018; Deshmukh et al., 2020; Park et al., 2020; Cotera Rivera and Bilton, 2021; Temirel et al., 2021; Tasoglu, 2022; Zhang et al., 2022). Sanitation data are critical for unlocking the full potential of intelligent sanitation, but utilising these data remains a challenge.

Data from IoT smart assets is being generated at an unprecedented rate. However, such data are useless unless they can be interpreted analytically (Marjani et al., 2017). Data analytics can be used to identify trends, predict outcomes, identify patterns, detect anomalies, and provide insights (Elgendy and Elragal, 2014; Elgendy and Elragal, 2016; Ge et al., 2018; Tsai et al., 2018). The combination of IoT and data analytics technology can help industries increase their efficiency by collecting data automatically and using it to optimise operating processes, customer experiences, and overall business strategy (Zhang et al., 2017; Sasaki, 2021; Sunhare et al., 2022).

Billions of smart objects collect, transmit, and share massive amounts of data that vary in volume, velocity, and variety in IoT solutions (Hariri et al., 2019; Sestino et al., 2020). Many industries face significant challenges in understanding and processing IoT data (Fawzy et al., 2022). Traditional data analysis methods are inefficient in terms of storing, processing, and analysing the rapidly growing amounts of IoT data (Bonomi et al., 2014; Simmhan and Perera, 2016; Sasaki, 2021). The limitations of traditional methods are evident in their restricted capacity, slow processing speed, and limited adaptability to different data structures. The resource-intensive nature of processing and analysing large-scale IoT data requires substantial computing power, memory, and storage capacity, posing challenges for traditional systems in efficient resource allocation and management. Advanced data analytics tools are required for successful IoT data analysis (Ge et al., 2018; Bansal et al., 2020). A variety of advanced data analysis algorithms, such as multivariable linear regression, time series forecasting, dimensionality reduction, clustering techniques, classification techniques, artificial neural networks, and support vector machines, have been developed to analyse IoT data efficiently (Ge et al., 2018; Adi et al., 2020; Perros, 2021; Sunhare et al., 2022). Advanced data analytics tools can provide a variety of intelligent services, such as anomaly detection, failure prediction, and predictive maintenance, to improve system operations and meet business demands (Mohammadi et al., 2018; Huang et al., 2020; Cakir et al., 2021; Sunhare et al., 2022). IoT solutions, when combined with advanced data analytics, can provide complex systems insight, make informed decisions, and improve user experience.

Sanitation facilities generate enormous amounts of valuable data every day, but these data are commonly difficult to collect and analyse. Traditional sanitation facilities are private and inaccessible, and the process of collecting sanitation data is largely hidden and intangible (World Health Organisation, 2022b). Traditional sanitation data are frequently collected through surveys, which are delayed, unreliable, and time consuming. Moreover, traditional sanitation data are regularly collected by local governments and organisations with limited resources, restricting access to sanitation data (World Health Organisation, 2018). To fully exploit sanitation data, it is critical to have access to reliable and real-time data, as well as efficient analytics and visualisation tools. However, the intelligent sanitation solutions are still in the early stages of developing data analytics capabilities. A standardised sanitation data collection, analysis, and management tool is required to improve sanitation practises.

The chapter proposes a Sanitation-IoT Data Analytics (San-IoT-DA) tool for intelligent sanitation solutions, including high-level architecture, data processing life cycle, and technical details. Effective sanitation data analytics strategies, processes, and tools are introduced to provide clear, immediate, and actionable insights. The proposed data analytics tool is applied to a case study of the Cranfield Circular Toilet in the Reinventing the Toilet Challenge (RTTC) project. The San-IoT-DA tool can detect patterns, identify trends, boost operational efficiency, predict problems, prevent breakdowns, and make better decisions.

The chapter provides practitioners, academics, engineers, technicians, policymakers, and other stakeholders with insights into how to use IoT and data analytics to improve the efficiency, sustainability, and safety of the sanitation industry. The contribution of the chapter are as follows:

- Investigating data analytics techniques used in existing intelligent sanitation applications and services from 2000 to 2022;

- Designing a San-IoT-DA tool as a foundation for intelligent sanitation solutions;

- Developing strategies, processes, and tools for sanitation data collection, analysis, and management;

- Implementing the tool in a case study of Cranfield Circular Toilet;

- Discussing a variety of sanitation data analytics challenges and opportunities.

The remainder of the chapter is organised as follows: Section 4.2 summarises the data analytics techniques used in the latest intelligent sanitation solutions. Section 4.3 introduces the San-IoT-DA tool for intelligent sanitation systems. Section 4.4 presents a case study of the Cranfield Circular Toilet. Section 4.5 discusses challenges and opportunities for the development of data-driven sanitation systems. Finally, conclusions are provided in Section 4.6.

4.2 Data Analytics Techniques Applied in Intelligent Sanitation

A comprehensive literature review is conducted based on the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) to identify high-impact intelligent sanitation applications and services from 2000 to 2022 (Liberati et al., 2009). The systematic literature search is conducted in the ACM, IEEE Xplore, PubMed, and Science Direct databases and publishers. The keywords *"sanitation" OR "toilet" AND ("intelligent" OR* *"smart" OR "IoT" OR "Internet of Things" OR "sensor")* are used in searches. Over 141 high-quality, highly cited, and innovative literature pieces were thoroughly reviewed to gain further insights into sanitation IoT solutions and their data analytics techniques (see Figure 4-1).

The use of data analytics in intelligent sanitation solutions encompasses a wide range of services, strategies, approaches, methods, and techniques. The chapter examines existing works on sanitation data analytics and discusses their employed processes and advanced technologies (see Table 4-1). From 2000 to 2011, early intelligent sanitation research primarily focused on the development of improved facilities, architectures, systems, and devices. Integrated data analytics solutions have gradually gained traction in recent years to make sanitation smarter. Most intelligent sanitation solutions integrated with data analytics provide system detection, health monitoring, and environmental monitoring services. A variety of similar data analytics processes have been used in these solutions, but no global consensus has been reached. There is no unified data analytics tool in the current sanitation industry, resulting in unstable and uncontrollable performance of intelligent sanitation solutions and a high reliance on specific experts. The chapter proposes a generalised data analytics tool to help in the translation of sanitation business problems into data analysis tasks, the use of appropriate data preparation techniques, and the improvement of the reliability, manageability, and sustainability of sanitation solutions.

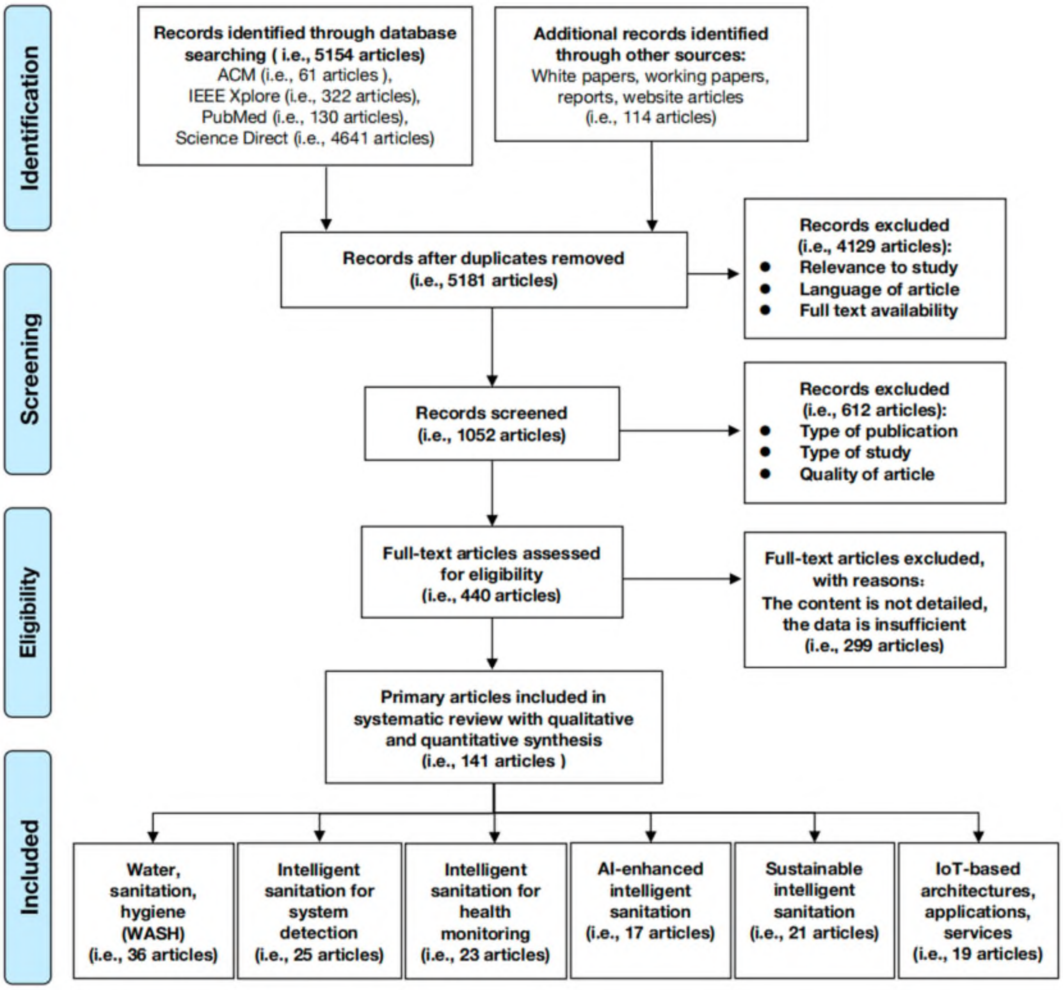


Figure 4-1 The PRISMA flowchart

Table 4-1 Summary of data analytics techniques for existing sanitation solutions

Reference	Intelligent Solutions			Data Analytics Processes										Advanced Technologies			
	sys.	**hea.**	**env.**	**bus.**	**dug.**	**dan.**	**dcp.**	**dse.**	**das.**	**dvn.**	**mod.**	**eva.**	**dep.**	**clo.**	**AI**	**com.**	**app.**
Panek et al. (2011)		✓		✓	✓	✓	✓	✓	✓	✓		✓	✓				✓
Schlebusch (2011)		✓		✓	✓	✓	✓	✓	✓	✓		✓	✓				
Huang et al. (2012)		✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓
Atta (2013)	✓			✓	✓	✓	✓	✓	✓		✓		✓		✓		
Taniguchi et al. (2014)		✓		✓	✓	✓		✓	✓	✓	✓		✓		✓	✓	✓

Table 4-1 Summary of data analytics techniques for existing sanitation solutions (continued)

Reference	Intelligent Solutions			Data Analytics Processes									Advanced Technologies			
	sys.	hea.	env.	bus.	dug.	dan.	dcp.	dse.	das.	dvn.	mod.	eva.	dep.	clo.	AI	com.	app.
Kodali & Ramakrishna (2017)	✓		✓	✓	✓	✓		✓					✓				
Pilissy et al. (2017)	✓			✓	✓	✓			✓			✓	✓				
Zakaria et al. (2017)	✓		✓	✓	✓	✓			✓			✓	✓				
Bae & Lee (2018)		✓		✓	✓	✓	✓	✓		✓			✓				✓

Table 4-1 Summary of data analytics techniques for existing sanitation solutions (continued)

Reference	Intelligent Solutions			Data Analytics Processes										Advanced Technologies			
	sys.	hea.	env.	bus.	dug.	dan.	dcp.	dse.	das.	dvn.	mod.	eva.	dep.	clo.	AI	com.	app.
Boonyakan et al. (2018)	✓			✓	✓	✓	✓	✓	✓				✓				
Namekar & Karthikeyan (2018)	✓		✓	✓	✓			✓		✓							✓
Zakaria et al. (2018)	✓			✓	✓	✓		✓	✓	✓		✓	✓				
Balaceanu et al. (2019)	✓	✓	✓	✓	✓	✓		✓		✓			✓				✓
Cai et al. (2019)	✓		✓	✓	✓	✓		✓	✓				✓				

Table 4-1 Summary of data analytics techniques for existing sanitation solutions (continued)

Reference	Intelligent Solutions			Data Analytics Processes										Advanced Technologies			
	sys.	hea.	env.	bus.	dug.	dan.	dcp.	dse.	das.	dvn.	mod.	eva.	dep.	clo.	AI	com.	app.
Shaikh et al. (2019)	√		√	√	√	√		√									
Shinganwade et al. (2019)	√		√	√	√	√		√		√							√
Tsuchiyama & Kajiwara (2019)		√		√	√	√		√		√		√	√				
Deshmukh et al. (2020)	√		√	√	√	√	√	√	√	√	√	√	√		√		√
Park et al. (2020)		√		√	√	√	√	√	√	√	√	√	√	√	√	√	

Table 4-1 Summary of data analytics techniques for existing sanitation solutions (continued)

Reference	Intelligent Solutions			Data Analytics Processes										Advanced Technologies			
	sys.	hea.	env.	bus.	dug.	dan.	dcp.	dse.	das.	dvn.	mod.	eva.	dep.	clo.	AI	com.	app.
Raendran et al. (2020)	✓		✓	✓	✓	✓		✓	✓			✓	✓				✓
Rary et al. (2020)		✓		✓	✓				✓								
Syafaah et al. (2020)		✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓
Turman-Bryant et al. (2020)	✓			✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓		
Cotera Rivera & Bilton (2021)	✓			✓	✓	✓	✓	✓	✓	✓		✓	✓				

Table 4-1 Summary of data analytics techniques for existing sanitation solutions (continued)

Reference	Intelligent Solutions			Data Analytics Processes										Advanced Technologies			
	sys.	hea.	env.	bus.	dug.	dan.	dcp.	dse.	das.	dvn.	mod.	eva.	dep.	clo.	AI	com.	app.
Zhang et al. (2021)		✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Akaho & Yoshioka (2022)		✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓		
Bimantara et al. (2022)	✓			✓	✓	✓	✓	✓	✓	✓		✓	✓				
Ge et al. (2022)		✓		✓	✓							✓	✓	✓			✓
Kumar et al. (2022)		✓		✓	✓	✓											✓

Table 4-1 Summary of data analytics techniques for existing sanitation solutions (continued)

Reference	Intelligent Solutions			Data Analytics Processes										Advanced Technologies			
	sys.	**hea.**	**env.**	**bus.**	**dug.**	**dan.**	**dcp.**	**dse.**	**das.**	**dvn.**	**mod.**	**eva.**	**dep.**	**clo.**	**AI**	**com.**	**app.**
SeeTo et al. (2022)	✓			✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓		
Tasoglu (2022)		✓		✓	✓												
Zhang et al. (2022)	✓			✓	✓	✓	✓	✓	✓	✓		✓	✓				✓

Where sys. = system detection, hea. = health monitoring, env. = environmental monitoring (air quality, cleanliness, user number), bus. = business understanding, dug. = data understanding, dan. = data acquisition, dcp. = data cleaning and preparation, dse. = data storage, das. = data analysis, dvn. = data visualisation, mod. = modelling, eva. = evaluation, dep. = deployment, clo. = cloud platform, AI = artificial intelligence, com. = computer vision, app. = applications for interaction and visualisation (web, mobile, tablet, computer software)

4.3 Generalised Data Analytics Tool for Intelligent Sanitation

According to the literature review, current intelligent sanitation solutions that incorporate data analytics are fragmented and unsystematic. Researchers have proposed a variety of intelligent sanitation solutions, the majority of which have a similar architecture that includes a perception layer, data link layer, network layer, transport layer, and application layer, to collect, process, and analyse data. By summarising the literature, the primary aspects of the data analytics process and lifecycle are data acquisition, data cleaning, data storage, data analysis, and data visualisation (Ge et al., 2018; Zhang et al., 2019; Fawzy et al., 2022).

Intelligent sanitation data are gathered from various sources and smart assets, which as volume, velocity, variety, veracity, variability, and value (Laney, 2001; Bansal et al., 2020). The cross industry standard process for data mining (CRISP-DM) is a widely used comprehensive data-process model for executing data on these characteristics (Wirth & Hipp, 2000). The CRISP-DM process model breaks the process of data mining into business understanding, data understanding, data preparation, modelling, evaluation, and deployment. The generic CRISP-DM process model can be used to comprehend, plan, and implement data analytics processes for intelligent sanitation solutions. However, the CRISP-DM is insufficient for modern data analytics tasks that involve massive amounts of data generated by IoT devices.

The chapter proposes a general San-IoT-DA tool based on the findings of the literature review and the CRISP-DM model to make IoT sanitation data easier to manage and analyse (Wirth and Hipp, 2000; Laney, 2001; Berry and Linoff, 2004; Vermesan and Friess, 2015; Elgendy and Elragal, 2016; Ge et al., 2018; Vermesan et al., 2022). The tool includes business understanding, data understanding, data acquisition, data cleaning and preparation, data storage, data analysis, data visualisation, modelling, evaluation, and deployment phases (see Figure 4-2). IoT is a closed-loop system, and the phases in the San-IoT-DA tool are not strictly ordered. The arrows in Figure 4-2 only indicate the most important and frequent dependencies between phases. The functionality of each phase in the San-IoT-DA is as follows:

- Business understanding: Analyse the current state of the sanitation business, comprehend the goals of IoT data analytics applications, identify potential methods, develop a process strategy, and provide an effective solution.
- Data understanding: Learn how smart assets are used, what data sanitation facilities generate, and how sanitation data can be used to inform decision-making and optimise operations.
- Data acquisition: Collect data from various sources, such as sensors, cameras, and other smart assets, to gain insight into the physical world.
- Data cleaning and preparation: Clean, filter, transform, and standardise the data for further analysis and application development.
- Data storage: Organise and store IoT data in an appropriate repository to facilitate data analysis.
- Data analysis: Use various techniques such as statistical analysis, pattern recognition, machine learning, and artificial intelligence to uncover valuable insights and trends.
- Data visualisation: Visualise the data with graphs, charts, and maps to make it easier to understand and interpret.
- Modelling: Design models and algorithms to further extract insights from IoT data to make better decisions and improve operations.

- Evaluation: Evaluate the accuracy, effectiveness, and performance of the data analytics process to against the expected outcomes.
- Deployment: Deploy data analytics tools on IoT solutions to gain insights and make decisions.

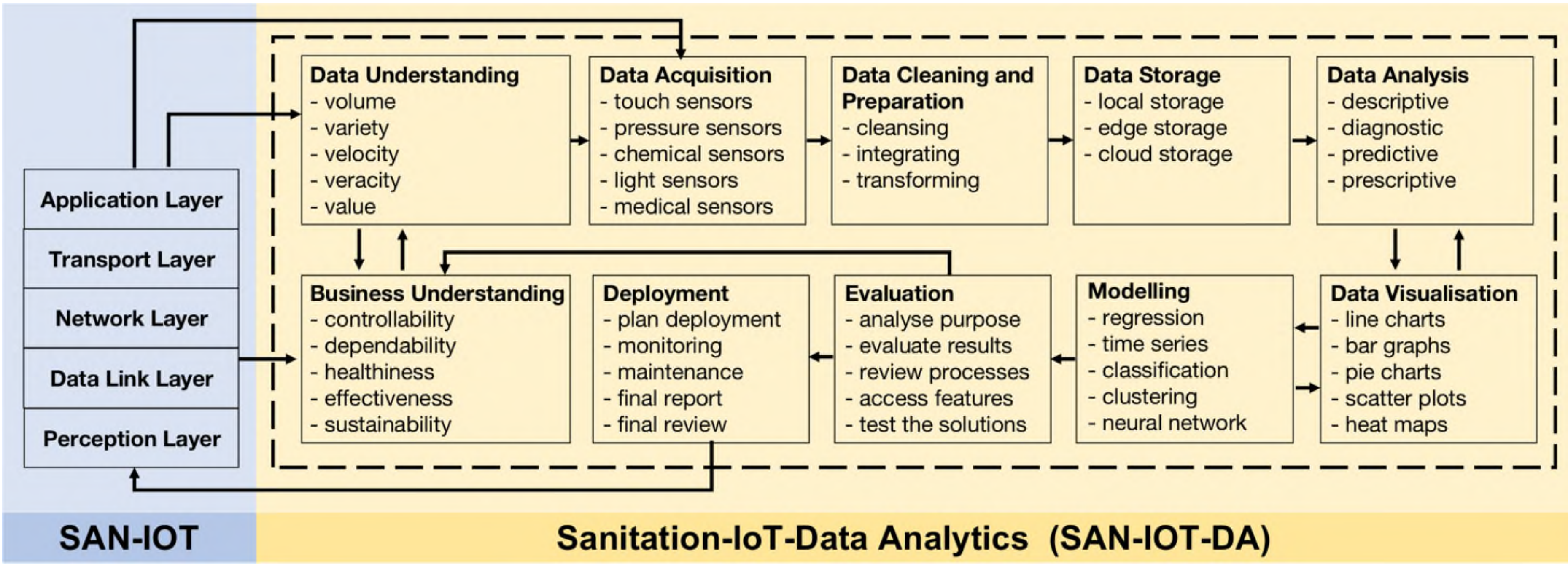


Figure 4-2 An overview of the generalised San-IoT-DA tool

4.3.1 Sanitation Business Understanding

IoT solutions help businesses gain valuable insights, investigate customer behaviour, discover usage patterns, reduce energy costs, and improve system performance (Salam et al., 2019; Fawzy et al., 2022; Vermesan et al., 2022). Intelligent sanitation enhances sanitation processes such as wastewater treatment, water reuse, and waste management, as well as making sanitation businesses more efficient, cost-effective, reliable, and sustainable (Molenbroek and De Bruin, 2011; Kone, 2012; Bongartz et al., 2016; Pereira and Marques, 2021; Tasoglu, 2022). System detection, health monitoring, and environmental monitoring are common businesses in the intelligent sanitation solutions (see Table 4-1). By monitoring and controlling smart assets, intelligent sanitation has the potential to significantly improve facility operational efficiency, safety, and performance (Cid et al., 2020; Deshmukh et al., 2020; Cotera Rivera and Bilton, 2021; Zhang et al., 2022; Zhao et al., 2022). Intelligent sanitation for continuous health monitoring detects disease earlier, prevents disease spread, lowers medical care costs, reduces the burden on healthcare systems, and ultimately improves public health (Bae and Lee, 2018; Park et al., 2020; Temirel et al., 2021; Tasoglu, 2022). With proper monitoring and analysis, human excreta such as urine and faeces can provide valuable insights into the health of individuals and the general public (Oyaert and Delanghe, 2019; Rary et al., 2020; Wang and Camilleri, 2020; Ge et al., 2022). A good business understanding of intelligent sanitation solutions can boost facility efficiency, public health, resource utilisation, and a healthier environment.

Sanitation business understanding is a preliminary phase of San-IoT-DA that focuses on comprehending project objectives and requirements before converting business goals into a data analytics problem definition. Business understanding is used to identify the background, objectives, and criteria of a project; evaluate the resources, requirements, assumptions, constraints, and risks of the current situation; and develop plans, processes, tools, and techniques for data analytics. The following perspectives can contribute to the sanitation business understanding (IBM, 2023):

- Determine organisational structure: Identify sanitation business units, project members, and their roles;

- Describe problem areas: Clarify the prerequisites, motivations, and current status of sanitation solutions;

- Describe the current solution: Investigate the advantages and disadvantages of the current sanitation solution, as well as the benefits and drawbacks of integrated data analytics solutions.

Traditional sanitation networks are designed, maintained, and inspected improperly. Outdated or insufficient data used in the design of traditional sanitation networks can result in overflows, blockages, and system failures. Additionally, the lack of integration of advanced technologies, real-time monitoring, predictive maintenance, or smart management systems, hampers their efficiency. Inadequate monitoring further exacerbates the problem, as it may lead to unnoticed issues escalating into more significant and costly challenges over time. To address these issues and meet the challenges posed by urbanisation and population growth, adopting modern technologies, data-driven approaches, and sustainable practices is becoming increasingly essential to ensure the effective functioning of sanitation systems (World Health Organisation, 2020). Intelligent sanitation can perform remote monitoring, remote control, anomaly detection, failure prediction, predictive maintenance, process automation, environmental monitoring, energy consumption optimisation, asset management, and quality management by integrating advanced technologies such as data analytics, simulation, cloud computing, and automation (Silvestri et al., 2020). For example, anomaly detection solutions classify data into normal and abnormal categories and make accurate predictions using machine learning methods (Chandola et al., 2009; Chalapathy and Chawla, 2019; Carrasco et al., 2021; Choi et al., 2021; Erhan et al., 2021; Pang et al., 2021; Rousopoulou et al., 2022). Failure prediction solutions identify potential threats, manage risks, and take preventive actions by analysing data from connected devices and sensors to reduce the likelihood of failure and ensure system health (Filz et al., 2021; Chowdhury et al., 2022; Li et al., 2022; Navajas-Guerrero et al., 2022; Yan et al., 2022). Predictive maintenance solutions involve condition monitoring, fault diagnosis, fault prognosis, and maintenance plans, which improve inventory management, eliminate unplanned downtime, and maximise equipment lifetime (Cachada et al., 2018; Ran et al., 2019; Zhang et al., 2019; Çınar et al., 2020; Zonta et al., 2020; Cakir et al., 2021; Serradilla et al., 2022; Ong et al., 2022). The section divides sanitation business understanding into controllability, dependability, healthiness, effectiveness, and sustainability (see Table 4-2). Intelligent sanitation using data analytics can reduce downtime, increase performance, reduce costs, improve safety, improve user experience, and avoid unnecessary repairs and replacements (Rieger et al., 2019; Silvestri et al., 2020; Ong et al., 2022).

Table 4-2 Intelligent sanitation solutions

Solution Categories	Solutions	Description
Controllability	System monitoring	Track the IoT system performance
	System control	Manage the IoT system performance
	Process automation	Automate the IoT system performance
Dependability	Anomaly detection	Detect anomalies in the IoT system
	Fault diagnosis	Find the source of problems
	Failure prediction	Identify potential problems
	Predictive maintenance	Predict early failure, schedule maintenance
	Remaining useful life prediction	Predict the length of time for continue use
Healthiness	Health monitoring	Monitor user health
	Excrement monitoring	Excreta analysis for health monitoring

	Friendly service	Provide special sanitation services
Effectiveness	Performance evaluation	Assess the IoT system performance
	Process optimisation	Improve the efficiency of the IoT system
	Asset management	Track and manage physical assets
	Quality management	Ensure high quality, reliable and secure
Sustainability	Environmental monitoring	Monitor the environment
	Energy consumption optimisation	Utilise energy sources effectively
	Water consumption optimisation	Optimise water usage
	Resource optimisation	Use resources efficiently and effectively

4.3.2 Sanitation Data Understanding

During the sanitation data understanding phase, first insights into the data are discovered, and hypotheses for hidden information are formed (IBM, 2023). To properly process sanitation data, it is critical to organise the data according to the context of the application, understand the data structure, format, and quality, and effectively extract meaningful information (Vermesan and Friess, 2015; Gulia and Chahal, 2020). The steps to implement sanitation data understanding are as follows：

- Describe sanitation data: Examine the amount of data, type of data, and coding schemes.

- Explore sanitation data: Form initial hypotheses about data, analyse attributes, reveal data characteristics, and rethink hypotheses.

- Verify sanitation data: Check for data quality such as data errors, coding errors, measurement errors, missing values, coding inconsistencies, and bad metadata.

According to the literature review, sanitation data have high volume, variety, velocity, veracity, and value, which presents challenges and opportunities for the sanitation industry (Bansal et al., 2020). The section describes the characteristics of sanitation data, as well as approaches for addressing challenges and expanding opportunities (see Table 4-3).

Table 4-3 Intelligent sanitation data characteristics

Characteristics	Sanitation	Challenges	Opportunities	Approaches
Volume	Massive data is generated by sanitation facilities all over the world	- More storage capacity - More network bandwidth	- Improve algorithm accuracy and performance	- Selective data retrieval - Size reduction - Optimised storage
Variety	Diverse multiple data sources generate various data formats, structures, and types	- Heterogeneous data sources - Complicated data integration	- Identify complex relationships, patterns, and trends	- Data integration and fusion - Hybrid storage
Velocity	Sanitation facilities are constantly in use, generating data	- Effective processing speed - Vary data ingestion speed	- Improve operational and business efficiency	- Parallelized processing. - Edge-based pre-processing
Veracity	Ensure sanitation data accuracy, completeness, and reliability	- Untrustworthy facilities - Uncertainty and chaos data	- Provide better security, service, and experience	- Trace data provenance - Trusted data transfer
Value	Use data-driven knowledge to gain insight into sanitation solutions	- Limited techniques - Insight less actions/decisions	- More effective strategies - Informed decisions	- Advanced data processing - Advanced data analytics

4.3.3 Sanitation Data Acquisition

Data acquisition is an essential phase in the San-IoT-DA tool. It involves the use of smart assets, device networks, and cloud services to collect, transfer, and store data. Data acquisition collects data from various sources, including physical systems, digital systems, and other sources, and then transfers the data to a network for further processing to obtain useful information. The section summarises the data obtained from existing intelligent sanitation solutions (see Table 4-4). Through IoT technology, some sanitation facilities monitor and control the system, obtaining sanitation data such as liquid volume in the water tank, urine volume, faecal volume, grey water volume, usage detection (infrared sensor, motion sensor), and environmental status (air quality, cleanliness, user number). Sensors are used to monitor system status; hardware components such as pumps, valves, and motors automate system regulation based on data feedback to reduce human labour and energy costs; embedded systems provide remote control and monitoring capabilities; wireless communication connects different system components; and data analytics helps to identify patterns and trends in system behaviour (Cid et al., 2020; Deshmukh et al., 2020; Cotera Rivera and Bilton, 2021; Zhang et al., 2022; Zhao et al., 2022). Some sanitation facilities monitor user health and collect sanitation data such as ECG, urine, faecal, and respiratory status. Human health data from intelligent sanitation can improve hygiene practises and inform health decisions (Oyaert and Delanghe, 2019; Rary et al., 2020; Wang and Camilleri, 2020; Ge et al., 2022). In sanitation facilities, many distributed sensors are installed to monitor and control the physical environment. Smaller, affordable, efficient, and sustainable sensors are preferred for intelligent sanitation solutions. Some common sensor types are listed below:

- Touch sensors: Detect physical contact or proximity.

- Temperature sensors: Measure temperature and convert it into an electrical signal.

- Pressure sensors: Measure the pressure of a liquid or gas.

- Environmental sensors: Measure and record the physical characteristics of the environment.

- Chemical sensors: Detect and respond to chemical substances.

- Light sensors: Detect the presence or amount of light.

- Location sensors: Collect the location of the smart asset or end user.

- Audio sensors: Capture and convert sounds like noise, music, speech into digital signals

- Medical sensors: Detect and measure physiological changes or other medical parametres.

Table 4-4 Sanitation data collected in existing solutions

Reference	liq.	urine.	fav.	grey.	usage.	envs.	ECG.	uri.	fae.	res.	others
Panek et al. (2011)											✓
Schlebusch (2011)							✓				
Huang et al. (2012)							✓				
Atta (2013)	✓										
Taniguchi et al. (2014)											✓
Kodali & Ramakrishna (2017)	✓	✓									
Pilissy et al. (2017)											✓
Zakaria et al. (2017)											✓
Bae & Lee (2018)								✓			✓
Boonyakan et al. (2018)	✓				✓						

Table 4-4 Sanitation data collected in existing solutions (continued)

Reference	liq.	urine.	fav.	grey.	usage.	envs.	ECG.	uri.	fae.	res.	others
Namekar & Karthikeyan (2018)	✓					✓					
Zakaria et al. (2018)	✓	✓	✓	✓							
Balaceanu et al. (2019)											✓
Cai et al. (2019)	✓				✓						
Shaikh et al. (2019)					✓	✓					
Shinganwade et al. (2019)	✓				✓						✓
Tsuchiyama & Kajiwara (2019)										✓	
Deshmukh et al. (2020)						✓					
Park et al. (2020)								✓	✓		

Table 4-4 Sanitation data collected in existing solutions (continued)

Reference	liq.	urine.	fav.	grey.	usage.	envs.	ECG.	uri.	fae.	res.	others
Raendran et al. (2020)	✓					✓					
Rary et al. (2020)											
Syafaah et al. (2020)								✓			
Turman-Bryant et al. (2020)	✓	✓	✓								
Cotera Rivera & Bilton (2021)	✓				✓	✓					
Zhang et al. (2021)							✓	✓			
Akaho & Yoshioka (2022)										✓	
Bimantara et al. (2022)	✓				✓	✓					
Ge et al. (2022)								✓			

Table 4-4 Sanitation data collected in existing solutions (continued)

Reference	liq.	urine.	fav.	grey.	usage.	envs.	ECG.	uri.	fae.	res.	others
Kumar et al. (2022)							√				
SeeTo et al. (2022)											√
Tasoglu (2022)											√
Zhang et al. (2022)	√										

Where liq. = liquid volume in the water tank, urine. = urine volume, fav. = faecal volume, grey. = grey water volume, usage. = usage detection (infrared sensor, motion sensor), envs. = environmental status (air quality, cleanliness, user number), ECG. = ECG status, uri. = urine status, fae. = faecal status, res. = respiratory status.

4.3.4 Sanitation Data Cleaning and Preparation

Data cleaning and preparation removes redundant and irrelevant data, corrects inconsistencies, and formats usable data. The data cleaning and preparation phase mainly includes cleansing, integrating, and transforming the data (Cielen and Meysman, 2016).

Cleansing data detects and corrects corrupt or inaccurate records in a dataset while organising it into a proper structure. The most common cleansing steps include removing duplicates and irrelevant data, standardising capitalisation, converting data types, dealing with outliers, fixing errors, and handling missing values.

Data integration combines data from multiple sources into a single and unified view. The terms data integration, Extract, Transform, Load (ETL), data fusion, and data aggregation are frequently used interchangeably in the IoT literature (Ge et al., 2018). Sanitation data come from a variety of places and sources, ranging in size, type, and structure from databases and Excel files to text documents. Data integration combines these sanitation data from various sources, such as sensors, pumps, metres, and other smart assets, to provide a comprehensive view of sanitation systems. It is possible to perform the joining, appending, and stacking operations. Data integration helps to better understand the relationships between data points and to gain a thorough picture of the entire solution.

Data transformation involves structuring, restructuring, or reorganising data to facilitate analysis, reporting, and data management. Data transformation includes aggregating data, extrapolating data, deriving measures, creating dummies, and reducing the number of variables, as well as other tasks that enable data to be used efficiently. Sanitation data transformation converts raw data from the current format into a usable form for analysis. The transformed data can be used to make decisions, generate insights, and improve processes. Data transformation makes data more accessible and allows for better decision-making.

Data quality management (DQM) is involved in the entire data cleaning and preparation phase. DQM ensures that data collected from IoT devices are accurate, timely, and of the desired quality. It entails identifying, evaluating, and correcting data quality issues such as data accuracy, completeness, consistency, and timeliness. By assessing and monitoring data quality, businesses can ensure that their IoT solutions are effective and deliver expected results. DQM in intelligent sanitation manages and monitors the quality of data collected from connected sanitation facilities to ensure accuracy, real-time, and reliability. This involves the implementation of standards, procedures, and processes to manage, monitor, assess, and improve the quality of collected data. However, there has been little research into DQM in the intelligent sanitation domain. DQM can help improve decision-making, user satisfaction, cost reduction, efficiency, and compliance.

4.3.5 Sanitation Data Storage

Data storage is an important phase in data analytics for ensuring that data are stored securely and efficiently. Various types of data storage solutions are available, including local, edge, and cloud storage, each with its own advantages and disadvantages (see

Table 4-5). Therefore, it is critical to select appropriate methods for specific sanitation applications and solutions.

Local storage allows data to be stored locally and efficiently, allowing it to be processed, analysed, and shared in real time. Local storage lowers latency and increases response time. Furthermore, it processes data in a secure manner without the need for a third-party platform or cloud provider. In intelligent sanitation, local storage can be used to store sanitation infrastructure data such as location, usage, and maintenance. The information can be used to improve the sanitation system performance and identify potential failures. The stored data can also be used to monitor sanitation-related services such as waste collection, water supply, and sewage treatment. Local storage is required for intelligent sanitation solutions to provide secure, reliable, and efficient data storage and retrieval.

Edge storage employs nodes located at the network edge, rather than in a centralised data centre to store and process data closer to the source. Edge storage nodes such as gateways, routers, or other local devices, typically contain small-scale storage such as flash memory, RAM, and a processor. Edge storage provides a method for lowering latency, increasing reliability, and optimising the application performance. Edge storage is becoming increasingly important for intelligent sanitation applications because it allows data to be stored and analysed locally, which improves the security of sensitive sanitation data and user privacy. Intelligent sanitation can also use edge storage to improve resource efficiency. The system can recognise when resources are being used more efficiently and make changes accordingly, to reduce waste and cost in the long run. Edge storage will become even more important in the future, as the demand for intelligent sanitation systems will increase.

Cloud storage stores data across multiple servers and locations. Cloud storage enables users to store, access, and manage data in the cloud easily and affordably. By leveraging cloud-based storage, businesses can reduce their reliance on on-premises data centres, which can be expensive and time consuming to maintain. Furthermore, cloud storage provides a scalable solution that can easily accommodate the massive amounts of data generated by IoT devices. Cloud storage platforms such as AWS, Azure, and Google Cloud provide secure and efficient data storage, as well as scalability, and flexibility. Cloud storage can be used to monitor and track the performance of sanitation systems such as pipes and pumps. The data can be utilised to identify trends and potential issues in system performance. Additionally, they assist in developing maintenance schedules and optimising the system for maximum efficiency. With the increase connected sanitation facilities, there is an ever-growing need to store and access data in the cloud. Cloud storage is becoming an essential component of intelligent sanitation, allowing solutions to remotely store and manage data from smart assets while also providing users with global access to valuable data.

Table 4-5 Summary of sanitation data storage methods

Methods	Description	Advantages	Disadvantages
Local storage	Store data on a local device or server	- Real-time data - Faster access - Improved security	- Limited capacity - Inaccessible in real time - Unavailable to others
Edge storage	Store data on the edge of the network, near the data source	- Reduced latency - Distributed storage - Scalability and flexibility	- Security risk - Limited bandwidth - Regular maintenance and update
Cloud storage	Store and access data globally via network connections	- Automated backups - Accessibility - Collaboration - Increased efficiency	- Security risks: cyber-attacks, data breaches, and unauthorized access - Dependency on network connection - Data loss: hardware failure, software bugs, technical issues

4.3.6 Sanitation Data Analysis

Data analysis is the phase of identifying patterns, correlations, and other insights into the data by looking for trends, uncovering relationships between variables, and identifying outliers. Data is filtered, aggregated, and analysed using powerful statistics and machine learning algorithms. Data analysis can help businesses make better decisions, optimise processes, and gain a competitive advantage. It can also be used to uncover potential problems, detect failures, and identify new opportunities. A combination of advanced techniques such as data mining, machine learning, and statistical methods, can be used to improve data analysis performance. Data mining identifies patterns and correlations in large datasets, statistical analysis identifies correlations between different variables, and machine learning develops models to forecast future trends and behaviours. Descriptive analysis, diagnostic analysis, predictive analysis, and prescriptive analysis are the most common intelligent sanitation data analysis methods. The section summarises the advantages and disadvantages of these four methods, as well as the sanitation problems addressed (see Table 4-6).

Table 4-6 Summary of sanitation data analysis methods

Methods	Descriptions	Advantages	Disadvantages	Solutions
Descriptive analysis	Summarise data and help identify patterns of behaviour	- Easy to understand - Summarises data - Identifies patterns	- Inability in cause & effect - Time consuming - Limited predictive ability	- What happened - When did it happen - How often did it happen
Diagnostic analysis	Understand the causes of events, problems, issues	- Early detection - Improved performance - Cost reduction	- Time-consuming - Reliant on data accuracy	- Why did it happen - What caused it - How it happened
Predictive analysis	Predict future outcomes	- Forecast trends and future behaviours - Predictive service	- Data-driven bias - Over-reliance on past performance	- What is likely to happen - When is it likely to happen
Prescriptive analysis	Identify the best course of action	- Accurate decision making - Improved efficiency	- Limited scope - High complexity	- What is the best decision - How to act in response

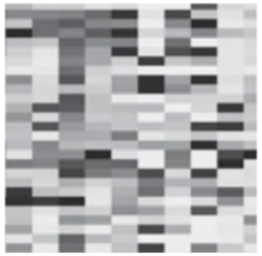
4.3.7 Sanitation Data Visualisation

Data visualisation in IoT refers to the phase of collecting data from physical objects and presenting it in a graphical or visual format to gain a better understanding of the data. Data visualisation can be used in IoT applications for monitoring, analysis, forecasting, and decision making. Data visualisation includes dashboards, charts, graphs, maps, and other visual representations of the data. Data visualisation assists in identifying correlations, patterns, and trends among various data points, forecasting future behaviour and issues, and making informed decisions. Although data visualisation is not required for all data analysis solutions, it is an important tool for understanding and managing complex systems.

Data visualisation helps offer insight into the performance of sanitation systems, allowing for identifying problems and potential improvements. The performance of the sensors such as temperature and pH, are tracked over time using data visualisation. Data visualisation can be used to compare different sanitation systems, providing a better understanding of their performance and how they compare to one another. Existing intelligent sanitation solutions lack data visualisation features. Most intelligent sanitation applications rely on user interaction software, such as the web and apps, to display real-time sensor readings, user feedback, and unprocessed data. However, existing intelligent sanitation software rarely processes the data, making it difficult for users to gain further meaningful insights. In intelligent sanitation, data visualisation is a graphical representation of data used to communicate complex information in an understandable format. The section lists the most common data visualisation methods, as well as their advantages and disadvantages (see Table 4-7).

Table 4-7 Summary of sanitation data visualisation methods

Methods	Advantages	Disadvantages	Examples
Line charts	- Simple - Straightforward - Identify trends	- Limited on massive data - Limited on multiple lines - Limited on multiple variables	
Bar graphs	- Easy - Understandable - Perform comparisons	- Limited on massive data - Show approximate values - Limited on scales difference	
Pie charts	- Show percentages - Show proportions - Compare data across different categories	- Limited on massive slices - Limited on showing trends - Labelling is difficult - Visually overwhelming	

Scatter plots	- Show correlation - Show trends - Identify outliers - Identify clusters	- Abundance of data points - Complex and cluttered - Limited on showing trends - Visually overwhelming	
Heat maps	- Easy to interpret - Quick comparison - Colour coding - Data clustering	- Required large amount of data - Limited on trends and cluster - Difficult to read for colourblind individuals	

4.3.8 Sanitation Modelling

Modelling is the phase of organising data into logical structures and establishing relationships between various pieces of data. Modelling involves analysing the data, creating a model, testing the model, and refining the model. Modelling is used to reduce data redundancy, improve data accuracy, identify potential problems, and gain data insight (Ahmed et al., 2016; Ran et al., 2019; Zonta et al., 2020; Filz et al., 2021; Rahmani et al., 2021; Serradilla et al., 2022). According to a review of the literature from 2000 to 2022, only a few intelligent sanitation solutions have passed through the advanced modelling phase. The section outlines these solutions and the algorithms that they employ (see

Table 4-8).

Statistical and machine learning techniques, such as regression, time series forecasting, dimensionality reduction, classification, clustering, and neural networks, are commonly used algorithms for creating models (Perros, 2021). Regression analyses IoT data by predicting the values of one or more dependent variables based on the values of several independent variables. Based on historical data, time series forecasting analyses IoT data by predicting future values of a variable. The number of features in a dataset is reduced using dimensionality reduction techniques, making it easier to analyse. Classification techniques categorise objects in IoT systems into various categories or classes, such as different types of devices or sensors. Clustering techniques group similar objects based on their features and attributes to identify outliers or anomalies. Neural networks are used to identify patterns and relationships in the IoT data. Assessing models is an essential part of the modelling phase to guarantee accuracy, identify potential enhancements, and uncover additional insights. To assess the modelling, several steps can be taken, including identifying the purpose of the model, testing and comparing it to other models, evaluating its accuracy and scalability, analysing the results, recording the model, and reviewing its performance over time.

Table 4-8 Summary of modelling algorithms for existing solutions

Reference	Regression	K-Means	SVM	RF	DL	CNN	RNN	LSTM	ARIMA
Huang et al. (2012)	✓								
Atta (2013)	✓								
Deshmukh et al. (2020)									✓
Park et al. (2020)					✓	✓			
Syafaah et al. (2020)		✓							
Turman-Bryant et al. (2020)	✓		✓						
Zhang et al. (2021)			✓		✓	✓	✓	✓	
SeeTo et al. (2022)	✓		✓	✓	✓	✓			

Where SVM = support vector machines, RF = random forest, DL = deep learning, CNN = convolutional neural network, RNN = recurrent neural network, LSTM = long short-term memory, ARIMA = autoregressive integrated moving average model.

4.3.9 Sanitation Evaluation

Evaluation is a phase in which data are collected and analysed to determine the effectiveness and efficiency of a result, process, or project. It entails assessing the performance of a model, algorithm, or solution using metrics such as accuracy, satisfaction, or user feedback. Evaluation assists businesses in identifying areas for improvement and in making better decisions. Model evaluation is an essential part of the evaluation phase, which can be used to assess a model's effectiveness, identify its strengths and weaknesses, and gain insight into how well it performs. The common model evaluation techniques include k-fold cross-validation, leave-one-out validation, and A/B testing. The selection of an appropriate evaluation technique is essential for ensuring that the model produces accurate results. Data scientists can determine which model produces the most accurate results by comparing different models. In IoT data analytics, evaluation is the process of assessing the quality of collected data and identifying any potential gaps in the data as well as any other inconsistencies, errors, or outliers. Evaluation ensures that the data collected are update and relevant, and that it can be used to make accurate predictions and decisions. Intelligent sanitation evaluation measures, evaluates, and analyses the performance and effectiveness of sanitation systems and processes. Evaluation ensures that the intelligent sanitation services meet the standards, meet the needs of users, and keep the systems operational. It is critical to measure both the short- and long-term effects to determine whether the intelligent sanitation system meets the predefined standards. Evaluation should be performed before deploying intelligent sanitation solutions. Some evaluation tips are as follows (IBM, 2023):

- Determine the purpose of the integrated data analytics solutions: Identify business success criteria, comprehend stated business objectives, and evaluate approved models that should meet.

- Evaluate the results: Review data, assess accuracy and reliability, compare results to expected outcomes, identify any errors or discrepancies, suggest ways to improve, validate research findings, and inform decision-making.

- Review the process: Assess the successes and weaknesses of the data analytics process.

- Access application features: Consider scalability and dependability, as well as the ability to integrate with other systems.

- Consider cost: Determine the cost of implementation and update.

- Analyse security: Ensure the privacy policies are in accordance with all applicable regulations.

- Test the solutions: Test the solution under a variety of conditions and scenarios to assess its performance.

- Determine the next steps: i) Continue to the deployment phase: analyse the current progress of the project, establish clear objectives, develop a timeline, establish a budget, identify resources, assign tasks, and monitor progress; ii) Refine or replace models or algorithms: refine the models and produce better results.

4.3.10 Sanitation Deployment

Deployment is the phase of integrating data analytics into existing systems to ensure that the data are accessible, usable, and secure. The deployment phase can range from producing a simple report to establishing a replicable data analytics process. The deployment of data analytics is a complex process that involves numerous steps and stakeholders. The results of the data analysis are presented in reports, allowing stakeholders to interpret the data and make informed decisions easily. Intelligent sanitation solution requires the deployment of hardware components such as sensors, gateways, and other devices, as well as the implementation of software components, including operating systems, applications, and analytics code, into their operational environment. To guarantee that the system performs optimally and provides the desired outcomes, it is imperative to integrate, test, and monitor the components correctly. The system must be checked regularly to ensure that it runs correctly. This involves assessing the performance of the system and resolving potential problems that may arise. Deploying a project is a process of transitioning from its development phase to its active use. This typically includes making a project available to users, either in a testing or production environment. Some deployment tips are as follows (IBM, 2023):

- Plan for deployment: Ensure a smooth and comprehensive deployment of data analytics results, including summarising both models and findings, developing a step-by-step plan for deployment and integration, developing a plan to disseminate information to decision-makers, identifying problems, and planning for contingencies.

- Plan monitoring and maintenance: Track the factors or influences on the model or findings, measure and monitor the validity and accuracy of each solution, rebuild and update the model with newer data or make minor adjustments, and document the process.

- Produce a final report: Create a detailed description of the solution overview, process outline, cost showing, result summary, and future recommendations.

- Conduct a final project review: Formulate project final impressions, summarise the lessons learned, analyse strengths and weaknesses of the solution, assess the value and benefits to stakeholders.

4.4 A Case Study of the Cranfield Intelligent Toilet

The proposed generalised San-IoT-DA tool is illustrated through a case study of the Cranfield intelligent toilet (i.e., Cranfield Circular Toilet), demonstrating its applicability for intelligent sanitation in practice. Traditional sanitation systems require significant capital investment and do not ensure reliable and sustainable waste treatment (World Health Organisation, 2021). There is an increasing need to combine advanced technologies to link, manage, and monitor sanitation systems (Sethi and Sarangi, 2017). The Cranfield Circular Toilet integrates the IoT and data analytics to create advanced, safe, independent, and manageable sanitation systems. The Cranfield Circular Toilet utilises the five-layer San-IoT framework (perception layer, data link layer, network layer, transport layer, and application layer) to collect, transfer, and process data. It also utilises the San-IoT-DA tool (business understanding, data understanding, data acquisition, data cleaning and preparation, data storage, data analysis, data visualisation, modelling, evaluation, and deployment phases) to analyse the data and gain insight. The San-IoT-DA enabled the Cranfield Circular Toilet to provide actionable data, enabling stakeholders to collaborate more effectively and make informed decisions. The data-driven sanitation solution allows increased efficiency and improved outcomes.

4.4.1 Business Understanding

The Cranfield Circular Toilet is composed of an ultra-low pre wetting module, liquids treatment module, solids treatment module, and control module (see Figure 4-3), as listed below:

- Ultra-low pre-wetting module: An effective rotating toilet flush with minimal water consumption;

- Liquids treatment module: A membrane distillation (MD) unit designed for high-performance liquid waste purification;

- Solids treatment module: A pathogen-free solid waste decomposition unit;

- Control module: A control unit for monitoring, controlling, and managing an intelligent toilet.

The ultra-low pre-wetting module and liquids treatment module are important components of the Cranfield Circular Toilet, which converts waste liquid from the front end into reusable water via a series of filtration and MD units. The section demonstrates the integration of data analytics for ultra-low pre-wetting module and liquids treatment module to gain a more comprehensive understanding of system performance and user urination events.

During the business understanding phase, it is necessary to analyse the system structure and hardware components of an intelligent toilet. The ultra-low pre-wetting module has been equipped with trigger sensors, such as open and closed lid switches, and an innovative designed rotating bowl flush. The liquids treatment module comprises an MD hot tank pump, MD cold tank pump, Peltier, and radiator fans. By understanding the hardware in an IoT solution, it is possible to ensure compatibility between the components, the IoT platform, and other devices. Additionally, this understanding can help to identify potential security risks, vulnerabilities, and compatibility issues. The Cranfield Circular Toilet is outfitted with several hardware components that contribute to its smartness. Some hardware components are listed in

Table 4-9.

Figure 4-3 The Cranfield intelligent toilet modules

Table 4-9 Understanding the hardware components

Product Code	Description	Features
Stock No.: 228-7489	Type K Thermocouple Rod 250mm Length, 3mm Diametre +1100°C	• Type K thermocouple temperature sensors • Temperature range: -100 to +1100°C
Stock No.: 896-8291	Square Antenna with IPEX Connector, 2G (GSM/GPRS), 3G (UTMS), 4G, 4G (LTE Cat-M), 4G (LTE), 5G (LTE), ISM Band, LoRaWan, NB IoT, NB-IoT	• GSM/GPRS/3G/ISM PCB antenna • Quad band: 850, 900, 1800, 1900 MHz • Frequency range: 699 → 6000 Mhz
Stock No.: 811-8538	Illuminated Momentary Push Button Switch, Panel Mount, SPDT, Blue LED, 250V AC	• Operating life: 50,000 cycles • Terminal type: quick connect
Stock No.: 668-8858	Axial Fan, 24V DC, 120 x 120 x 25mm	• Air flow: 144.4m³/h • Fan speed: 2200rpm
Stock No.: 920-9966	Heating Element, 415 W, 230V AC	• Nozzle heaters • Up to 1000°F
Stock No.: 705-9327	Diaphragm Electric Operated Positive Displacement Pump, 3.8L/min, 2.5 Bar, 24V DC	• Maximum flow rate: 3.8L/min • Maximum working pressure: 2.5 bar

By understanding the system performance patterns, it is possible to identify areas for improvement, improve the overall efficiency of the system, detect potential issues, and facilitate faster troubleshooting. The section demonstrates the integration of data analytics with the sanitation IoT solution on the Cranfield Circular Toilet. The system enables the identification of system patterns, productivity enhancements, process optimisation, real-time insights, and informed decision-making.

The section simulates urination events from a family of five consisting of two males and three females, through experiments (see

Table 4-10). The section examines urination events to gain a comprehensive business understanding, thus enabling more effective utilisation of the collected data for further data analytics. The experiment is as follows:

- Urination events occurred between 9:00 am -12:00 pm, to simulate a busy morning, when the toilet is most frequently used.

- A family of five, consisting of two males and three females, took part in the urination events, where M^1 = father (work during the day), F^1 = mother (home all day), F^2 = young child (home all day), M^2 = teenage boy (school during the day), and F^3 = teenage girl (school during the day).

- According to ISO 30500 standards, each individual urinates a total volume of 1-1.2L per day.

- Each urination event activates cascade flushing, and the females clean the rotating bowl with the front nozzle.

- Male behaviour sequence: lift lid -> pre-wet -> urination -> closed lid.

- Female behaviour sequence: lift lid -> pre-wet -> urination -> two times short press flushing -> closed lid.

- Every time the user uses the toilet, all the sensors on the front end will be triggered.

- When the waste liquids accumulate to a specific quantity in the tank, the MD module will activate its operations.

- The control module monitors and governs the entire urination events, while the IoT system transmits generated operational data to the cloud platform for further analysis.

- The experiment only approximates the urination events of a family of five, and the results may differ from what is observed in reality. The implementation of the experiment is constrained by personnel, resources, time, and other factors.

Table 4-10 Simulate the intelligent toilet usage process of a family of five

Simulated Participants	**Time**										
	09:10	**09:13**	**09:35**	**09:42**	**10:09**	**10:13**	**10:23**	**10:35**	**10:48**	**11:10**	**11:36**
M^1	×										
F^1		×				×				×	
F^2			×				×				×
M^2				×				×			
F^3					×				×		

Where M^1 = father (work during the day), F^1 = mother (home all day), F^2 = young child (home all day), M^2 = teenage boy (school during the day), F^3 = teenage girl (school during the day).

4.4.2 Data Understanding

Cranfield Circular Toilet uses data understanding to identify patterns and relationships in data. It enables analysts to identify potential trends and outliers, as well as generate hypotheses about the data. Furthermore, data understanding helps to determine the best methods for further analysis, such as statistical or machine learning techniques. Understanding data helps to create a better understanding of the underlying business problem, which can lead to better decisions and solutions. Cranfield Circular Toilet engineers use an LCD to display the toilet's operating status in real time. The section examines the LCD display message and corresponding action when the system is in operation. The analysis of the LCD display aids in enhancing the comprehension of the characteristics of the data produced by the system. Some LCD content analysis samples are presented in

Table 4-11. The section examines the data structure, type, format, and range of the Cranfield Circular Toilet to gain insights into data patterns, trends, and outliers. The findings are summarised in Table 4-12.

Table 4-11 Examples of LCD displays for MD liquids operations

Message on LCD	Duration (sec)	Description / Action
Membrane Distillation BP: 96 DP: 0 21:33	3	Membrane Distillation Process in Session - LCD Message 1: Brine Pump and Distillation Pump Speeds (in byte forms) and time display in mm:ss
Membrane Distillation PEL: 1 FAN: 255 21:37	3	Membrane Distillation Process in Session - LCD Message 2: Peltier Module Operation (0-1) Radiator Fans Speed (in byte form) and time display in mm:ss
ColdIn ColdOut HotIn HotOut 31º 62º 68º 36º	6	Temperature readings at the AGMD cylinder's inlets and outlets, in this order: Cold In, Cold Out, Hot In, Hot Out

Table 4-12 Examples of the toilet data understanding

Measured Components	Code	Name	Value Range	Description	Pre-Calculation	Measurement Unit
Temperature Recordings	T00	MD Cold In Temperature	0 - 999	Temperature in Deg.C	-	ºC
	T01	MD Cold Out Temperature	0 - 999	Temperature in Deg.C	-	ºC
	T02	MD Hot In Temperature	0 - 999	Temperature in Deg.C	-	ºC
	T03	MD Hot Out Temperature	0 - 999	Temperature in Deg.C	-	ºC
System Outputs	O00	Toilet Cleaning Valves Operation	0,1,2,4,8	Pan Front Nozzle, Pan Cascade, Bowl Left Nozzle, Bowl Right Nozzle: 0: - , 1: OPEN	0b0000X000: Pan Front Nozzle 0b00000X00: Pan Cascade 0b000000X0: Bowl Left Nozzle 0b0000000X: Bowl Right Nozzle	-

Table 4-12 Examples of the toilet data understanding (continued)

Measured Components	Code	Name	Value Range	Description	Pre-Calculation	Measurement Unit
System Outputs	O01	Toilet Cleaning Pump Speed	0 - 255	Speed in Bytes	Divide by 2.55, round up to no decimals	% Duty Cycle
	O02	Auger Screw Motor Speed	0 - 510	Speed in Bytes + Direction	Subtract 255, then divide by 2.55, round up to no decimals	% Duty Cycle
	O03	Evacuation Pump Speed	0 - 510	Speed in Bytes + Direction	Subtract 255, then divide by 2.55, round up to no decimals	% Duty Cycle
	O04	Peltier Module Operation	0,1	0: OFF, 1: ON	-	-
	O05	Radiator Fans Speed	0 - 255	Speed in Bytes	Divide by 2.55, round up to no decimals	% Duty Cycle

Table 4-12 Examples of the toilet data understanding (continued)

Measured Components	Code	Name	Value Range	Description	Pre-Calculation	Measurement Unit
System Outputs	O06	MD Distillate Pump Speed	0 - 255	Speed in Bytes	Divide by 2.55, round up to no decimals	% Duty Cycle
	O07	MD Brine Pump Speed	0 - 255	Speed in Bytes	Divide by 2.55, round up to no decimals	% Duty Cycle
System Inputs	I00	Lid Closed Float Switch	0,1	0: - , 1: Seat Lid Closed	-	-
	I01	Lid Open Float Switch	0,1	0: - , 1: Seat Lid Open	-	-
	I02	Flush Button Press	0,1	0: - , 1: Pressed	-	-
	I03	MD Brine Tank Lower Float Switch	0,1	0: - 1: HIGH	-	-

4.4.3 Data Acquisition

Data acquisition enables analysts to access and analyse data from multiple sources and formats in a timely and accurate manner. It ensures that the data are reliable and up to date, allowing efficient and effective data analysis. The perception layer of the Cranfield Circular Toilet facilitates data acquisition by hosting all smart objects and end devices. It effectively bridges the gap between the physical and digital worlds (see Figure 4-4). Smart objects integrated within the Cranfield Circular Toilet have been designed to meet the demands of simplicity, usability, versatility, open-architecture, connectivity, scalability, and security. The smart objects are intelligent and autonomous, providing accurate and real-time data collection. Through simple operation, the system can convert analogy data into digital signals with comprehensive data reporting. The installed devices are renowned for their impressive water resistance, robustness, low energy consumption, reliable signals, and easy maintenance. The collected data are then transferred through communication connection established at the data link layer, network layer, and transport layer. The Cranfield Circular Toilet utilises global, scalable, stable, cross-platform, easy-to-migrate, and highly compatible communication protocols. These protocols facilitate sending data to the cloud platform for further processing.

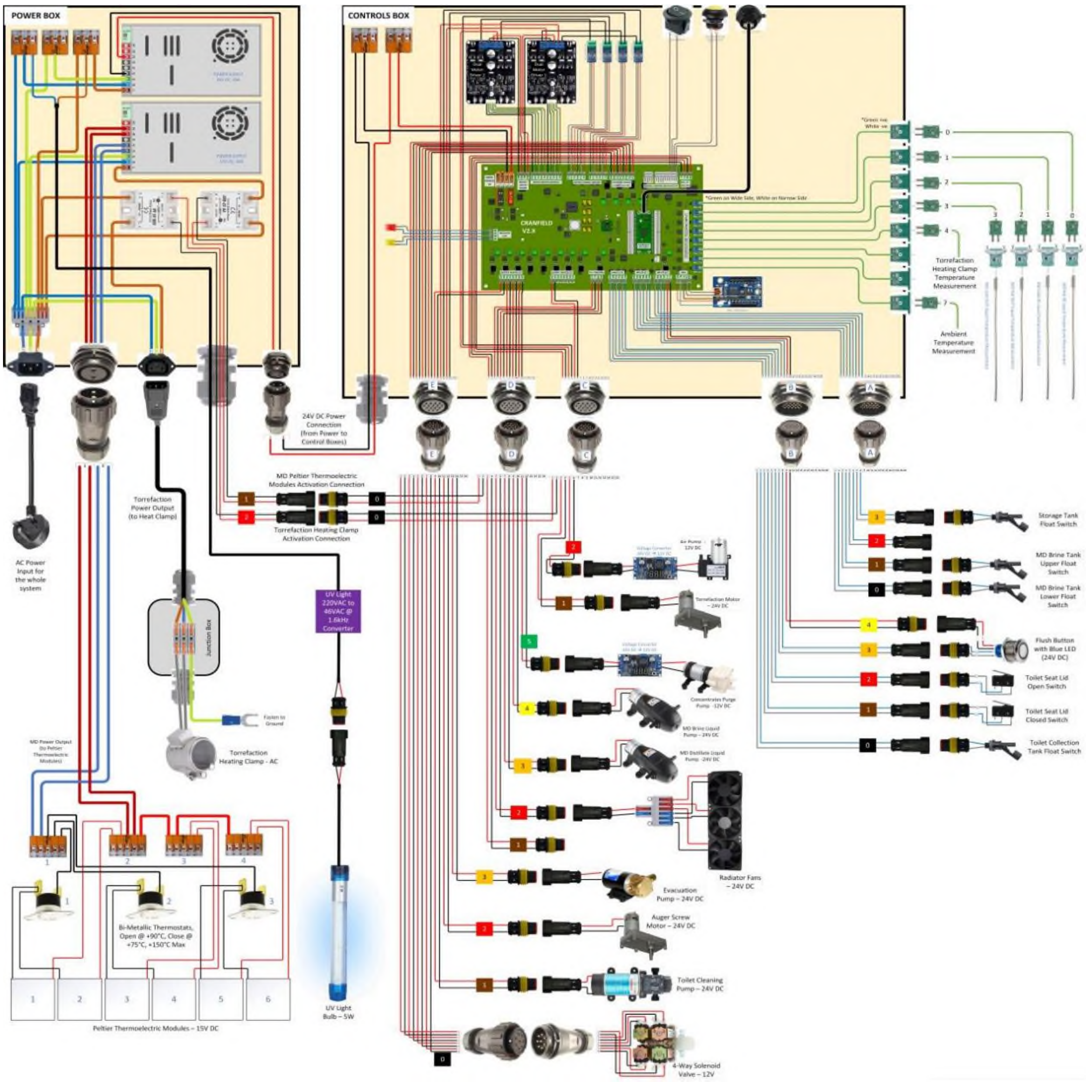


Figure 4-4 An overview of Cranfield intelligent toilet smart objects

4.4.4 Data Cleaning and Preparation

Cranfield Circular Toilet collects raw data from the IoT solution, and then cleaned and prepared them to usable ones. The section focuses on the data generated by the sensors that are triggered during a urination event, and excludes other data. The sensors triggered during the event are identified and numbered. The section identifies and fixes errors and inconsistencies in the data, combines data from various sensors, and adds context to the data, to ensure that the sanitation data are accurate, complete, and useful. The section processes the collected sanitation data into a data list consisting of sensor type, sensor data, and sensor time (see Table 4-13). The section uses visualisations to present the raw data, making it easier to identify outliers and missing values (see Figure 4-).

Table 4-13 Examples of collected toilet data

Sensor Type	Sensor Data	Sensor Time	Sensor Type	Sensor Data	Sensor Time
31	0	1678439185	...	...	...
9	4	1678439190	2	52	1678450015
10	77	1678439190	3	65	1678450021
9	0	1678439190	2	53	1678450027
10	0	1678439190	3	66	1678450033
32	1	1678439190	2	54	1678450039
51	1	1678439190	3	67	1678450045
1	11	1678439203	2	55	1678450051
8	12	1678439203	3	68	1678450057
9	2	1678439230	2	56	1678450064
10	77	1678439230	3	69	1678450071
32	0	1678439230	2	57	1678450080
31	1	1678439230	3	70	1678450089
9	1	1678439235	2	58	1678450097
9	0	1678439235	3	71	1678450106

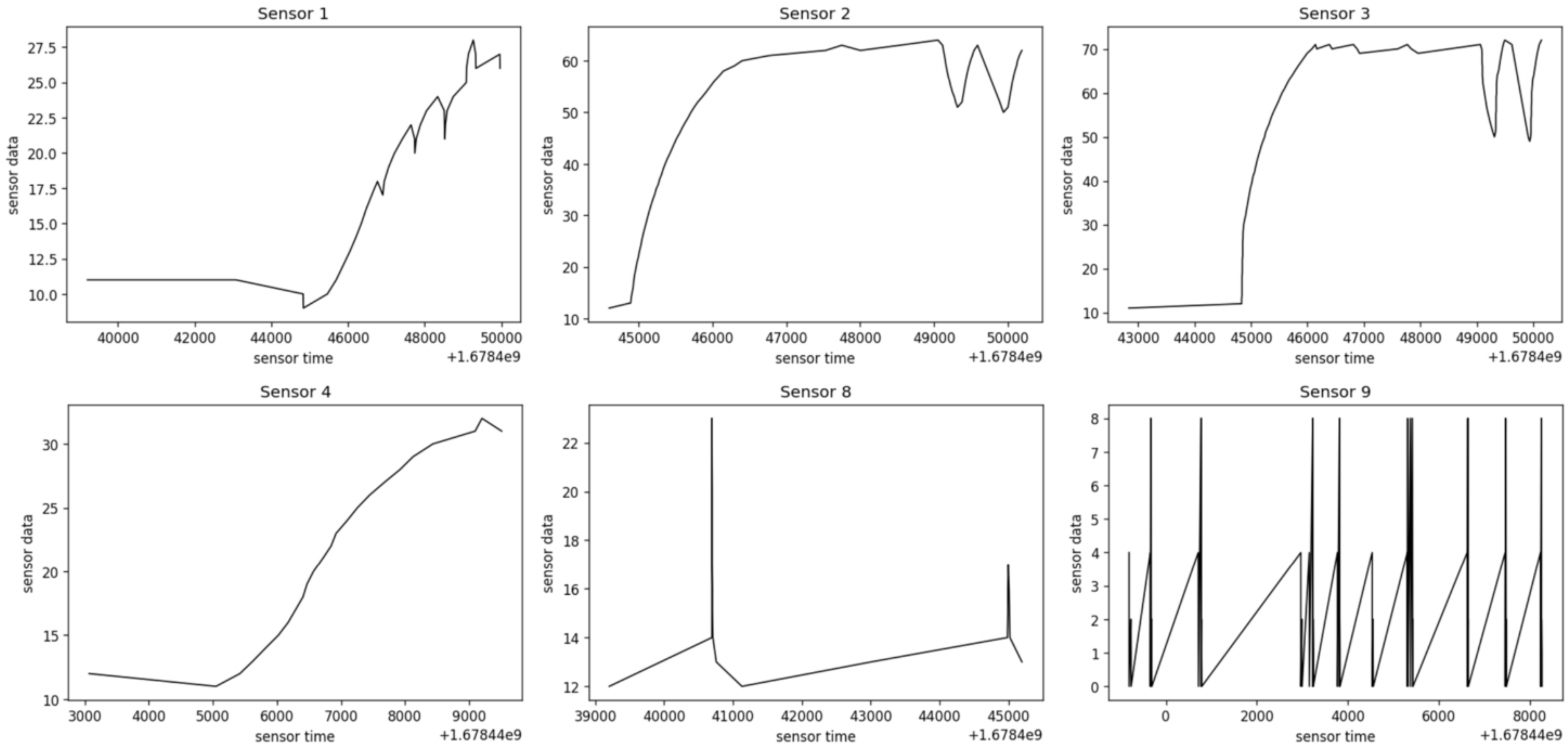


Figure 4-5 Visualise collected toilet data (sensors 1, 2, 3, 4, 8, 9)

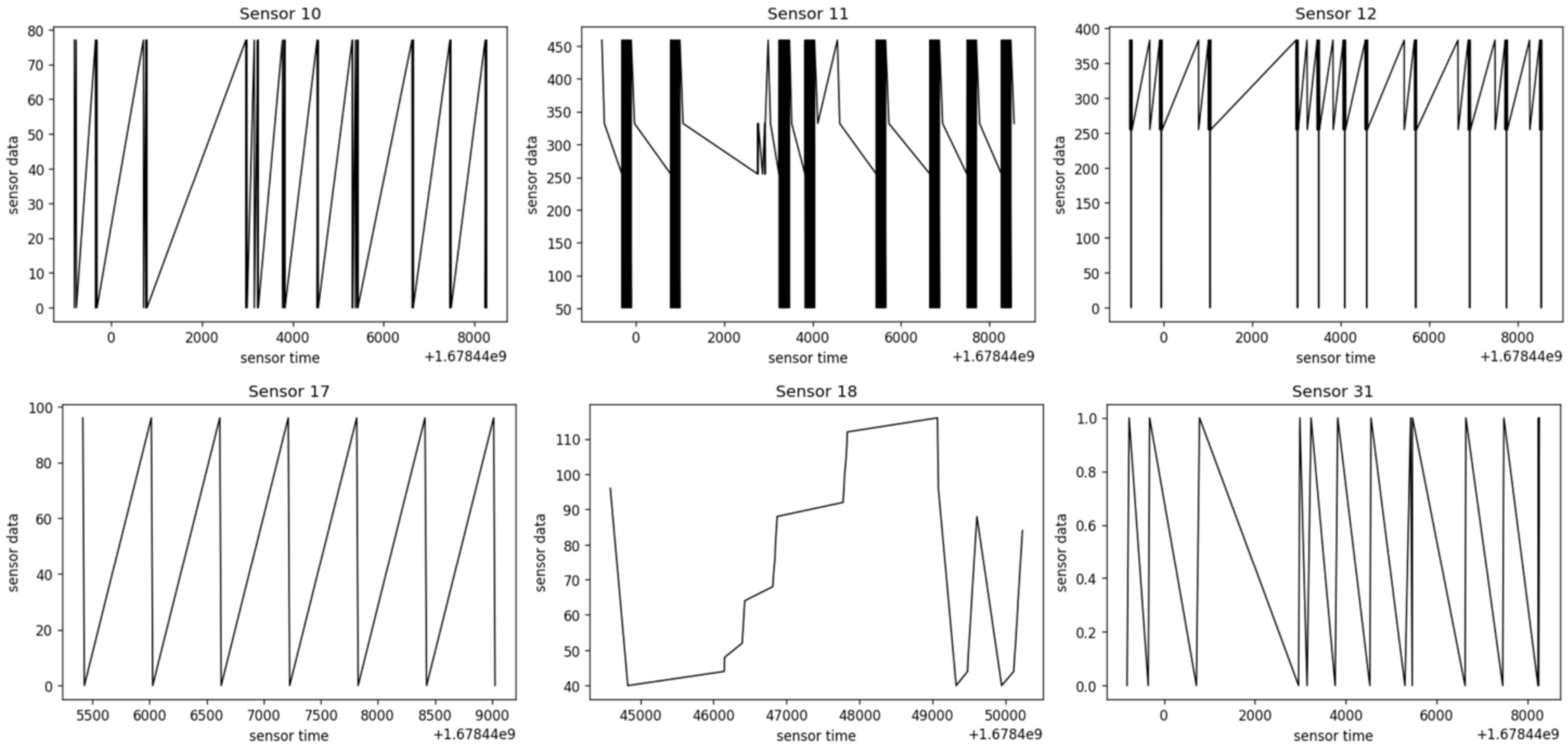


Figure 4-5 Visualise collected toilet data (sensors 10, 11, 12, 17, 18, 31)

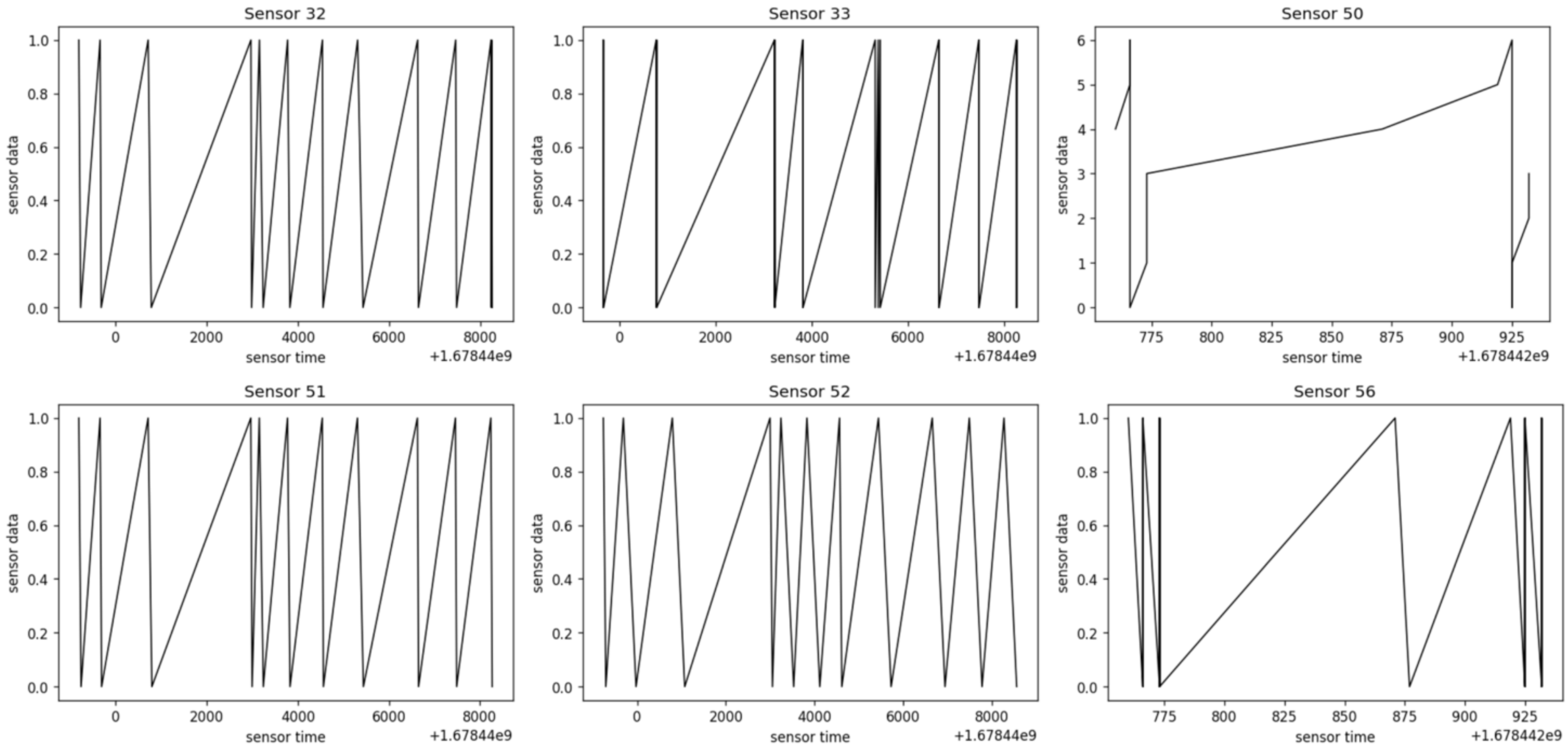


Figure 4-5 Visualise collected toilet data (sensors 32, 33, 50, 51, 52, 56)

4.4.5 Data Storage

The processed data from Cranfield Circular Toilet is securely stored both locally and, in the cloud, in an easy-to-understand format. A large quantity of time-stamped data, ranging from the amount of liquid to the performance of the equipment, is produced daily by sanitation facilities. These data are valuable for facility managers, toilet users, and environmental regulators, as they offer a comprehensive view of the operations of the facility and can be utilised to make informed decisions.

Cold data, which are used less frequently, are an essential for uncovering patterns and trends, as well as hidden relationships between variables. By analysing cold data related to toilet components, researchers and engineers can gain valuable insights into how these components interact and affect the system. The information can then be used to create more efficient and effective toilet systems that are better suited to the environment and are easier to maintain. Moreover, cold data can be employed to identify weak points in the system that require repairs or additional maintenance. Hot data, which are used more frequently, are processed for retrieval and visualisation. Hot data are a crucial source of information for data visualisation because they reflect the current system state. Hot data visualisation aids in making sense of massive amounts of data and improves the comprehension of trends, patterns, and relationships.

The Cranfield Circular Toilet can take advantage of cloud servers to store the vast amount of cold data generated by its sensors. Cloud servers allow for far more storage capacity than a local server, and makes it easier to access the data from anywhere and at any time for analysis and decision-making. In addition, the data are kept more secure on the cloud because of their remote location, which makes them resistant to physical damage or theft. Local storage of hot data as a rolling backup is an effective way to protect against accidental system errors and data corruption. By taking regular snapshots of the data and keeping a record of all changes made in between, rolling backups ensure that the most recent version of the data can be quickly restored in the event of unexpected system failures. Storing the backup locally on the same computer or server as the original data provides greater control and reliability, as it can be managed and monitored directly by analysts.

4.4.6 Data Analysis

Using data analysis, the Cranfield Circular Toilet can make more informed decisions, optimise its processes, and increase its efficiency. Removing the temporal component from the data allows analysts to observe trends and patterns that are not influenced by time, and to focus on the root cause of their analysis (see Figure 4-6). Time series decomposition is used in the Cranfield Circular Toilet to explore underlying patterns, identify long-term trends, short-term fluctuations, and outliers in a dataset (see Figure 4-7). Histograms are used to identify the shape of a distribution, compare different distributions, and estimate the likelihood of a given value occurring (see Figure 4-8). By plotting a histogram, analysts can determine the range of values and identify outliers or other unusual trends in the data. Comparing multiple histograms can help to identify similarities or differences between different distributions, which can be useful for understanding relationships between different datasets or for finding potential correlations between different variables. Kernel density estimation (KDE) is used to estimate the probability density function of sanitation datasets (see Figure 4-9). By providing a smooth, continuous estimate of the underlying probability distribution, KDE offers greater visual clarity and more accurate inferences from the data. Additionally, KDE is resistant to outliers, requires a smaller sample size, and has low computational cost. Box plots are used to provide a graphical summary of sanitation data, showing the median, quartiles, range, and outliers in a single graph. Box plots make it easier to compare multiple groups, identify outliers, and understand the distribution of data (see Figure 4-10). Statistical techniques such as mean, standard deviation, min, Q1, median, Q2, max, and IQR, are be used to analyse the sensor data collected during the experiment (see Table 4-14). Statistical analysis can provide insight into the data distribution and help identify outliers. Statistical analysis can reveal potential risks and opportunities, allowing toilet managers to make more strategic decisions.

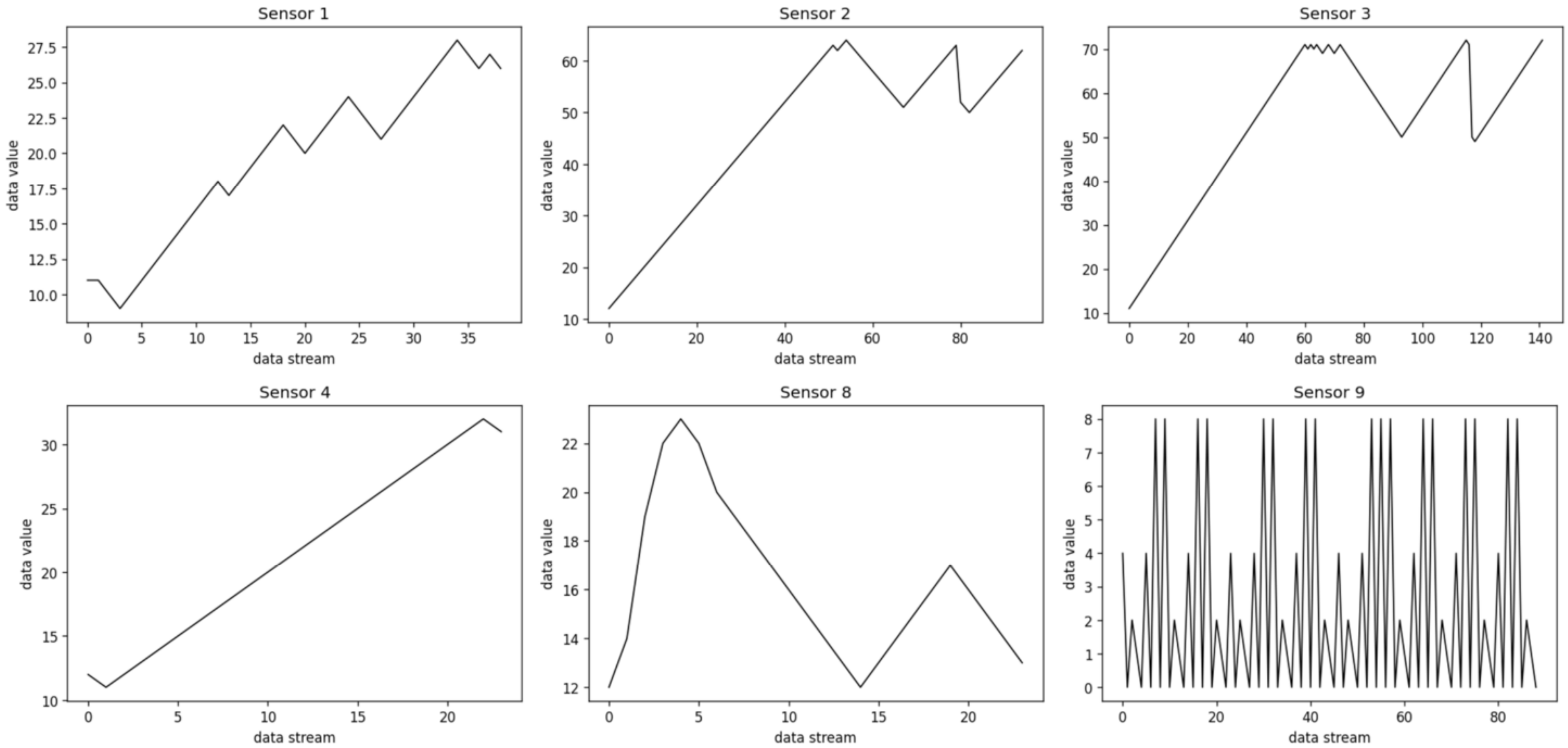


Figure 4-6 Sanitation data examples removal temporal effects (sensors 1, 2, 3, 4, 8, 9)

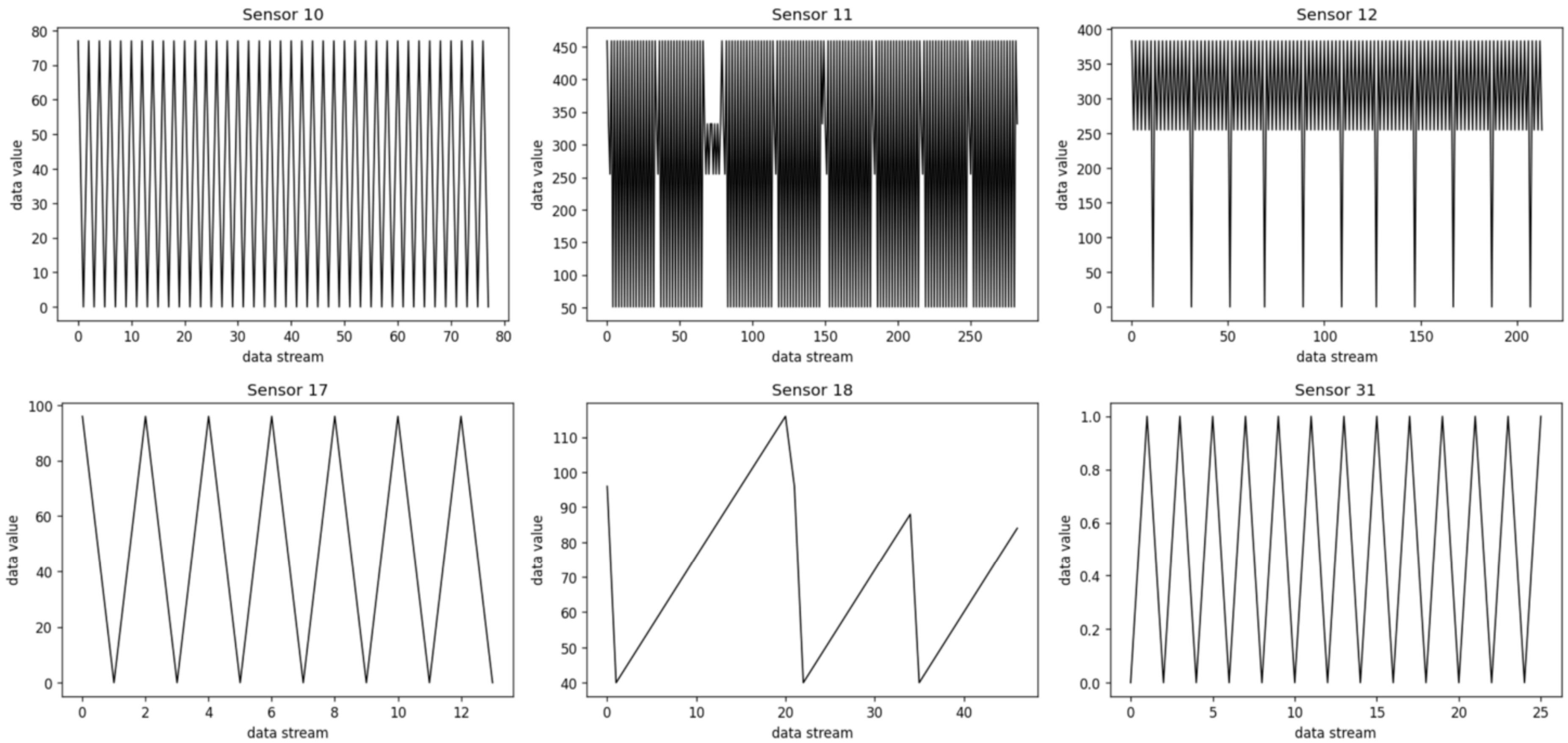


Figure 4-6 Sanitation data examples removal temporal effects (sensors 10, 11, 12, 17, 18, 31)

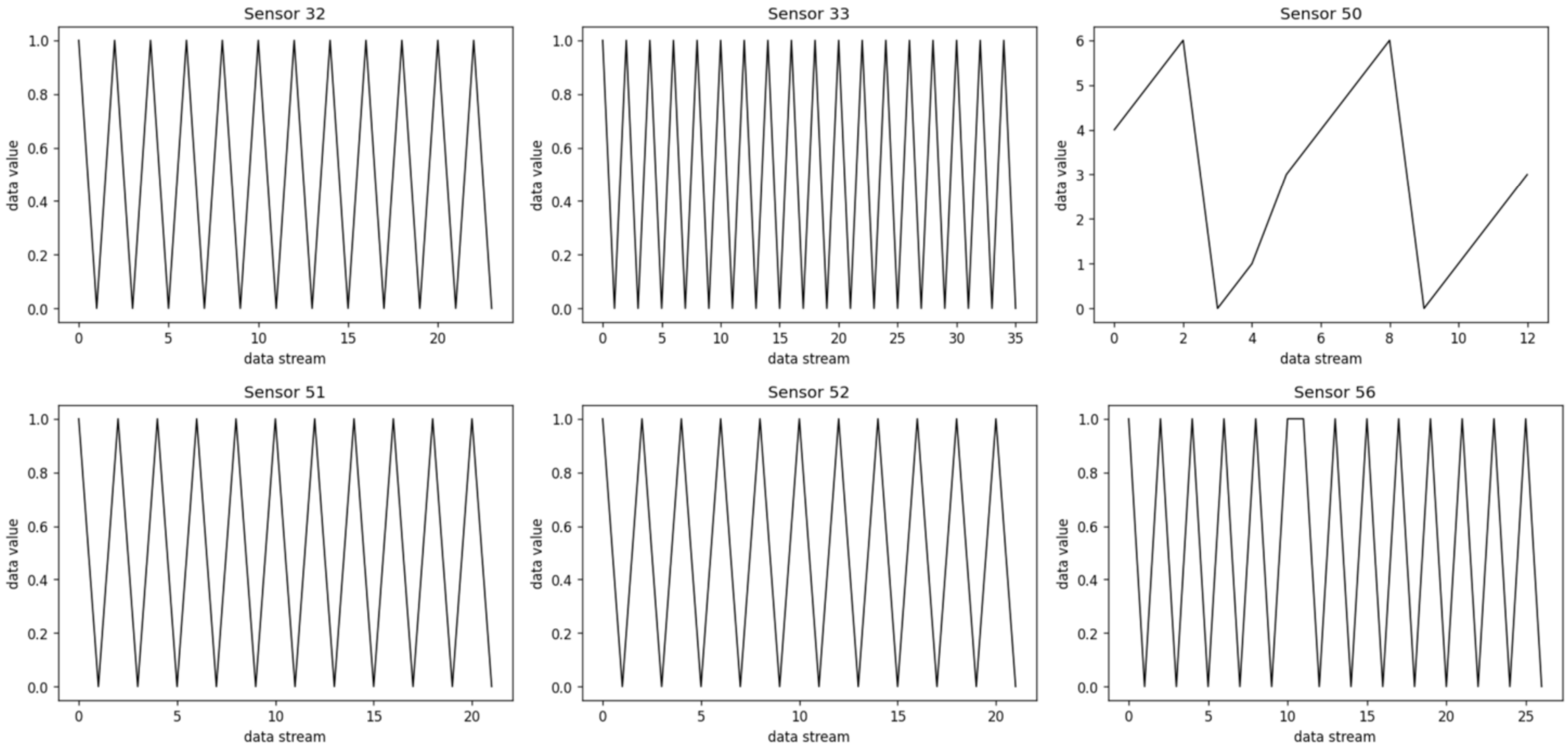


Figure 4-6 Sanitation data examples removal temporal effects (sensors 32, 33, 50, 51, 52, 56)

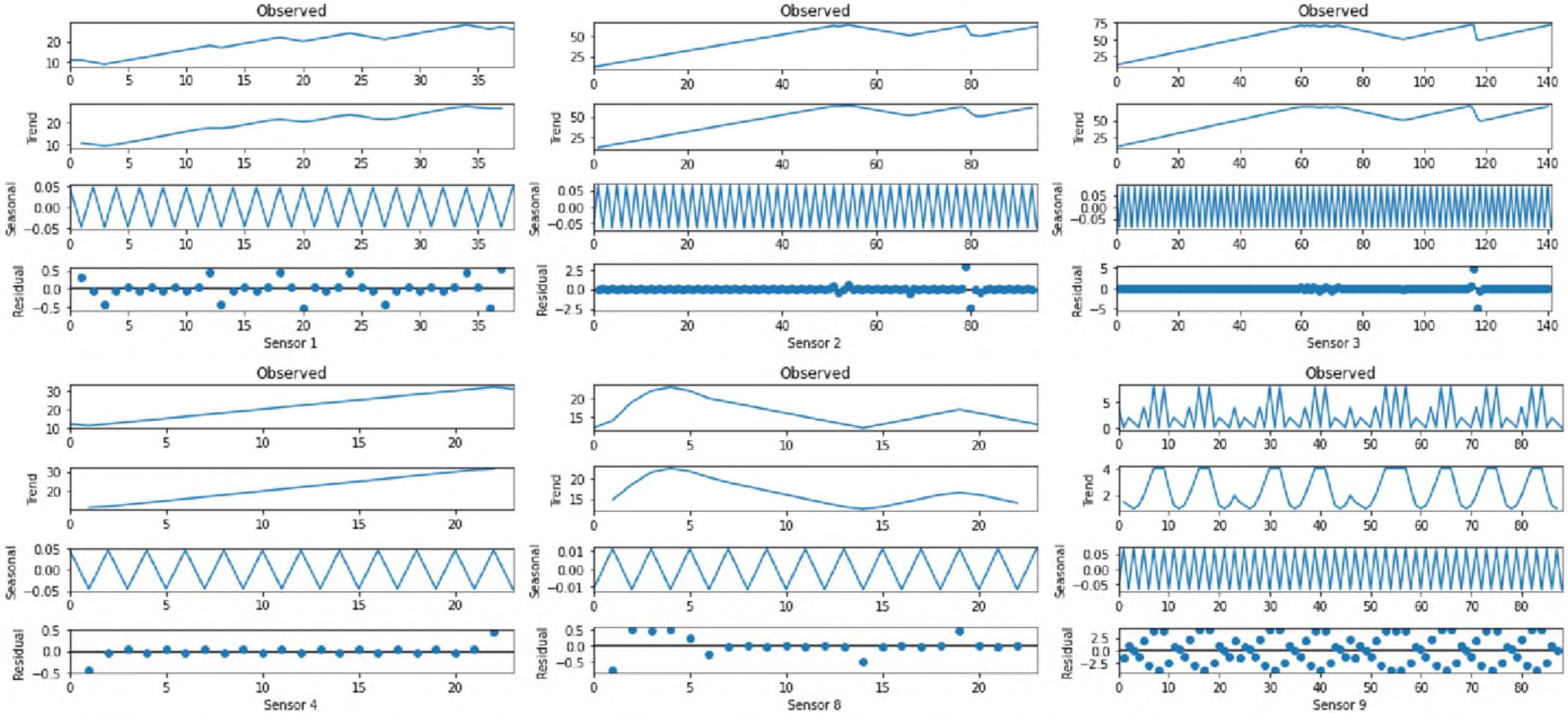


Figure 4-7 Sanitation data examples of time series decomposition (sensors 1, 2, 3, 4, 8, 9)

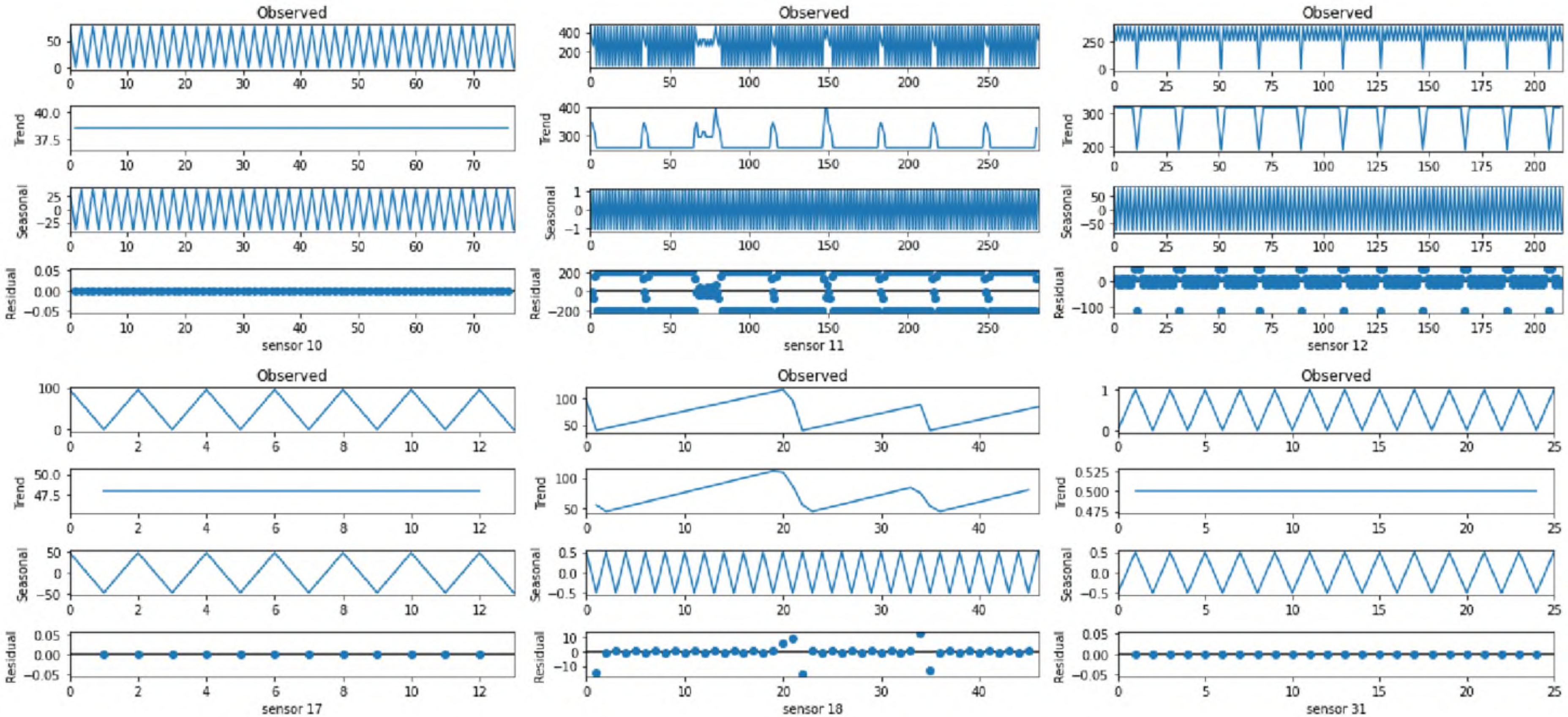


Figure 4-7 Sanitation data examples of time series decomposition (sensors 10, 11, 12, 17, 18, 31)

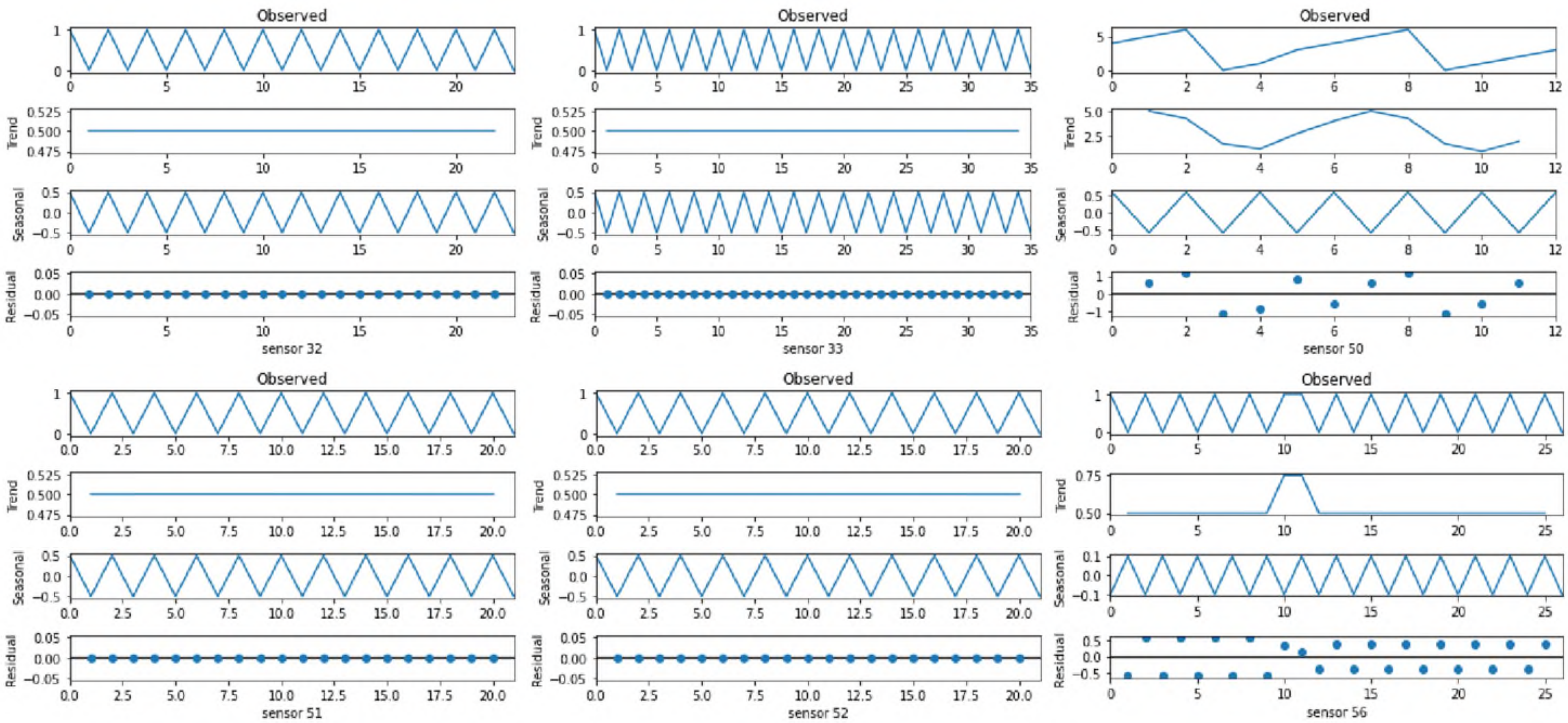


Figure 4-7 Sanitation data examples of time series decomposition (sensors 32, 33, 50, 51, 52, 56)

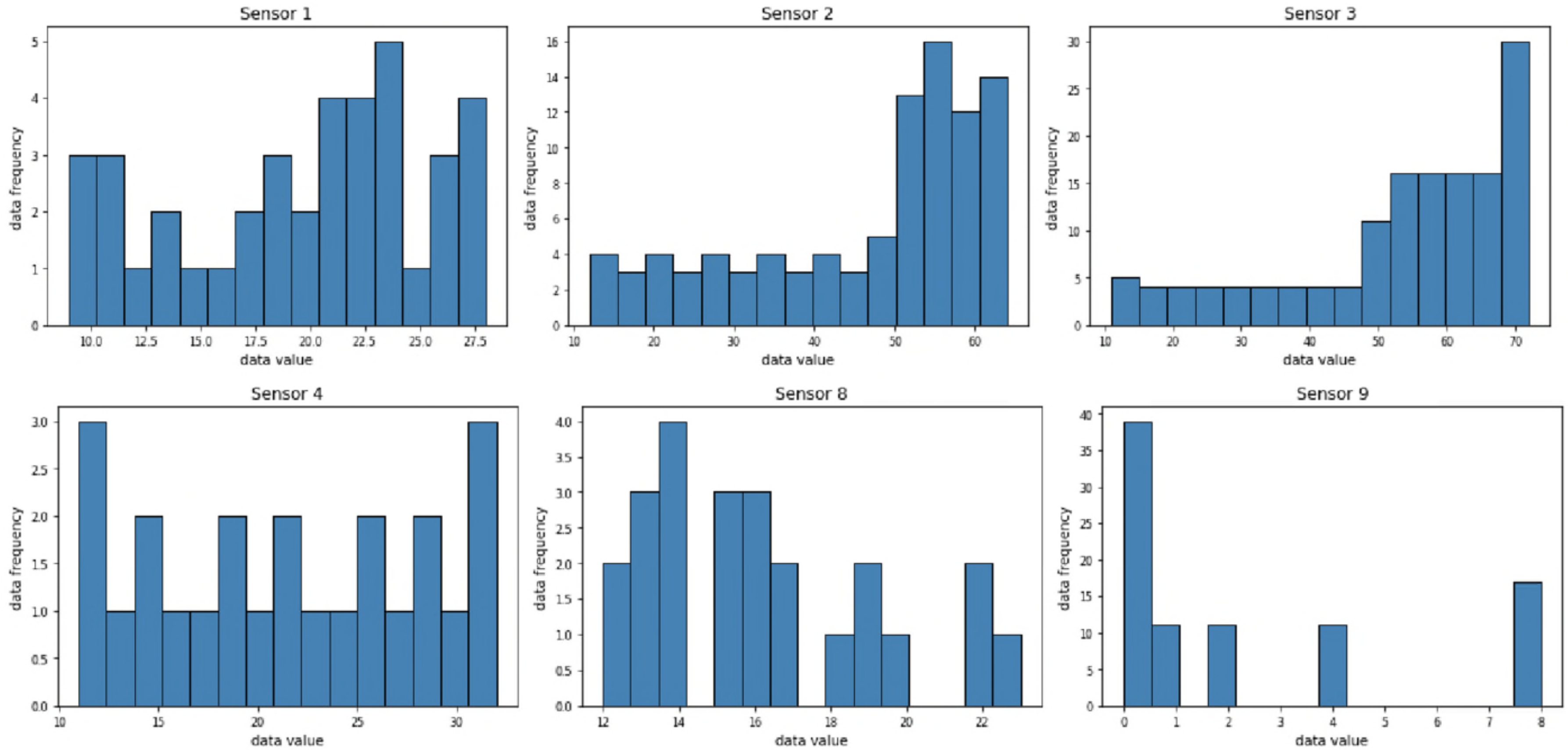


Figure 4-8 Sanitation data histograms plot examples (sensors 1, 2, 3, 4, 8, 9)

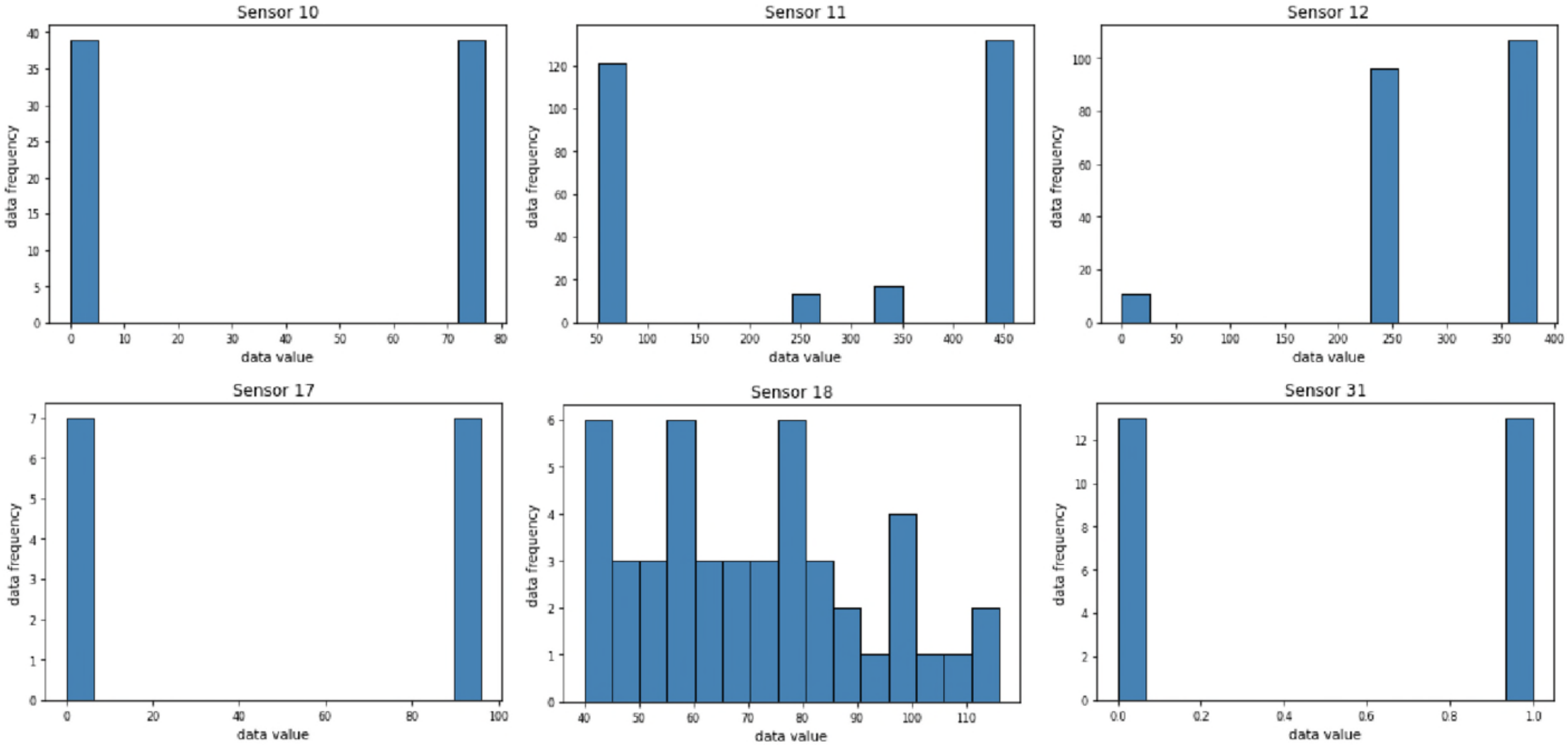


Figure 4-8 Sanitation data histograms plot examples (sensors 10, 11, 12, 17, 18, 31)

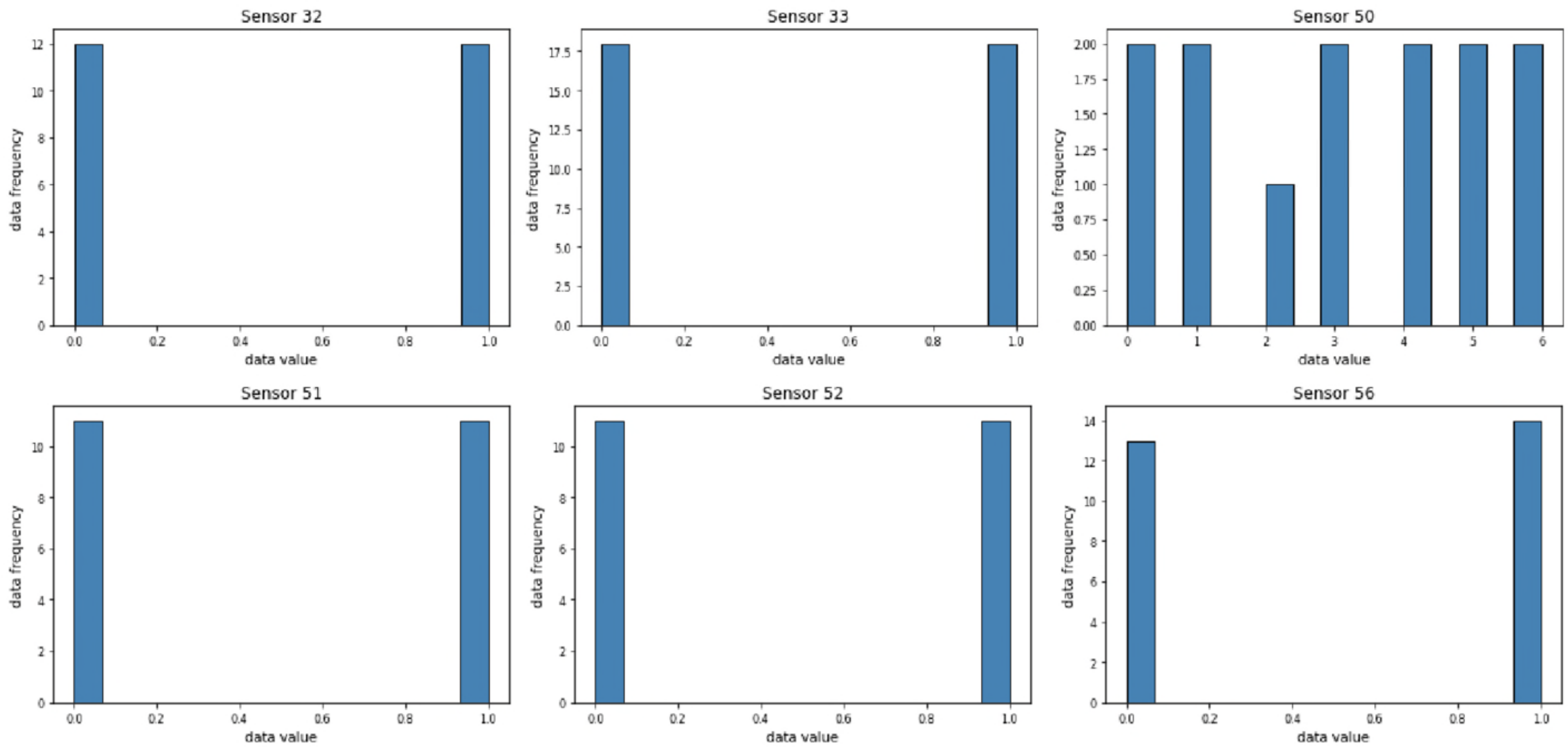


Figure 4-8 Sanitation data histograms plot examples (sensors 32, 33, 50, 51, 52, 56)

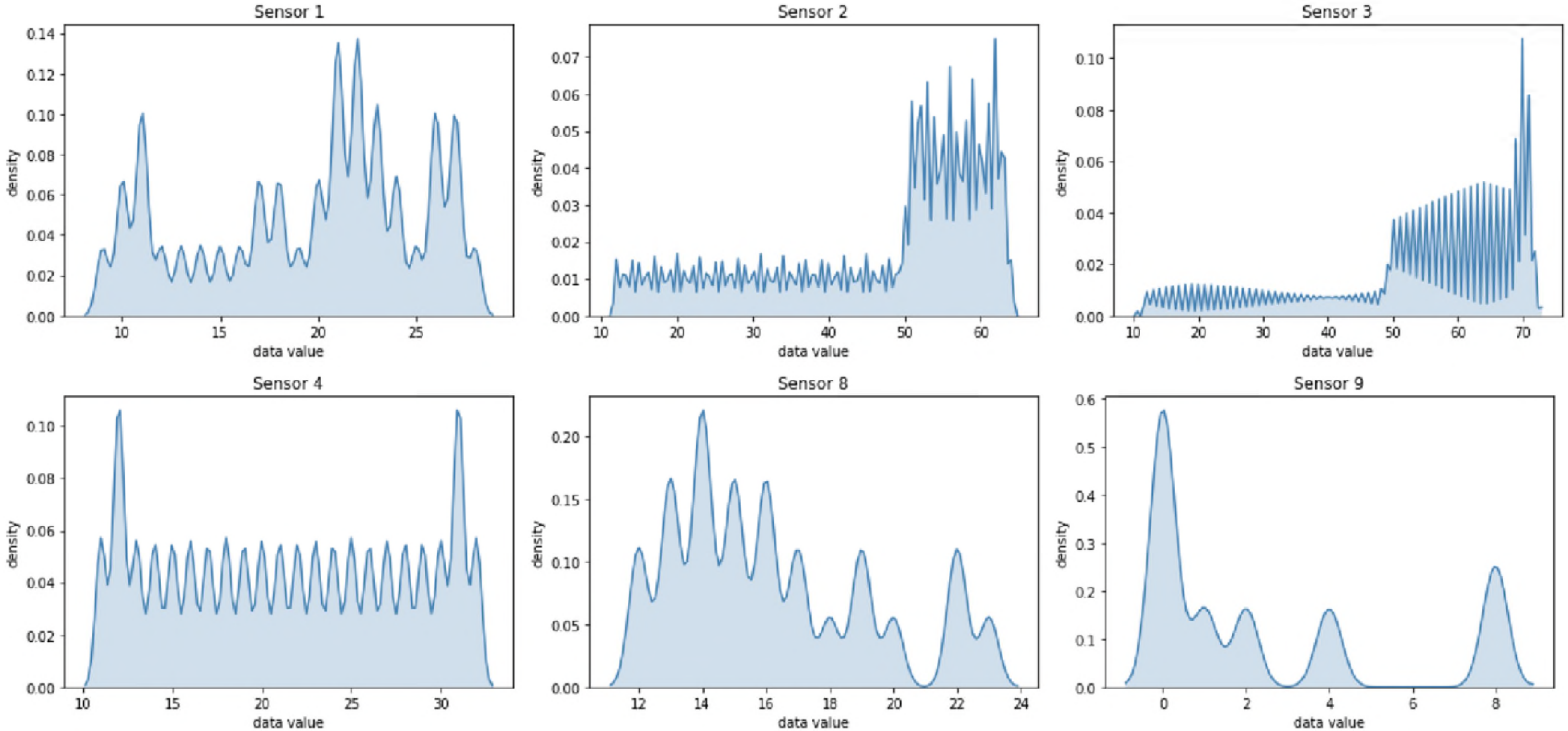


Figure 4-9 Sanitation data kernel density estimate plot examples (sensors 1, 2, 3, 4, 8, 9)

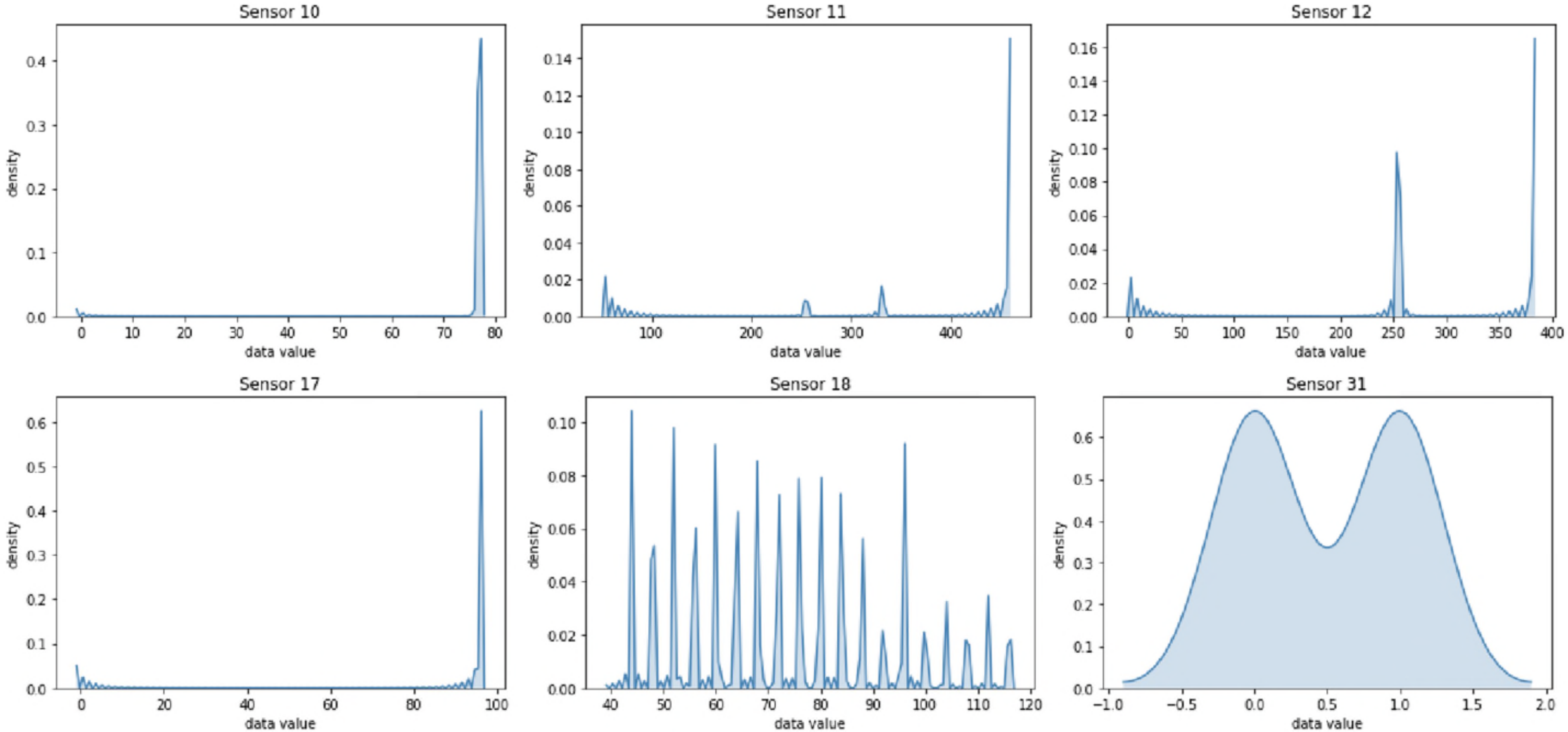


Figure 4-9 Sanitation data kernel density estimate plot examples (sensors 10, 11, 12, 17, 18, 31)

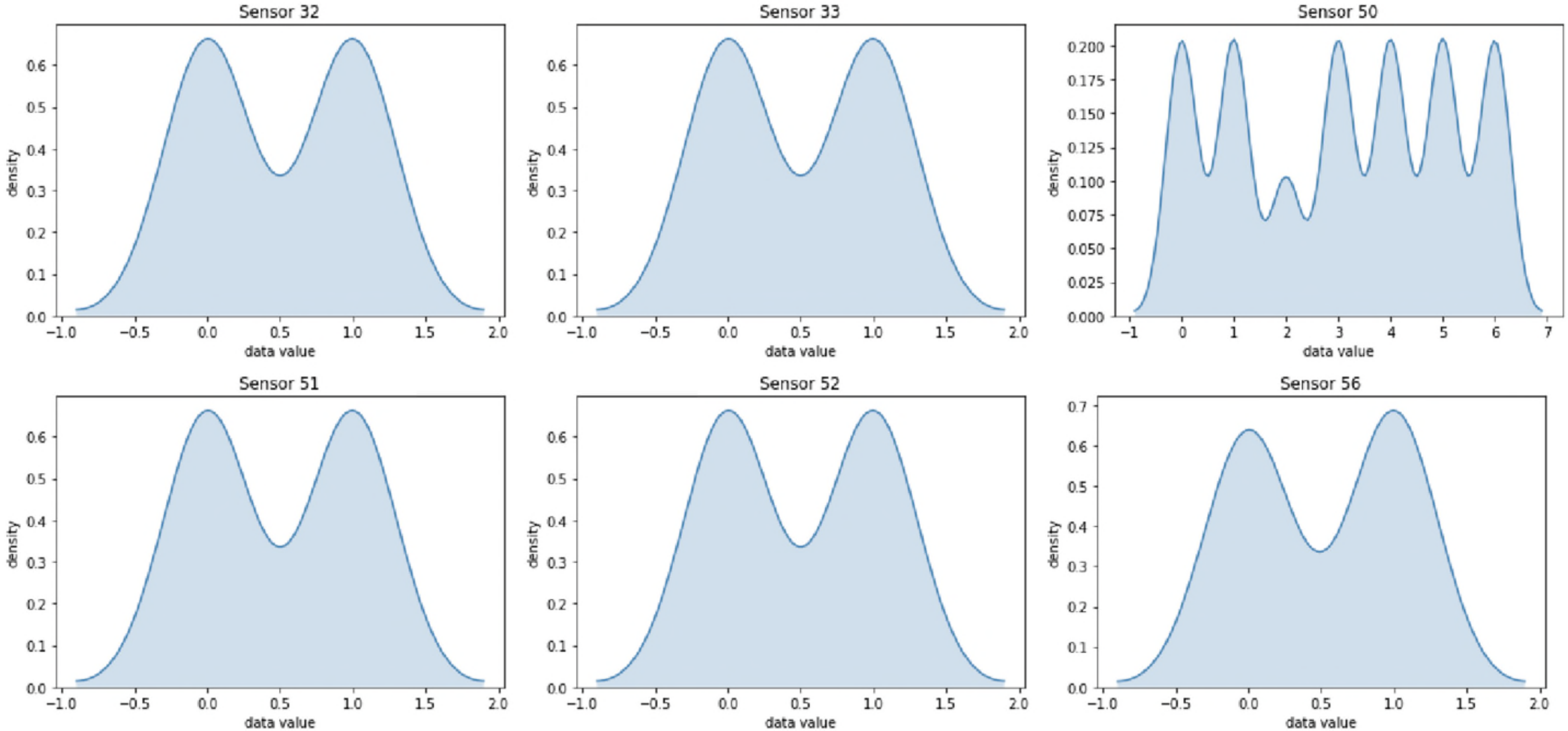


Figure 4-9 Sanitation data kernel density estimate plot examples (sensors 32, 33, 50, 51, 52, 56)

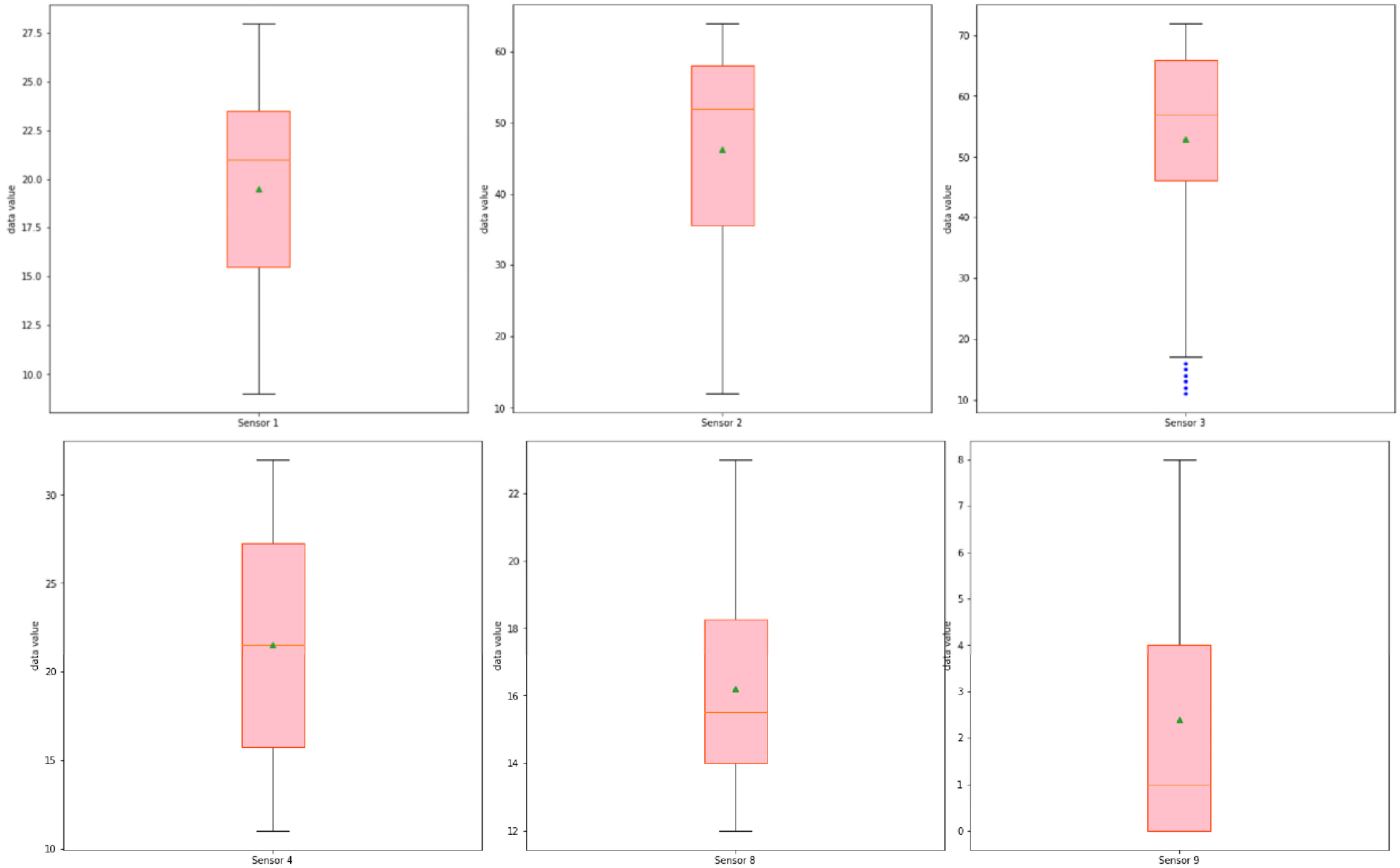


Figure 4-10 Sanitation data box plot examples (sensors 1, 2, 3, 4, 8, 9)

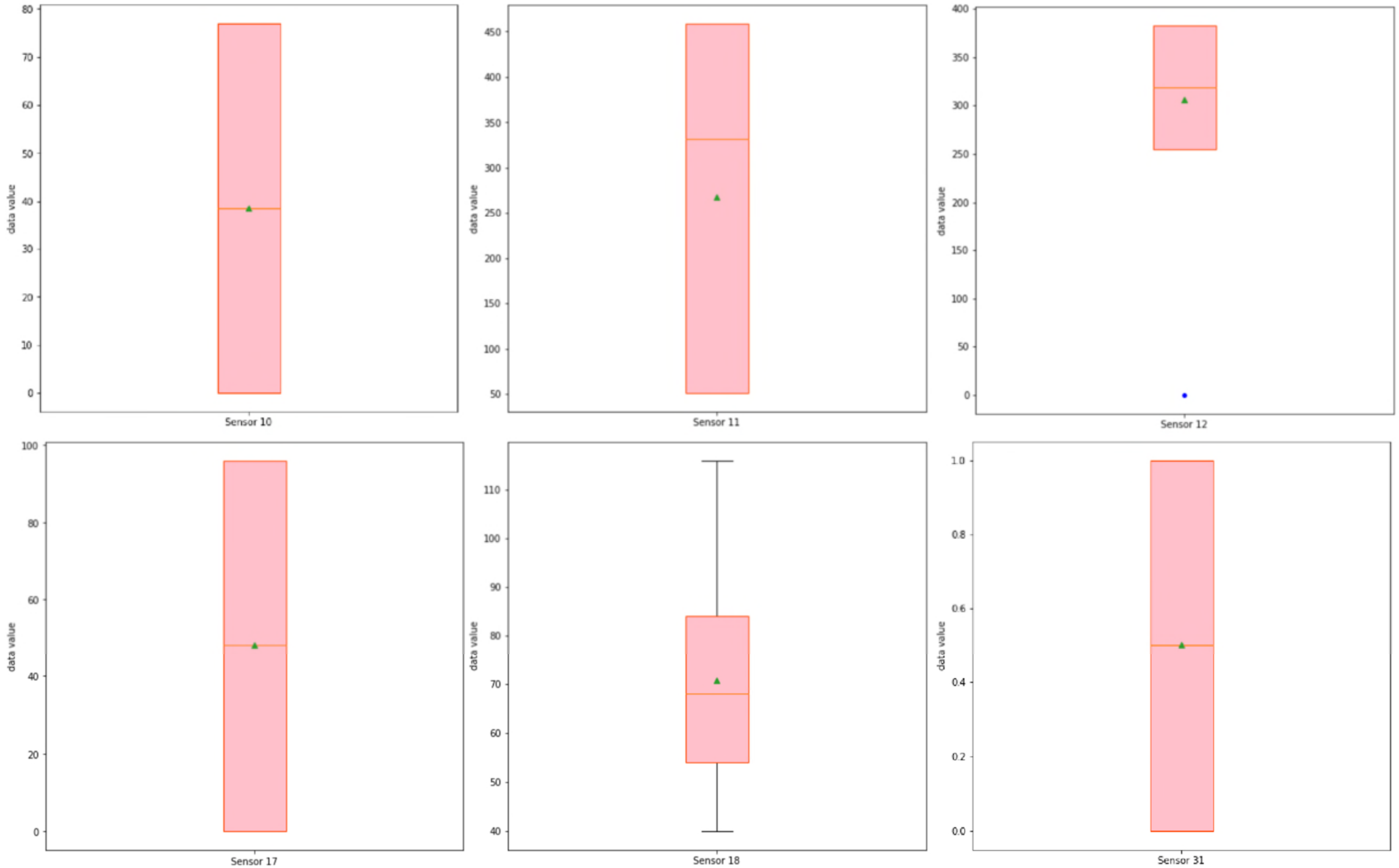


Figure 4-10 Sanitation data box plot examples (sensors 10, 11, 12, 17, 18, 31)

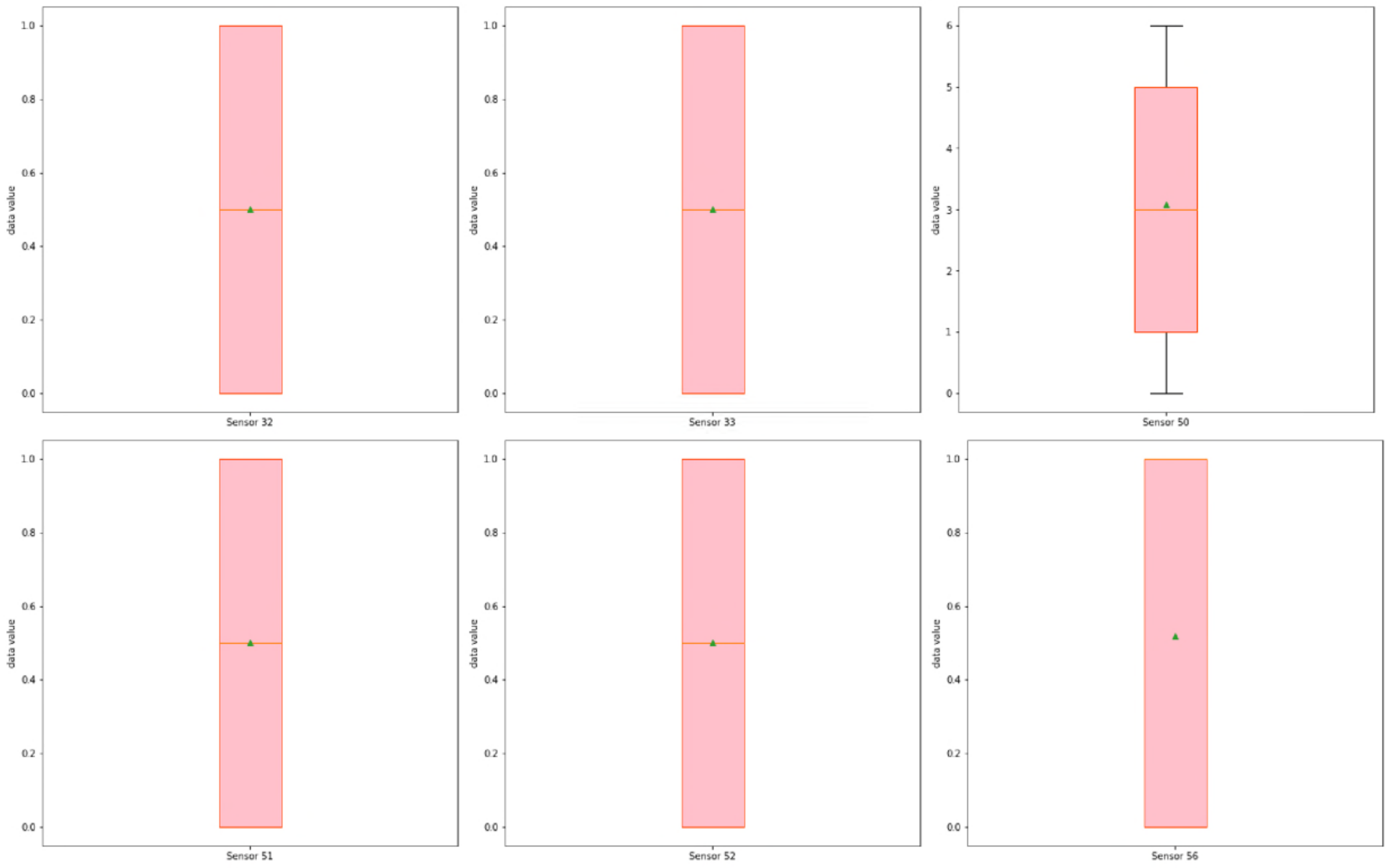


Figure 4-10 Sanitation data box plot examples (sensors 32, 33, 50, 51, 52, 56)

Table 4-14 Analyse sanitation data using statistical techniques

Sensor Type	S01	S02	S03	S04	S08	S09	S10	S11	S12	S17	S18	S31	S32	S33	S50	S51	S52	S56
Mean	19.54	46.33	53.02	21.50	16.21	2.39	38.50	267.5	305.9	48.00	70.81	0.50	0.50	0.50	3.08	0.50	0.50	0.52
Standard Deviation	5.61	15.07	16.49	6.81	3.22	3.03	38.75	193.7	94.80	49.81	20.68	0.51	0.51	0.51	2.14	0.51	0.51	0.51
Min	9.00	12.00	11.00	11.00	12.00	0.00	0.00	51.00	0.00	0.00	40.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Q1	15.50	35.50	46.25	15.75	14.00	0.00	0.00	51.00	255.0	0.00	54.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00
Median	21.00	52.00	57.00	21.50	15.50	1.00	38.50	332.0	319.0	48.00	68.00	0.50	0.50	0.50	3.00	0.50	0.50	1.00
Q2	23.50	58.00	66.00	27.25	18.25	4.00	77.00	459.0	383.0	96.00	84.00	1.00	1.00	1.00	5.00	1.00	1.00	1.00
Max	28.00	64.00	72.00	32.00	23.00	8.00	77.00	459.0	383.0	96.00	116.0	1.00	1.00	1.00	6.00	1.00	1.00	1.00
IQR	8.00	22.50	19.75	11.50	4.25	4.00	77.00	408.0	128.0	96.00	30.00	1.00	1.00	1.00	4.00	1.00	1.00	1.00

4.4.7 Data Visualisation

Data visualisation is a powerful tool for data analysis. It allows analysts to quickly identify correlations, outliers, and trends in complex datasets that may not be evident from the raw data. The section uses data visualisation in data analysis phase to help analysts gain a better understanding of the data and draw meaningful ideas (see Figures 4-5 to 4-10). The Cranfield Circular Toilet has created a graphical user interface to visualise sanitation data for global stakeholders (see Figure 4-11). The application is developed using a web-front end and a Python back-end, making it accessible to any type of portable device, such as iOS, Android, tablets, laptops, and desktops, and providing the most up-to-date information. The application helps users and engineers monitor toilet operation and behaviour in real time by displaying sensor-measured toilet data such as operation mode, hot liquid temperature, lid status, and MD hot tank upper switch status (see Figure 4-11_a). The application processes, integrates and analyses the data to gain meaningful insights and present them in visually appealing charts (see Figure 4-11_b). In the event of an emergency system failure, user interface colours become more visible to attract user attention (see Figure 4-11_c). The application facilitates beneficial user, product, and service interactions, thereby promoting stakeholder collaboration, boosting productivity, and reducing operational costs.

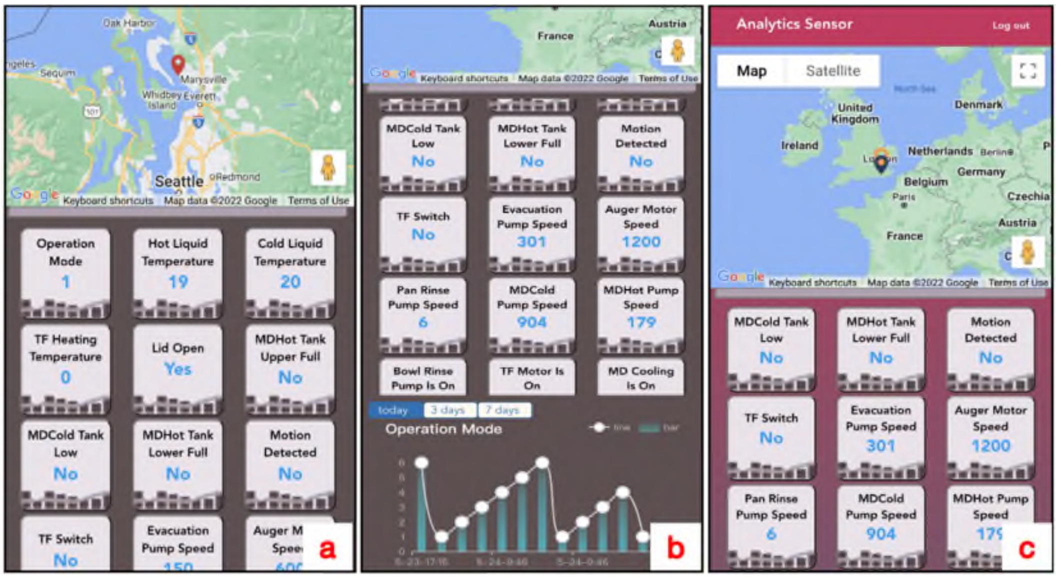


Figure 4-11 Data visualisation in intelligent toilet user interface

4.4.8 Modelling

The section investigates the data collected by the Cranfield Circular Toilet for performing anomaly data detection, regression analysis, and time series forecasting. Anomaly detection helps to identify unusual patterns in large datasets. By highlighting potential outliers, analysts can detect potential problems or opportunities that may otherwise have gone unnoticed. As illustrated in Figure 4-12, which shows an example of anomaly data detection on the No. 12 sensor data, data points suspected of being anomalous are highlighted in red. Through further analysis, analysts can then rule out the possibility of anomalies and gain a more comprehensive understanding of system performance. Regression analysis is used to investigate trends of sanitation data, as shown in Figure 4-13. The results concluded that the data from temperature sensors 1-5 could be well fitted by the regression model, while the switch data was more difficult to fit. Time series forecasting is used to help the Cranfield Circular Toilet make informed decisions about its future performance. Time series forecasting can help the toilet anticipate potential problems before they arise, detect changes in performance over time, and optimise its usage. The simple moving average (SMA) algorithm is applied to the data collected by sensor No.3, as shown in Figure 4-14, and evaluated in

Table 4-15. By utilising time series forecasting, the smart devices and sensors can be used in the most efficient and effective way possible.

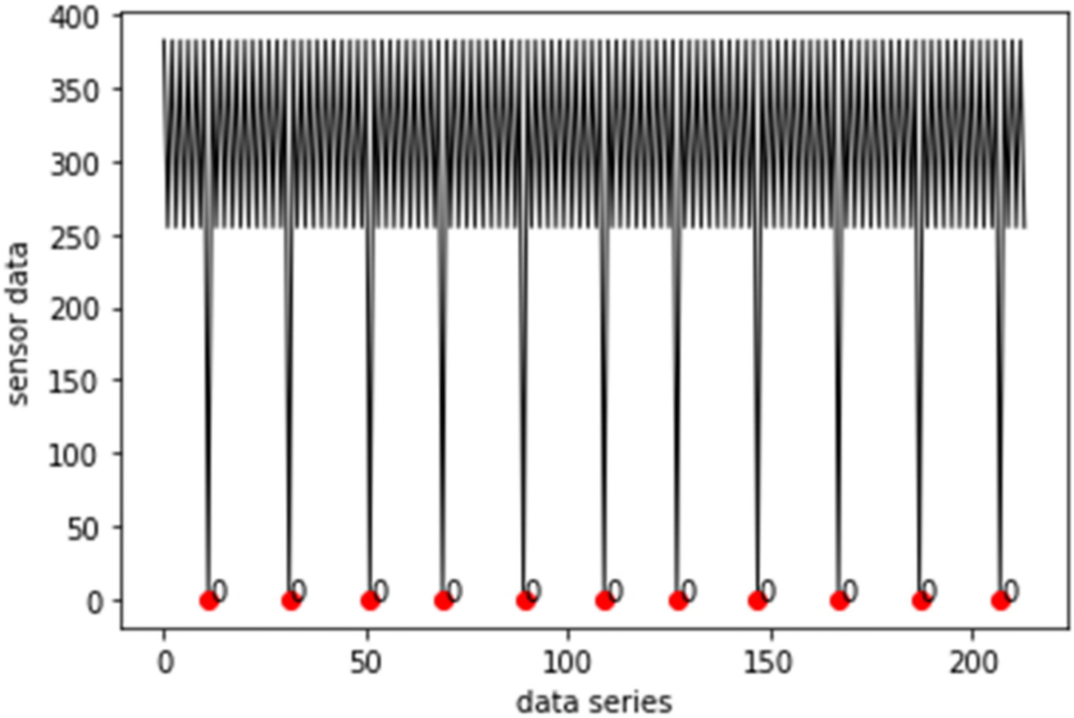


Figure 4-12 Sanitation data anomaly detection for sensor No.12

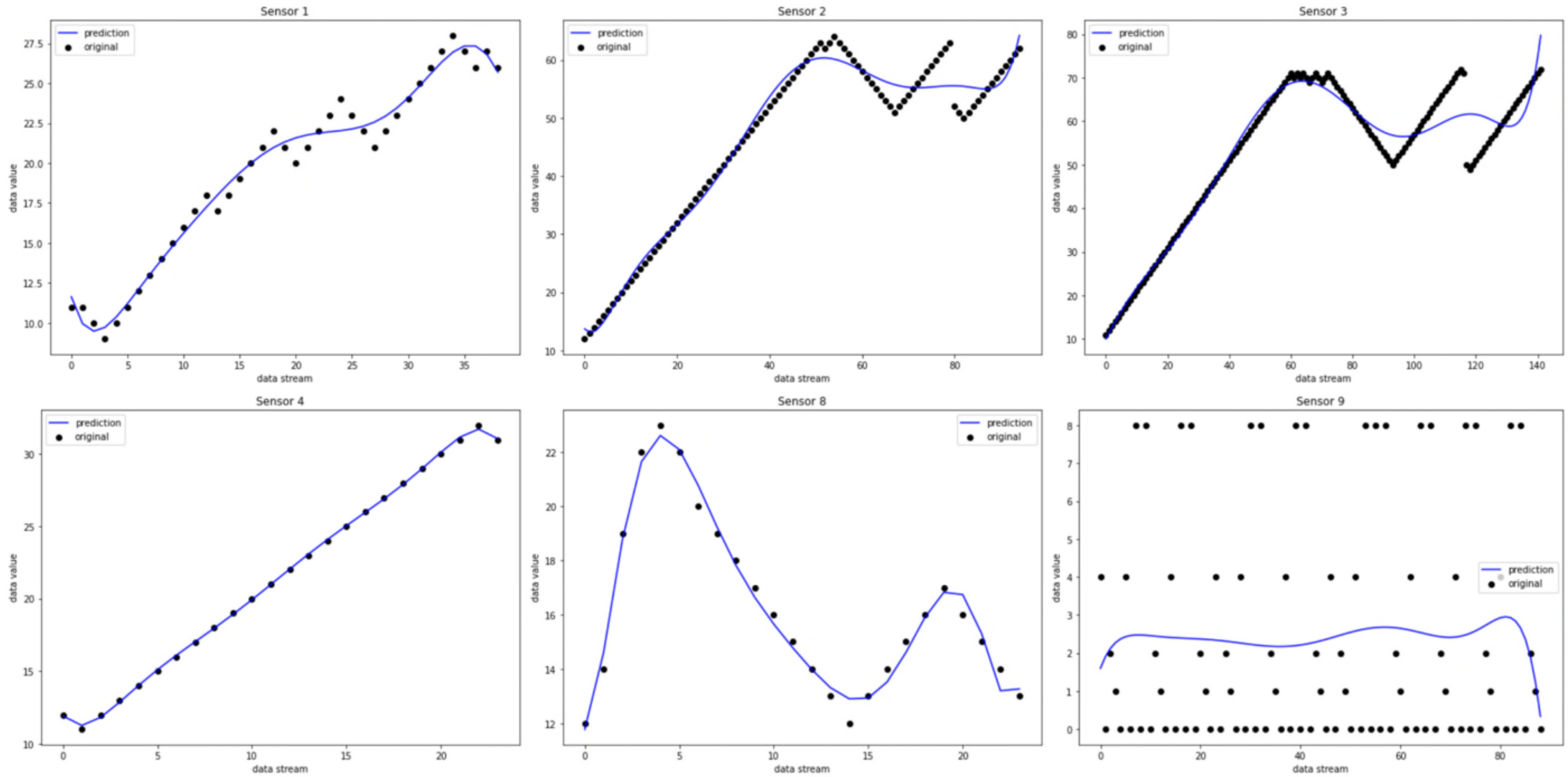


Figure 4-13 Sanitation data regression analysis examples (sensors 1, 2, 3, 4, 8, 9)

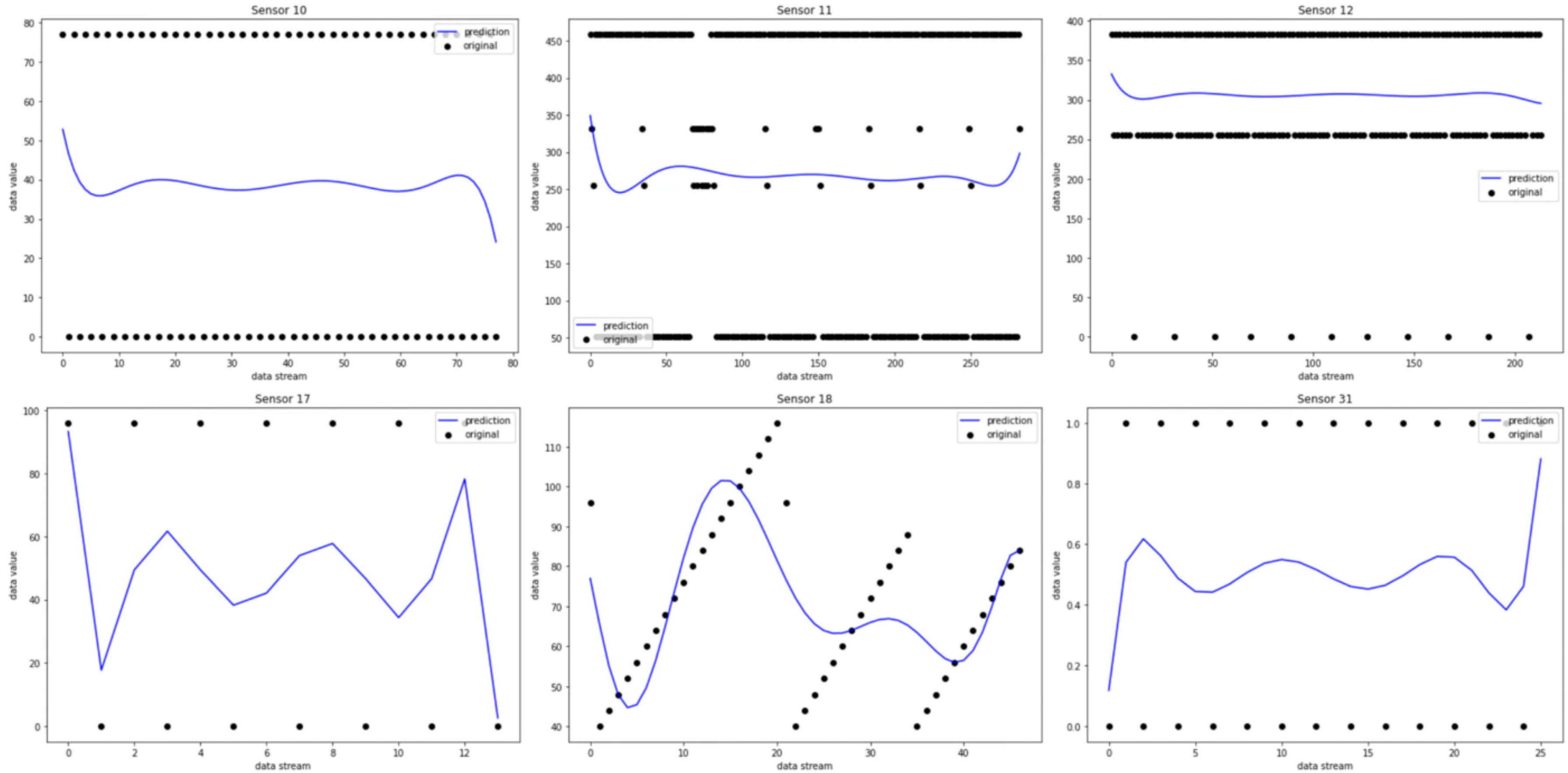


Figure 4-13 Sanitation data regression analysis examples (sensors 10, 11, 12, 17, 18, 31)

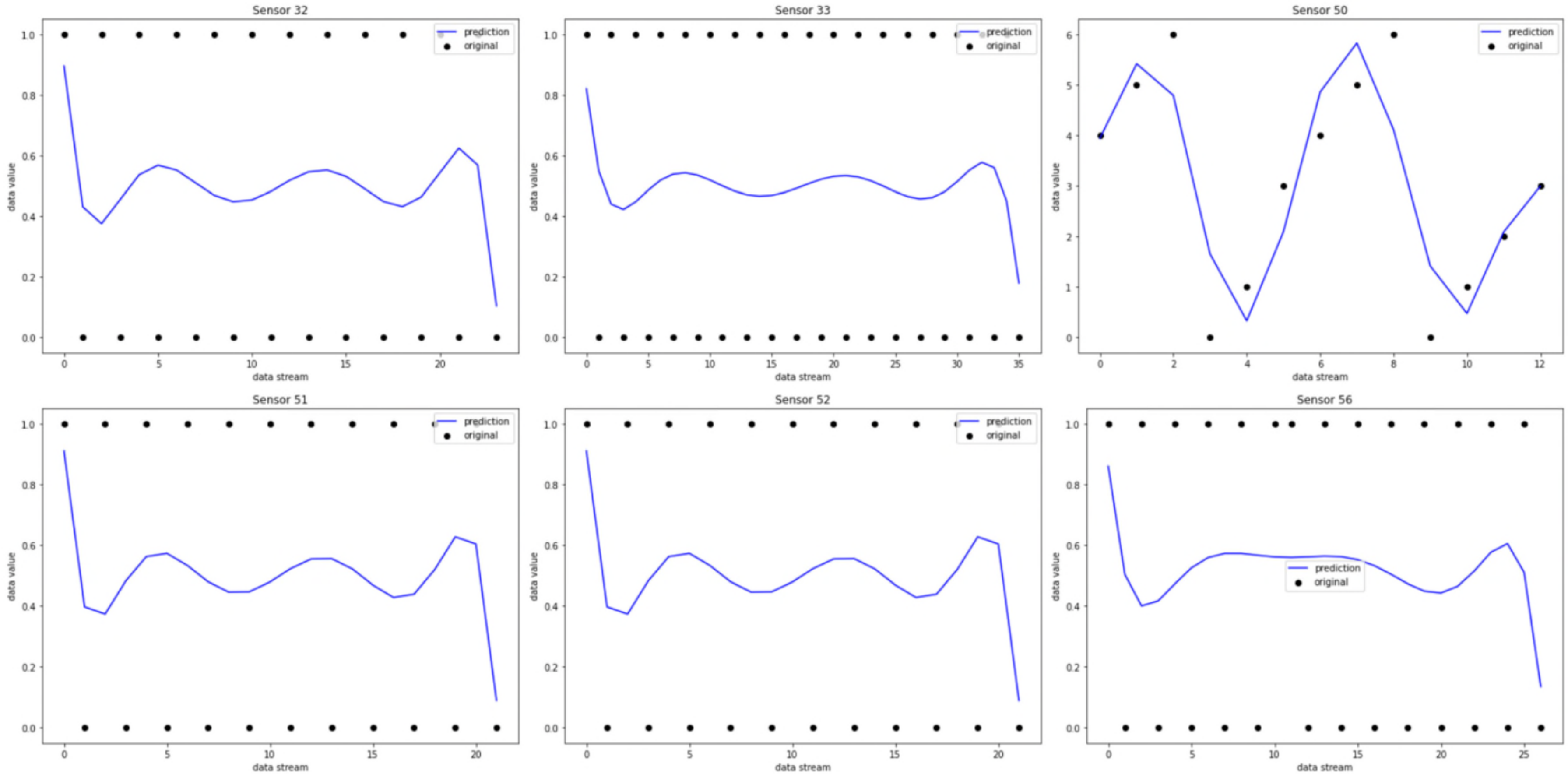


Figure 4-13 Sanitation data regression analysis examples (sensors 32, 33, 50, 51, 52, 56)

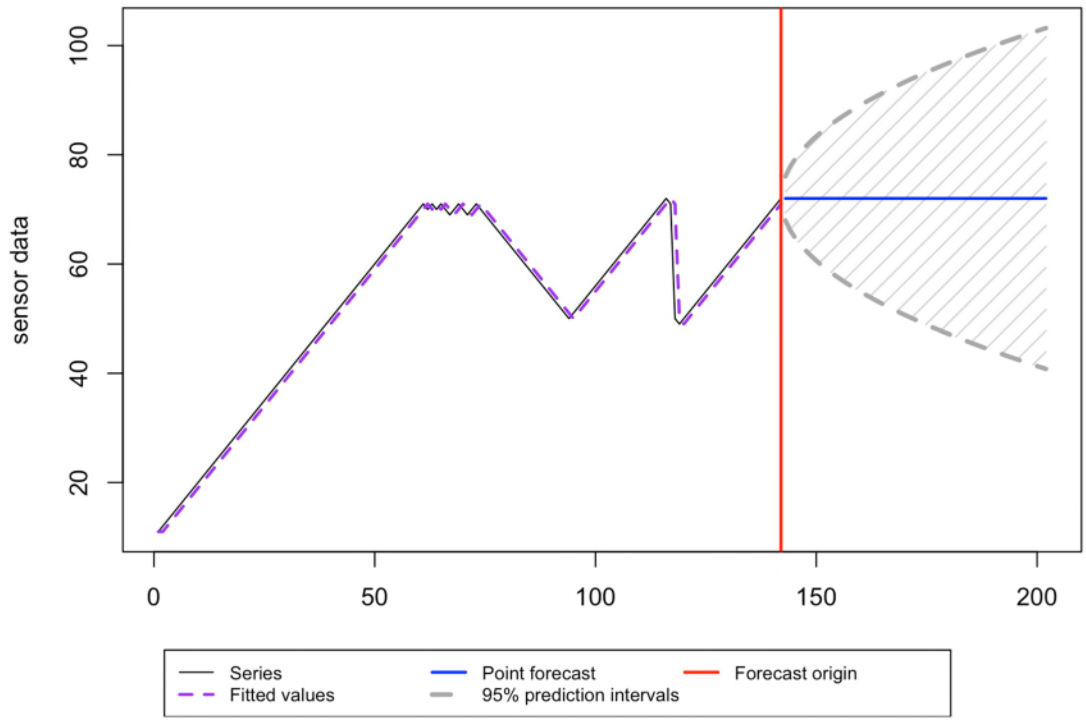


Figure 4-14 Sanitation data time series forecasting example

Table 4-15 Evaluation of time series forecasting model for sensor No. 03

LFT	LFV	ESD	AIC	AICc	BIC	BICc
MSE	4.0915	2.0372	607.0457	607.1320	612.9574	613.1713

Where LFT = loss function type, LFV = loss function value, ESD = error standard deviation, AIC = Akaike information criterion, AICc = the small-sample corrected Akaike Information Criterion, BIC = Bayesian information criterion, BICc = the small-sample corrected Bayesian information criterion.

4.4.9 Evaluation

Evaluation is essential for the success of the Cranfield Circular Toilet project, as it allows analysts to measure the performance of the project and identify any potential risks or issues. Through regular meetings, project managers and stakeholders can assess the cost-effectiveness of the project, ensuring that the project is worth the time, money, and resources invested in it. Evaluation also helps the project team to ensure that the project is running efficiently and that any changes necessary to keep it on track are implemented in a timely manner. During the evaluation phase, the project will be implemented in its intended environment. The process may involve setting up hardware, installing software, configuring settings, creating user accounts, and more. Once satisfactory progress has been made in the evaluation phase, the project can move onto the deployment phase.

4.4.10 Deployment

Deployment of the Cranfield Circular Toilet will bring the project to life and make it accessible to users. The deployment process allows the project team to test the project in its intended environment, ensuring its functionality and suitability for the end users. The Cranfield Circular Toilet project is going to be deployed and tested through functional, performance, and user acceptance tests. After successful testing, the project may be released to the public or a specific group of users. Deployment is the final step in the project lifecycle and is crucial for its success. Once deployed, the project can be accepted or rejected based on its performance.

4.5 Challenges and Opportunities

Availability

Intelligent sanitation should address a wide variety of the IoT data for storing, accessing, processing, analysing, and visualising. Data availability can be a challenge because of the complexity of accessing datasets, that may be stored in different formats or across multiple sanitation systems. Sanitation data may be managed by multiple teams or organisations, creating an obstacle to accessing the data required for analysis. Additionally, sanitation data can become obsolete quickly, necessitating the need to frequently update datasets to ensure their use in the analysis. By leveraging data availability, sanitation businesses can gain invaluable insights into system behaviour, operational trends, and a deeper understanding of their products and services. With the increasing availability of data, businesses can access the knowledge required to make informed decisions and gain a competitive edge.

Reliability

The fault tolerance and smooth operation of the intelligent sanitation system should be ensured in the face of untrusted IoT data from unreliable sensors, unclear imagery, or imperfect raw data, by utilising various event handlers. By taking appropriate measures to guarantee the accuracy, trustworthiness, and security of data, sanitation businesses can ensure that the data they use are reliable and trustworthy. Data validation can help business detect and rectify errors in their data, whereas data cleansing can involve eliminating duplicate entries, correcting spelling mistakes, and standardising data formats. By utilising advanced strategies, sanitation industry can trust the validity of their data analytics and make informed decisions based on reliable results.

Security

It is essential to address data security at all layers of the intelligent sanitation solutions. Sanitation data require secure storage across multiple systems and locations. The sharing of data between different parties for analytical purposes can create security risks. Data security is the practice of safeguarding data from unauthorised access, use, modification, or destruction. Data analysts protect sanitation data by deploying security measures, such as encryption, access control, and data loss prevention. The sanitation industry should adopt policies that guarantee the proper storage, usage, and disposal of all data.

Scalability

As the amount of sanitation data increases, its analysis and interpretation become more challenging and can lead to decreased accuracy and diminished performance. To address the scalability issue, a unified system should be designed to process all kinds of sanitation data. The intelligent sanitation system should be able to integrate data from multiple sources and use various analysis techniques to process it efficiently. Cloud computing provides an ideal solution for intelligent sanitation, allowing for easy access to data without major investments in hardware and software, while also enabling scalability with minimal effort.

Reusability

Designing reusable systems can help intelligent sanitation systems to effectively manage the increasingly complex data requirements of IoT solutions. Reusable data makes it easier and more valuable for data analysts to access and utilise. This eliminates the need for analysts to spend time collecting and analysing the same data repeatedly. Reusability enables sanitation solutions to maximise the benefits of their data by creating more accurate predictive models and gaining greater insight. Moreover, reusability facilitates collaboration between organisations, making it easier to share data and insights.

Interoperability

The integration of heterogeneous data sources, protocols, interfaces, and database for communication and information exchange is essential for intelligent sanitation solutions. Interoperability is a challenge when translating data between different IoT systems. These systems may use different data formats, communication protocols, and data structures. Integrating data from multiple sources can be a time consuming, costly, and complex process that may lead to inaccurate or incomplete analytical results. Through interoperability, data from multiple sources can be combined and analysed, allowing for more informed decisions and a deeper understanding of trends and patterns.

4.6 Conclusions

Intelligent sanitation solutions are revolutionising the way user interact with sanitation facilities. Intelligent sanitation systems can monitor and detect operational status and their surroundings, and then use data analytics to make more informed decisions, automate processes, and optimise operating efficiency. The chapter proposed a novel San-IoT-DA tool to enable intelligent sanitation solutions that are integrated with data analytics. The San-IoT-DA tool was developed after an extensive examination of intelligent sanitation solutions in terms of technology, architecture, service, application, function, and device. The tool comprises of the following phases: business understanding, data understanding, data acquisition, data cleaning and preparation, data storage, data analysis, data visualisation, modelling, evaluation, and deployment. The chapter introduced the most commonly employed strategies, processes, and tools for collecting, analysing, and managing sanitation data. The San-IoT-DA tool can enhance the performance, detect potential issues, and predict future trends for intelligent sanitation solutions, providing valuable insights. The tool provides a generalised approach to data analytics integrated intelligent sanitation solutions, enabling other technicians and developers to more easily select the appropriate technology for their projects. The San-IoT-DA tool was effectively demonstrated with the Cranfield Circular Toilet case study, demonstrating its applicability and feasibility for the sanitation industry. The chapter explored the business and data understanding of the Cranfield Circular Toilet, as well as the data processing steps necessary for efficient data analytics. The San-IoT-DA enables the Cranfield Circular Toilet to convert data into meaningful insights, thereby improving global stakeholder decision-making. The chapter examined the challenges and opportunities of sanitation data analytics, including availability, reliability, security, scalability, reusability, and interoperability. Although the generalised San-IoT-DA tool performed well in intelligent sanitation practice, further improvements are required. As intelligent sanitation solutions continue to expand their global presence, safeguarding data security, minimising maintenance costs, and delivering reliable services are essential. The San-IoT-DA can leverage advanced technology to make data access, information sharing, and process automation simpler and more efficient. Using AI and intelligent computing, the next wave of intelligent sanitation solutions can provide advanced predictive maintenance, facility management, operating efficiency, and user analysis.

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5 Chapter 5: Discussion and Limitations

5.1 Summary of Key Findings

The section provides a summary of the key findings and demonstrates how they have achieved the stated objectives.

Objective 1: *Conducting a comprehensive literature review on intelligent sanitation to identify recent advances and research gaps.*

- A comprehensive review of intelligent sanitation solutions was conducted in the thesis, covering aspects such as development history, system detection, health monitoring, artificial intelligence enhancement, sustainability, opportunities, and challenges. Existing studies and potential research topics are identified to determine knowledge gaps. The IoT-based intelligent sanitation concept (San-IoT) was introduced for the sanitation industry. San-IoT can revolutionise the way user interact with sanitation facilities, by providing device connection, reliable connectivity, and efficient analytics for system detection, healthcare, and sustainable development. The review discussed the opportunities and challenges of intelligent sanitation, and can serve as a foundation for future research and development in intelligent sanitation systems.

Objective 2: *Designing a generalised framework for IoT-based sanitation networks to improve their connection, operation, and management.*

- The design for an IoT-based sanitation framework (San-IoT) was presented in the thesis to facilitate efficient management of the intelligent sanitation network, allowing access to and utilisation of the large amounts of data generated by sanitation facilities. The most current and widely used hardware, technologies, and protocols are introduced, along with their characteristics, benefits, and drawbacks. The San-IoT framework can enable system monitoring and control, analyse user behaviour, enable user health monitoring, facilitate global stakeholder decision-making, improve water usage efficiency, reduce energy consumption, and promote sustainable development. The generalised San-IoT intelligent sanitation framework has the potential to enable other developers to select the most appropriate technology for their sanitation projects.

Objective 3: *Developing an analytics tool for sanitation data intelligence to provide efficient data processing and improve decision making.*

- The San-IoT-DA tool was developed to provide insights into sanitation data. By incorporating commonly used strategies, processes, and tools, the San-IoT-DA can efficiently collect, analyse, and manage sanitation data. The tool has the potential to improve operational performance, detect potential issues, and predict sanitation system trends. The data-driven intelligent sanitation solution can increase productivity, optimise resource usage, promote user health, facilitate industrial digitisation, and support environmental sustainability. A standardised approach was offered to selecting appropriate technology for intelligent sanitation projects, which can assist other researchers, technicians, and developers.

Objective 4: *Demonstrating the performance of the generalised IoT-based sanitation framework and data analytics tool on the case study of Cranfield Circular Toilet.*

- The case study of Cranfield Circular Toilet was used to demonstrate the applicability and efficiency of the San-IoT framework and San-IoT-DA tool for the sanitation industry. The San-IoT solution assisted Cranfield Circular Toilet in optimising operations, while the San-IoT-DA empowers the Cranfield Circular Toilet to transform data into actionable insights.

5.2 Research Implications

5.2.1 Theoretical Value

- A comprehensive review of intelligent sanitation literature published between 2000 and 2022 was presented to fill current gaps in the topic. The literature review discussed system detection, health monitoring, artificial intelligence integration, and sustainability for intelligent sanitation. The San-IoT concept was introduced as a foundation for further research. The knowledge gaps, limitations, and potential solutions were identified and explored. Additionally, the current state-of-the-art IoT architecture, applications, and services was examined to determine the opportunities and challenges of the future intelligent sanitation systems.

- A generalised IoT-based sanitation framework, San-IoT, was proposed to revolutionise the current backward state of intelligent sanitation. The traditional sanitation industry has been hindered by the absence of a unified approach. The comprehensive San-IoT framework combined cutting-edge IoT technologies to monitor and manage sanitation solutions. The San-IoT framework introduced advanced IoT strategies, processes, and tools for efficiently collecting, transmitting, storing, analysing, and managing data. The system architecture, network topologies, communication protocols, data processing, and system deployment of intelligent sanitation was presented in the framework. The San-IoT framework comprised a three-layer IoT architecture - nodes layer, fog layer, and cloud layer, as well as a general five-layer IoT stack model comprised of the perception layer, data link layer, network layer, transport layer, and application layer. The San-IoT based sanitation solutions has the potential to collect, store, and analyse data from system operations, which can gain valuable insights and help decision makers optimise sanitation activities. The San-IoT framework can be served as a foundation for future research into IoT-based sanitation solutions.

- A generalised data analytics tool for intelligent sanitation, San-IoT-DA, was proposed to improve understanding of sanitation data and provide a comprehensive analytics process for industry practitioners. The San-IoT-DA tool comprised business understanding, data understanding, data acquisition, data cleaning and preparation, data storage, data analysis, data visualisation, modelling, evaluation, and deployment phases. The most employed strategies, processes, and tools are introduced for collecting, analysing, and managing sanitation data. The San-IoT-DA tool has the potential to help detect patterns, identify trends, predict problems, prevent breakdowns, and make better decisions. The thesis provides valuable insights to relevant stakeholders on leveraging IoT and data analytics for enhancing safe, efficient, and sustainable sanitation services.

- The proposed San-IoT framework and San-IoT-DA tool have been applied to a case study of the Cranfield intelligent toilet (i.e., Cranfield Circular Toilet), which is part of the Reinvent the Toilet Challenge (RTTC) launched by the Bill and Melinda Gates Foundation. The case study demonstrated the applicability and feasibility of the proposed intelligent sanitation framework and tool. It also provided practitioners, academics, engineers, technicians, policymakers, and other stakeholders with valuable insights into the development and implementation of intelligent sanitation solutions.

5.2.2 Industrial Value

- The San-IoT framework provided a unified foundation for the development of sanitation industrial IoT solutions, enabling the use of common strategies, processes, and tools in system architecture, network topologies, communication protocols, data processing, and system deployment. The framework can facilitate collaboration between numerous stakeholders, enabling the creation of more effective and efficient solutions. It can offer a secure and reliable IoT-based sanitation platform that can be easily extended and maintained. A solid foundation for the development of innovative IoT-based solutions was provided to the current and future sanitation challenges.

- The San-IoT-DA tool has the potential to help industry professionals to gather, transfer, store, analyse, and manage sanitation data, thereby enhancing transparency and visibility of sanitation facilities status and efficiently tracking and controlling system operations. The San-IoT-DA tool provided sanitation sector a comprehensive solution for managing and analysing sanitation data. It offered a variety of analytical capabilities that can be deployed quickly and easily in the sanitation systems. San-IoT-DA provided a powerful platform for sanitation data analysis with scalability and reliability.

- The case study of Cranfield Circular Toilet has the potential to assist industry practitioners in exploring the potential of San-IoT and San-IoT-DA for intelligent sanitation solutions. The case study showcased the opportunity for businesses to create more efficient, economical, and environmentally friendly sanitation solutions. The proposed solutions can stimulate industries to identify strategies for reducing resource consumption, enhancing system operation, and implementing more effective methods to monitor and collect sanitation data.

5.2.3 Societal Value

- Data-driven intelligent sanitation systems can contribute to the achievement of Sustainable Development Goal 6 (SDG 6) by improving access to safe and sustainable sanitation services for all. By monitoring and managing sanitation facilities in real-time, intelligent sanitation systems can ensure that they are clean, functional, and safe to use. Smart toilets can adjust the amount of water used for flushing based on the needs of the user, thereby reducing water usage. By monitoring waste levels in real-time, data-driven intelligent sanitation systems can ensure that waste is collected and disposed of in a timely and sustainable manner. Intelligent sanitation can improve access to safe and sustainable sanitation services, reduce the spread of diseases, conserve water, manage waste more efficiently, increase accessibility to sanitation facilities, and promote environmental sustainability.

- Implementing intelligent sanitation solutions can bring numerous benefits to both the public and private sectors, such as improved public health and efficient resource utilisation. These solutions allow for the collection and analysis of data that can be used to inform important decisions related to water management, resource allocation, and health tracking. Through the usage of advanced sensors, potential health threats can be identified and prevented. Intelligent sanitation solutions can help to reduce water wastage and improve the sustainability of water resources, while also helping to optimise the efficiency of sanitation services and reduce associated costs.

- Adequate sanitation is a fundamental human right, and intelligent sanitation systems can help ensure that everyone has access to basic sanitation services. Intelligent sanitation uses a combination of advanced technology and data-driven decision-making to improve the efficiency, safety, and cost-effectiveness of sanitation services. Intelligent sanitation can be used to provide predictive maintenance and alert operators to potential problems, as well as to integrate into existing infrastructure to reduce energy costs and water usage.

- Intelligent sanitation can help governments, academic institutions, local organisations, non-governmental organisations (NGOs), and private businesses provide efficient and safe sanitation services. Governments and private businesses can use intelligent sanitation to improve the quality and effectiveness of their services. Academic institutions can use it to conduct research and develop new technologies and systems for sustainable sanitation services. Local organisations and NGOs can use it to improve the delivery of sanitation services in their communities. Furthermore, intelligent sanitation can be used to raise public awareness on the importance of sanitation services.

5.2.4 Environmental Value

- The use of intelligent sanitation and IoT-based facilities can help to manage sanitation resources and services more efficiently. Sanitation data can be used to improve resource management, waste management, and provide greater visibility and insights into the condition of sanitation facilities. Data collected by intelligent sanitation can be used to inform decisions related to resource allocation, policy making, and urban planning.

- Intelligent sanitation systems can significantly reduce water consumption, with some advanced models (e.g., Cranfield Circular Toilet) saving up to 90% more water compared to traditional toilets. By detecting leaks and other issues early on, these systems can help save hundreds of gallons of water annually, preventing unnecessary water waste. Through the utilisation of sensors and monitoring devices, intelligent sanitation can efficiently detect and monitor contaminants, resulting in a substantial reduction in hazardous waste generation. Studies have shown that intelligent sanitation systems can cut down hazardous waste production by over 50%, thus contributing to a cleaner and healthier environment. Moreover, intelligent sanitation systems play a crucial role in preventing water contamination and the spread of infectious diseases. By swiftly identifying and addressing potential health risks, these systems can improve public health outcomes, preventing illness outbreaks and saving lives.

- By studying the Cranfield Circular Toilet case study, industry practitioners can gain a greater understanding of novel, non-sewer intelligent sanitation systems that are more sustainable and use less water than traditional systems. The case study offers a comprehensive look at the process of designing and implementing an intelligent sanitation system, providing valuable insight that can be applied to the development of such systems in other contexts.

5.2.5 Economic Value

- Traditional sanitation systems result in staggering economic losses amounting to US$260 billion annually, with 2.9 million reported cases of diseases and 95,000 deaths each year. Despite these alarming figures, the implementation of improvements to traditional sanitation remains a challenging task. Intelligent sanitation provides a solution, as it is more efficient, cost-effective, and accessible to low-income households, particularly in densely populated areas. Intelligent sanitation can help tackle the shortcomings of traditional sanitation systems and prevent further losses and deaths. Intelligent sanitation provides a more efficient and cost-effective solution, as it reduces the need for manual maintenance and labor costs. Intelligent sanitation can help prevent further losses and deaths due to sanitation-related illnesses by providing timely detection of problems and quick response times. Intelligent sanitation can help inform policymakers and citizens of the current state of sanitation and help them develop better sanitation policies and practices.

- Improved sanitation has a significant impact on economic development, with studies revealing that access to proper sanitation facilities can enhance population productivity by up to 18%. Furthermore, intelligent sanitation plays a crucial role in improving public health, with communities having access to proper sanitation facilities experiencing up to a 70% reduction in the prevalence of waterborne diseases, leading to substantial enhancements in overall well-being.

- Through cross-sectoral and cross-border collaboration, the Cranfield Circular Toilet project mission is to design and develop a modular, low-cost circular toilet system. The research creates a concept for sharing practice, resources and knowledge to facilitate the wider adoption of the intelligent sanitation. Intelligent sanitation can help provide an affordable, sustainable and scalable solution to the global sanitation crisis.

5.3 Limitations

Data quantity and quality: The Cranfield intelligent toilet (i.e., Cranfield Circular Toilet) case study was used in the research to demonstrate the applicability and feasibility of the proposed generalised IoT-based sanitation framework (San-IoT) and sanitation data analytics tool (San-IoT-DA). The Cranfield Circular Toilet is still in the early stages of development and research, making the quantity and quality of data collected through it far from perfect. Nevertheless, progress is being made in order to bring this revolutionary invention to fruition for the sanitation industry. The data collected in the research is sufficient to demonstrate the feasibility of the proposed San-IoT framework and San-IoT-DA tool. However, it is limited due to time, resources, and laboratory availability constraints. The limited data may not be sufficient to provide a complete picture of all type of sanitation data, may not be able to prefect predict future performance of the facility, and may make it hard to draw meaningful insights about the entire sanitation industry. Data quality issues may arise from unexpected errors in data collection or entry, inaccurate instrument calibration, inadequate sampling techniques, measurement bias, inefficient data management and storage, and inadequate data analysis. Global testing of the Cranfield Circular Toilet will be conducted in multiple locations around the world to address data quantity and quality issues soon. The remote testing approach allows the team to leverage mobile testing tools and cloud-based platforms to effectively collect data from different environments, over extended periods of time, and from multiple sources. The comprehensive data gathered from the field testing will provide stakeholders with a better understanding of the system performance.

Generalisability: The Cranfield Circular Toilet case study may be too specific to accurately represent the sanitation industry on a global scale. The research was limited to a particular geographical area, making it difficult to extrapolate the findings to other regions. Additionally, the experiment may not have accurately simulated the way all households use sanitation facilities, or not be able to accurately simulate the trends or changes in the whole day. It is crucial to consider the local environment and cultural context when testing the toilet, as the testing process and results can vary greatly depending on these factors. The experiment was conducted with a specific method in a particular setting, which may limit the generalisability of the findings to other settings or methods. Furthermore, practical constraints such as resources, personnel, time, and budget, are a crucial factor to consider. When designing, developing, and implementing the intelligent sanitation solutions, certain practical limitations, such as limited data availability, limited resources, and intense research period, had to be taken into account.

6 Chapter 6: Conclusions and Further Research

The chapter presents a summary of the key findings, methodology, and case study, and elucidates the contribution of the research to knowledge. It also offers potential avenues for further research.

6.1 Summary of Thesis

The exploration of data-driven intelligent sanitation as a transformative solution to the global sanitation crisis was performed. The proposed solution has the potential to make a valuable contribution to the broader discourse on sustainability, innovation, and technological advancement in sanitation services. A comprehensive literature review was conducted, covering various aspects of intelligent sanitation, including historical development, system detection, health monitoring, artificial intelligence integration, sustainability, opportunities, and challenges. It provided a thorough overview of relevant studies and identified potential knowledge gaps. Additionally, the concept of San-IoT was introduced as a potential foundation for further research. A generalised IoT-based sanitation framework (San-IoT) was proposed for efficient sanitation network management. The system architecture, high-level network topologies, communication protocols, data processing, and system deployment of the intelligent sanitation solutions were explored. A generalised data analytics tool (San-IoT-DA) was proposed to support decision making in the sanitation industry. The most used strategies, processes, and tools for collecting, analysing, and managing sanitation data were discussed. The applicability and feasibility of the proposed San-IoT framework and San-IoT-DA tool have been demonstrated through a case study of the Cranfield intelligent toilet (i.e., Cranfield Circular Toilet). The thesis will make a significant contribution to driving the reform of the sanitation industry by providing academics, industry practitioners, and other stakeholders with solutions on how to use IoT and data analytics to address global sanitation challenges. The integration of IoT and data analytics has the potential to revolutionise the way world approach sanitation issues and improve the effectiveness of sanitation systems. The IoT-based framework and analytics tool have the potential to improve resource utilisation, increase efficiency, promote sustainability, and enhance the quality of life for communities around the world. By enabling system monitoring and control, user health monitoring, and user behaviour analysis, the proposed framework and tool can lead to cost savings, environmental benefits, and better sanitation services. By presenting advanced frameworks and tools, practical solutions and insights, the research can inspire further innovation and research in the field of intelligent sanitation and foster the growth of safe, efficient, effective, and sustainable sanitation solutions.

6.2 Summary of Aim Achievement

The section provides a summary of the aim achievement and demonstrates how it has achieved.

Aim: The research aims to develop an IoT system for efficient sanitation management and decision making.

- Objectives 1-4 are all interconnected and contribute to the achievement of the aim.

By achieving *Objective 1*, a comprehensive understanding of the current state of intelligent sanitation was attained, which includes recent advancements, challenges, and research gaps. Conducting a thorough literature review enabled the identification of potential research questions and opportunities for innovation in the IoT-based sanitation system.

By achieving *Objective 2*, a generalised IoT framework was designed, which can serve as the basis for developing future intelligent sanitation solutions. The framework has the potential to enhance the connection, operation, and management of the sanitation network, leading to greater efficiency and sustainability on a global scale.

By achieving *Objective 3*, a standardised sanitation data analytics tool was developed, which can serve as a foundation for data-driven intelligent solutions. The tool has the potential to offer valuable insights to facilitate decision-making.

By achieving *Objective 4*, a case study of Cranfield Circular Toilet was conducted, which can serve as a compelling example to illustrate the feasibility and practicality of the proposed IoT-based intelligent sanitation framework and analytics tool.

Through the accomplishment of Objectives 1-4, an IoT system for efficient sanitation management and decision making has been developed.

The proposed solution has the potential to enrich the wider discourse on sustainability, innovation, and technological advancement in sanitation services.

The adoption of data-driven intelligent sanitation has the potential to enhance public health, decrease environmental impact, and improve the efficiency and cost-effectiveness of sanitation services. The thesis offers practitioners, academics, engineers, policymakers, and global stakeholders valuable insights into the application of IoT and data analytics to promote the efficiency, accessibility, and sustainability of the sanitation industry.

6.3 Contribution to Knowledge

6.3.1 Comprehensive Literature Review for Intelligent Sanitation

A comprehensive review was conducted on intelligent sanitation to counter the challenges posed by conventional fragmented and immature literature, and to aid in taking full advantage of the IoT revolution for the sanitation industry. The literature review explored the development history, system detection, health monitoring, artificial intelligence integration, sustainability, opportunities, and challenges of intelligent sanitation. After a comprehensive review of on intelligent sanitation and sustainable sanitation solutions, prior research on the subject was summarised, knowledge gaps were identified, and the limitations and prospects of sustainable intelligent sanitation were discussed. The Sanitation-IoT (San-IoT) framework presented in the thesis lays the foundation for future research in intelligent sanitation. Through investigating state-of-the-art IoT architecture, applications, and services, the research can foster the further development of intelligent sanitation.

6.3.2 Generalised IoT-based Sanitation Framework (San-IoT)

A generalised IoT-based sanitation framework (San-IoT) was introduced to revolutionise the current backward state of intelligent sanitation that has been impeded by a lack of unified approach. The San-IoT, an innovative framework, can be utilised as a basis for further investigations into IoT-based sanitation solutions. The San-IoT framework can enhance the connection, operation, and management of sanitation networks. The proposed framework includes a system architecture, high-level network topologies, communication protocols, data processing, and system deployment. In the framework, advanced IoT strategies, processes, and tools were introduced to efficiently collect, transmit, store, analyse and manage data. The San-IoT framework can be employed to decrease water and energy utilisation, leading to a more sustainable approach to sanitation. The solid foundation laid out by the San-IoT framework enabled the creation of cutting-edge IoT-based solutions to current and future sanitation problems. The practitioners, academics, engineers, technicians, and other stakeholders can use the generalised framework to assist in selecting the proper IoT technologies for their intelligent sanitation projects.

6.3.3 Generalised Sanitation Data Analytics Tool (San-IoT-DA)

A generalised data analytics tool (San-IoT-DA) was introduced to take advantage of valuable sanitation data. The San-IoT-DA tool enables organisations to effectively collect, transmit, store, analyse, and manage data, by utilising sophisticated strategies, processes, and tools. The tool includes the business understanding, data understanding, data acquisition, data cleaning and preparation, data storage, data analysis, data visualisation, modelling, evaluation, and deployment phases. The data analytics techniques employed in intelligent sanitation applications and services was investigated. It also examined the challenges and opportunities associated with analysing sanitation data, providing a thorough analytics procedure for industry participants to gain a greater understanding and make use of intelligent sanitation data.

6.3.4 Cranfield Intelligent Toilet Case Study

The applicability and feasibility of the San-IoT framework and San-IoT-DA tool were demonstrated through a case study of Cranfield intelligent toilet (i.e., Cranfield Circular Toilet). The San-IoT solution can help the toilet maximise its efficiency, while the San-IoT-DA enables the toilet to turn data into actionable knowledge. The case study of Cranfield Circular Toilet has the potential to inspire data-driven innovative sanitation solutions. It gave practitioners, academics, engineers, technicians, policymakers, and relevant stakeholders with valuable insights into the development and implementation of intelligent sanitation solutions. The case study presented an opportunity to establish a more efficient, cost-effective, and eco-friendly sanitation system. The thesis can encourage industries to develop strategies to decrease resource utilisation, optimise system performance, and create more efficient ways of monitoring and collecting sanitation data. By building on intelligent sanitation solutions and continuing to explore new approaches, it is possible to develop more effective, sustainable, and equitable sanitation systems that can enhance facility performance, improve public health, protect the environment, and promote sustainable development.

6.4 Further Research

Updated Literature Review: As technology continues to progress, the literature review of intelligent sanitation solutions can be regularly updated to reflect the newest developments. An in-depth review of the literature can be conducted to uncover unexplored research areas. By thoroughly analysing the current literature and other sources of information, new gaps in the research can be identified. These findings can then be used to generate new hypotheses or research questions. Additionally, the implications of the literature for policy, practice, and society can be explored with the help of interdisciplinary research. Moreover, a more comprehensive taxonomy of the literature can be created to better predict future trends in intelligent sanitation. Furthermore, new interpretations or explanations can be sought out, and any further investigation on literature review can be highlighted. Some plans can be formulated to carry out additional research. It can address any gaps in the literature and contribute new insights to the field of study.

Novel Intelligent Sanitation Solution: As the IoT technology continues to advance, novel intelligent sanitation solutions will be proposed that leverage the latest advancements in the perception layer, data link layer, network layer, transport layer, and application layer. These solutions will be more efficient, stable, reliable, and sustainable, providing solutions to the challenges of sanitation industry. Smart assets are essential for the evolution of the San-IoT, becoming more affordable, efficient, and accessible. With advanced connectivity, low-cost data transmission, and stable networks, smart assets are increasingly connected and sharing data. Smartphones are becoming more widespread, enabling better human-toilet interaction. AI-enabled smart assets can analyse collected data to identify issues, predict future events, and develop optimal solutions. As the number of interconnected smart assets continues to grow, the need for reliable, low-latency connectivity is becoming increasingly important. Data quality management is essential for properly managing the vast amounts of data collected by sensors. To quickly identify and remove errors and inconsistencies, automated tools such as data wrangling software or batch processing via scripting can be used. As the volume of data generated and managed by San-IoT solutions increases, cutting-edge technologies can be used to shape data storage trends. Artificial intelligence can be leveraged to automate mundane tasks and interpret data faster. Machine learning based storage solutions offer improved capabilities in data compression, deduplication, and real-time analytics. Advanced technologies will be used to automate the analysis and decision-making process, as well as to uncover patterns. The San-IoT will be able to deliver a wealth of applications and services, including remote monitoring and control, interactive visualisation, predictive maintenance, optimised resource usage, and improved healthcare.

Novel Data Analytics Technologies: As data analytics technology continues to evolve, intelligent sanitation solutions will be developed with more efficient methods for data storage, processing, analysis, and visualisation. Machine learning can be utilised to enhance the performance and accuracy of data storage. Algorithms can be applied to detect patterns and correlations in data, which can help identify redundant data and optimise storage. Additionally, machine learning can be deployed to detect potential security threats and abnormalities in data storage systems. Advanced data integration can combine data from various sources into a comprehensive view. The sanitation data can be extracted from multiple sources, cleaned and transformed into the desired format. Advanced data cleaning techniques can be used to identify the source of the data, verify its accuracy and security, and eliminate inaccurate, incomplete, and irrelevant data. Advanced tools, technologies, and algorithms can be employed to process and analyse sanitation data to gain insights and facilitate better decision-making. Clustering analysis, regression analysis, neural networks, factor analysis, data mining, time series analysis, and decision trees can be used to analyse high-volume and rapidly changing sanitation data. The integration of data security and analytics can help to reduce the risk of data breaches and cyberattacks. Data encryption, authentication protocols, and access controls can enhance the security of data. Augmented reality can provide innovative and engaging ways to visualise sanitation data. By overlaying digital sanitation data onto physical facilities, users and technicians can gain a better understanding of the data and see real-time changes in the sanitation facilities.

Extensive Global Deployment: The Cranfield Circular Toilet is still in its early stages of development and research, but a global testing is soon to be launched. The comprehensive data gathered from the global field tests will offer stakeholders a comprehensive understanding of the system and the data it produces. To ensure the interoperability of devices, platforms, and technologies, advanced San-IoT and San-IoT-DA solutions can make use of common languages, protocols, and open-source standards. This is especially important for the international implementation of intelligent sanitation solutions, as different standards can cause sanitation facilities to be incompatible with one another. The implementation of intelligent sanitation solutions on a global scale could raise worries about privacy and security. To ensure data security, secure connections need to be developed between smart assets and sanitation data must be shielded from unauthorised access. All stakeholders in the sanitation industry can work together to create security policies and laws, employ privacy-enhancing technologies, tools, and standards, establish secure network connections, and control the sharing of private information.

APPENDICES

The appendices can serve as supplementary materials to provide additional support for the main content. The appendices focus on several specific areas, including design, prototyping, experiments, field testing, software user interface, programming code examples, and data examples. The images, figures, and photos provide visual aids to enhance the understanding of the Cranfield intelligent toilet project. The programming code and software user interface examples offer a more technical perspective on the software development process. The data examples are used to provide insights into the characteristics and properties of the sanitation data. The appendices can significantly enhance the comprehensiveness of the thesis, providing more information and context.

Appendix A Cranfield Intelligent Toilet Project

A.1 Design

The phase of designing the toilet is crucial in the development of an intelligent sanitation system. A toilet that is designed well and includes the required sensors and data collection features is fundamental to creating an IoT-based sanitation system. The design of the toilet determines the type and placement of sensors that will be used to collect data on water usage, system temperature, and other relevant parametres. The toilet design can have an impact on the ease of use and acceptability to users. The section presents some design images to visually illustrate the technical features of the Cranfield intelligent toilet (see Figure A-1 to Figure A-9). These images can serve as a useful information for readers to comprehend the intricate details of the Cranfield intelligent toilet system.

Figure A-1 An example of design sketch

Figure 6-2 An example of 3D design model

Figure 6-3 An example of module design

Figure 6-4 An example of rendered 3D model

Figure 6-5 An example of prototype modules design

Figure 6-6 An example of prototype design

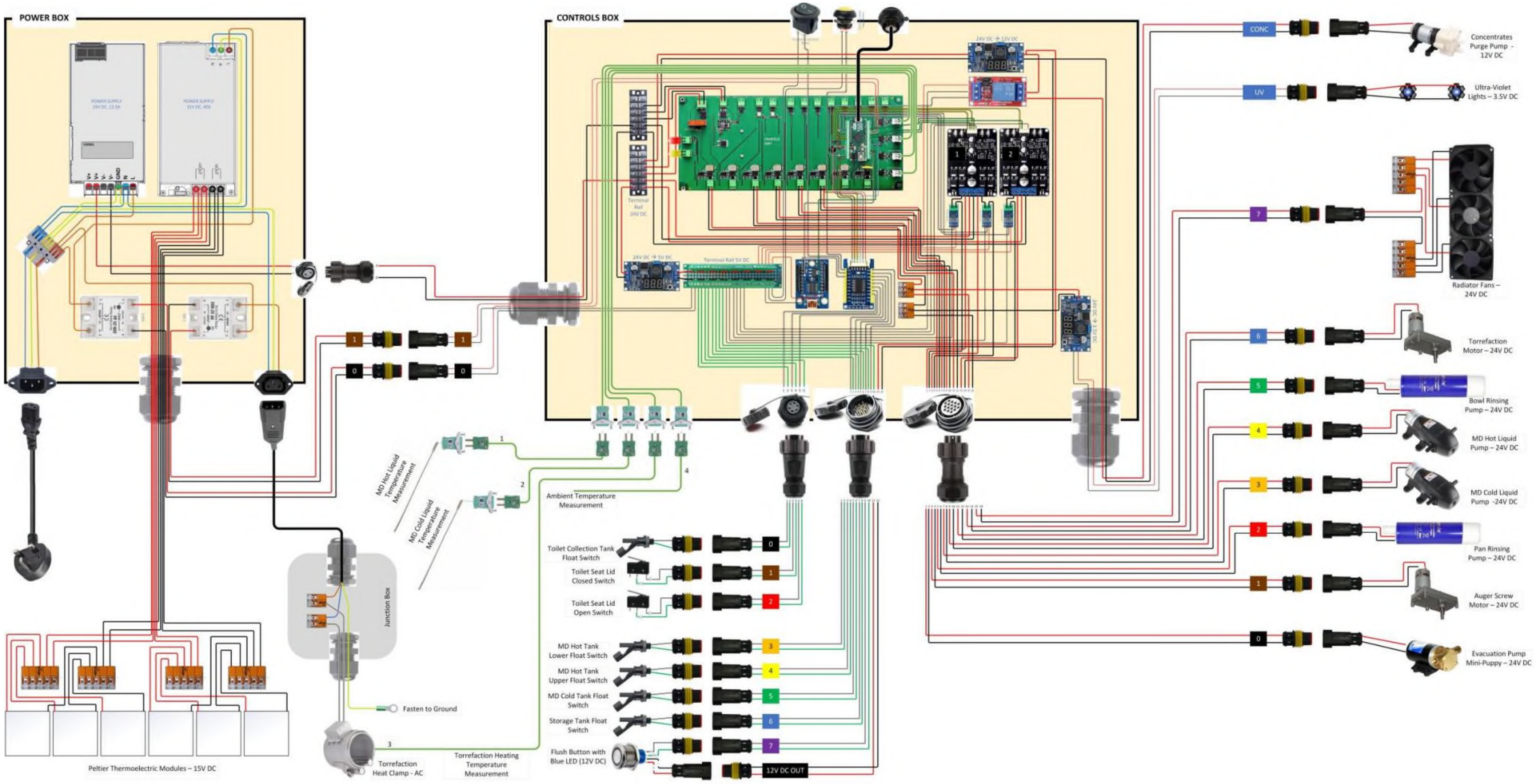

Figure 6-7 The first version of sensor integrated electronics design

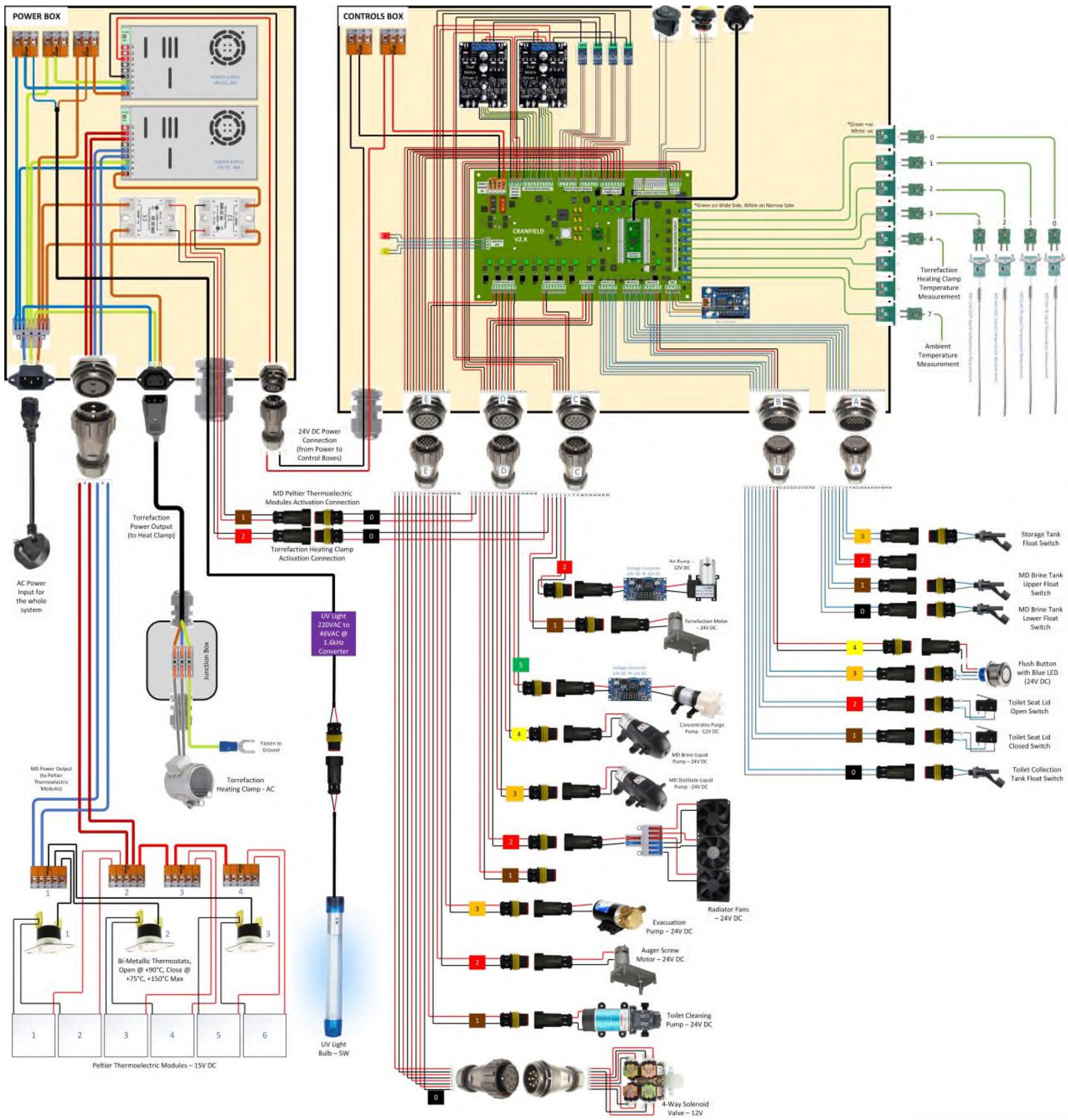

Figure 6-8 The second version of sensor integrated electronics design

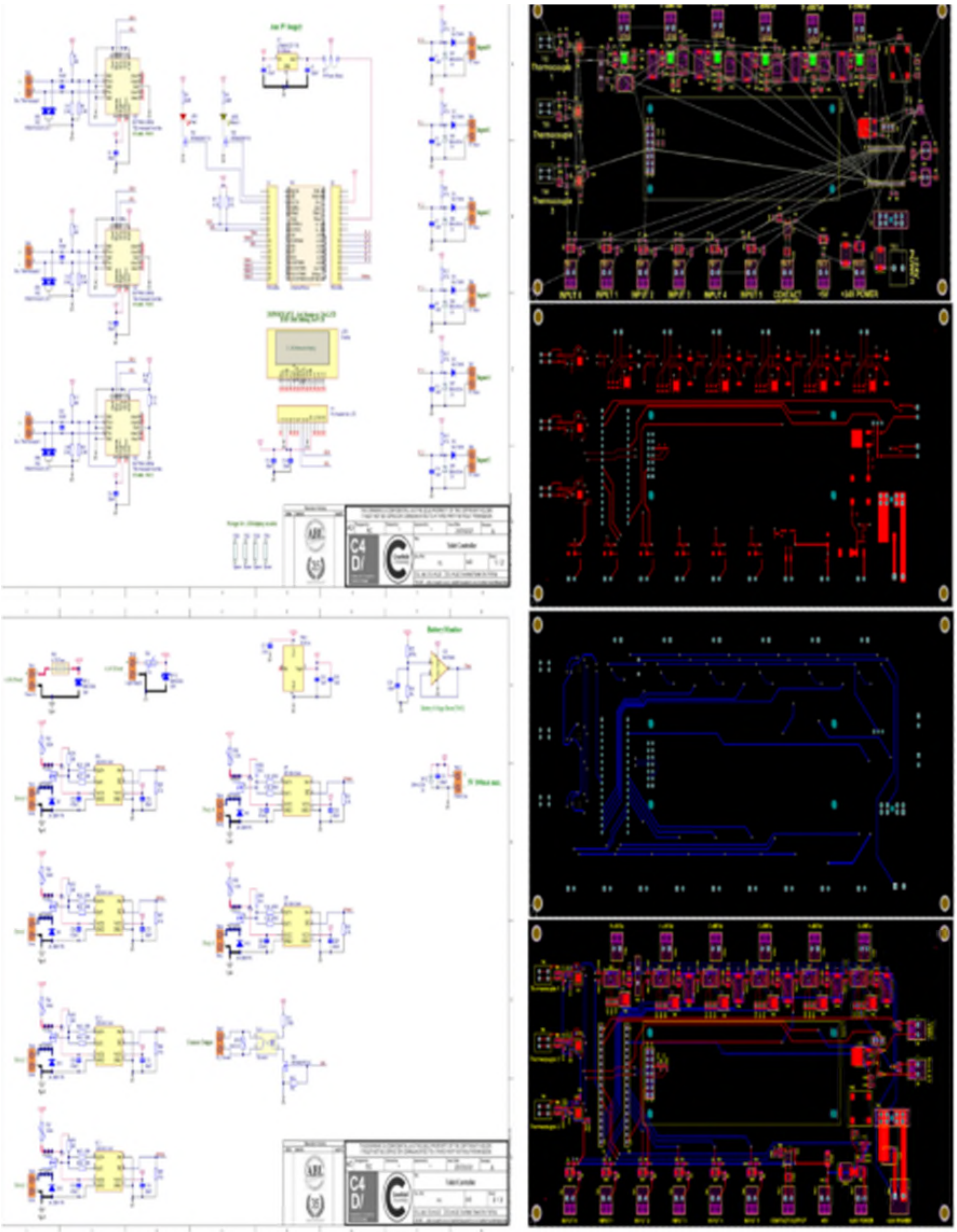

Figure 6-9 The electronics sketch examples

A.2 Prototyping

Prototyping is an important step in the development process for an IoT-based intelligent toilet. It allows developers, engineers, and technicians to test the system functionality, improve user experience, and make iterative design changes. By creating a prototype, the team can identify any bugs, design flaws, or usability issues that need to be addressed. The section showcases several prototype images to augment the presentation of the Cranfield intelligent sanitation concept (see Figure A-10 to Figure A-12).

Figure 6-10 An example of toilet module prototype

Figure 6-11 An example of whole toilet prototype

Figure 6-12 Electronic component prototype examples

A.3 Lab testing and Experiments

Experiments are essential for the development of Cranfield intelligent toilet. Laboratory experiments allow for the testing and validation of various features and functionalities of the toilet. Through laboratory testing, the team can simulate different scenarios and test the performance under various conditions. This can include evaluating the accuracy of sensors, the reliability of the communication between the toilet and other IoT devices, and the effectiveness of data processing algorithms. Experiments can also be conducted to gather data on user behaviour. The data can be analysed to improve the design of the toilet and to develop features that better meet the needs of users. The section includes several photos of lab testing and experiments to enhance the clarity, credibility, and contextual understanding of the Cranfield intelligent toilet system (see Figure A-13 to Figure A-18).

Figure 6-13 Cranfield intelligent toilet in the lab

Figure 6-14 Experiments conducted on Cranfield intelligent toilet

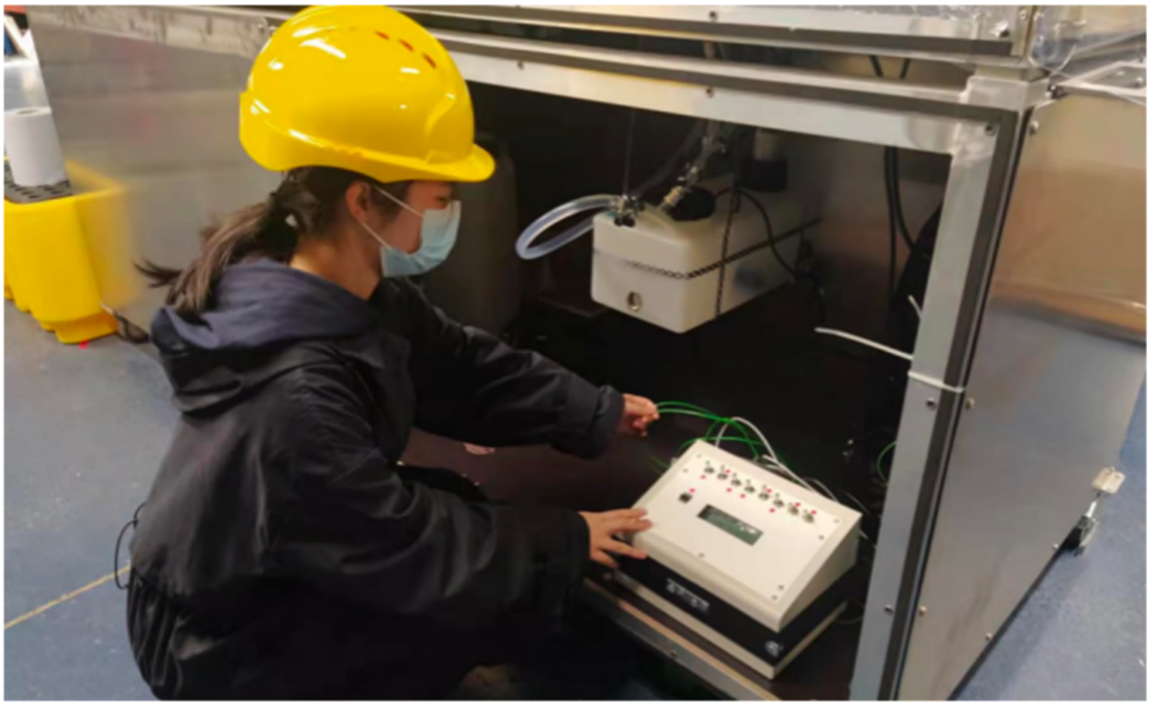

Figure 6-15 Experiments conducted on electronic control box

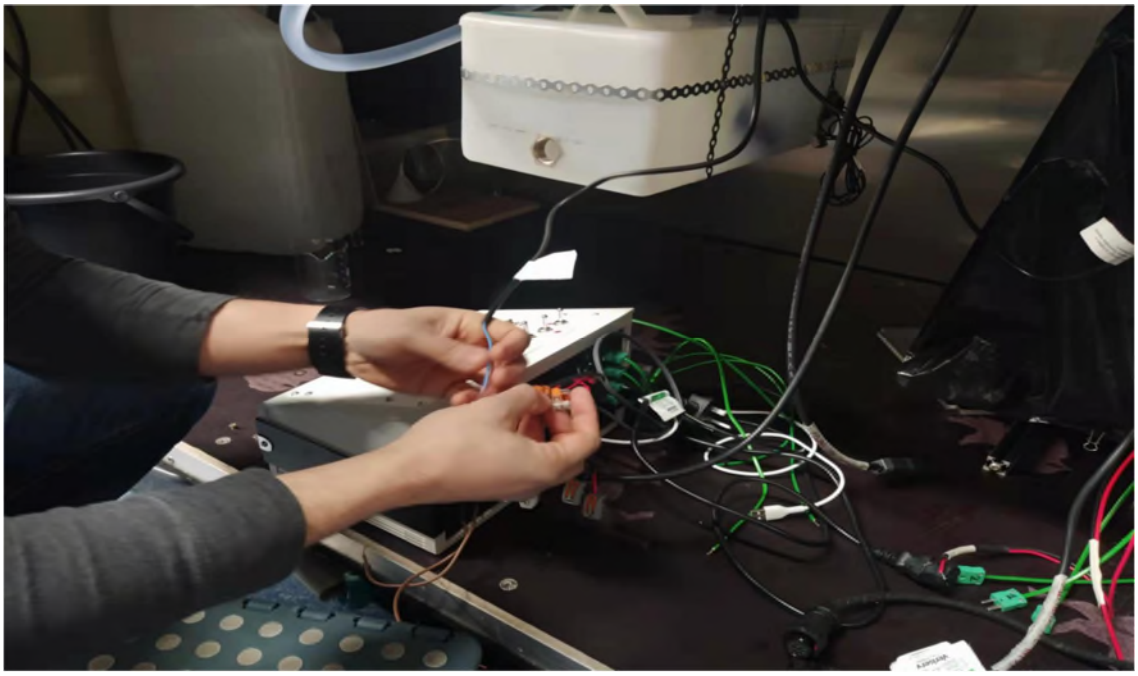

Figure 6-16 Experiments conducted on wiring and sensor installation

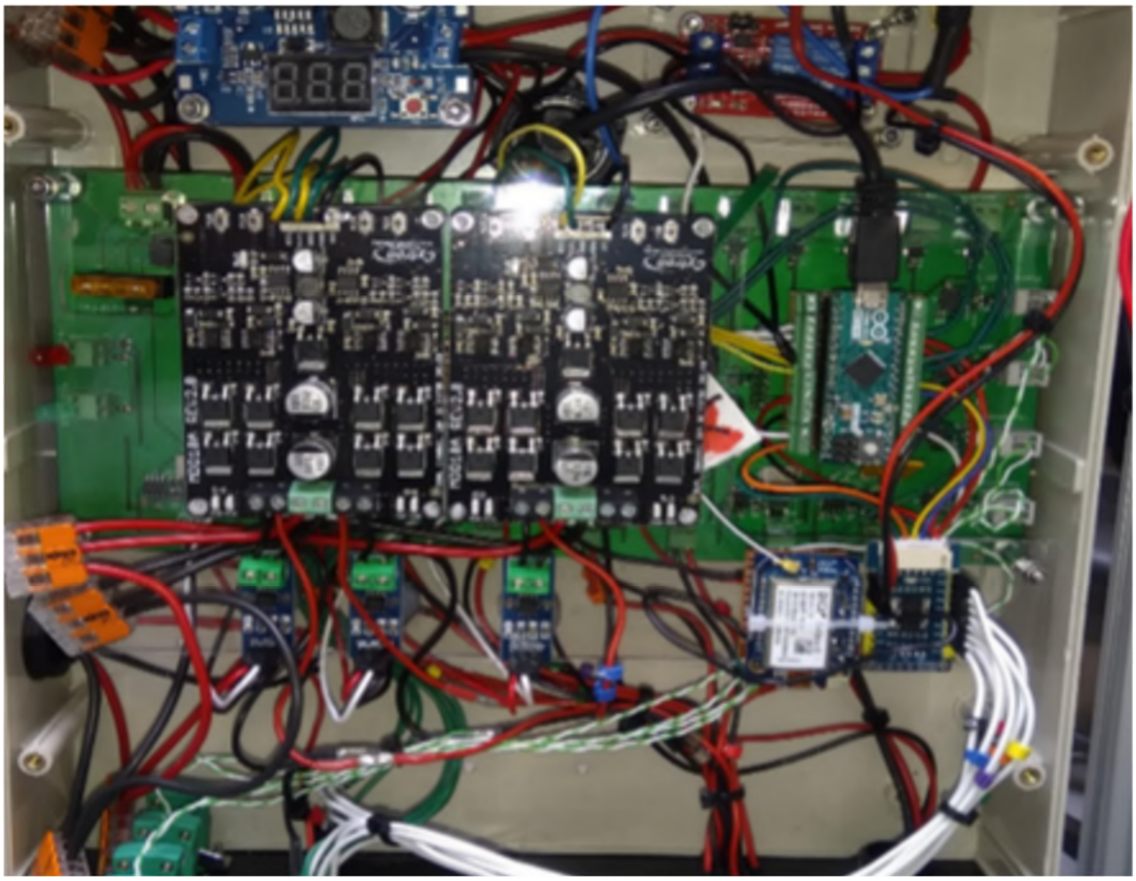

Figure 6-17 Experiments conducted on electronic control box

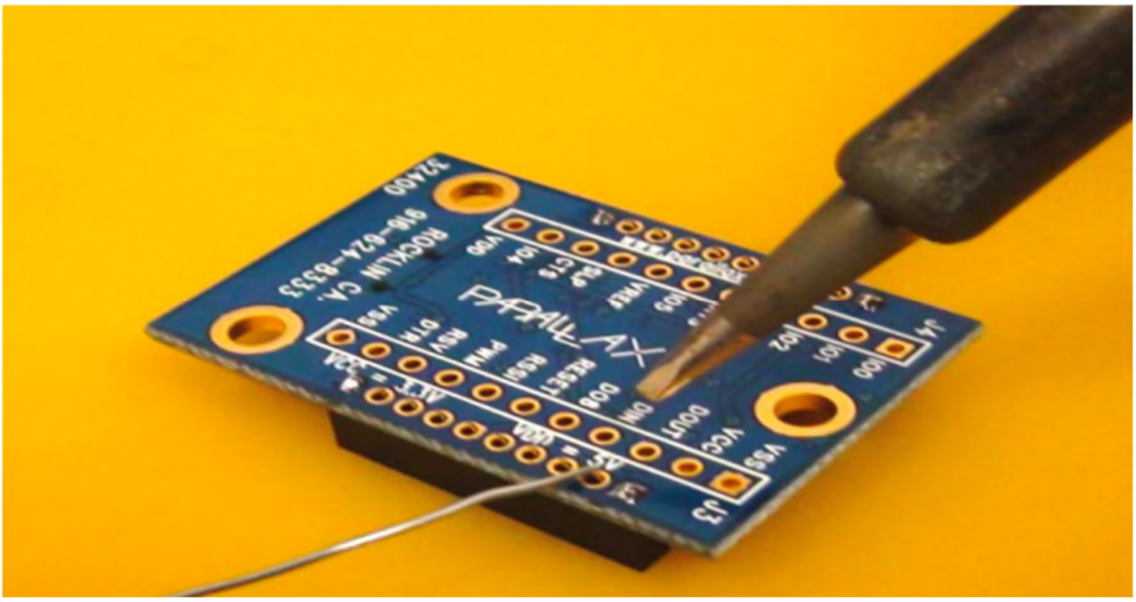

Figure 6-18 Experiments conducted on electronic components

A.4 Field Testing

Field testing can provide valuable insights into real-world usage scenarios, user behaviour, and product performance, ultimately leading to a more effective and user-friendly product. While laboratory testing provides valuable information, it cannot simulate all the variables and complexities of actual usage scenarios. The section presents several field-testing photos that demonstrate the actual implementation of the system in a real-world environment (see Figure A-19 and Figure A-20). These photos serve as evidence of the system functionality and reliability, and help readers better understand the capabilities of the Cranfield intelligent toilet.

Figure 6-19 Field testing in a trailer

Figure 6-20 Field testing in a house

A.5 Software User Interface

The software user interface is the primary tool for data visualisation, analytics, and decision-making in the Cranfield intelligent toilet project. The software application has the potential to simplify data interpretation, improve data quality, and increase user engagement. Additionally, the user interface can provide real-time data analysis and visualisation, enabling developers and users to monitor and control the system performance efficiently. The section presents some user interface design figure (see Figure A-21), App interactive demo photos (see Figure A-22), and data visualisation images (see Figure A-23 and Figure A-24) to demonstrate the features and functionality of the software, app and the IoT system.

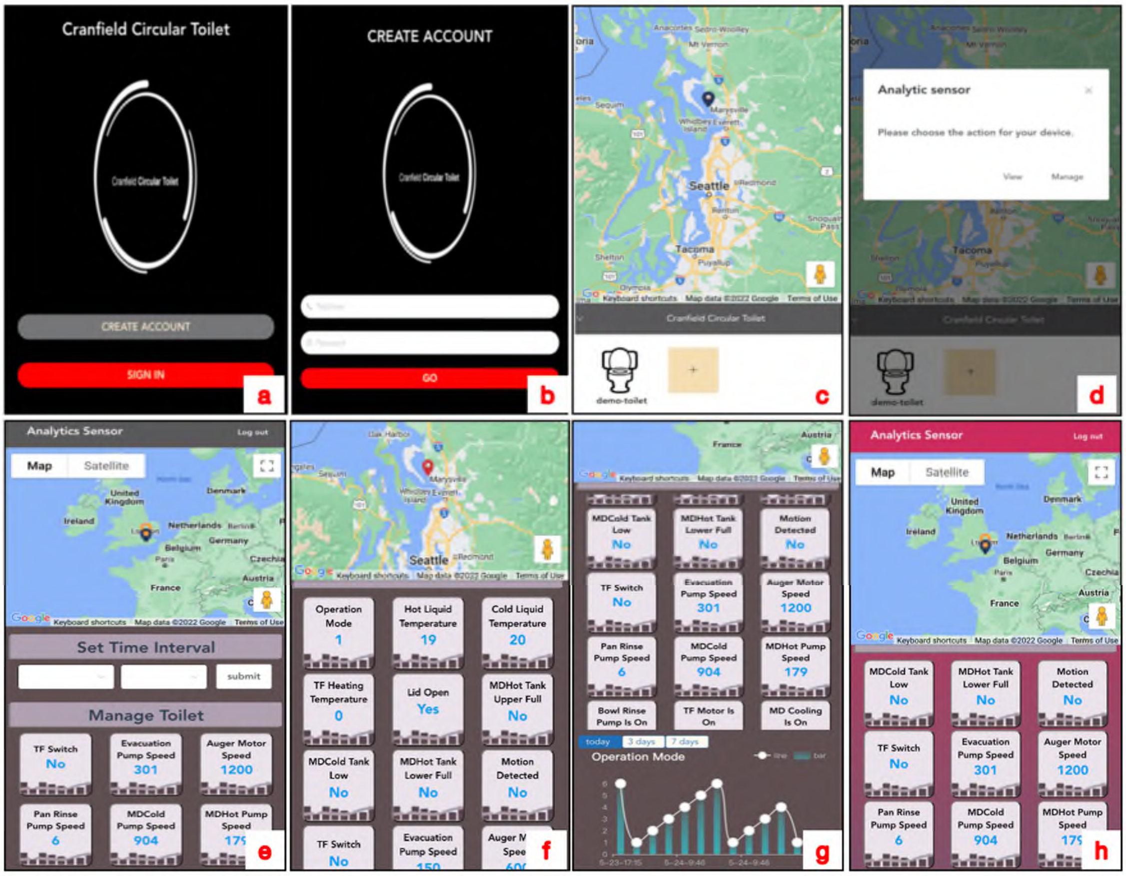

Figure 6-21 User interface design for software application

Figure 6-22 Software interactive demonstration

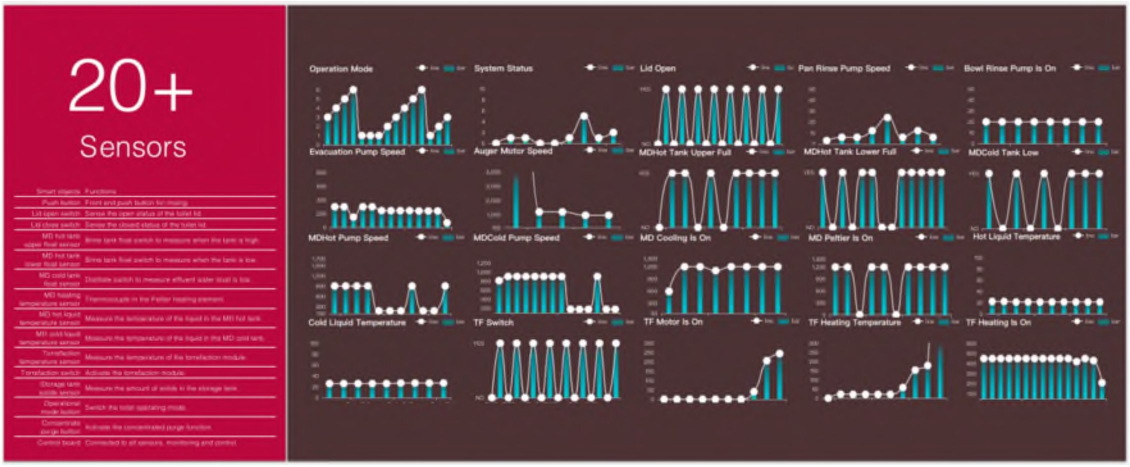

Figure 6-23 Data visualisation in software

Figure 6-24 Software for displaying 3D models of Cranfield intelligent toilet

A.6 Software Programming Code

Cranfield intelligent toilet are a complex system that require the integration of various hardware and software components, including sensors, microcontrollers, communication modules, cloud services, and interactive user interface. programming code is essential for integrating these components and creating a cohesive system that can collect and process data, communicate smart assets, and provide useful insights to users. The software code is also responsible for the functionality of the user interface, data visualisation, and data analysis capabilities of the intelligent toilet system. The section provides an in-depth view of the software architecture, programming languages, methods, and techniques employed, as well as the data analytics tools and algorithms utilised, to offer a comprehensive understanding of the technical aspects of the development of the toilet data management tool. The details of Arduino, frontend, backend, XBEE communication, database programming, and code management are presented in the section (see Figure A-25 to Figure A-30).

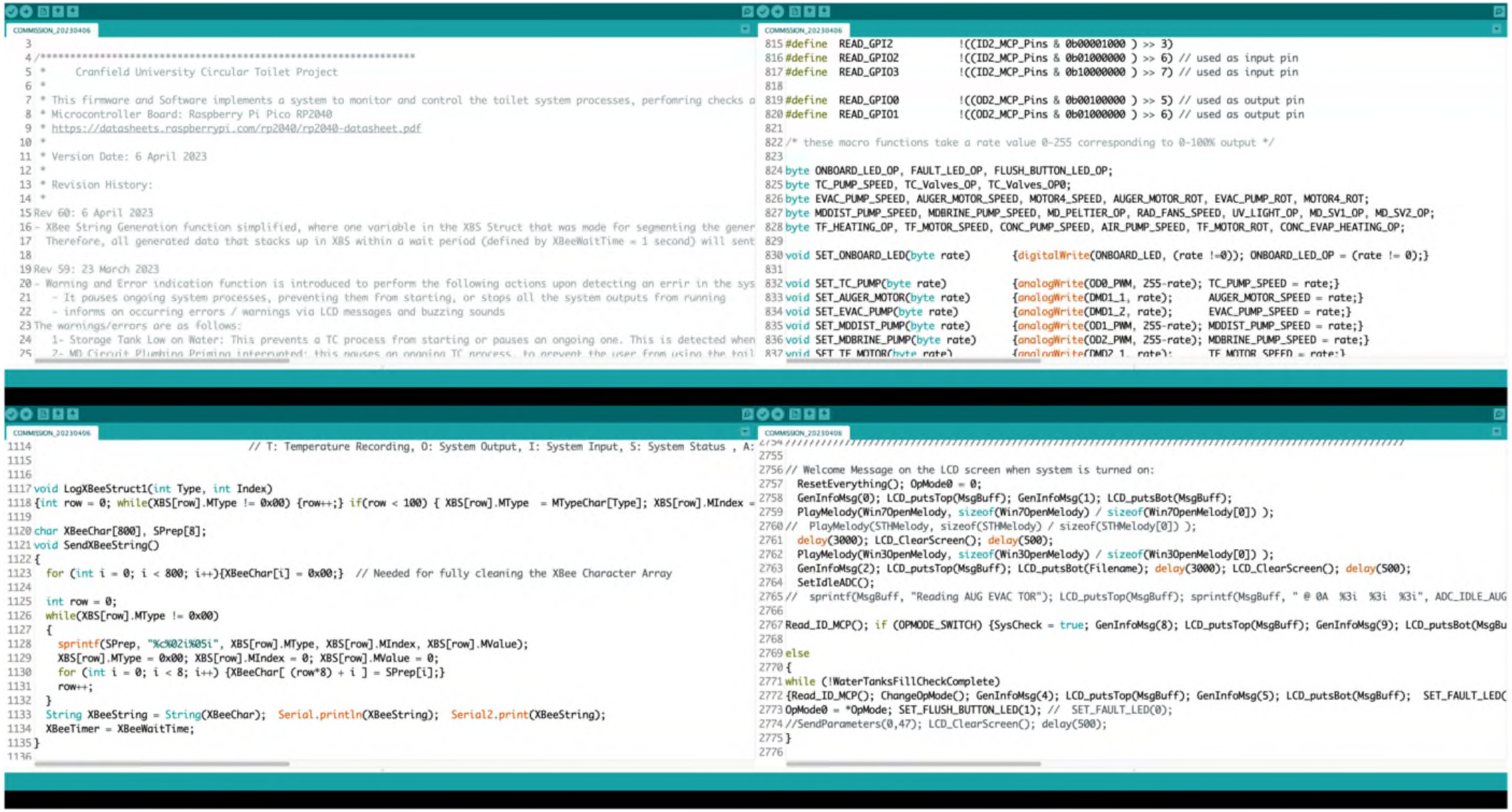

Figure 6-25 Software Arduino programming code examples

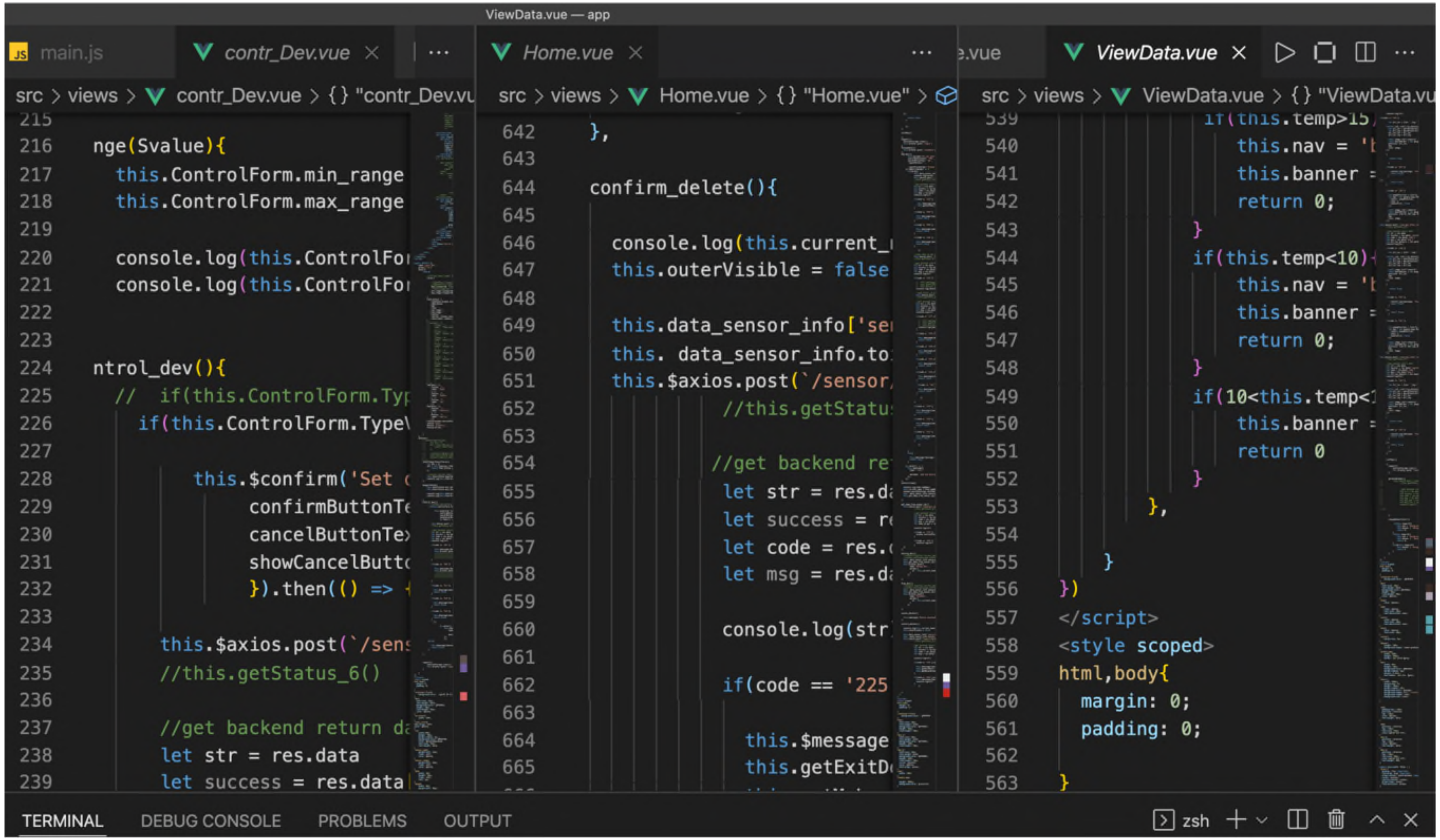

Figure 6-26 Software front-end programming code examples

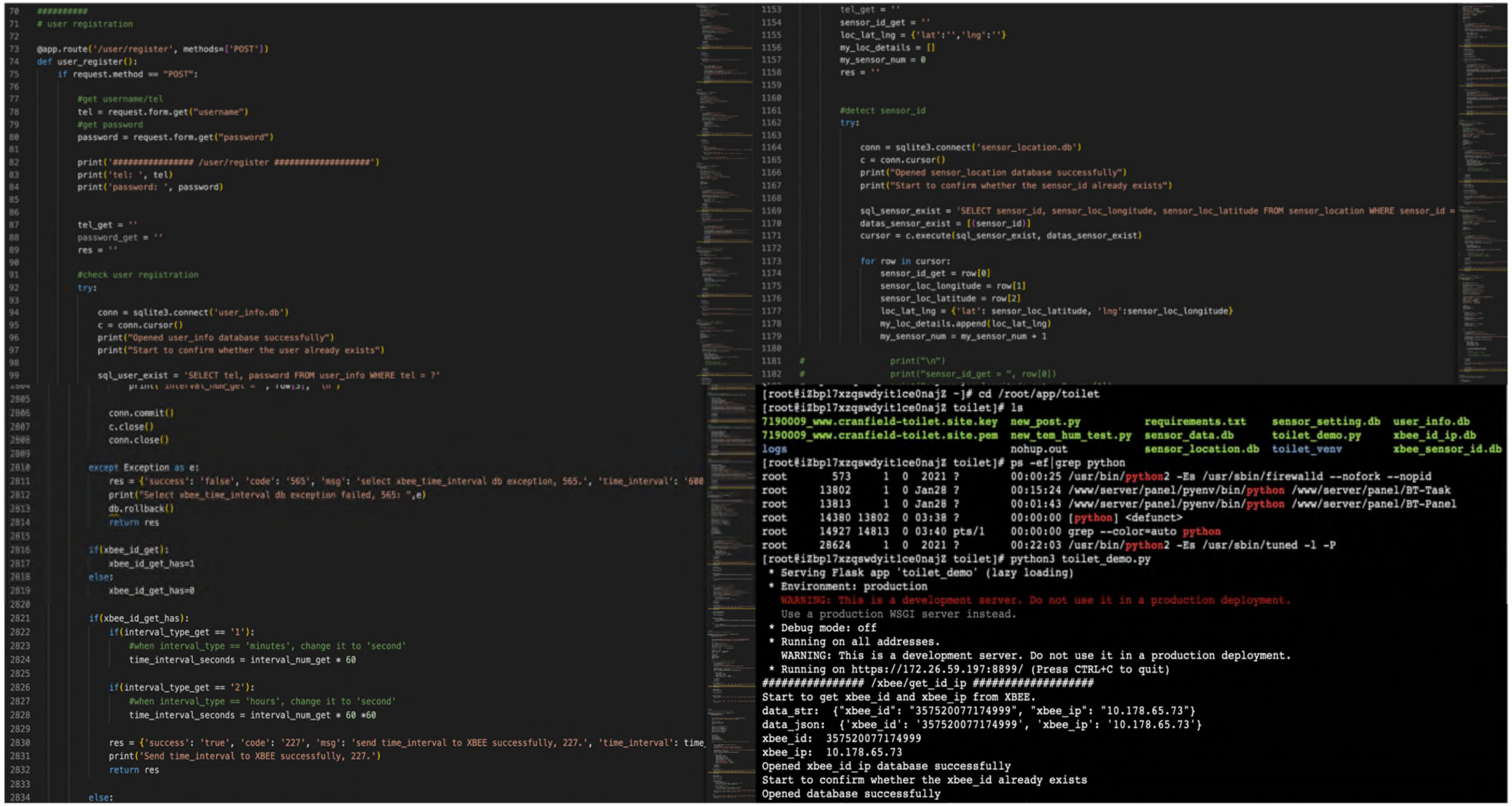

Figure 6-27 Software back-end programming code examples

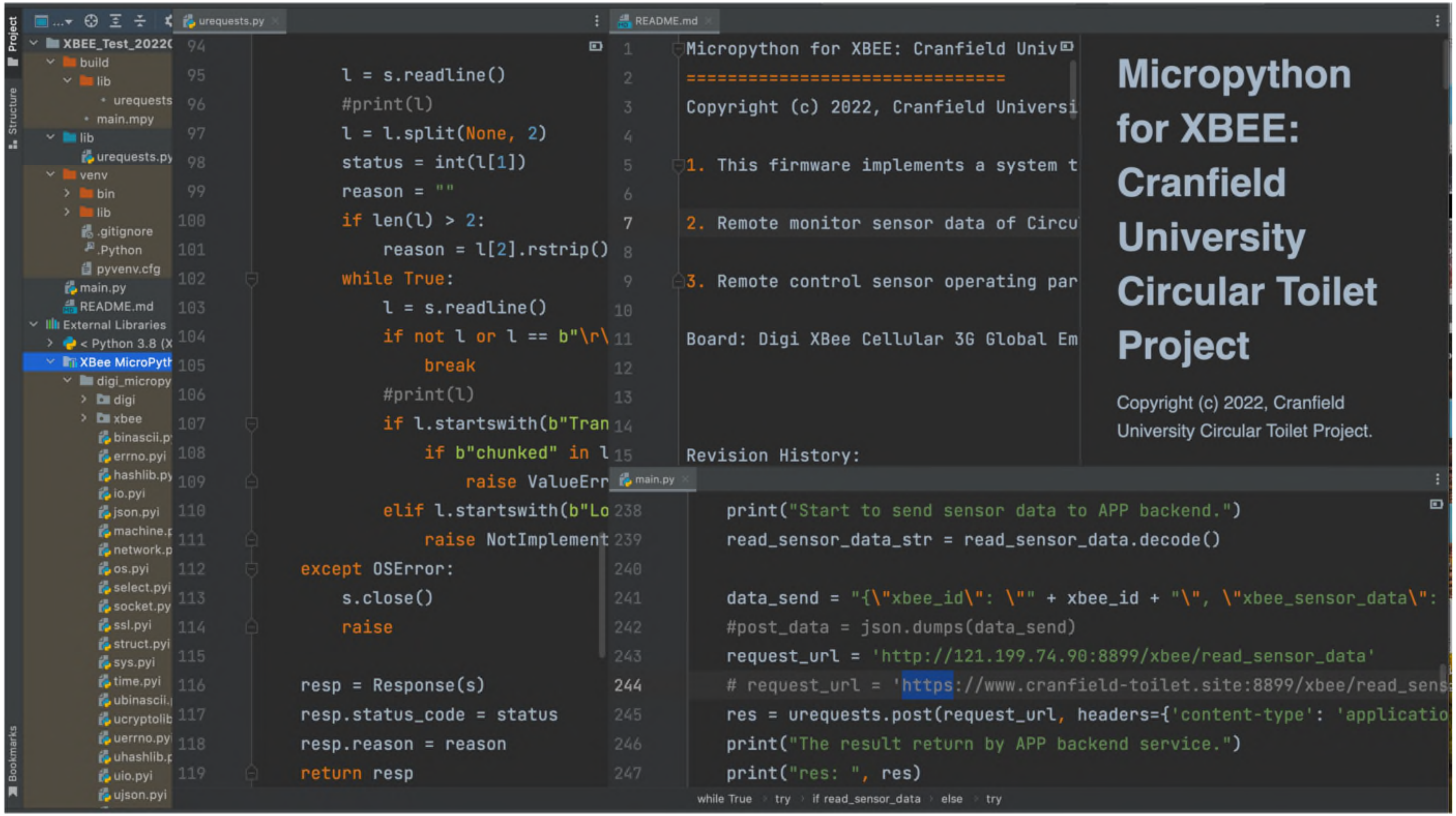

Figure 6-28 Software XBEE communication programming code examples

	sensor_id	sensor_type	current_data	sensor_time	id
	过滤	过滤	过滤	过滤	过滤
3975	cranfield123_demo-toilet	19	1200	1658890965	40...
3976	cranfield123_demo-toilet	19	1104	1658893565	40...
3977	cranfield123_demo-toilet	19	1200	1658894365	40...
3978	cranfield123_demo-toilet	19	593	1658898565	4087
3979	cranfield123_demo-toilet	19	1200	1658910965	40...
3980	cranfield123_demo-toilet	20	593	1658473565	40...
3981	cranfield123_demo-toilet	20	1200	1658480765	40...
3982	cranfield123_demo-toilet	20	0	1658497165	4091
3983	cranfield123_demo-toilet	20	1069	1658497265	40...
3984	cranfield123_demo-toilet	20	1200	1658499565	40...
3985	cranfield123_demo-toilet	20	0	1658554365	40...
3986	cranfield123_demo-toilet	20	1200	1658555165	40...
3987	cranfield123_demo-toilet	20	1200	1658557565	40...
3988	cranfield123_demo-toilet	20	0	1658565965	40...
3989	cranfield123_demo-toilet	20	0	1658572365	40...
3990	cranfield123_demo-toilet	20	593	1658574565	40...
3991	cranfield123_demo-toilet	20	1200	1658620765	4100
3992	cranfield123_demo-toilet	20	1200	1658624365	4101
3993	cranfield123_demo-toilet	20	1200	1658627965	4102
3994	cranfield123_demo-toilet	20	0	1658653565	4103
3995	cranfield123_demo-toilet	20	0	1658714365	4104
3996	cranfield123_demo-toilet	20	1200	1658721565	4105
3997	cranfield123_demo-toilet	20	1200	1658728765	4106
3998	cranfield123_demo-toilet	20	1200	1658739965	4107
3999	cranfield123_demo-toilet	20	1200	1658757165	4108
4000	cranfield123_demo-toilet	20	593	1658787965	4109
4001	cranfield123_demo-toilet	20	1200	1658829165	4110
4002	cranfield123_demo-toilet	20	1200	1658832765	4111
4003	cranfield123_demo-toilet	20	0	1658846365	4112
4004	cranfield123_demo-toilet	20	0	1658857165	4113

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Figure 6-29 Software database programming code examples

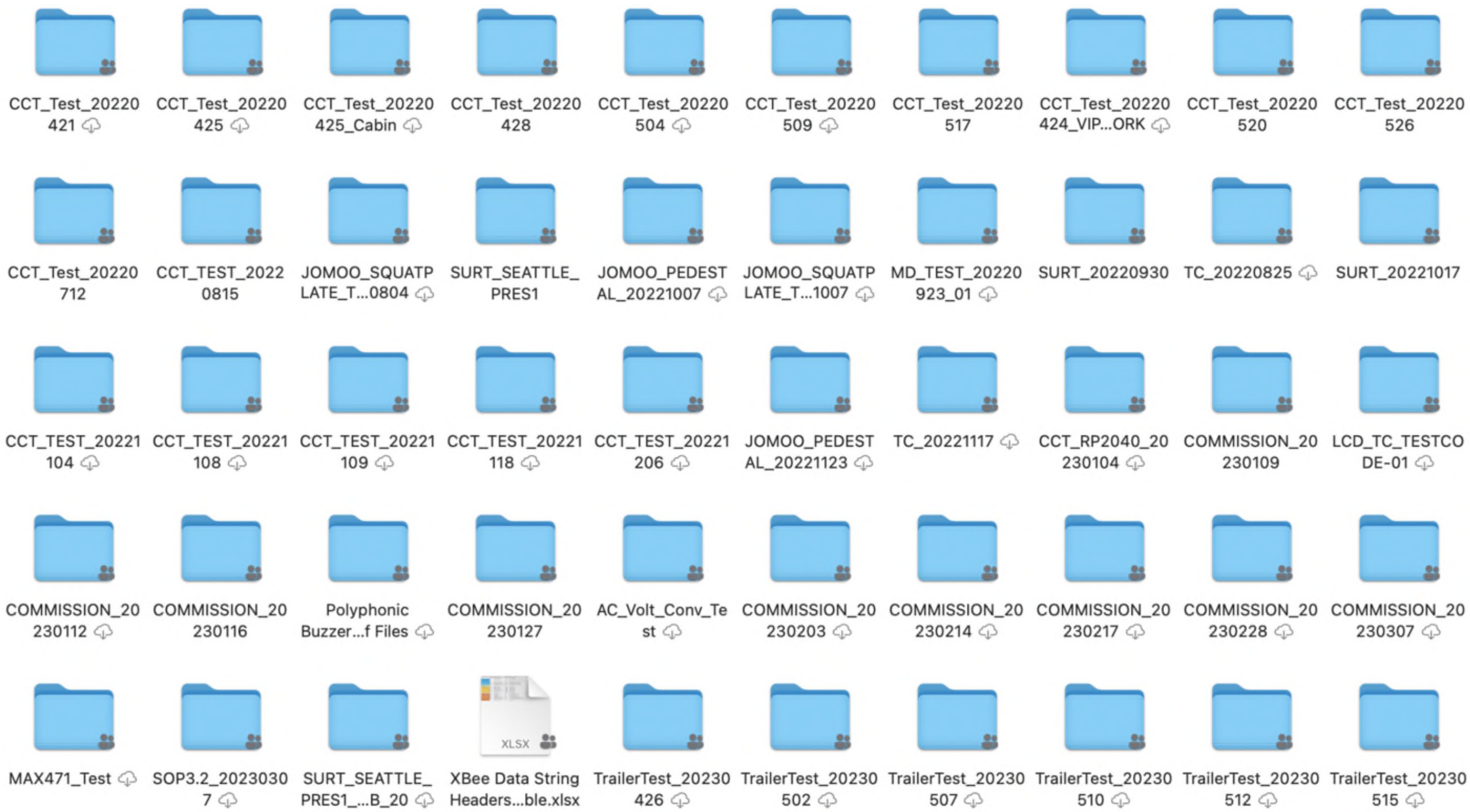

Figure 6-30 Programming code management examples

A.7 Data Examples

Data empowers designers and developers to enhance the performance of the toilet system, monitor and maintain it effectively, evaluate its efficacy, and establish trust and credibility in the project. Data analytics can identify areas for improvement and tailor the toilet system to better meet the needs of users. The section show some data examples to demonstrate the performance and effectiveness of the Cranfield intelligent toilet (see Table A-1).

Table 6-1 Examples of data collected from Cranfield intelligent toilet

Sensor Type	Data Value	Timestamp
31	0	1678439185
9	4	1678439190
10	77	1678439190
9	0	1678439190
10	0	1678439190
32	1	1678439190
51	1	1678439190
1	11	1678439203
8	12	1678439203
9	2	1678439230
10	77	1678439230
32	0	1678439230
31	1	1678439230
9	1	1678439235
9	0	1678439235
10	0	1678439235
11	459	1678439239
12	383	1678439239
51	0	1678439239
52	1	1678439239

Table A-1 Examples of data collected from Cranfield intelligent toilet (continued)

Sensor Type	Data Value	Timestamp
12	255	1678439244
12	383	1678439248
12	255	1678439248
12	383	1678439252
12	255	1678439259
12	383	1678439259
12	255	1678439264
12	383	1678439264
12	255	1678439268
12	383	1678439268
12	0	1678439272
12	383	1678439272
12	255	1678439277
41	1	1678439277
12	383	1678439281
12	255	1678439285
12	383	1678439290
12	255	1678439290
11	332	1678439295
52	0	1678439295

Table A-1 Examples of data collected from Cranfield intelligent toilet (continued)

Sensor Type	Data Value	Timestamp
31	0	1678439652
9	4	1678439657
10	77	1678439657
9	0	1678439657
10	0	1678439657
32	1	1678439657
51	1	1678439657
9	8	1678439667
10	77	1678439667
33	1	1678439667
33	0	1678439667
9	0	1678439672
10	0	1678439672
9	8	1678439672
10	77	1678439672
33	1	1678439672
33	0	1678439672
9	0	1678439676
10	0	1678439676
3	58	1678449972

Table A-1 Examples of data collected from Cranfield intelligent toilet (continued)

Sensor Type	Data Value	Timestamp
3	56	1678449966
1	26	1678449966
3	57	1678449966
3	58	1678449972
3	59	1678449972
3	60	1678449972
3	61	1678449978
3	62	1678449984
3	63	1678449990
2	51	1678450003
3	64	1678450009
2	52	1678450015
3	65	1678450021
2	53	1678450027
3	66	1678450033
2	54	1678450039
3	67	1678450045
2	55	1678450051
3	68	1678450057
2	56	1678450064

Table A-1 Examples of data collected from Cranfield intelligent toilet (continued)

Sensor Type	Data Value	Timestamp
3	69	1678450071
2	57	1678450080
3	70	1678450089
2	58	1678450097
3	71	1678450106
18	44	1678450113
2	59	1678450119
18	48	1678450125
2	60	1678450133
18	52	1678450139
3	72	1678450145
18	56	1678450151
2	61	1678450157
18	60	1678450163
18	64	1678450173
18	68	1678450185
2	62	1678450191
18	72	1678450197
18	76	1678450209