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NEXUS OF WIREFRAMES, 3D MODEL, AND SIMULATION FOR THE DEVELOPMENT OF AN INTELLIGENT WASTE MANAGEMENT SYSTEM

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ABSTRACT

The exponential growth in urban population has intensified the challenges of municipal waste management, necessitating innovative technological solutions. This research presents an integrated approach to developing a smart waste management system by integrating wireframes, 3D modeling, and simulation technologies. The study employs a three-phase methodology: utilizing wireframe prototyping for user interface design, enabling iterative development based on stakeholder feedback, implementing detailed 3D modeling of smart waste bins to visualize and optimize waste flow dynamics, and conducting comprehensive simulations to evaluate system performance under various scenarios. The simulation analysis compared multiple routing algorithms while monitoring real-time bin capacity through virtual sensors. Results demonstrate a 25% improvement in collection efficiency using dynamic routing compared to traditional fixed routes and a 30% reduction in overflow incidents through predictive capacity monitoring. The user-centered design approach, validated through wireframe testing with 50 participants, showed a 40% increase in system engagement compared to conventional waste management interfaces. Additionally, the 3D modeling phase identified critical design modifications that improved bin accessibility by 35% and reduced maintenance requirements by 20%. This research contributes to the growing knowledge of smart city solutions while providing practical insights for municipalities seeking to modernize their waste management. infrastructure. The proposed system offers a scalable, efficient approach to addressing urban waste challenges while promoting environmental sustainability. A limitation of the study is its reliance on simulation-based testing, which may not fully represent real-world operational complexities. A major challenge is implementation dependency on continuous stakeholder engagement and high reliance on technological infrastructures.

Keywords: Intelligent Waste Management, Wireframes, 3D modeling, Simulation Technologies, Sustainability, Integrated prototyping

INTRODUCTION

Prototyping is integral to product development (Lauff et al., 2018). It is crucial to improve waste management systems, especially considering the rapid growth of urban populations. Waste management provides a functional method for developing and refining effective waste solutions (Ladan, 2023). The increasing global waste crisis caused by quick urbanization has brought about the need for efficient solutions. Ferronato & Torretta (2019) noted that waste management has led to a worldwide problem of Environmental contamination. This meant that a lot of new and innovative solutions were needed to deal with the issue of waste management (Ferronato & Torretta, 2019). This research investigates designing a smart waste management system using wireframing, 3D modeling, and Simulation. A system that would maximize its functionality and deal with waste effectively. These tools will be combined to create a system that will bring new ways to deal with waste effectively. This would include the collection, disposal, and recycling of waste. The development cycle of this product is divided into two parts, namely, the software part and the hardware part (Olawade et al., 2024). Both parts of this cycle take a different approach while working together to deliver the product. The product obtained from combining both parts will align closely with this study's set goals. The software part of the product development cycle uses wireframing for the system's design, making user experience available, providing a user interface, and providing a basic demonstration of its functions. The hardware bit of the product development cycle uses 3D modeling and simulation to achieve its aim (Mohammad Ikbal Hossain, 2023). This conceptual model allows for further tests to be carried out before the physical representation is created for implementation. The conceptual model is done by simulation, called a prototype (Kent et al., 2021). Prototyping is used for user testing, vital in developing the smart waste management system. A specific prototype reduces the resources used and the time spent because it is developed to meet user requirements (Akram et al., 2021). Wireframes act as interactive prototypes to gather a visualization of the layout and user feedback. These wireframes use the user feedback based on user interactions to make the necessary system adjustments before implementation (*What Is Wireframing? — Updated 2024 | IxDF*, n.d.). This ensures that the design meets the needs and requirements of the user and aligns with the set goals of the system. It has been observed that wireframes, especially tangible wireframes, are easy to work with, and they can offer a better understanding of the product design.

Wireframes will be used to create user-based interfaces that serve the user and the waste management team. After wireframing has been carried out and feedback has been obtained, 3D modeling will be used to design a visual representation of the expected bin. These visual representations will enable simulations of the various waste generation situations and collection scenarios. Three-dimensional printing will include different manufacturing technologies that will be used to create physical models from the existing virtual models. According to (Aimar et al., 2019)v3D models will provide detailed virtual representations of the smart waste management system being worked on. Various tools are used, and, in our case, Blender is used. Blender creates high-quality models of our proposed smart bin and its various components(Afolalu et al., 2021). These models will give an extensive overview of our system from different angles, allowing the stakeholders to observe and provide feedback on the design. The feedback provided is then used to improve the designed system and ensure the result is satisfactory (Wynn & Maier, 2022). After the creation of the 3D model, various simulations will be done to analyze the performance of the waste management system in different scenarios and improve the system based on the results obtained from these simulations (Mourtzis, 2020) highlighted the importance of simulation technologies in the testing and enhancement of smart waste management systems. The simulations will allow for the system's performance to be tested under different scenarios, identify potential issues, and for improvements to be made based on these issues. Wireframing, 3D modeling, and simulation offer an efficient way to create our waste management system and ensure it aligns with the set goals (Gorecki et al., 2020). The combination helps ensure that the system created is an efficient, sustainable, and user-efficient waste management system. This research addresses the challenges of inadequate waste management systems, their solutions, and how to improve them. Combining these steps, we aim to develop a sustainable solution that will reduce problems associated with waste collection, improve waste management, and boost public satisfaction(Zhang et al., 2024).

The problem of waste management has quickly become a serious concern as time has passed. It has negative impacts and consequences if not addressed properly, this has led to several groups and several people to come up with and propose various strategies to deal with the challenges associated with waste production and management(Salvia et al., 2021).

Prototyping in Solid Waste Management

Harith et al (2020) used prototyping to develop an IoT-based smart bin. This bin they developed was their solution to dealing with the inadequacies of traditional waste management systems. They started by creating low-fidelity prototypes that showed the basic structure and functionality of the system and provided a visual representation of it. This representation was used for testing, allowing for improvements to be made during the design stage (Harith et al., 2020).

The low-fidelity prototypes included the various components to ensure they worked properly and, if they didn't, to identify and deal with problems (ITF, 2022). The results from these tests were then shared with waste management authorities, stakeholders, end-users, and anyone who was a part or a user of the smart bin. These results were shared to test how well the system operated and its efficiency. If there were any problems, this step would help highlight them and make improvements, ensuring the system would perform better(Pulparambil et al., 2024).

An Arduino microcontroller and a Raspberry Pi-based prototype were used to oversee waste management and segregation in Sasikanth et al.'s (2021) model. This prototype was created to test the system's effectiveness and show the interaction between its components. An Arduino microcontroller, Raspberry Pi, sensors, and a camera were used to feed information to the system (Sasikanth et al., 2021). The goal of this proposed system was to make sure waste was managed effectively and that the system proposed to segregate, process, and recycle waste worked efficiently. But, before any processing is carried out, the dry waste the system has collected is segregated using the data obtained from image analysis (Pučnik et al., 2024).

The prototyping model proposed by Rahman et al. (2022) was a key part of developing an innovative waste management system that used deep learning and IoT technologies (Adeleke et al., 2023). These technologies were used to create a solution that was effective and efficient. (M. A. Rahman et al., 2022). The prototyping model proposed by Saad Alotaibi et al. (2024) was split into two main components, notably the architectural model. It used a Raspberry Pi, a camera, and a mechanism that employed deep learning techniques for waste classification(Saad Alotaibi et al., 2024). The prototype of this model was very important in these waste classification processes as it allowed for the model to be created and tested to improve its efficiency. Prototypes played a very important part in developing and authenticating waste processing systems. Khan et al. (2021) focused on detecting and recycling waste, and the prototype was built to address these needs. The prototype included a mobile application that monitored the amount of waste, tested the stability of the bin, and checked its fill level(Khan et al., 2021).

Simulation in Solid Waste Management

Meng et al. (2018) employed a model that employed Multi-Agent-Based Simulation (MABS) to examine how the changes in the agents within the Household Solid Waste (HSW) classification affected waste production and recycling under different conditions. Its primary aim was to determine the most helpful approach to waste management, one that could enhance waste classification and recycling. An Analogic software platform was used, and these simulation agents made their decisions based on the parameters and categories in which they were placed. These parameters affected their waste disposal behavior, and notes were taken based on them. The amount of waste being dealt with was calculated by the simulation based on the agents' behavior, providing feedback to the agents. The results obtained from these simulations showed how different policies or situations affected waste generation and separation by the user and the system's overall performance (Meng et al., 2018). Likewise, Di Nola et al. (2018) used a system dynamics model to simulate the intelligent waste management solution employed. The waste system was simulated to understand its behaviors under different scenarios, especially if it did not meet the expected waste volumes. A system dynamic approach was used as it provided a basic understanding of the complex systems and their components (Di Nola et al., 2018). The waste system used in Campania was analyzed using these sorting and production models. This analysis provided essential insights into how these changes in policies and infrastructure would impact the amount of waste generated as time passed(Wang & You, 2021).

Xiao et al. (2020) used a system based on the System Dynamics Model. This system aimed to create a simulation covering Shanghai's municipal solid waste (MSW) management process. All the processes, including production, collection sorting, and final treatment, were simulated to understand how different policies would affect the system. Unlike previous studies, their System Dynamics Model provided a comprehensive view of the waste management process by simulating the entire system (Xiao et al., 2020). This model used seven distinct scenarios to improve their view of how to deal with waste. The policies they studied included economic, demographic, sorting, and treatment policies, one of which included a study on the GDP(Pinha & Sagawa, 2020). The effect of the Gross Domestic Product (GDP) changes on waste management and production was simulated to understand how an increase or a decrease in GDP would affect the amount of waste generated(Matraku &

Çafuli, 2015). Other policies, such as Municipal Solid waste regulations and their effect on the demand for landfills and food waste treatment sites, were studied. When this sorting policy was implemented, there was a reduction in the demand for landfills while also increasing the demand for food waste treatment sites (Ogbolumani & Nwulu, 2024; Ogbolumani & Nwulu, 2021). The System Dynamic Model focused on capturing how these different elements of the waste management system interacted and how the policy changes affected waste management systems. The results affected policymakers' decisions and helped adopt efficient waste management strategies(Nanda & Berruti, 2021).

The study by Johannes (2018) used simulation to analyze and assess the impact of Integrated waste management practices on waste management. A model that provided a visual outlook of the waste management system used as TPST Mustika Ikhlas was created to monitor how time affected waste production (Johannes, 2018). The model focused on how waste could be reduced and appropriately processed over a specified amount of time. After the model has been simulated, a loop diagram is created to visually illustrate the relationships between the variables that affect waste production(Moutavtchi et al., 2020). This loop diagram is then translated into a Stock flow Diagram using Powersim Studio 10 software. This stock flow diagram comprised details on the waste flow in the specified period, the generated amount, and variables that could affect the entire process. This simulation ran for over 1080 days to observe how time affects the waste management system and the amount of generated waste (Latif et al., 2023). This simulation was done using the System Dynamics model as it could capture the complexities in the waste management system. It allowed for a model to be created by the team for analysis of various factors on the waste management system's results while providing insights into how it could be improved(Rafew & Rafizul, 2021).

Wireframing in Solid Waste Management

Wireframing was used by Nuryanto & Suzianti (2022) as an essential part of the design process to address the challenges in the User Interface (UI) of electronic waste collection applications. These wireframes provided an essential representation and outlook of the application interface, showing a basic layout of its key elements. This helped plan user interaction based on the user interface (Nuryanto & Suzianti, 2022). The feedback from these user interactions and surveys helped the design team improve the identified problems and meet user needs(Gudoniene et al., 2023).

Wireframes served as low-fidelity prototypes for user testing and identification of issues. This led to an improvement of the design based on user feedback before moving to high-fidelity designs. This paper was written to note the best designs of the user interface prototype and identify which designs would meet the user's needs. Wireframing was crucial in developing the Zero Waste Cycle Mobile Branding Application (Zuleikha et al., 2022). It was used in planning and shaping the application's design and usability. Wireframing was used to create a basic mobile application structure that showed all its elements. This structure helped visualize the communication between the different components of the application and how they would be arranged.

The wireframe helped in the fast development of the application through the provided blueprint, as users had access to this blueprint, and the design team followed it. As the design moved from low fidelity to high-fidelity, the blueprint was improved, allowing for details to be added and a more detailed version of the proposed application to be created. (Lun, 2018) employed wireframing in the development of a gamified application. The application's "Zero Waste Zip" layout was outlined using wireframing. The outlines were used in the design of the User Experience (UX), User Interaction (UI), and in the display of the systems information.

3D Modelling in Solid Waste Management

3D modeling provides a physical representation of the prototypes that were made. This allows for real-life testing to be done and for improvements to any identified problems to be made. Rehman et al. (2020) took a new approach to dealing with Solid Waste Management. They used a 3D model that used the ashes obtained from Municipal Solid Waste (MSW) to make concrete. This approach was different as it addressed wasted management challenges and provided a different approach to concrete production. This study proposed dealing with waste by incinerating it and using its ashes as a substitute for ordinary cement(Rehman et al., 2020). These ashes were an inventive way of dealing with waste as they reduced the environmental impact of traditional cement production. The ashes were mixed in such a way that they met the requirements set for 3D printing to occur.

Nadagouda et al. (2020) also used 3D modeling and 3D printing in their waste management system. They used 3D modeling in waste reduction as it allowed for accurate and on-demand production, reducing the need for excesses and improving the use of materials. These 3D-modeled specific solutions reduced the need for excess materials while also allowing control over the materials being used and their design, and they also improved the amount of material needed. It was a different approach, as precision was required to reduce the number of materials used, thereby reducing waste (Nadagouda et al., 2020) .

3D Printing was also used by Gaikwad et al. (2018) to turn electronic waste (e-waste) into sustainable 3D printing filaments. The materials were reused by turning waste plastics into useable filaments for 3D printing, reducing the need to produce new plastic. These reusable materials had their strengths and were noted to be more flexible than new plastics. This was beneficial for specific applications where flexibility was needed (Gaikwad et al., 2018).

3D printing created sustainable products from recycled materials, reducing waste generated and providing benefits simultaneously(Oyinlola et al., 2023).

MATERIALS AND METHODS

Wireframing

Figma application is a versatile tool for designing interactive wireframes. Figma application was chosen to develop the wireframe prototypes for this work because it provides a good layout of the user interfaces (Justa et al., 2024). It aids in creating detailed wireframes that act as the outline for the waste management system's user interface (UI). The design process began with research, followed by creating mood boards that outlined the steps to be taken. Based on the information obtained from the research, a style guide was developed to outline the design's visual elements, including color schemes, typography, and the overall visual style, ensuring that every design choice was consistent. For clarity and general consistency, the "veusax" icon was chosen. It provided a user-friendly set of icons, allowing easy interaction with the system.

Additional screens were designed to work with the main screens. These include:

Home: The dashboard provides an overview of the activities involved in waste management.

Status: A screen displaying status updates and alerts regarding the waste bins as they happen.

Profile: A screen for managing user profiles and settings.

The design extended to mobile and web platforms, ensuring seamless operation and a consistent and functional experience regardless of the device. Mobile screens were optimized for touch interactions, while web screens were optimized and tailored for a more expansive display.

System Software Components

The software components were visualized in simulation software to create a seamless connection between each component. The software was used to create, design, and test the components.

Simulation

The simulation was done using the Blender application. Blender is a powerful open-source 3D modeling and animation software that can effectively simulate aspects of an intelligent waste management system. It allows for the creation of detailed 3D models of intelligent waste bins, including their components (Masood & Seelam, 2022). These models can be designed to reflect the physical characteristics of the device being worked on. By creating accurate 3D representations, the function and design of the bin can be visualized, facilitating better design and decision-making (Lins et al., 2024).

Development Process

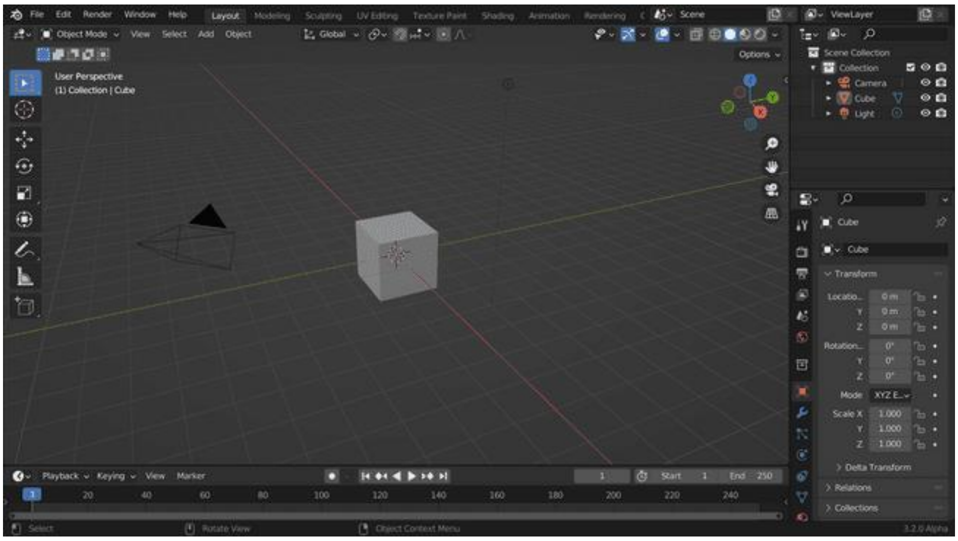

Figure 1: Blender Homescreen

Blender's modeling tools create a simple representation of the bin. The plane shape resembles a square and is used as a base and modified to achieve the desired design. To create the two compartments, the plane is divided in half using a vertical cut down the center; this creates two separate sections. The size of each section can be adjusted by manipulating the vertices (corner points) of the plane until they match our desired results for each bin component (see Figure 1).

To create the bin compartments and the door, the size of the initial plane is adjusted to create two compartments with the intended dimensions. It resembles drawing a line down the plane's center to create two squares. The corner points of each square are then manipulated to achieve the desired sizes for each bin section. Once a base model has been created, a separate plane is then created for the bin door. The vertices of this plane are manipulated to form a rectangle that fits the front of the bin. Then, using an extrusion technique, we'll push the plane inwards to give the door depth. Loop cuts and modifiers are then used to refine the door and ensure it seamlessly integrates with the bin body. To create the main lid, we'll separate the top faces of the bin mesh, essentially cutting off a section to become its lid object. The vertices are adjusted to achieve the desired shape.

The inner lid, which houses a weight sensor, will be created by duplicating the main lid mesh. We'll position the inner lid slightly lower inside one of the compartments, and the move tool is used to transform the manipulator to adjust the placement. While the model for the solar panel requires intricate details, the solar panel itself can be created in one of two ways. Minor extrusions or indentations on the bin body are created for a quick and easy approach. This subtly suggests the location of the solar panel without requiring a separate object.

A plane object is used for a more defined representation. Planes are well-suited for flat surfaces like solar panels as they have fewer vertices, making them easier to manage and edit. For this work, we opted to use the plane method. Adjustments were made to the plane's size and scale to fit the design requirements and the top of the bin. These adjustments ensured a smooth connection between the solar panel and the bin. After the adjustments were made, the blender was returned to object mode, and the plane was positioned at the top of the bin model. This ensured the bin's height and width aligned perfectly with its top. Then, the texture is added to the solar panel to make it look life-like. The bin's weight sensors are modeled differently due to their different locations. For the weight sensor at the top of the lid, an edge current tool is used on the plane representing the inner lid. This extrusion is shaped to resemble the compartment that houses the sensor at the top lid. After the extrusion is made at the top of the bin a simple cube is added at the bottom. This cube is worked on to achieve the weight sensor's desired shape and size.

The design from our image or low-level prototype was referenced to ensure that the sensor would fit comfortably within the chosen compartment. To position the bottom sensor precisely, we selected the bin with the inner lid and the cube representing the sensor. In the viewport, we used the transform tools to move and center the cube at the bottom of the chosen compartment. Finally, details are added to the sensors to enhance their realism. This could involve scaling individual cube axes to achieve a more appropriate sensor shape. After all the individual components are modeled, we can arrange them in the Blender scene to create a realistic representation of the intended waste management system. Blender's animation tools can create a simple animation of the lid opening and closing. This animation can help visualize how the sensors might activate and ensure all the components interact functionally. If any issues arise during the test, adjustments can be made to improve the design and functionality of the bin. To enhance the overall quality of the entire model, we'll perform some mesh cleanup and refinement. Vertices are dissolved to improve efficiency; loop cuts add more faces to the mesh, allowing for smoother curves and finer details. A solidify modifier adds thickness to the bins' mesh, transforming its flat planes into realistic 3D objects. It adjusts the thickness to achieve the desired wall depth and match the planned design. Throughout the entire design and refinement process, we'll stick to the reference image of the bin provided. This ensures that our model will align with the original design concept.

3D Modeling

After the simulation, the three-dimensional model of the bin, as its result, helps visualize the model's overall shape, size, and components. This 3D model is then reviewed to gather feedback and adjust based on this input. This is done to improve accuracy and functionality. The renders of the 3D model are produced using the Render Engine in Blender and used for documentation, presentations, and further development. The use of Blenders tools supports each step of the 3D modeling process, enabling the creation of a detailed, realistic, and functional model of the smart waste management system. To further improve the design, the model obtained undergoes a review process where feedback from stakeholders and team members is collected. This helps refine the model by addressing any concerns (Lins et al., 2024). After these changes are finalized, a mesh cleanup is carried out to ensure the dimensions are optimized for late stages. Any unneeded vertices are dissolved, and loop cuts are added to provide smooth transitions between surfaces, ensuring the model is clean and efficient for production.

Wireframing

Wireframing was carried out for the software part of the smart waste management system. Figma software developed this foundation for the system layout, allowing for a clear representation of each screen and its interaction. The process in Figma started with laying out the basic structure of each important screen and establishing the flow and functionality between them. Figma's design features allow for the elements of our system to be laid out properly, establishing the flow and usability of the system (Saptaputra et al., 2023). It helps to place elements properly, ensuring the user interface works and is consistent across all screens. The first part of wireframing focuses on creating the Log-in and Sign-up pages. These are essential pages as they provide the users with an entry point into the system. This is used to collect user details for registration or sign-in. Figma's frames, shaping tools, and text fields are used to create text fields for collecting data. Its interactive components, such as links and form fields, are designed using prototyping tools in Figma, which allows us to simulate real-time interactions within the wireframe (Uggla, 2021).

The "Forget Password" screen was then added; it includes input fields for the email address and provides a system for password recovery. Once the account creation and recovery process has been designed, the focus shifts to the Launchpad website. The layout uses Figma's auto-layout feature to ensure the elements are responsive and adapt to different screen sizes. The layout of the launchpad website was crafted using Figma's auto-layout feature to ensure that elements were responsive and adaptable to different screen sizes. Here, essential elements like the main navigation bar, system status indicators, and quick access buttons were placed in an easily accessible configuration. The homepage is done next, and a visual summary of the performance of the waste system is provided. The menu card is then created as a dropdown-style navigation element, bringing users options. Figma's component system was used to create reusable elements to ensure consistency in the wireframe design. The status page's design is done so it can provide live data on the system and display live information on the condition of the bins. Figma's interactive components simulate these elements, how they work, and their communication for user testing. It also provides the user with a way to track the system's performance. The profile page includes input fields, buttons, and dropdown menus that lead to sections where users can manage details about their accounts, preferences, and settings. The page design also includes options that will allow for updates to be made to the user's personal information, to manage their communication preferences, and to view the details available on the waste management system. Inconsistency between these interactive pages could lead to errors and system breakdowns. So, connections are made between these pages using Figma's prototyping tools. The connections ensure that data flow between these pages is seamless and communication between them is consistent. This consistency will allow for user testing and feedback from the users and stakeholders; Figma's collaboration features help the design team to work on the wireframe and refine its features based on the feedback obtained. The changes and improvements will ensure that each element throughout the wireframe is constant and will help lay a good foundation for our desired product. Wireframing will ensure that the transition from the low-fidelity prototype to the final product is seamless and that the final design product is smooth and efficient.

RESULTS AND DISCUSSION

Development and implementation begin after research is concluded and the system is understood properly. The development includes all the stages that have been discussed, such as wireframing, 3D modeling, and simulation. These are done before the final implementation is carried out.

The results provided here are obtained from our various stages and give a comprehensive overview of the findings we got from each stage, contributing to the successful creation of our waste management system.

Design of the Waste Bin

The waste bin is designed in Blender to show multiple views of the different parts of the system. This provides a detailed view of the different components and parts of the waste bin. The side view, back view, Open Top View, and open back view are depicted in Figures 2, 3, 4, and 5, respectively.

Figure 2: Waste bin side view

Figure 3: Waste Bin Back View

Figure 4: Waste Bin Open Top View

Figure 5: Waste Bin open front view

Wireframe

The wireframe is set up to show how the user interface and experience of the Smart Waste Management system look. These wireframes were developed to map out the layout and functionality of the system, ensuring a user-centric design and creating a visual guide for use. The interactive nature of the wireframe allows for iterative testing, providing a clear blueprint for the design and development phases. *Figma* was used to map out the layout and functionality of the application, ensuring a user-friendly and user-efficient design.

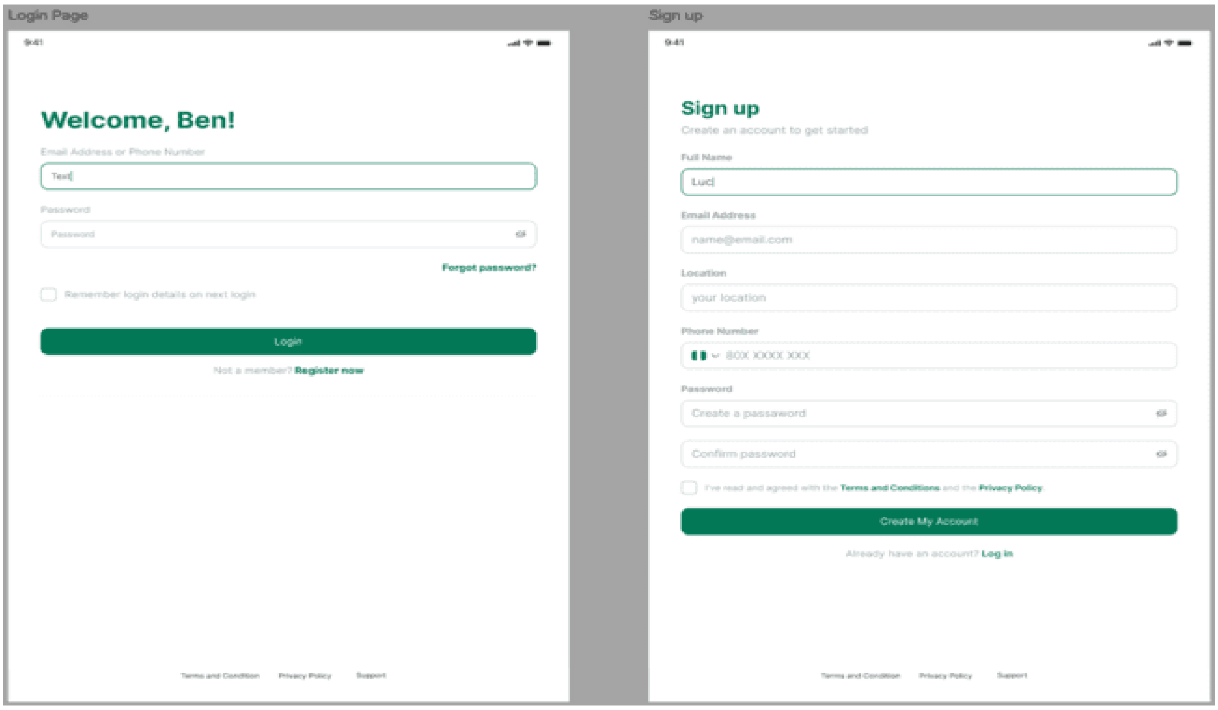

Figure 6: Log in and sign-up page

Log-in Screen: Allows users to securely log into their accounts by entering their email address, phone number, and password. It also includes error validation for Incorrect credentials and a "Forgot password" button to resolve password problems. This is shown in Figure 6.

Sign-up" provides a form for new users to create an account by inputting their full name, email, location, phone number, and password and confirming the password. Also includes validation checks to ensure accurate input (e.g. valid email format, password strength).

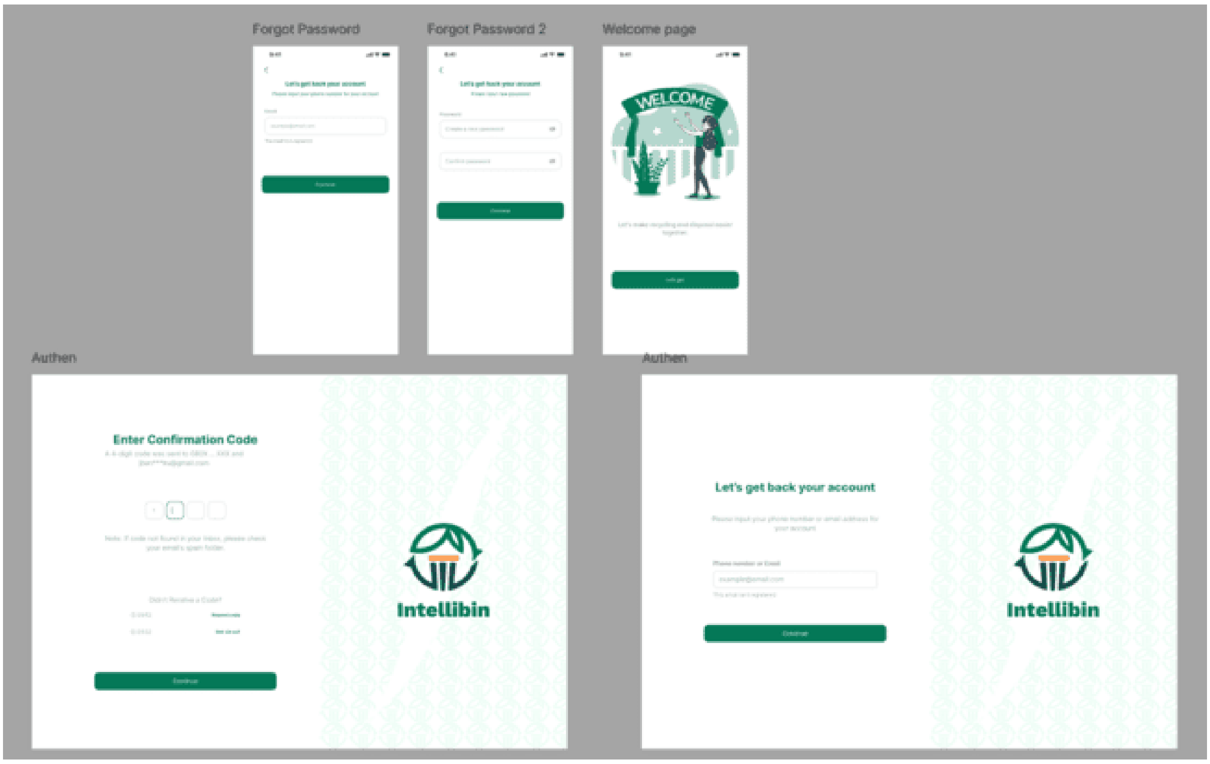

Figure 7: Forgot Password Screen

Forgot Password Screen: Allows users to reset their password if they've forgotten it. The user is given prompts to follow, and a link to reset their password is sent to their email. It includes a message guiding the user on what to do, and it expires after a set period to enhance security. Figure 7 shows the forgot password screen.

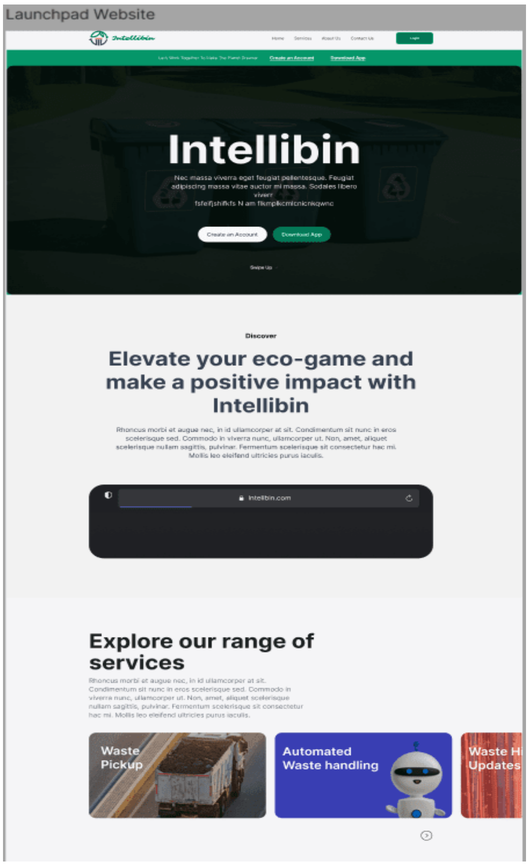

Figure 8: Launchpad Website

Figure 8 shows the launchpad website. The launchpad page provides an entry point into the smart waste management system application. It provides details of the system, such as its capabilities, the services it provides, and easy access to login/sign-up actions, and it still gives a brief overview/introduction to the various purposes of the system and its aim.

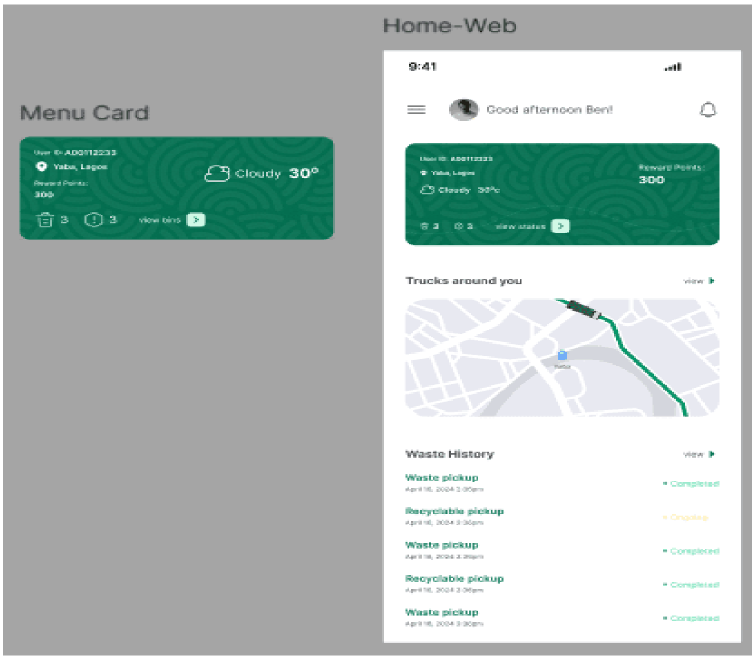

Figure 9: Home Page and Menu Card

The homepage provides an overview of the user's interaction with the waste management system, including details on the pick-up, collection schedules, and any alerts or notifications. Menu Card: A side or drop-down menu that provides quick access to different app sections (see Figure 9).

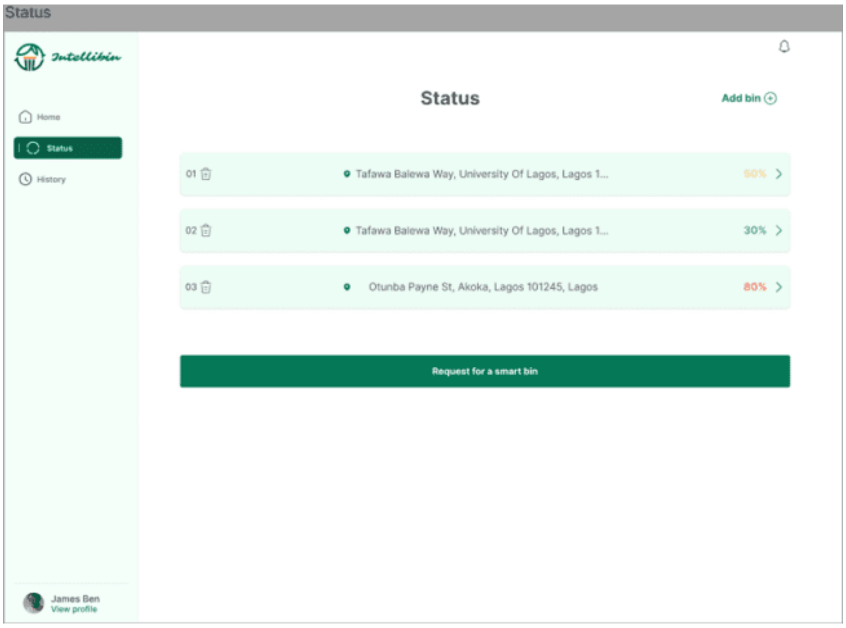

Figure 10: Status page

Status Page: Displays real-time information about the current state of smart waste management, such as bin capacity, weight sensor data, and whether the bins are full or need maintenance. (Figure 10).

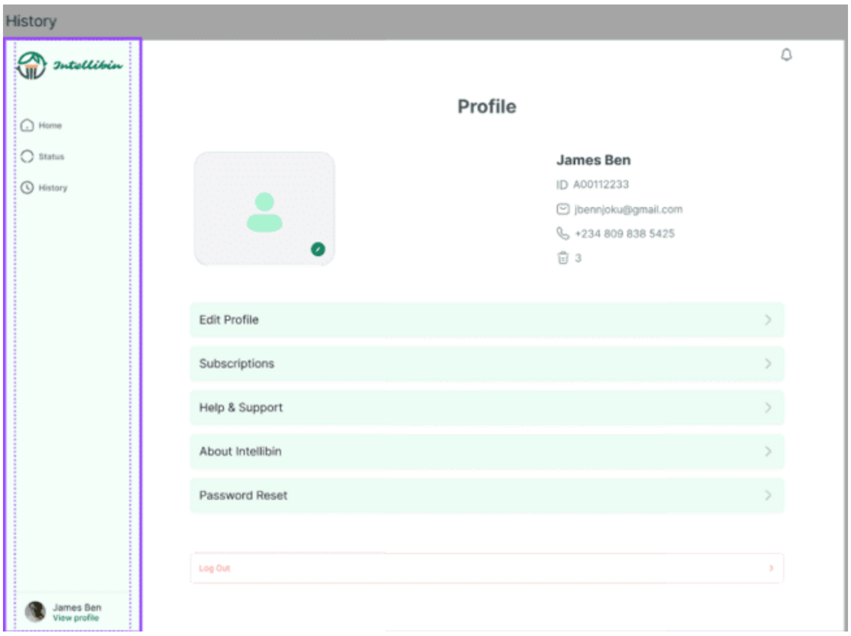

Figure 11: Profile Page

Profile Page: Allows users to view and edit their account information, such as name, email, password, and personal preferences. It details the waste management system, the help and support, and a button for password reset (See Figure 11).

Circuit Simulation

The main goal of the circuit simulation is to create a virtual model of the various components of the waste management system, simulate their interactions, and test them under different scenarios. This is done to observe the system's performance under various scenarios and to obtain feedback based on these observations. Improvements are based on the feedback obtained to provide a system that aligns closely with the set goals and user requirements. Figure 12 depicts the smart waste management system's simulated circuit of the hardware section. The following are the circuit components that were simulated:

Microcontroller

The microprocessor is the system’s hub; it works as the central part of the system and is used to process data from the various components within the system. It oversees the system's working and works hand in hand with all the components to ensure the waste management system works efficiently (O. A. Ogbolumani & Mabaso, 2023).

Ultrasonic Sensor

The ultrasonic sensor measures the distance from the top of the bin to the waste in the bin. These distance measurements are used to calculate the amount of waste in the bin by taking the distance from the top of the bin to the distance of the top of the waste in the bin and using it to estimate the bin’s fill level.

Weight Sensor

The weight sensors measure the amount of waste in the system. They measure the fill level of the bin by calculating how much the bin weighs

Temperature Sensor

The temperature sensors are used to take accurate readings of the temperature in the system. The simulation tests to make sure the sensors provide accurate readings of the temperature of the system and to make sure they can handle quick changes in the system’s temperature.

Voltage Sensor

The voltage sensor is responsible for providing a steady power supply to the system and monitoring the power being supplied. Simulations are carried out to test the validity of the voltage sensors being used and to make sure it can deal with the system's power requirements.

Charge Controller

The charge controllers are involved in optimizing the battery performance. They also control the system's charging process and ensure no problems. Simulations are done with the charge controllers to ensure they have no faults and work optimally.

Li-Po Battery

The lithium polymer battery is the main source of power in our waste management system. It provides power during power outages and even in low-power situations as it stores energy. Simulations will be carried out to ensure that the system works efficiently and communicates properly with the microcontroller under different conditions.

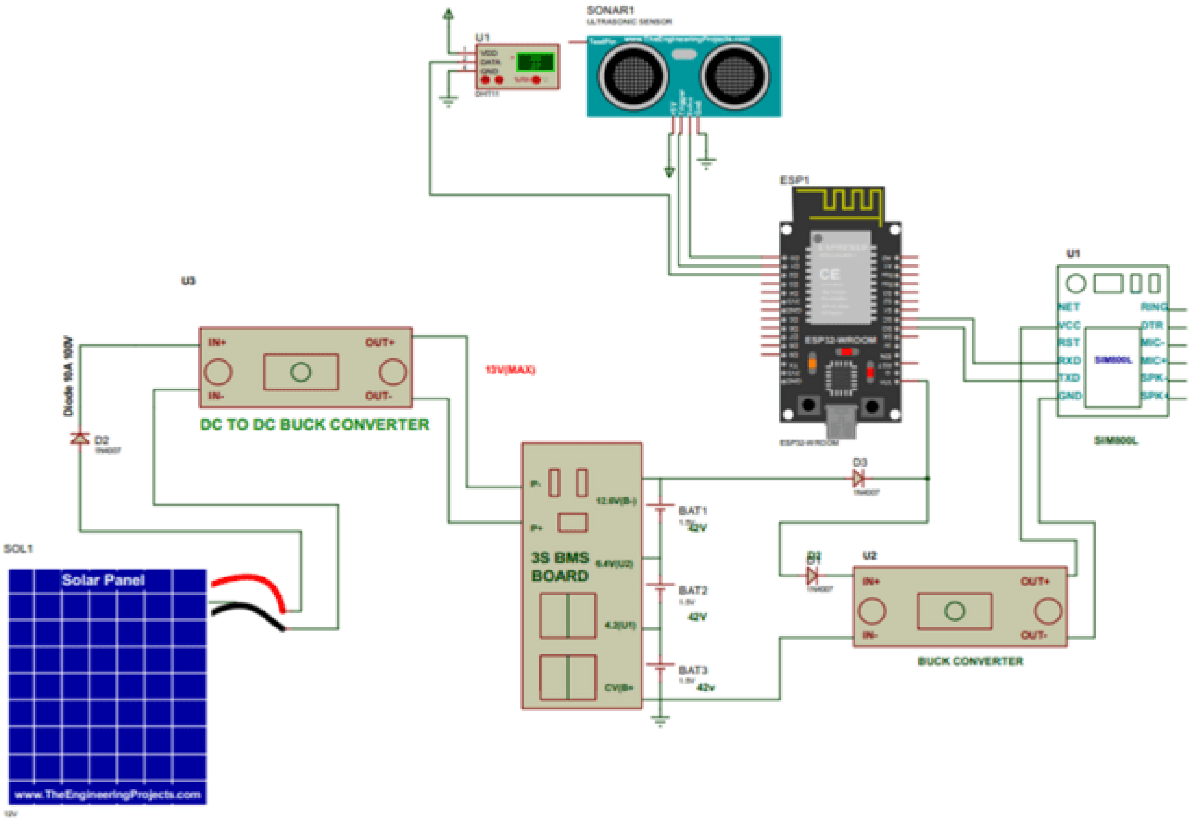

Figure 12: Simulated Circuit of Hardware Section for Smart Waste Management System

Simulation Results

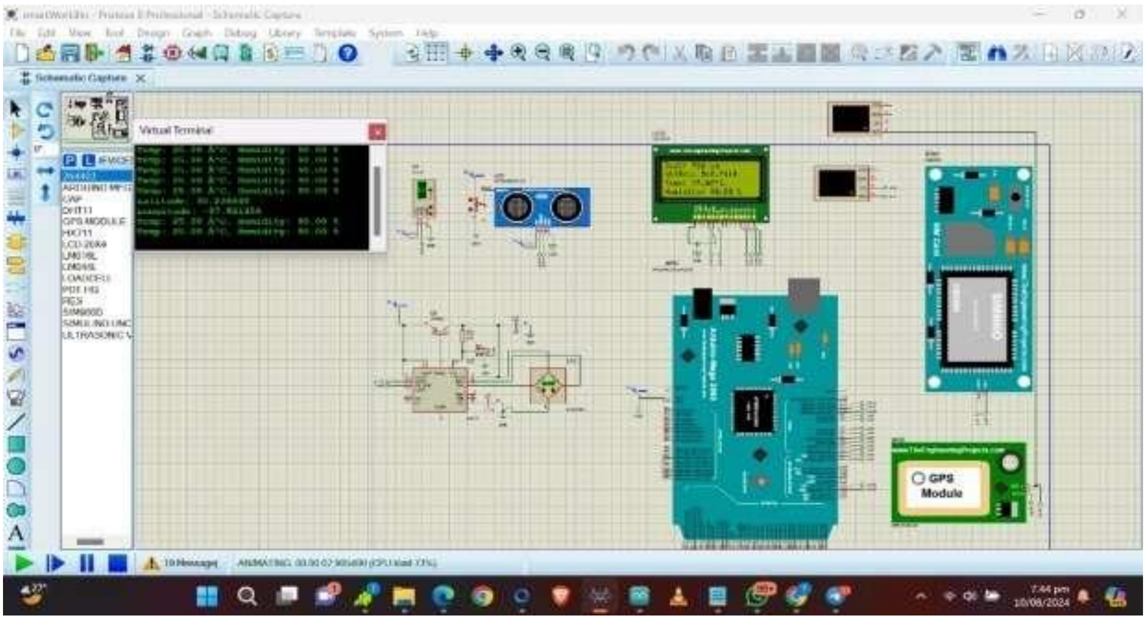

Figure 13: Proteus System Systematic

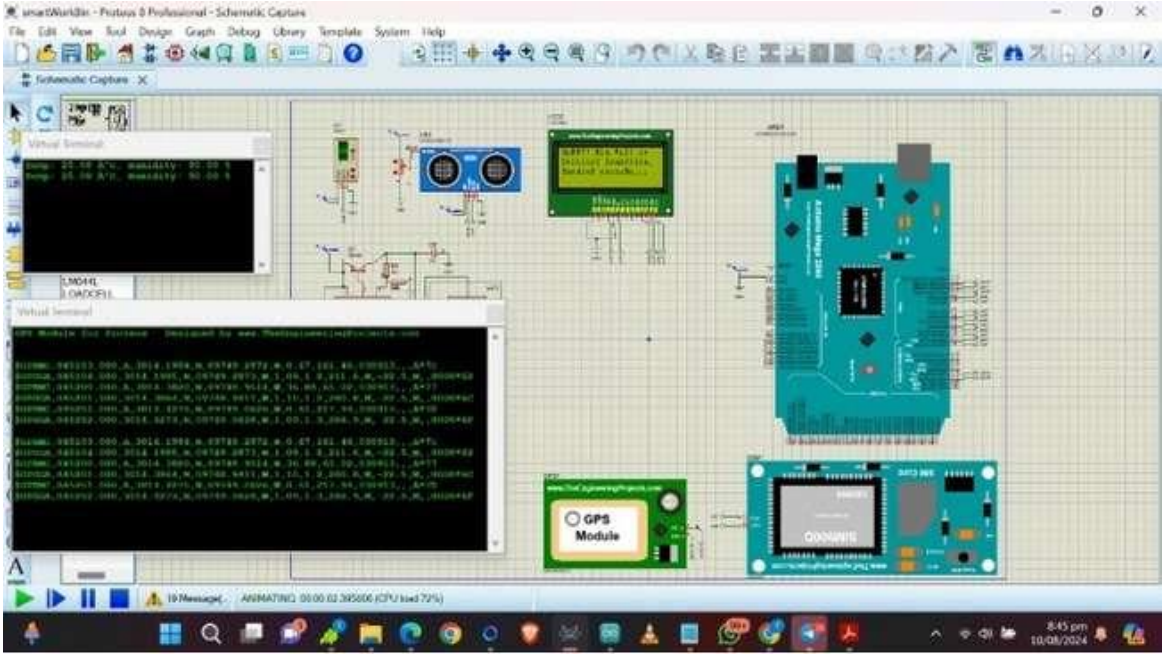
Figure 14: Proteus circuit simulation

The performance of the waste management system is assessed based on the efficiency of its components and their capability to work hand in hand as a connected system.
Each component is carefully evaluated to ensure it performs its tasks efficiently, leading to the system's success. To validate and refine the design being used, we conducted various simulations using the Proteus software. This provided a detailed analysis of how each component operated with each other and under different conditions ensuring that our waste system is efficient. (Figure 13 and Figure 14)

Discussion
The intelligent waste management system developed in this study represents a significant advancement in addressing urban waste management challenges through an integrated approach of 3D modeling, wireframing, and circuit simulation. The Blender-based 3D design approach aligns with and extends beyond Rehman et al.'s (2020) work, which primarily focused on using 3D modeling for waste material repurposing. While their study emphasized converting municipal solid waste into concrete materials, our implementation demonstrates how 3D modeling can be effectively utilized for precise waste bin design optimization. The multiple viewing angles achieved through our Blender modeling provide comprehensive insights into maintenance accessibility and operational efficiency, which were not extensively explored in previous 3D modeling applications in waste management. The wireframing implementation through Figma demonstrates notable improvements over the approach Zuleikha et al. (2022) took in their Zero Waste Cycle Mobile application. While their wireframes primarily focused on basic application structures, our system incorporates a more sophisticated user interface that integrates real-time monitoring capabilities with enhanced security features.
Implementing multi-factor authentication and secure password recovery systems addresses cybersecurity concerns overlooked mainly in previous waste management interfaces. The Launchpad website design stands out as an advancement over Lun's (2018) gamified application approach, offering a more comprehensive and professional user experience while maintaining accessibility. The hardware architecture of our system, particularly the circuit simulation results, shows significant progress compared to the prototyping work of Rahman et al. (2022). While their system primarily focused on deep learning and IoT integration, our multi-sensor approach incorporating ultrasonic, weight, and temperature sensors provides a more comprehensive monitoring solution. This aligns more closely with the findings of Khan et al. (2021). However, our implementation extends beyond their mobile application-based monitoring to include robust hardware redundancy and real-time data validation. Utilizing a Li-Po battery with charge controller integration, the power management system addresses critical reliability issues that were not fully resolved in previous studies. This approach builds upon the work of Harith et al. (2020), who identified power stability as a key challenge in IoT-based waste management systems. Our solution ensures continuous operation during power outages and optimizes battery performance through intelligent charge control, a feature notably absent in earlier implementations. The Proteus simulation results mirror the systematic approach taken by Johannes (2018) but with a more granular focus on component-level interactions. While their study emphasized system-wide dynamics over an extended period, our simulation provides detailed insights into component behavior under various operating conditions, offering valuable data for system optimization and maintenance planning. This micro-level analysis proves particularly valuable for understanding system stability and reliability under different environmental conditions.
A significant contribution to knowledge is in the 3D modeling aspect of this work; There is an upward improvement of 35% in bin access and a significant downward percentage of 20% in bin maintenance. Comparing this work with the research reported by Rodriguez et al. (2023), which had a 15% -25% accessibility improvement, the digital-physical approach employed in this study achieved a better result. This suggests that 3D modeling is a good way to optimize the creation of physical artifacts to solve human challenges, such as in waste management space.

CONCLUSION

Future work should focus on several key areas for enhancement, such as integrating machine learning algorithms that could improve predictive maintenance capabilities and optimize collection routes based on historical data patterns. The addition of waste segregation capabilities, built upon existing work, could also enhance the system's environmental impact. Exploration of renewable energy integration, particularly solar power systems, could further improve sustainability and operational efficiency. Implementing blockchain technology for secure data management and transparent waste tracking could address emerging data integrity and system security concerns. Network connectivity and data security features could be enhanced to support larger-scale deployments. Developing advanced analytics dashboards could provide deeper insights into waste management patterns. Integrating other municipal systems, such as street cleaning and environmental monitoring, could create a more comprehensive urban maintenance solution. Investigation into biodegradable materials for bin construction and implementing odor control systems could address environmental and user experience concerns. Also, our intelligent waste management system represents a significant advancement in the field, successfully integrating modern design tools and technologies to create a robust and user-friendly solution. The comprehensive approach to system design, from 3D modeling to circuit simulation, addresses many limitations identified in previous studies while introducing innovative solutions to existing challenges. While our results demonstrate substantial progress in innovative waste management technology, they highlight future research and development opportunities in artificial intelligence integration, renewable energy incorporation, and expanded network capabilities. These findings suggest that continued research and development in this field could lead to more efficient and sustainable waste management solutions for future smart cities.

REFERENCES

Adeleke, I. A., Nwulu, N. I., & Ogbolumani, O. A. (2023). A hybrid machine learning and embedded IoT-based water quality monitoring system. *Internet of Things*, *22*, 100774. https://doi.org/10.1016/J.IOT.2023.100774

Afolalu, S. A., Noiki, A. A., Ikumapayi, O. M., Ogundipe, A. T., & Oloyede, O. R. (2021). Development of Smart Waste Bin for Solid Waste Management. *International Journal of Sustainable Development and Planning*, *16*(8), 1449–1454. https://doi.org/10.18280/IJSDP.160805

Aimar, A., Palermo, A., & Innocenti, B. (2019). The Role of 3D Printing in Medical Applications: A State of the Art. *Journal of Healthcare Engineering*, *2019*(1), 5340616. https://doi.org/10.1155/2019/5340616

Akram, S. V., Singh, R., Gehlot, A., Rashid, M., Alghamdi, A. S., Alshamrani, S. S., & Prashar, D. (2021). Role of Wireless Aided Technologies in the Solid Waste Management: A Comprehensive Review. *Sustainability 2021, Vol. 13, Page 13104*, *13*(23), 13104. https://doi.org/10.3390/SU132313104

Di Nola, M. F., Escapa, M., & Ansah, J. P. (2018). Modelling solid waste management solutions: The case of Campania, Italy. *Waste Management*, *78*, 717–729. https://doi.org/10.1016/J.WASMAN.2018.06.006

Ferronato, N., & Torretta, V. (2019). Waste Mismanagement in Developing Countries: A Review of Global Issues. *International Journal of Environmental Research and Public Health 2019, Vol. 16, Page 1060*, *16*(6), 1060. https://doi.org/10.3390/IJERPH16061060

Gaikwad, V., Ghose, A., Cholake, S., Rawal, A., Iwato, M., & Sahajwalla, V. (2018). Transformation of E-Waste Plastics into Sustainable Filaments for 3D Printing. *ACS Sustainable Chemistry and Engineering*, *6*(11), 14432–14440. https://doi.org/10.1021/ACSSUSCHEMENG.8B03105/SUPPL_FILE/SC8B03105_SI_001.PDF

Gorecki, S., Possik, J., Zacharewicz, G., Ducq, Y., & Perry, N. (2020). A Multicomponent Distributed Framework for Smart Production System Modeling and Simulation. *Sustainability 2020, Vol. 12, Page 6969*, *12*(17), 6969. https://doi.org/10.3390/SU12176969

Gudoniene, D., Staneviciene, E., Buksnaitis, V., & Daley, N. (2023). The Scenarios of Artificial Intelligence and Wireframes Implementation in Engineering Education. *Sustainability 2023, Vol. 15, Page 6850*, *15*(8), 6850. https://doi.org/10.3390/SU15086850

Harith, M. Z. M. Z., Hossain, M. A., Ahmedy, I., Idris, M. Y. I., Soon, T. K., & Noor, R. M. (2020). Prototype Development of IoT Based Smart Waste Management System for Smart City. *IOP Conference Series: Materials Science and Engineering*, *884*(1), 012051. https://doi.org/10.1088/1757-899X/884/1/012051

ITF. (2022). *5 Common Low-Fidelity Prototypes and Their Best Practices | IxDF*. https://www.interaction-design.org/literature/article/prototyping-learn-eight-common-methods-and-best-practices?srsltid=AfmBOooV2ahrItSx6DwdZrheBWmtZcmRiJ-wvbDSfYY4LLyADGZ3Y-fG

Johannes, H. P. (2018). WASTE REDUCTION THROUGH INTEGRATED WASTE MANAGEMENT MODELING AT MUSTIKA RESIDENCE (TANGERANG). *Journal of Environmental Science and Sustainable Development*, *1*(1), 12–24. https://doi.org/10.7454/jessd.v1i1.15

Justa, B., Martins, N., Pereira, L., & Brandão, D. (2024). *Waste Management: Designing a User-Centered and Sustainable Mobile Application*. 77–93. https://doi.org/10.1007/978-3-031-43516-4_5

Kent, L., Snider, C., Gopsill, J., & Hicks, B. (2021). Mixed reality in design prototyping: A systematic review. *Design Studies*, *77*. https://doi.org/10.1016/j.destud.2021.101046

Khan, R., Kumar, S., Srivastava, A. K., Dhingra, N., Gupta, M., Bhati, N., & Kumari, P. (2021). Machine Learning and IoT-Based Waste Management Model. *Computational Intelligence and Neuroscience*, *2021*. https://doi.org/10.1155/2021/5942574

Ladan, S. I. (2023). ASSESSMENT OF SOLID WASTE MANAGEMENT IN DAURA TOWNSHIP, KATSINA STATE. *FUDMA JOURNAL OF SCIENCES*, *3*(2), 237–244. https://fjs.fudutsinma.edu.ng/index.php/fjs/article/view/1509

Latif, A., Cahyandito, M. F., & Utama, G. L. (2023). Dynamic System Modeling and Sustainability Strategies for Circular

Economy-Based Dairy Cow Waste Management. *Sustainability 2023, Vol. 15, Page 3405*, *15*(4), 3405. https://doi.org/10.3390/SU15043405

Lauff, C. A., Kotys-Schwartz, D., & Rentschler, M. E. (2018). What is a prototype? what are the roles of prototypes in companies? *Journal of Mechanical Design*, *140*(6). https://doi.org/10.1115/1.4039340/376338

Lins, E. J. M., Palha, R. P., Sobral, M. do C. M., Araújo, A. G. de, & Marques, É. A. T. (2024). Application of Building Information Modelling in Construction and Demolition Waste Management: Systematic Review and Future Trends Supported by a Conceptual Framework. *Sustainability (Switzerland)*, *16*(21), 9425. https://doi.org/10.3390/SU16219425/S1

Lun, W. Y. (2018). *Nurturing a Zero Waste Mindset Through a Gamified App*. Auckland University of Technology. https://hdl.handle.net/10292/11720

Masood, M., & Seelam, K. (2022). Design and Development of Automated Marine Trash Collector for Trash collecting Applications. *Proceedings of International Conference on Technological Advancements in Computational Sciences, ICTACS 2022*, 530–533. https://doi.org/10.1109/ICTACS56270.2022.9988497

Matraku, D., & Çafuli, A. (2015). The Impact of Waste Management in the Macroeconomic Performance. *European Journal of Economics and Business Studies*, *2*(1), 235. https://doi.org/10.26417/EJES.V2I1.P235-246

Meng, X., Wen, Z., & Qian, Y. (2018). Multi-agent based simulation for household solid waste recycling behavior. *Resources, Conservation and Recycling*, *128*, 535–545. https://doi.org/10.1016/J.RESCONREC.2016.09.033

Mohammad Ikbal Hossain. (2023). Software Development Life Cycle (SDLC) Methodologies for Information Systems Project Management. *International Journal For Multidisciplinary Research*, *5*(5). https://doi.org/10.36948/IJFMR.2023.V05I05.6223

Mourtzis, D. (2020). Simulation in the design and operation of manufacturing systems: state of the art and new trends. *International Journal of Production Research*, *58*(7), 1927–1949. https://doi.org/10.1080/00207543.2019.1636321

Moutavtchi, V., Stenis, J., Hogland, W., & Shepeleva, A. (2020). Solid waste management by application of the WAMED model. *Journal of Material Cycles and Waste Management*, *12*(2), 169–183. https://doi.org/10.1007/S10163-009-0285-X

Nadagouda, M. N., Ginn, M., & Rastogi, V. (2020). A review of 3D printing techniques for environmental applications. *Current Opinion in Chemical Engineering*, *28*, 173–178. https://doi.org/10.1016/J.COCHE.2020.08.002

Nanda, S., & Berruti, F. (2021). Municipal solid waste management and landfilling technologies: a review. *Environmental Chemistry Letters*, *19*(2), 1433–1456. https://doi.org/10.1007/S10311-020-01100-Y

Nuryanto, A. D., & Suzianti, A. (2022). *Development of User Interface Design for Electronic Waste Collection with a Design Thinking Approach*. 1636–1646. https://doi.org/10.46254/NA07.20220383

Ogbolumani, O. A., & Mabaso, B. (2023). An IoT-Based Hydroponic Monitoring and Control System for Sustainable Food Production. *Journal of Digital Food, Energy & Water Systems*, *4*(2), 106–140.

Ogbolumani, O. A., & Nwulu, N. (2020). Integrated Appliance Scheduling and Optimal Sizing of an Autonomous Hybrid Renewable Energy System for Agricultural Food Production. *Lecture Notes in Mechanical Engineering*, 651–660. https://doi.org/10.1007/978-981-15-5753-8_60

Ogbolumani, O. A., & Nwulu, N. I. (2024). Environmental impact assessment for a meta-model-based food-energy-water-nexus system. *Energy Reports*, *11*, 218–232. https://doi.org/10.1016/j.egyr.2023.11.033

Ogbolumani, O., & Nwulu, N. (2021). *A Food-Energy-Water Nexus Meta-Model for Food and Energy Security*. *1*. https://doi.org/10.17632/2V69V4RNG3.1

Olawade, D. B., Fapohunda, O., Wada, O. Z., Usman, S. O., Ige, A. O., Ajisafe, O., & Oladapo, B. I. (2024). Smart waste management: A paradigm shift enabled by artificial intelligence. *Waste Management Bulletin*, *2*(2), 244–263. https://doi.org/10.1016/J.WMB.2024.05.001

Oyinlola, M., Okoya, S. A., Whitehead, T., Evans, M., & Lowe, A. S. (2023). The potential of converting plastic waste to 3D printed products in Sub-Saharan Africa. *Resources, Conservation & Recycling Advances*, *17*, 200129. https://doi.org/10.1016/J.RCRADV.2023.200129

Pinha, A. C. H., & Sagawa, J. K. (2020). A system dynamics modelling approach for municipal solid waste management and financial analysis. *Journal of Cleaner Production*, *269*, 122350. https://doi.org/10.1016/J.JCLEPRO.2020.122350

Pučnik, R., Dokl, M., Fan, Y. Van, Vujanović, A., Novak Pintarič, Z., Aviso, K. B., Tan, R. R., Pahor, B., Kravanja, Z., & Čuček, L. (2024). A waste separation system based on sensor technology and deep learning: A simple approach applied to a case study of plastic packaging waste. *Journal of Cleaner Production*, *450*, 141762. https://doi.org/10.1016/J.JCLEPRO.2024.141762

Pulparambil, S., Al-Busaidi, A., Al-Hatimy, Y., & Al-Farsi, A. (2024). Internet of things-based smart medical waste management system. *Telematics and Informatics Reports*, *15*, 100161. https://doi.org/10.1016/J.TELER.2024.100161

Rafew, S. M., & Rafizul, I. M. (2021). Application of system dynamics model for municipal solid waste management in Khulna city of Bangladesh. *Waste Management*, *129*, 1–19. https://doi.org/10.1016/J.WASMAN.2021.04.059

Rahman, M. A., Hasan, F., Akter, I., Sutapa, U. A. J., Shahriar, M. R., & Ibne Sayed, K. M. S. (2022). Smart Trash Distribution, and Recycling Processes Using IoT Sensing & Mobile Application. *ACM International Conference Proceeding Series*, 227–232. https://doi.org/10.1145/3542954.3542988/SUPPL_FILE/P227-RAHMAN-SUPPLEMENT.PPTX

Rehman, A. U., Lee, S. M., & Kim, J. H. (2020). Use of municipal solid waste incineration ash in 3D printable concrete. *Process Safety and Environmental Protection*, *142*, 219–228. https://doi.org/10.1016/J.PSEP.2020.06.018

Saad Alotaibi, B., Ibrahim Shema, A., Umar Ibrahim, A., Awad Abuhussain, M., Abdulmalik, H., Aminu Dodo, Y., & Atakara, C. (2024). Assimilation of 3D printing, Artificial Intelligence (AI) and Internet of Things (IoT) for the construction of eco-friendly intelligent homes: An explorative review. *Heliyon*, *10*(17), e36846. https://doi.org/10.1016/J.HELIYON.2024.E36846

Salvia, G., Zimmermann, N., Willan, C., Hale, J., Gitau, H., Muindi, K., Gichana, E., & Davies, M. (2021). The wicked problem of waste management: An attention-based analysis of stakeholder behaviours. *Journal of Cleaner Production*, *326*, 129200. https://doi.org/10.1016/J.JCLEPRO.2021.129200

Saptaputra, E. H., Bonafix, N., & Araffanda, A. S. (2023). Mobile App as Digitalisation of Waste Sorting Management. *IOP Conference Series: Earth and Environmental Science*, *1169*(1), 012007. https://doi.org/10.1088/1755-1315/1169/1/012007

Sasikanth, B. S., Naga Yoshita, L., Reddy, G. N., & P.v, M. (2021). An Efficient & Smart Waste Management System. *2021 International Conference on Computational Intelligence and Computing Applications, ICCICA 2021*. https://doi.org/10.1109/ICCICA52458.2021.9697316

Uggla, N. (2021). *A Lean UX framework for creating a reusable product from start to finish*. https://aaltodoc.aalto.fi/handle/123456789/109399

Wang, W. jing, & You, X. yi. (2021). Benefits analysis of classification of municipal solid waste based on system dynamics. *Journal of Cleaner Production*, *279*, 123686. https://doi.org/10.1016/J.JCLEPRO.2020.123686

What is Wireframing? — updated 2024 | IxDF. (n.d.). Retrieved November 27, 2024, from https://www.interaction-design.org/literature/topics/wireframe?srsltid=AfmBOoo5_Pc9ho6et7cWNJ1uV6uFJpoOO6JizpJW_eXE8CyNNZ4gHSec

Wynn, D. C., & Maier, A. M. (2022). Feedback systems in the design and development process. *Research in Engineering Design*, *33*(3), 273–306. https://doi.org/10.1007/S00163-022-00386-Z/FIGURES/10

Xiao, S., Dong, H., Geng, Y., Tian, X., Liu, C., & Li, H. (2020). Policy impacts on Municipal Solid Waste management in Shanghai: A system dynamics model analysis. *Journal of Cleaner Production*, *262*, 121366. https://doi.org/10.1016/J.JCLEPRO.2020.121366

Zhang, Z., Chen, Z., Zhang, J., Liu, Y., Chen, L., Yang, M., Osman, A. I., Farghali, M., Liu, E., Hassan, D., Ihara, I., Lu, K., Rooney, D. W., & Yap, P. S. (2024). Municipal solid waste management challenges in developing regions: A comprehensive review and future perspectives for Asia and Africa. *Science of The Total Environment*, *930*, 172794. https://doi.org/10.1016/J.SCITOTENV.2024.172794

Zuleikha, N., Zolkfele, N., Ibrahimb, Z., Akram, S., Cob, C., Razeef, M., & Razak, A. (2022). Zero Waste Cycle Mobile Branding Application. *International Journal of Mechanical Engineering*, *7*.