Evaluating the Usability of Different Methods for Visualizing Constituent Parts in a Digital Twin of a Soy Farm

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June 2024

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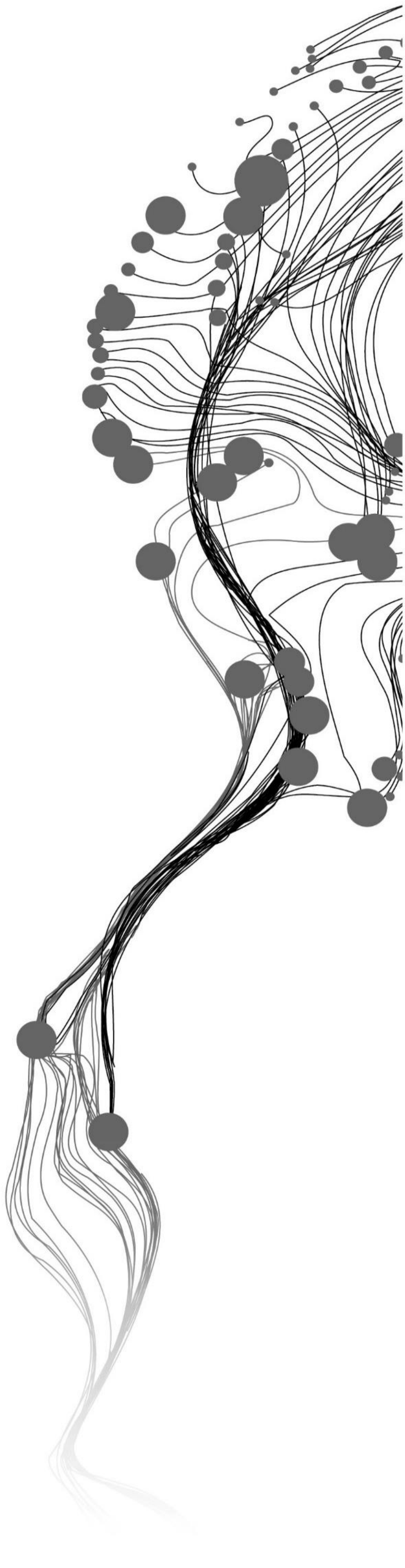

Evaluating the Usability of Different Methods for Visualizing Constituent Parts in a Digital Twin of a Soy Farm

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DISCLAIMER

ABSTRACT:

The pressing need to enhance agricultural efficiency and sustainability necessitates innovative approaches to farm management. This research investigates the utilization of Digital Twins (DTs) in the storage and packaging processes of soy yogurt on a soy farm. Specifically, it compares the effectiveness of text-based and hybrid visualization approaches within a DT system. The study involved creating a detailed 3D model of the farm, implementing a DT system with both visualization methods, and conducting usability testing with a group of users, including a farmer and geo-data users from ITC.

Results indicate that the hybrid approach, which combines textual data with visual aids, significantly enhances user efficiency and effectiveness in task completion compared to the text-based method. Eye-tracking data and user feedback reveal that users find the hybrid method more intuitive and accessible, facilitating quicker and accurate decision-making. Additionally, the study underscores the importance of 3D environments in aiding user understanding of farm processes, providing a realistic representation that enhances spatial and operational comprehension.

The research highlights the need for scalable and adaptable DT systems capable of accommodating future changes in farm infrastructure. By integrating user feedback, dynamic data handling, and modular design principles, DTs can evolve to meet the diverse needs of modern agriculture. This study contributes to the growing body of knowledge on DT applications in agriculture, providing insights for optimizing digital tools to support sustainable and efficient farming practices. The findings suggest that incorporating visual aids and 3D environments into DTs can significantly improve usability, making them more effective for real-world agricultural management.

Keywords
Digital Twin, Visualization, Usability Testing, Eye Tracking, Farm management

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1. Introduction:

1.1. Motivation:

As agriculture remains an important component of the global economy, innovations that improve productivity and operational efficiency are very important. Digital Twins (DTs) represent a transformative technology capable of revolutionizing agricultural practices by providing insights into predictive analytics, and actionable data. The integration of DTs into agricultural education and training programs can also play a pivotal role. By simulating real-world farming scenarios, DTs can provide an immersive learning experience for new and existing farmers, thereby improving their understanding and skills in managing modern agricultural technologies. This educational aspect underscores the broader impact of DTs beyond immediate operational benefits, contributing to the long-term sustainability and advancement of the agricultural sector. Additionally, DTs offer significant potential for enhancing traceability in agricultural supply chains. By maintaining a comprehensive digital record of the processing and storing stages, DTs can facilitate better control and compliance. Such advancements have the potential to improve operational efficiencies. However, the effective visualization of these digital representations remains a significant challenge.

In particular, the storage and packaging processes of soy yogurt within soy farms present complex scenarios. This may require visualization to facilitate better decision-making and operational management. Current research has extensively explored various visualization techniques, but there is a notable gap in comparative analyses between text-based and hybrid visualization approaches within DTs, especially in the agricultural sector.

It is critical to address the challenge of comparing different visualization techniques within a DT. Moreover, the adoption of DTs can directly contribute to reducing wastage by improving precision in inventory management and detecting potential issues in storage conditions before they escalate. This research aims to provide a DT platform that can help farmers optimize their storing and packaging operations and make informed decisions. The motivation for this research is from the pressing need to enhance agricultural efficiency and sustainability in the face of growing global food demands and environmental challenges.

1.2. Background:

Agriculture is a major contributor to the economies of many nations. With rising global populations and increasing demand for food, there's an urgent need for efficient, sustainable, and technologically advanced farming practices (Thornton, 2010). By improving efficiency and productivity, it can generate more income for farmers (Herrero et al., 2013).Digital Twins (DT), with their ability to provide real-time insights, predictive analytics, and actionable data, can play an important part in addressing these challenges.

Digital twins are virtual duplicates of physical objects, systems, or processes that are fed with data and functionalities enabling them to understand and provide simulations, enabling analysis, prediction modeling, and optimization. By integrating data from sensors, Internet of Things (IoT) devices, and other sources, DTs offer a holistic view of the physical or real world and enable proactive management, predictive maintenance, and personalized experiences of the targeted domain. The DT is not merely a digital replica of a physical entity; it's a dynamic, evolving system that mirrors its real-world counterpart in real time. This real-time synchronization, combined with the ability to simulate, analyze, and optimize, sets DTs apart from traditional digital three-dimensional models (Jeong et al., 2022). The agriculture sector stands to benefit greatly from DT technology, notably in terms of improving agricultural product production, processing, and distribution efficiency. Soy farming, for example, can use DTs to forecast output and manage resources more efficiently. In the manufacturing of soy yogurt, DTs have the potential to help expedite storage and packaging processes, assuring quality control, and reducing waste. DTs can also play an important role in farm transitions, especially in situations where not all facilities have been properly built for soy growing. In such cases, DTs can considerably improve usability by offering a virtual picture of the farm, enabling precise planning and optimization. They allow farmers to model various techniques and anticipate results without affecting actual farm operations. By visualizing potential improvements and highlighting inefficiencies, DTs aid in the adaptation to unusual or suboptimal settings. This skill is especially useful for ensuring that the farm transitions smoothly, optimizing output and sustainability even in less-than-ideal conditions. Another notable benefit is the training of new farmhands. DTs offer an engaging and immersive learning environment in which new employees may become acquainted with agricultural operations, machinery, and processes without the hazards associated with hands-on training. This results in faster and more successful onboarding. Furthermore, DTs raise awareness among all stakeholders by offering a complete picture of the farm's operations. Farmers, managers, and other stakeholders may readily access and analyze real-time data, allowing for better decision-making and a more in-depth understanding of the farm's overall production. This way DTs can be important for conveying farmers' perspectives and needs, bridging the communication gap between farmers and policymakers. This enhanced communication can lead to better resource allocation, and policies that are more closely aligned with the realities of farming.

Furthermore, effective visualizations within such DTs can enhance user comprehension and engagement. These visual tools make complex data more understandable and actionable (Ware, 2012). Text-based visualizations primarily use detailed numerical data and descriptive material to convey insights. Tables, detailed logs, and reports providing a full overview of the data are examples of such documents. However, text-based representations can be intimidating, especially when comparing different scenarios, and may fail to highlight important trends or anomalies (Few, 2006). Hybrid visualizations, on the other hand, integrate textual data with visual elements like hue, size, etc. This methodology combines the qualities of both methodologies to provide a more straightforward and accessible method of data analysis (Shneiderman, 1996). This dual method aims to improve decision-making by offering a more comprehensive perspective of the data (Card et al., 1999).

There is a need to identify the appropriate visualization techniques in utilizing DT technology for a farm setting. The findings demonstrate the advantages of hybrid visualizations in terms of user comprehension and operational efficiency in the context of soy yogurt packaging and storing. By addressing the sector's specific needs, this study delivers useful insights that can inform future improvements in DT visualization and contribute to the larger goal of sustainable and efficient farming methods.

1.3. Goal:

This thesis aims to evaluate the usability of different visualization methods for visualizing constituent parts in Digital Twins (DTs) in agricultural contexts, specifically focusing on the processes involved in storing and packaging soy yogurt within a soy farm environment. This research seeks to compare two visualization methodologies employed within DTs: the traditional text-based representation approach and a hybrid approach combining textual descriptions and visual variables. Usability testing will be conducted on the DT and its two visualizations with an emphasis on efficacy, efficiency, and user satisfaction. Effectiveness assesses how accurately users execute assigned tasks, emphasizing the DT's decision-making assistance. Efficiency assesses how long users take to perform tasks, providing information about the practicality of various data representation approaches. User satisfaction is measured by surveys and feedback on the DT's ease of use, visual appeal, and realism. The study's diversified participant group includes farm owners, managers, and ITC staff, ensuring a thorough review from both technological and practical farming viewpoints. This study assumes that improving a DTs usability could offer huge benefits. Improving usability is likely to lead to better decision-making and operational efficiency on the farm. Farmers and managers may make more precise and timely decisions using more intuitive and effective DTs, which would have a direct impact on crop production and resource management.

Through analysis and comparison of these visualization techniques, the study aims to determine the best method in terms of usability for end-users, particularly farmers, operating within the dynamic setting of a soy farm. By conducting usability testing and comparative analysis, the study aims to uncover insights that can inform more efficient decision-making, streamlined operations, and improved user satisfaction within agricultural contexts utilizing DT technology.

Moreover, this research aims to offer practical implications for the agricultural community. By using DT technology, the study aims to equip farmers with insights to enhance farm management practices. Ultimately, the research seeks to facilitate the advancement of DT technology in agriculture, contributing to the sustainability, productivity, and resilience of agricultural systems amidst evolving global challenges.

1.4. Research Gap:

The research gap in the study lies in the comparative analysis of visualization methodologies within Digital Twins (DTs) specifically tailored for agricultural settings, with a focus on soy farm operations. While existing literature extensively explores various visualization techniques in DTs and their applications across different domains, there is a notable dearth of studies that directly compare the effectiveness and usability of text-based representation versus hybrid approaches incorporating both textual representation and visual variables within agricultural contexts.

Furthermore, while individual studies have investigated the usability of DTs in agriculture, particularly in crop management and resource optimization, there remains a gap in understanding the specific visualization methods that are more effective for conveying information related to the storage and packaging processes of soy yogurt production within a soy farm setting. This research aims to fill this gap by conducting a comparative analysis of these visualization methodologies, thereby providing insights into the optimal approach for enhancing decision-making, efficiency, and user satisfaction in agricultural operations.

1.5. Research Problem:

Settings such as a soy farm, comprises of various constituent parts, from crop lands to storehouses for soybeans, and yoghurt production. The visualization method by which these parts and processes are represented in a DT can significantly impact its usability. This research aims to compare two primary methods of visual representation: illustrating the attributes or geometric objects using textual representation vs hybrid approach utilizing both text-based representations and visual variables. Hybrid approach, on the other hand, offers a detailed representation but comes with its own set of possible challenges, including easy of understanding for a novice user. But which of the two approaches offers the most usability in a real-world soy farm scenario? The study aims to resolve this problem by assessing and determining what visualizations work best in this particular setting by performing usability testing. In conclusion, the aim is to identify the best way to visualize Digital Twins in the complex environment of a soy farm. In the end, the objective is to provide an optimal visualization approach that finds the ideal ratio between easy interpretability by end-user and high usability. The findings of this research may have the potential to contribute for the improvement of Digital Twins' effectiveness and usability, but more importantly, they can offer useful information that will strengthen the position of end-user farmers and other stakeholders.

2. Literature review:

Most recently, researchers have developed sophisticated modelling and simulation techniques for production of accurate and dynamic digital twins. This includes physics-based models, data-driven approaches, and the integration of machine learning algorithms to capture complex system behaviours (Deren et al., 2021) Other research has focused on developing efficient data integration frameworks and analytics algorithms to collect and process data fed from multiple data sources (Merino et al., 2022). Digital twins offer the potential for predictive maintenance by integrating real-time data and analytics. Researchers have studied the usage of machine learning and advanced algorithms to predict failures, improve performance, and support decision-making (Kaur et al., 2020). This technology has the capability to serve cities and communities making them more resilient to changing conditions. It has the capability to revolutionize healthcare by enabling customized diagnosis and treatment based on medical knowledge and patients' history (Sun et al., 2023). Lehtola et al. (2022) examined DTs in urban planning, emphasizing their potential for improving city management through real-time data integration. This strategy enhances decision-making, resource management, and sustainability by giving comprehensive information about infrastructure and services. Digital twins also play an imperative role in smart manufacturing with great deal of applications in industries. Moreover, the technology emphasizes its role in reducing production costs, improving efficiency, and enabling agile decision-making (Bamunuarachchi et al., 2021). This technology has the potential to contribute to development of smart cities, sustainable urban planning, green infrastructure benefiting the environment and the quality of life. As discussed by Caprari et al (2022). with the aid of simulations and optimizations of urban systems, such as transportation, energy, and infrastructure; Digital twins help improve resource allocation, reduce energy consumption, and enhance sustainability. It also has applications in asset management and predictive maintenance by continuously managing the condition of physical assets and systems with the help of IoT devices, sensors, and real time data analytics. This helps organizations optimize maintenance schedules, reduce downtime, and prevent costly failures. Digital twins have also been proved useful in optimizing transport. As discussed by Dirnfeld et al. (2022), digital twins are used for the maintenance of railway tracks using predictive maintenance analytics, resulting in improved reliability, reduced maintenance costs, and enhanced safety. With their ability to imitate real-world processes and their ability to deliver insightful information for improved decision-making in the agricultural sector, digital twins, or DTs, have become a game-changing technology. Alves et al. (2019) provides more evidence of the usefulness of digital twin technology in agriculture by utilizing it to develop a cyber-physical system for equipment and resource management. DT technology has the potential to improve agricultural production and efficiency. Nasirahmadi et al. (2022) also explored its use in many agricultural contexts, such as soil, irrigation, robotics, and post-harvest food processing.

How a symbol or object in a Digital Twin can be altered to provide information can be described by visual variables or textual representations. Visual variables include colour hue, size, orientation, shape, arrangement, texture, sharpness, colour value, transparency, etc. and are logically used for data visualization (Roth, 2017a). Through the use of visual variables like colour, size, and texture, (Li et al., 2020) investigated how information can be transformed into visual forms in geovisualization, thereby addressing the issue of information overload in the human-cyber-physical world. On the other hand, data can also be conveyed in words. Written text is frequently used as labels when data representation is expressed through language (Brath & Banissi, 2016). Determining the label's purpose or placement are also crucial and can denote various meanings in text-based representations (Deeb et al., 2014). Despite being old, text-based visualizations are still used to depict data within DTs. Text-based visualizations are especially beneficial in scenarios requiring extensive numerical data, providing accurate values that are crucial for monitoring and analysis (Card et al., 1999b). Graphical visualizations, on the other hand, use visual components such as charts, graphs, and maps to communicate data in a more intuitive manner. These visuals can instantly communicate trends, patterns, and anomalies that would otherwise be difficult to detect in text-based formats. In the context of DTs, these visual tools improve the ability to forecast outcomes and manage farm operations by simplifying complex data (Ware, 2012).

Several studies have shown the efficacy of various visualization approaches in agriculture. For example, Wolfert et al. (2017) investigated the application of big data analytics and visualizations in smart farming. The researchers emphasized the value of visual tools for analysing and interpreting massive amounts of data from IoT devices and sensors put on farms. They stressed the importance of graphical visualizations for spatial data analysis, such as geographic information system (GIS) maps and 3D models, which allow farmers to effectively monitor crop health and optimize resource allocation. In another study, Marjani et al. (2017) investigated the architecture and applications of big data analytics in agriculture, emphasizing on the significance of visualizations in making sense of large datasets. The researchers discovered that visual dashboards with both graphical and textual features dramatically increased farmers' capacity to interpret and act on data insights. These dashboards delivered real-time updates and visual summaries of critical performance metrics, allowing for prompt and informed decision-making. Comparative studies have also been undertaken to assess the efficacy of various visualization approaches used in DTs. For example, Larkin and Simon (1987) conducted a seminal study comparing the use of diagrams against prose to convey information. They discovered that diagrams could dramatically lower cognitive strain for users, allowing them to grasp complicated concepts more quickly and accurately. This conclusion is significant for DTs in agriculture, where the capacity to swiftly comprehend data can have a direct impact on farm management and productivity. Asseng et al. (2014)investigated the influence of rising temperatures on worldwide wheat output and used various visualization techniques to convey their findings. The researchers used graphical visualizations, such as climate maps and crop production estimates, to demonstrate the possible effects of climate change on agriculture. These visualizations gave a clear and compelling image of the data, allowing stakeholders to better comprehend the consequences and make appropriate decisions.

Although research on data visualization, specifically about the use of hybrid visualization and text representations, has advanced significantly, there are still several research gaps in existing knowledge about their use in the context of Digital Twins. While numerous studies have been conducted on independent textual variables or visual representations, there is lack of comparative analyses between textual and a hybrid approach which incorporates both textual and visual representation. Comprehensive knowledge of which of these methods is better or how these methods influence the usability of a Digital Twin remains unexplored. Notably, less research has been done on a hybrid approach that utilizes both visual variables and text-based representations. Thus, there is room for further research. These research gaps must be filled by a comparative analysis of these approaches used for visualisation of information in a Digital Twin.

3. Main Objective:

The main objective of this study is to assess and compare the usability of two different Digital Twin visualizations focusing on the storage and packaging of produced soy yogurt from soybeans within the soy farm context. The research will explore two distinct approaches: text-based representation and a hybrid approach utilizing both text-based representation and visual variables.

3.1. Sub-Objectives:

1. To conduct a requirement analysis to determine the essential components and functionalities to be added to the Digital Twin (DT) system for representing the storage and packaging processes of soy yoghurt within the soy farm context.
2. To create a detailed 3D model of the soy farm infrastructure, including facilities for processing, storage, and packaging.
3. To develop and implement a DT system utilizing two distinct visualization techniques: text-based representation and a hybrid approach combining textual descriptions with visual variables. This system will illustrate the processes involved in packaging and storing of soy yogurt, allowing for comparison.
4. To perform usability testing of the developed DT system and compare the usability of the two visualization techniques in conveying information to users.

3.2. Research Questions:

RQ1: What specific data inputs and parameters are necessary to represent the packaging and storage processes of soy yogurt within the DT system?

RQ2: How can the DT be enhanced to ensure scalability and adaptability for potential future modifications or expansions of the soy farm infrastructure?

RQ3: Does the 3D environment aid the user in better understanding the processes happening at the farm?

RQ4: In the context of usability evaluation for Efficiency, how efficient are the different visualizations in conveying information to the users to perform tasks related to the packaging and storage of soy yogurt using the different visualizations?

RQ5: In the context of usability evaluation for Effectiveness, to what extent do different digital twin visualizations prove effective in conveying information for users in making informed decisions related to the packaging and storage of soy yogurt using the different visualizations?

RQ6: In the context of usability evaluation for Satisfaction, what is the level of satisfaction among users when interacting with the different visualizations?

RQ7: How does the usability of a text-based digital twin compare to that of a hybrid digital twin, when focusing on the packaging and storage of produced soy yogurt?

Hypothesis: The digital twin utilizing the hybrid approach provides more usability for soy yogurt packaging and storage than the textual approach.

4. Study Area and datasets:

4.1. Study Area

The study area, De Nieuwe Melkboer, is a soy farm based in Enschede, Netherlands. It is the first plant-based dairy farm in the Netherlands and their soy yoghurt has recently been made available since July 2023. The soy farm mainly encompasses of the agricultural land dedicated to soybean cultivation and the barn area facilitating the production, packaging, and storage of soy yogurt. The digital twin model includes the soy fields, the barn area and the farmer's house. This study focuses on the digital representation of the farm's infrastructure and the attributes associated with packaging and storing of soy yoghurt. The map in figure 1 shows the study are map of De Nieuwe Melkboer.

***Figure 1**: This image is the study area map of the farm.*

Infrastructure in De Nieuwe Melk Boer’s digital twin consists of the following:

1. **Barn Area**: The barn area is a multipurpose area that is used for storing equipment or for other farm operations. It consists of a building with multiple rooms. One such room is equipped with establishments like filling machine where the produced soy yogurt is packed. Another room acts as a refrigerator used for storing the yoghurt packages.

2. **House**: It is the residential space used by farm owners. The house is modelled only from the outside due to privacy reasons. The interior has not been modelled as it is not relevant to the objectives of this study or to the farmer's requirements.

3. **Surrounding Land**: It is the land surrounding the barn and the house. It comprises of an open space with trees and grass.

4.2. Datasets

4.2.1. Details of the farm

A crucial part of the data collection consisted of acquiring the architectural and environmental details of the De Nieuwe Melkboer farm. An exact and scaled depiction of the farm was provided by the farmer in a Computer-Aided Design (CAD) file, which forms the basis for creating the Digital Twin (DT). The CAD file was a few years old and wasn't up to date with some of the latest changes related to the interior of the barn. Figure 2 shows the CAD file of the barn when it was a livestock barn. The barn was originally designed to keep cows and other animals which was then converted for the purpose of soy yoghurt production. Nonetheless, this file provided specifics of the farm and had exact measurements of the farm's major physical structures, including the barn and its comprising building.

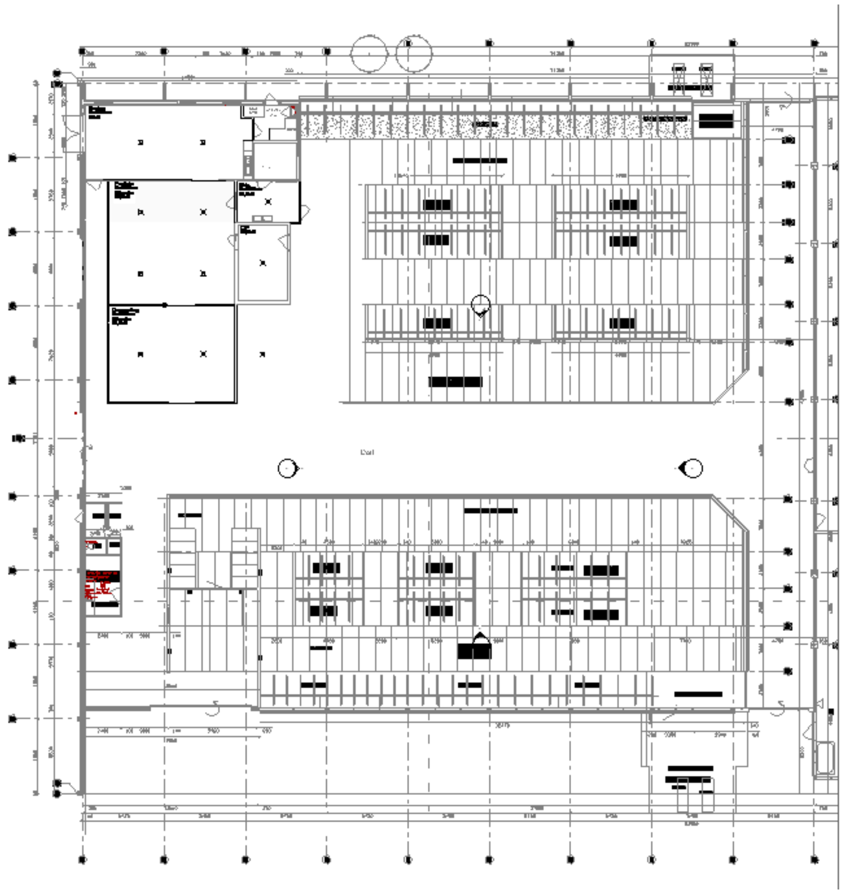

***Figure 2**: Computer Aided drawing of the barn when it was a livestock barn.*

4.2.2. Visual Media

To improve the visual appearance of the Digital Twin, pictures and videos of the farm were taken with permission from the farmer. To accompany the measurements from the CAD file, these visual media files were essential for recreating the physical look and environment of the farm in the Digital Twin 3D model. This covers things like where the equipment is located, how the fields are maintained, and how various farm structures are arranged in relation to one another. The images and videos were very helpful and offer thorough visual references, facilitating faithful depiction of the distinct features and layout of the farm. Figure 3 shows some photos from the barn.

***Figure 3**: Photos from the farm including the barn and filling machine.*

4.2.3. Information About Machineries

This dataset includes extensive information about the machinery used inside the barn. This data was collected through on-field observations and an interview with the farmer. It covers various operational aspects, including information on how long each machine takes to perform specific tasks, details on the electricity required to operate the machinery, amount of manual Labor required to operate each machine, etc. This information details quantities and measurements relevant to the machinery's operation. Table 1 gives a brief description of the machineries involved in packaging and storing process.

***Table 1**: Description of machineries.*

Machine	Brief Description
Tank 01	Yoghurt pasteurizer and storage until package.
Tank 02	Yoghurt pasteurizer and storage until package.
Filling Machine	Fills in yoghurt in multiple container sizes and with multiple flavours.

5. Methodology:

This chapter covers the approach utilized for developing and assessing the Digital Twin (DT) of De Nieuwe Melkboer farm. The technique is built into several major phases: requirement analysis, construction of a 3D environment, exporting to a gaming engine, integrating capabilities in Unreal Engine, building varying versions of the DT, defining activities for usability analysis, and conducting the usability analysis. Figure 4 shows the methodological flowchart followed by the research.

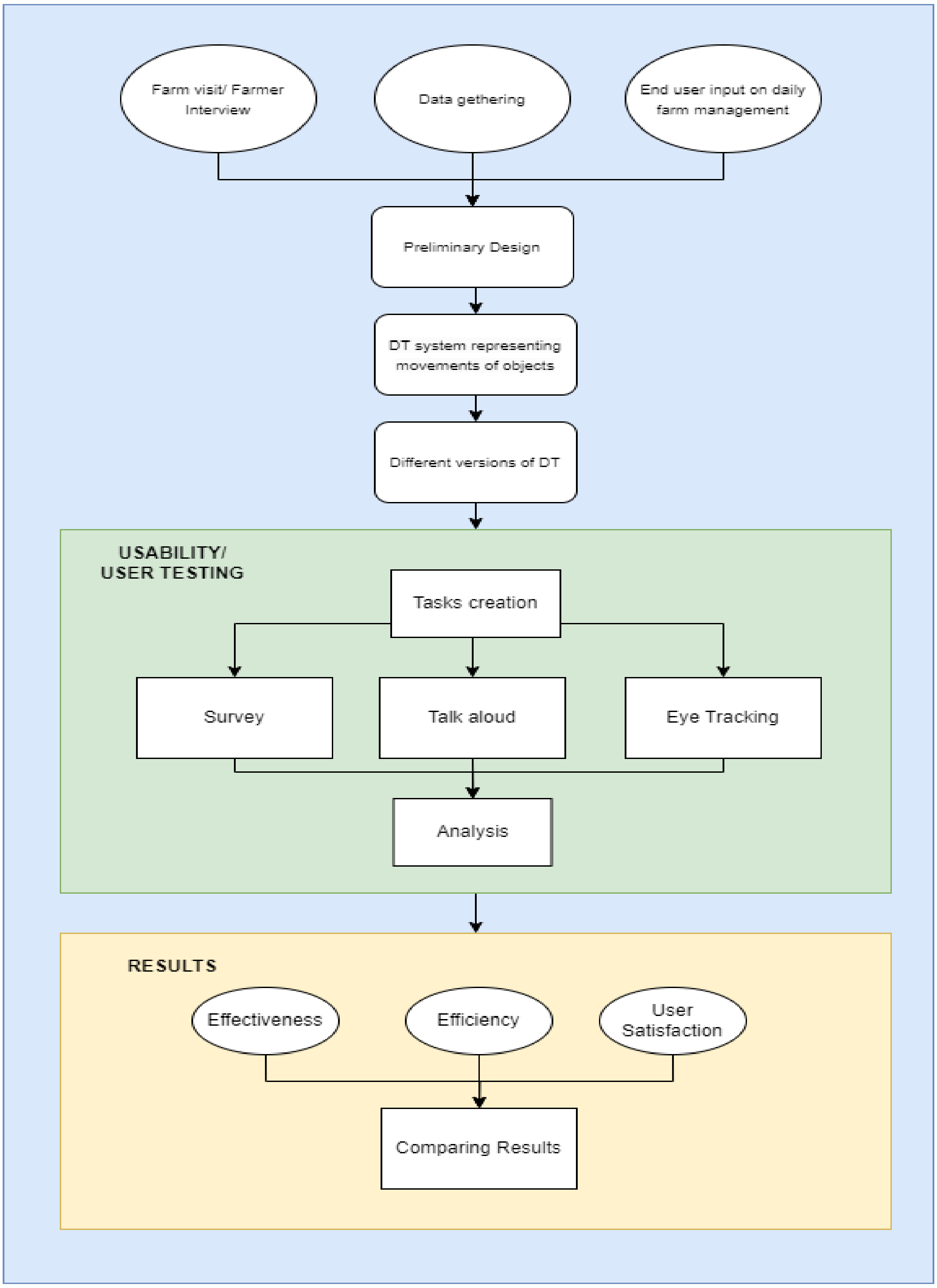

Figure 4*: The flowchart depicts the methodological flow followed in this research.*

5.1. Requirement Analysis:

The initial phase of the methodology involved a thorough requirement analysis. This phase was critical for defining the scope of the DT, ensuring it meets the needs of the farmer as well as the objectives of this study. To determine the exact measurements and configurations of the farm's physical structures, a comprehensive CAD file provided by the farmer was examined. The file contained measurements of every detail in the barn including the walls, door, window, etc. Self -acquired photos and videos of the farm were used as visual references to capture the farm's layout and exterior appearance, including the placement of machinery and the arrangement of other structural elements.

The flowchart in figure 5 outlines the entire process of soy yogurt production, from the initial harvest to the final storage of the finished product. This research limits itself entirely to the packaging and storage of soy yoghurt. Thus, information about the machinery was collected on the operational aspects of the machines involved with the packaging and storage processes. The process begins with the harvest-in stage, where fresh soybeans are brought into the production facility. These soybeans undergo initial processing in the Soybeans stage, preparing them for subsequent steps. The next critical phase is soy cleaning, where the soybeans are thoroughly cleaned to remove impurities, ensuring that only high-quality beans proceed. Once cleaned, the soybeans move to the Soy Yogurt Production stage, where they are transformed into soy yogurt through a series of processes, including soaking, grinding, and boiling.

Following yogurt production, the process continues with Pasteurizing, where the soy yogurt is heated to kill harmful bacteria and ensure safety and shelf stability. After pasteurization, the yogurt enters the yoghurt packaging phase, is packaged into containers, and is ready for distribution. The final steps involve Yoghurt Storage, where the packaged yogurt is stored under controlled conditions to maintain its freshness and quality until it is ready to be shipped out. The process ensures that the soy yogurt is produced efficiently and meets quality standards from the initial harvest to the final Yoghurt Out stage.

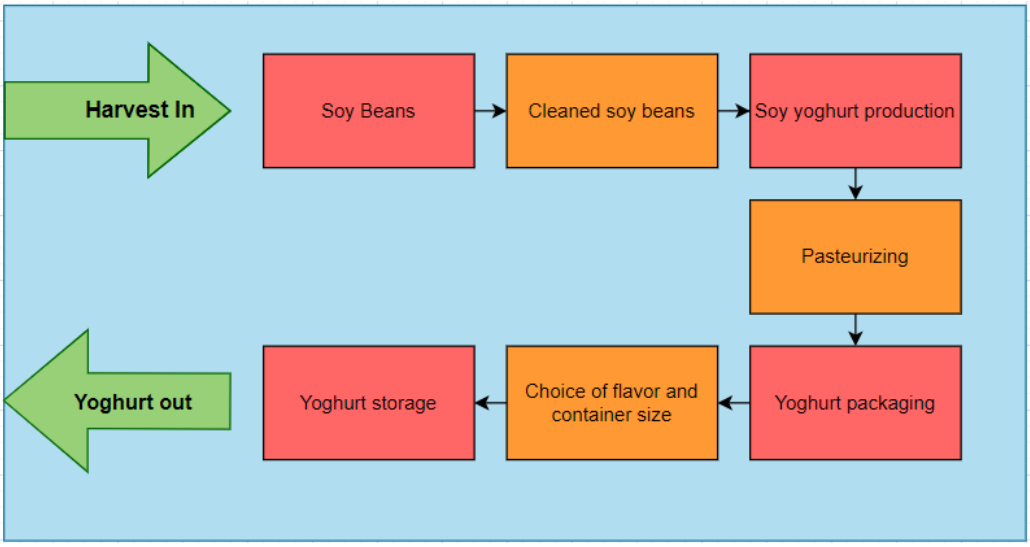

***Figure 5**: The flowchart depicts the processes happening at the farm.*

After discussions with the farmer, it was decided to focus on the following seven key attributes:

1. Tank 1 volume

Tank 1 has 500 litres of soy yogurt. During the container-filling process, yogurt is first utilised from Tank 1. The machine doesn't begin drawing yogurt from Tank 2 until Tank 1 has been completely emptied. By following this order, the yogurt flow through the packaging system is optimized and Tank 1 is used to the fullest before Tank 2 is used. This attribute tells how much yoghurt is left in the Tank 1 at any time.

$$Tank\ 1\ (L) = amount\ of\ yoghurt\ left\ in\ Tank\ 1\ (L)$$

2. Tank 2 volume

Tank 2 is larger, with a capacity of 1000 litres. It functions as another supply and only comes into use after Tank 1 is empty. This staged utilization minimizes downtime related to tank swapping and aids in maintaining a continuous packing process. This attribute will tell how much soy yoghurt is left in the Tank 2 at any time.

$$Tank\ 2\ (L) = amount\ of\ yoghurt\ left\ in\ Tank\ 2$$

3. Amount of yoghurt

The total quantity of yogurt packed (in Litres) during the packaging process is referred to as the total amount of yogurt. The farm provides 500 millilitre (mL) and 5 litre (L) packaging containers. There are three flavour choices as well: vanilla, forest fruit, and plain. Plain yogurt containers are filled to the brim (500ml or 5L). On the other hand, vanilla and forest fruit flavoured yoghurt containers are filled to a capacity of 460 ml in 500 mL containers and 4.6 L in 5 L containers of yogurt respectively, in order to also accommodate the flavours which are 40ml for 500ml container and 0.4L for 5L container. Thus, this attribute will provide the total amount of soy yoghurt packed.

$$Amount\ of\ yoghurt\ (L) = 0.5n_{sp} +* 5n_{bp} + 0.46n_{sf} + 4.6n_{bf}$$

Where,
n_{sp} = number of 500 mL size (small) containers of plain flavoured soy yoghurt
n_{bp} = number of 5 L size (big) containers of plain flavoured soy yoghurt
n_{sf} = number of 500mL size (small) containers of vanilla and forest fruit flavoured soy yoghurt
n_{bf} = number of 5 L size (big) containers of vanilla and forest fruit flavoured soy yoghurt

4. Time taken:

The total duration required to fill, pack, label, and store the yogurt containers includes filling a 500 ml container which takes 10 seconds. Out of these 10 seconds, 7 seconds are allocated for filling, 2 seconds for stickering and boxing, and 1 second for moving the container to the fridge because a single container is not moved to the fridge a large number of boxes are moved at once using a hand lifter. The total time required to fill, pack, label, and store a 5-liter container is approximately 1 minute and 13 seconds. Out of this, 1 minute and 10 seconds are allocated for filling, 2 seconds for stickering and boxing, and 1 second to move the container to the fridge.

Equation 1: Time taken for producing certain amount of yoghurt.

$$\text{Time taken (s)} = 10n_s + 73n_b$$

Where:

n_s = total number of 500 mL (small) containers to be packed,

n_b = total number of 5 L (big) containers to be packed

5. Energy consumed:

The machinery used for filling and packaging consumes 3 kW of electricity per hour. This attribute is helpful in figuring out the total energy used based on how long the packaging process takes. It can also help the farmer in evaluating the process's operating expenses or per day expense.

$$Energy\ consumed\ (kWh) = 3\ kW * (time\ taken\ in\ hours)$$

6. Man hours:

The formula to compute man hours is given below in Equation. This calculation takes into consideration that ideally two people are required for the packaging and storing process: one person to handle the filling and packing of the containers, and another to label them and put them in storage boxes. Furthermore, there are 3 fixed hours every day—one hour in the morning for preparation and two hours in the evening for cleaning—dedicated to these tasks. This attribute aids in manpower planning by giving a thorough grasp of the labour needed for the processes.

$$Man\ hours\ (hours) = time\ taken\ (in\ hours) * 2 + 6$$

7. Fridge capacity:

The fridge capacity indicates the number of storage boxes containing packed containers that are placed inside the refrigeration chamber. 6 containers of 5 L fill up one entire storage box. Similarly, 16 containers of 500 mL each can be stored in one storage box. The two types of containers cannot be combined. A storage box is kept in the refrigerator when it is completely filled. The number of boxes that is currently stored is dynamically updated on the fridge capacity attribute. The model permits an infinite number of boxes to be stored in the refrigeration room, even though it is not realistic. This is because the farmer did not reveal the actual fridge capacity limit which is why it is acknowledged as a constraint to the study.

$$Fridge\ Capacity = \left\lfloor \frac{n_{500ml}}{16} \right\rfloor + \left\lfloor \frac{n_{5L}}{6} \right\rfloor$$

Where:

$\lfloor x \rfloor$ represents the floor function, which rounds down to the nearest integer.

n_{500ml} = Total number of 500 millilitre containers packed

n_{5L} = Total number of 5 litre containers packed

As a result, the details of the attributes were obtained in this first methodological step. The formulas along with them were necessary to correctly simulate the operations of the machines in the Digital Twin. The Digital Twin was made using Revit and Unreal engine so C++ blueprints were utilized to incorporated these formulas. This guaranteed that the machines' virtual representations functioned correctly and mirrored their real-world performance. By integrating these specifications into the Digital Twin, the study aims at providing valuable insights for optimizing farm operations.

The blueprint in Figure 6 is an Unreal Engine-created visual representation intended to determine the total amount of yogurt and the amount of time needed to fill a given number of yogurt containers with each of the three flavours. Each portion of the blueprint represents a single yogurt flavour, and it takes user input to calculate the volume of yogurt in total and the amount of time needed to fill the containers. The blueprint facilitated dynamic calculation of volume and filling time of various yogurt flavours based on user input.

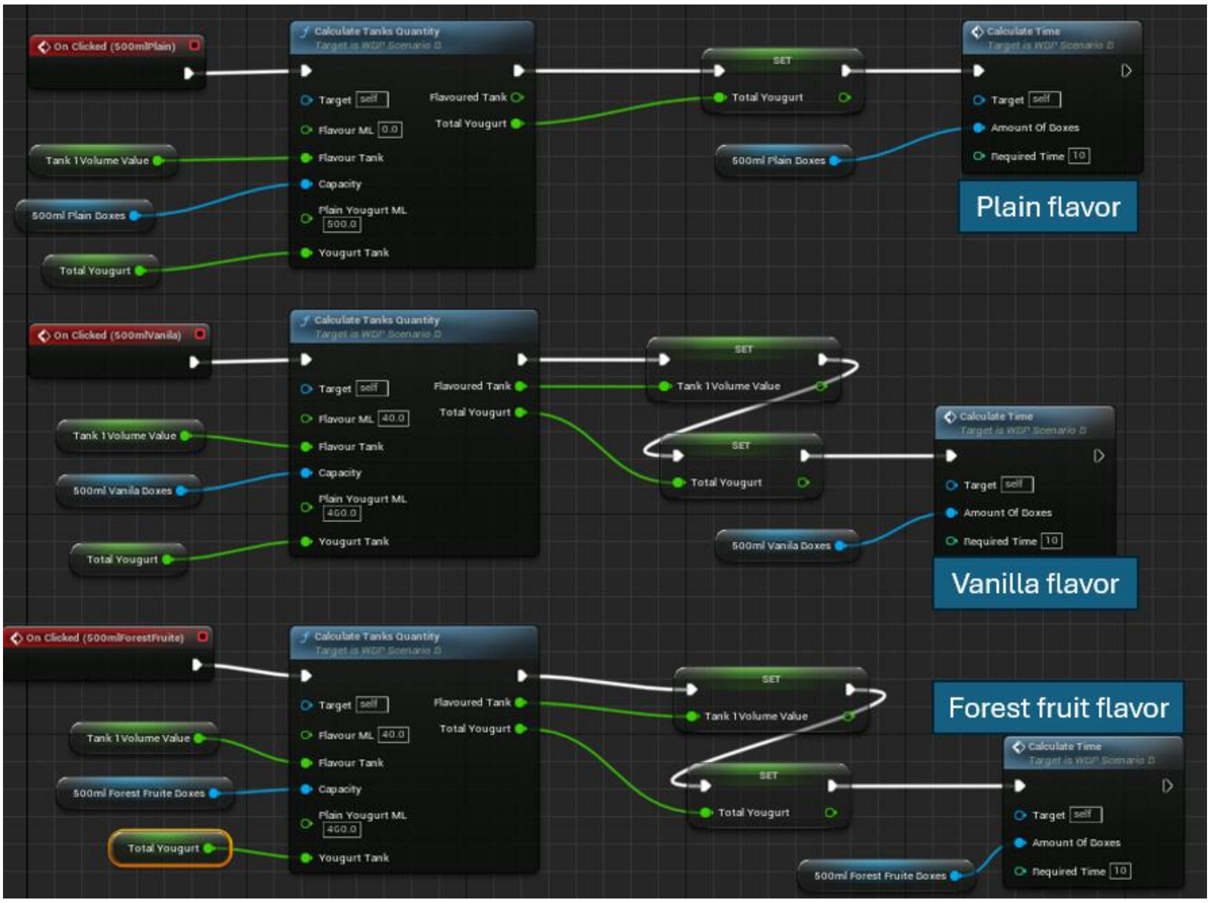

***Figure 6**: The image shows one of the blueprints codes used to calculate attributes.*

5.2. Creation of 3d Environment:

After the requirements were defined, the next stage was to build a 3-Dimensional model of the De Nieuwe Melkboer farm. This step comprised the creation of an 3D model of the farm and was done entirely on the Revit model due to its robust capabilities in architectural design and modelling. Using the CAD files the external and interior spaces of the farm were modelled. Since the CAD file was not up to date with some of the physical elements of the farm, visual media was also used as reference to create a detailed floor plan of the farm on Revit. The initial 3D model of the farm was created according to this floor plan. The farmer's house, the barn, and the surrounding ground made up the exterior. The interior of the house was not modelled since it was unrelated to the goals of the study and raised privacy concerns for the farmer. The barn area and its interior are the most significant areas for this study because they include rooms that consist of the yogurt-filling machinery and refrigerators for storing the yogurt. The farmer's description and the visual media's observations of the actual locations of the machines were used to place them into the 3D model. Figures 7, 8, and 9 show the Revit floorplan and 3D model. Realistic representations of the doors and windows were made using “Revit families”, which are detailed 3D models from online repositories. This required choosing the right kinds of windows and doors from Revit's vast library and tailoring them to match the precise dimensions and architectural designs of the farm's buildings. Twin Motion a software extension in revit was used to export this 3D model to Unreal Engine software.

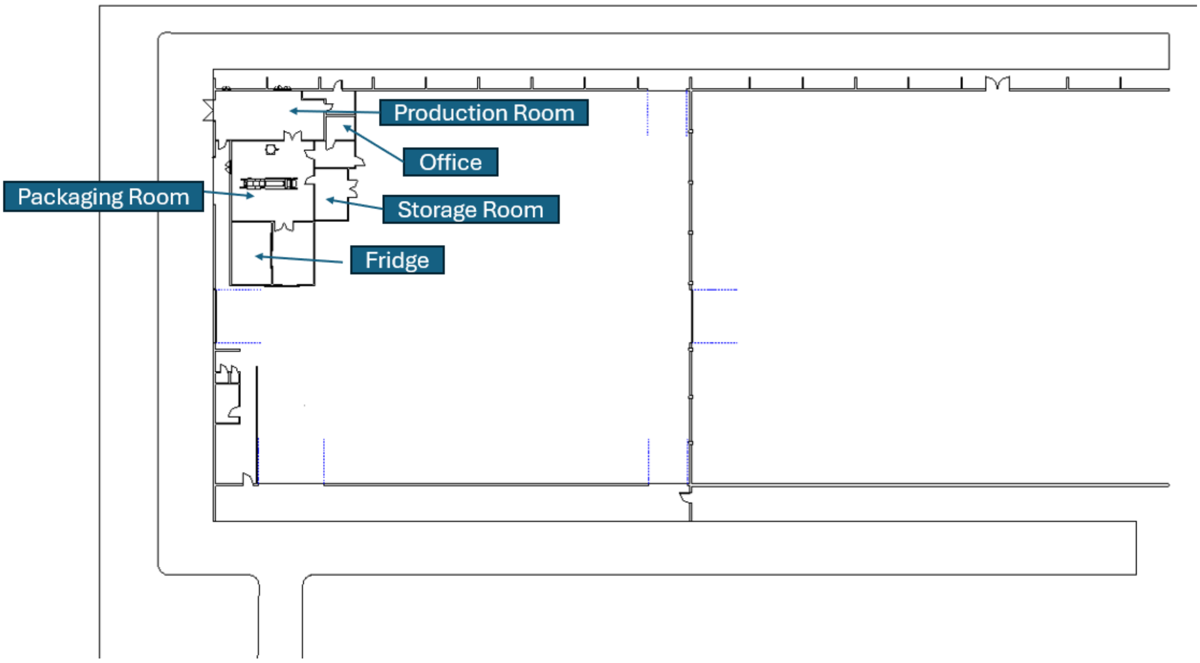

Figure 7*: Computer-aided drawing of the ground floor plan of the barn.*

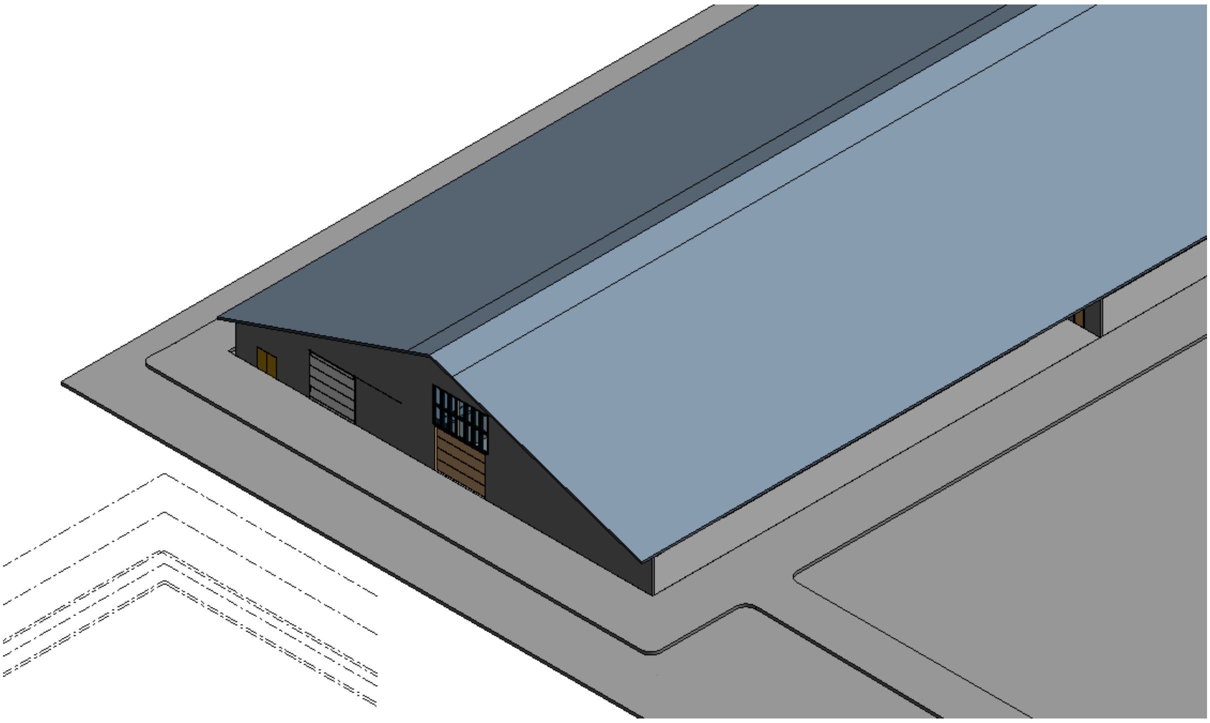

***Figure 8**: 3D model of the outside of the barn as modelled in Revit.*

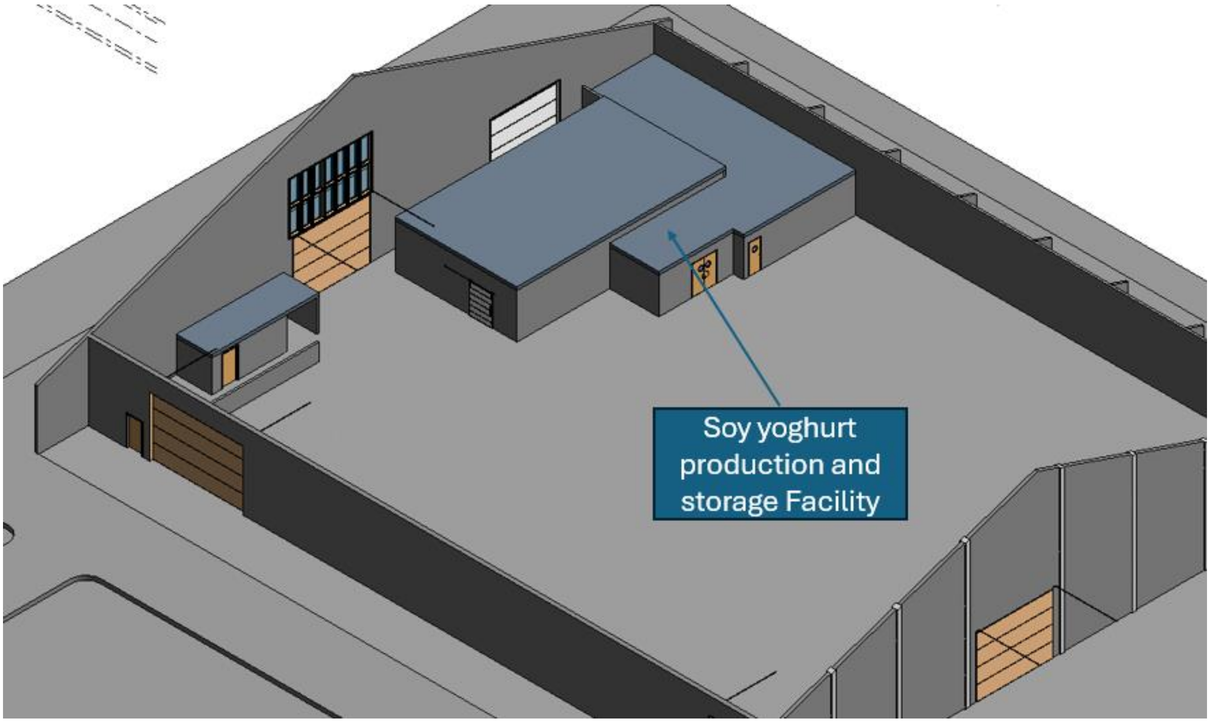

***Figure 9**: Spatial Layout of the inside of the barn (3D).*

5.3. Exporting to Unreal Engine and adding functionalities

After finishing the 3D model in Revit, Twin Motion was used to export it to Unreal Engine (UE). Twin motion was selected for this shift because of its user-friendliness. Updates are seamless because of the direct connection between Revit and Unreal Engine through Twin Motion; modifications made in the Revit model are immediately reflected in the Unreal Engine environment which makes the 3D model scalable. Because of its scalability, the Digital Twin is guaranteed to be accurate and up-to-date, allowing for continual modifications and enhancements as required. This method guaranteed precision and detail in the 3D environment while also streamlining the workflow. Furthermore, the attribute definitions in the requirement phase of the study were incorporated in Unreal Engine using C++ blueprints.

Improving the model's functionality and interactivity was the next step. Because of its advanced capabilities for simulating interactions, Unreal Engine was considered ideal for this task. A main character (MC) was introduced to enable walking or navigating through the entire farm's model, which was accomplished by building a blueprint in Unreal Engine. This gives the users a third-person view of the farm setting. The DT has some features that let people explore the farm and engage with various items. For example, the users can walk around the barn and modeled area, open doors, and retrieve information about packing and storing machinery. Interacting with the machine by clicking on the machine packaging and storing machinery would present details about the seven before mentioned attributes.

The main character in the Digital Twin environment navigates using the AWSD keys for movement, allowing the user to traverse the virtual soy farm effectively. Additionally, the camera perspective can be adjusted using the mouse, providing a view of the surroundings. This functionality has been implemented through a blueprint in Unreal Engine, ensuring a seamless and interactive user experience. The blueprint script defines the character's movement mechanics and camera controls, integrating user input to create a responsive navigation system within the digital representation of the farm.

During the export process into Unreal Engine through Twin motion, a problem with door pivots was identified. When working on a blueprint to open the doors the door's pivot position was placed in the wrong positions, the original Revit family was the source of this issue. In order to fix this operation, doors were regenerated, and their opening and closing mechanisms were fixed in Unreal Engine. When the user moves towards any door, a buffer around the main character interacts with the door and the door opens seamlessly.

Figure 10*: Main character inside barn.*

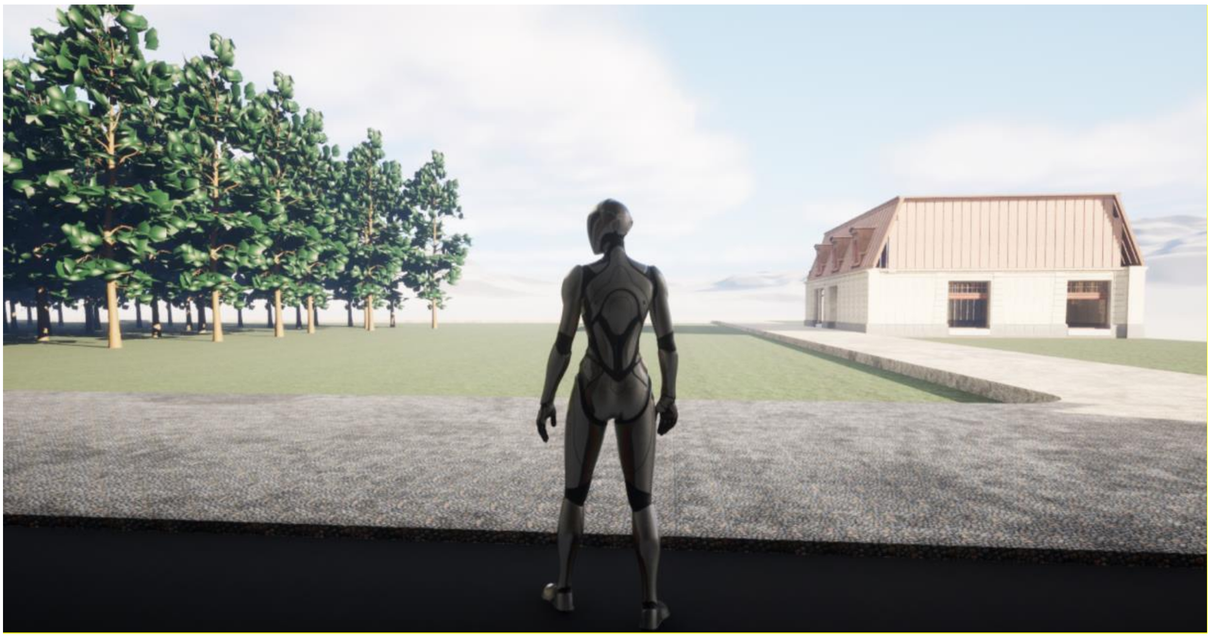

Figure 11: *Outside view of the farmer's house and a small forest area.*

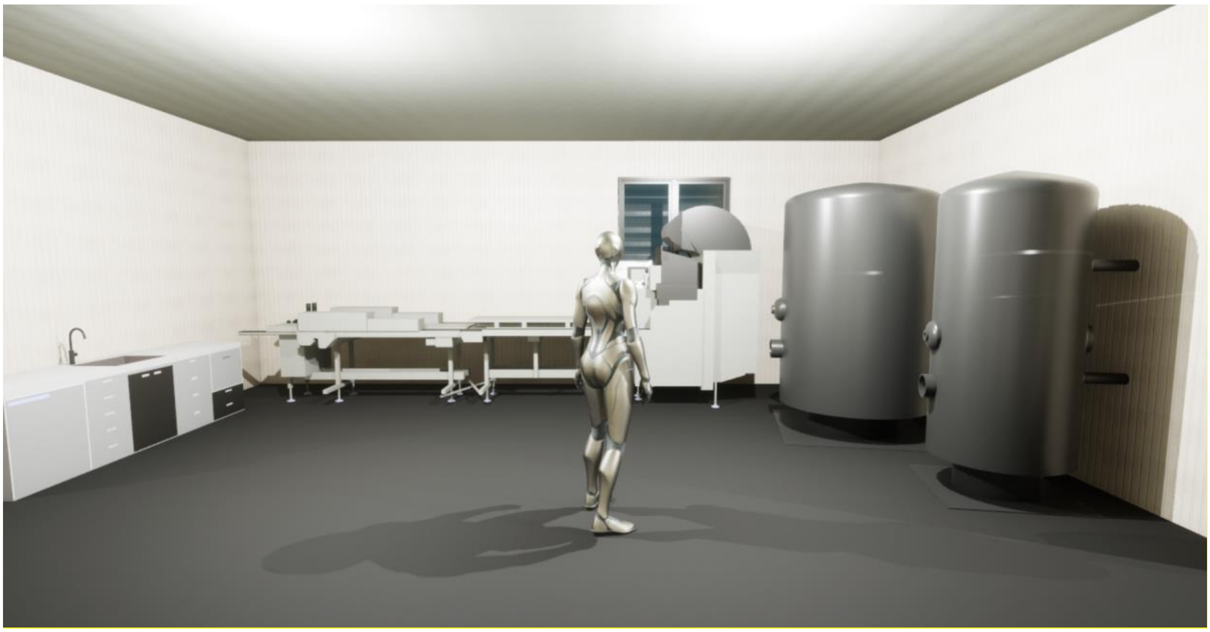

***Figure 12**: Packing room with 2 tanks 500m and 1000ml, Filling machine.*

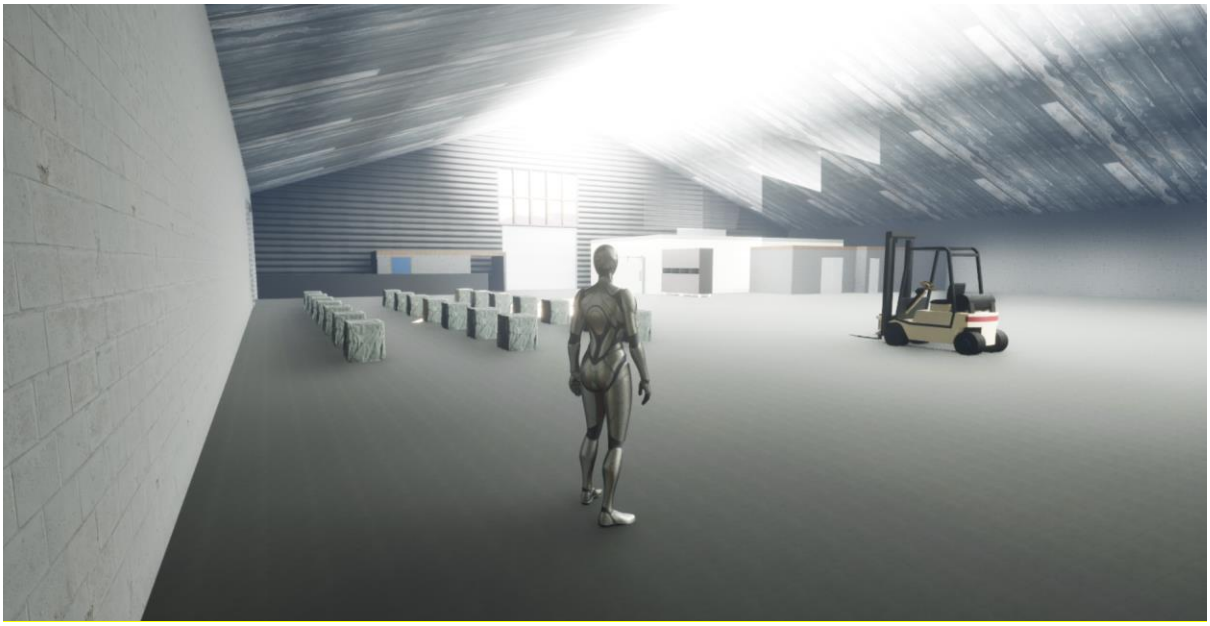

***Figure 13**: Inside of the barn with the soybean boxes and folk lift.*

To provide a better user experience, realistic textures and lighting were applied to the 3D model. To improve the Digital Twin's visual attractiveness and realism, this involved modifying the lighting to resemble interior lighting conditions of the barn and natural sunshine that was entering through the windows. Furthermore, props like machines and other farm equipment were added to different rooms. Taking reference from the visual media dataset, gear and equipment was precisely positioned inside the barn and its rooms. The open areas surrounding the house and barn were also modelled with props like grass, trees, and other natural elements to improve realism.

Quixel Bridge was used for texturing and props in Unreal Engine. Figure 14 shows the Quixel bridge dashboard. It is a powerful plugin and application designed for 3D content creators. It provides users with access to the extensive Mega Scans library, which includes high-quality 3D assets, textures, surfaces, and materials. With Quixel Bridge, users can seamlessly import these assets directly into Unreal Engine for immediate use. Figures 10, 11, 12, and 13 show the interior of the barn after adding the textures and

The use of Quixel Bridge significantly enhanced the workflow in Unreal Engine, particularly in the areas of texturing and material creation. The ease of access to a vast array of textures and surfaces allowed to quickly and efficiently apply them to the projects. This tool has been instrumental in enabling to create photorealistic and detailed environments, thereby elevating the quality of the 3D environment.

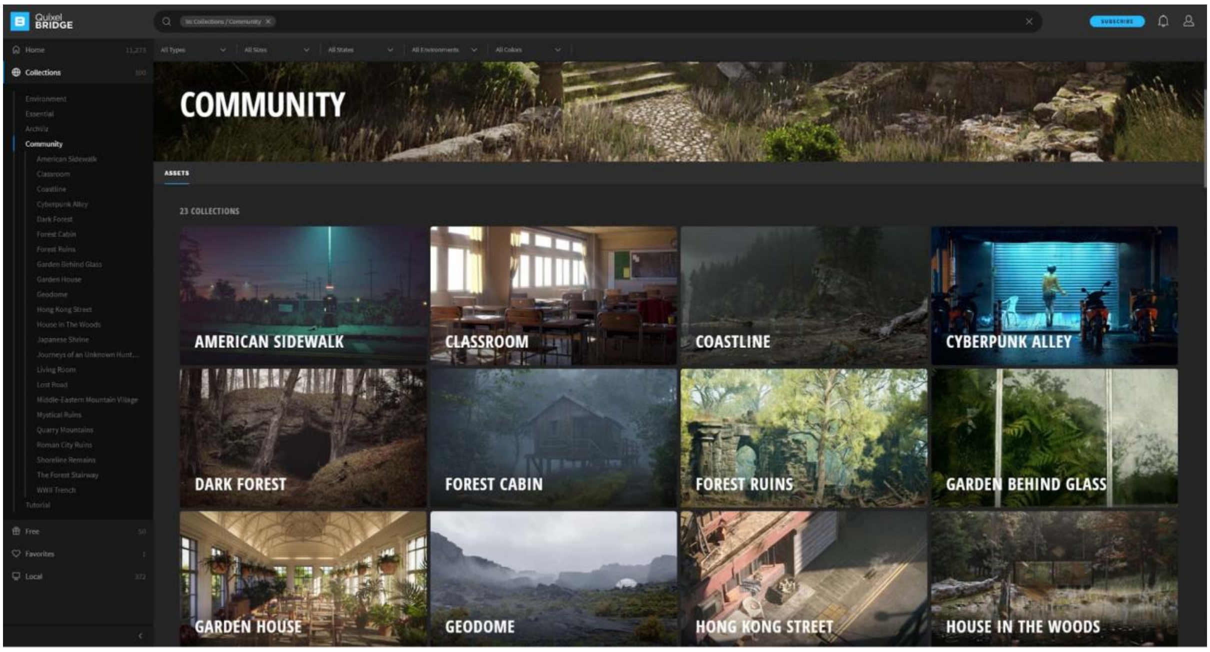

***Figure 14**: Quixel bridge library.*

Data visualization was integrated into the DT in the form of a dashboard, allowing users to visualize key attributes such as energy usage, man-hours required, production output, etc. to aid in decision-making during the packaging and storing of soy yogurt.

5.4. Data Visualization Approach

A key objective of this research involves using different types of approaches within the DT to visually represent data. Two types of visualizing techniques were developed, each employing different strategies for data representation- a text-based representation and a hybrid (combination of textual, graphical, and visual variables) representation. These versions visualize the same data but do so using different approaches. Each approach aimed to maximize efficiency by focusing on presenting only essential information for quick decision-making.

These data visualizations can be seen when interacting with the yogurt packaging machinery. A dashboard-like view pops up which gives the option to try out up to three different scenarios according to the user's requirements. Scenario A, Scenario B, and Scenario C are placed adjacent to each other which gives it its "dashboard-like view" (see Figure 15).

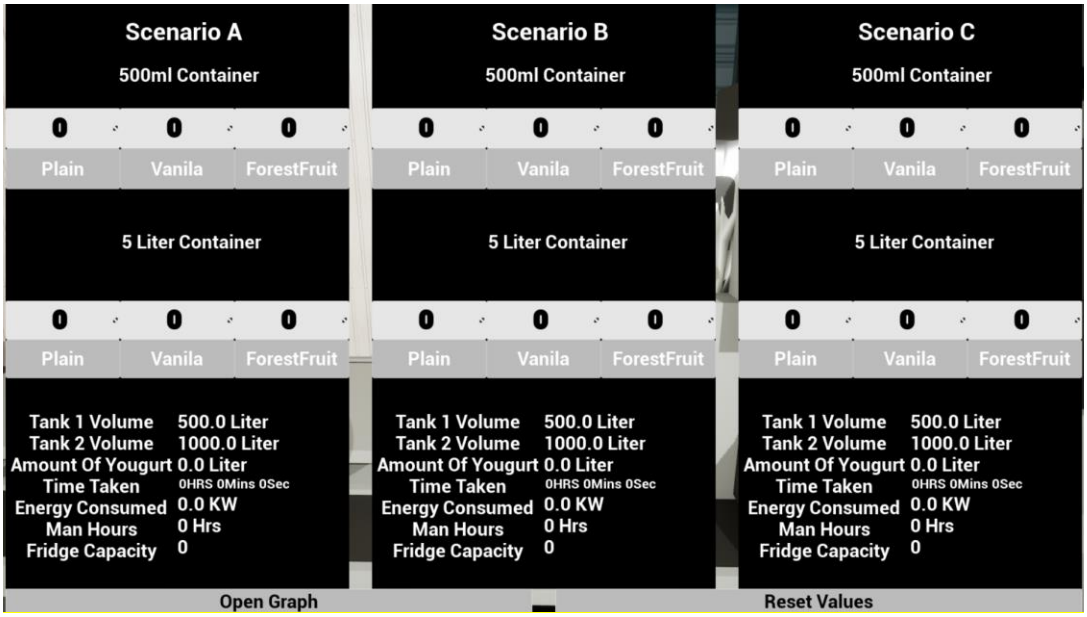

Figure 15*: Three Scenarios with text-based representation.*

This was done to improve user interaction and make it simpler to compare various operational scenarios. This method offers a straightforward interface that enables users to browse through data and make informed decisions simply by putting in some values. Moreover, two types of approaches were utilized for visualization of data to explore their impact on user experience.

5.4.1. Creating Three Scenarios

The creation of three scenarios (A, B, and C) within the Digital Twin (DT) model was intended to provide a tool for decision-making and operational planning for the farmer. These scenarios allow for the comparison of different operational strategies under various conditions, thereby offering a versatile approach to optimizing farm management.

The three scenarios are defined by production amounts of yoghurt which would affect the multiple attributes resulting in costs of time and money. The primary reason for developing multiple scenarios is to enable the farmer to evaluate the impact of different variables and operational decisions on the farm's productivity and efficiency. By comparing these scenarios side-by-side, the farmer can gain insights into the potential outcomes of different actions without having to implement changes in the real world first, which could be costly or disruptive.

5.4.2. Use Case Scenario

For instance, consider a use case where the farmer needs to decide the optimal packaging strategy based on the expected demand for different yogurt flavours. Scenario A could simulate a situation where there is a high demand for plain yogurt, Scenario B might represent a balanced demand across all three flavors (plain, vanilla, and forest fruit), and Scenario C could simulate a scenario with a high demand for flavored yogurts (vanilla and forest fruit). By comparing these scenarios, the farmer can determine the best approach to allocate resources, such as deciding how many containers of each size (500 ml and 5L) are needed and how much yogurt should be produced and stored for each flavor.

Consider a specific use case scenario where the farmer has received two distinct orders that need to be fulfilled. Scenario A represents fulfilling Order 1, which requires a specific quantity and type of yogurt packaging. Scenario B represents fulfilling Order 2, which has different requirements for yogurt packaging. Scenario C combines the requirements of both Order 1 and Order 2 to provide a comprehensive view of the combined operational demands.

Order 1 requires a high quantity of plain yogurt packaged in 500 ml containers. This scenario simulates the farm's operations focused solely on fulfilling this specific order, assessing the resources needed, production time, and storage requirements for plain yogurt in 500 ml containers.

Order 2 requires a mix of vanilla and forest fruit yogurt, primarily in 5L containers. This scenario evaluates the farm's operations dedicated to fulfilling this mixed flavour order, examining the production processes, energy consumption, and man-hours required to meet this demand.

Scenario C combines the requirements of both Order 1 and Order 2. This scenario helps the farmer understand the cumulative impact on the farm's resources and operations. By simulating the combined orders, the farmer can determine the total production volume, packaging needs, and storage requirements for all yogurt types and container sizes. This scenario also helps identify potential bottlenecks and resource constraints when fulfilling both orders simultaneously.

By comparing these three scenarios, the farmer can analyze the operational efficiency and resource allocation for each order individually and in combination. This comparison provides insights into how to optimize production schedules, manage inventory, and allocate labour effectively. Additionally, it allows the farmer to anticipate and mitigate any potential issues that may arise from fulfilling multiple orders concurrently.

5.4.3. Text-Based

The text-based representation is a crucial component of the Digital Twin (DT) system for the soy farm. This approach focuses on presenting data in a straightforward, textual format, making it easy for users to quickly read and understand the information. By providing clear, concise textual data, this method supports quick decision-making and efficient monitoring of the farm's operations. This format is particularly useful for users who prefer or require straightforward, numerical data without the need for visual aids. It supports quick assessments and decision-making by providing a direct view of the farm's operational status.

By using a text-based approach, the DT system accommodates different user preferences and needs. It complements the graphical and hybrid representations, offering a tool that enhances the overall user experience and ensures that critical information is easily accessible to all stakeholders. Figure 16 shows the text-based representation for the 3 scenarios.

***Figure 16**: Text-based representation.*

5.4.4. Visual Variable

To create an effective Digital Twin (DT) of a soy farm that produces yogurt, it is essential to choose appropriate graphic variables to represent information. These variables should be easy to understand and accurately represent the data collected from the farm. The concept of visual variables involves ways that a symbol can be modified to convey information (Roth, 2017b). These visual variables include location, size, shape, orientation, arrangement, texture, hue, value, saturation, transparency, crispness, and resolution.

The DT uses size, which refers to the dimensions of an element in the design. Size can be used to create emphasis, hierarchy, and balance. It effectively represents the quantity of various attributes, allowing users to easily interpret differences in magnitude. For example, larger bars in the bar graphs signify greater quantities, making it straightforward to compare the levels of different attributes.

The DT also employs the use of color hue, which describes the specific color of an element and represents categorical differences. Color hue is an effective way to differentiate between various scenarios because it is a non-ordered variable, meaning it does not imply any inherent order. This makes it ideal for representing distinct categories without suggesting any priority or sequence among them. By assigning different colors to scenarios A, B, and C, users can easily distinguish and compare the data associated with each scenario.

5.4.5. Hybrid Approach

The hybrid approach groups the seven attributes graphically using bar graphs to show the values of each attribute. Figure 17 shows the attributes using the hybrid approach. Bar graphs were specifically chosen because they are an effective means to represent discrete variables, which in this case include all seven attributes of the machinery. Bar graphs display categorical data by using bars of different lengths, which makes it easier to compare values across different categories or scenarios.

Three separate scenarios (A, B, and C) are indicated by various colors (hues) to make scenario comparison easier. For instance, the Tank 1 bar graph has three distinct bars, each of which represents a different scenario: Scenario A, Scenario B, and Scenario C. Every attribute—Tank 2, Amount of Yogurt, and so on—follows the same pattern. This method of data organization makes it simple for users to examine side-by-side the effects of each scenario on the different attributes to enhance clarity while allowing them to assess differences and make well-informed decisions.

For instance, when Tank 1 is full (500 L), the length of the bar graph will reach the top. Simultaneously, the amount of yogurt left in Tank 1 will also be written above the bar. The length of the bar graph will decrease accordingly to represent any reduction in the amount of yogurt. The bar graph will be half in size, for instance, if half of the yogurt has been consumed, meaning that there are 250 L of yogurt remaining in the tank. This visual representation through bar graphs allows for a quick and intuitive understanding of the data, making it an ideal choice for the DT.

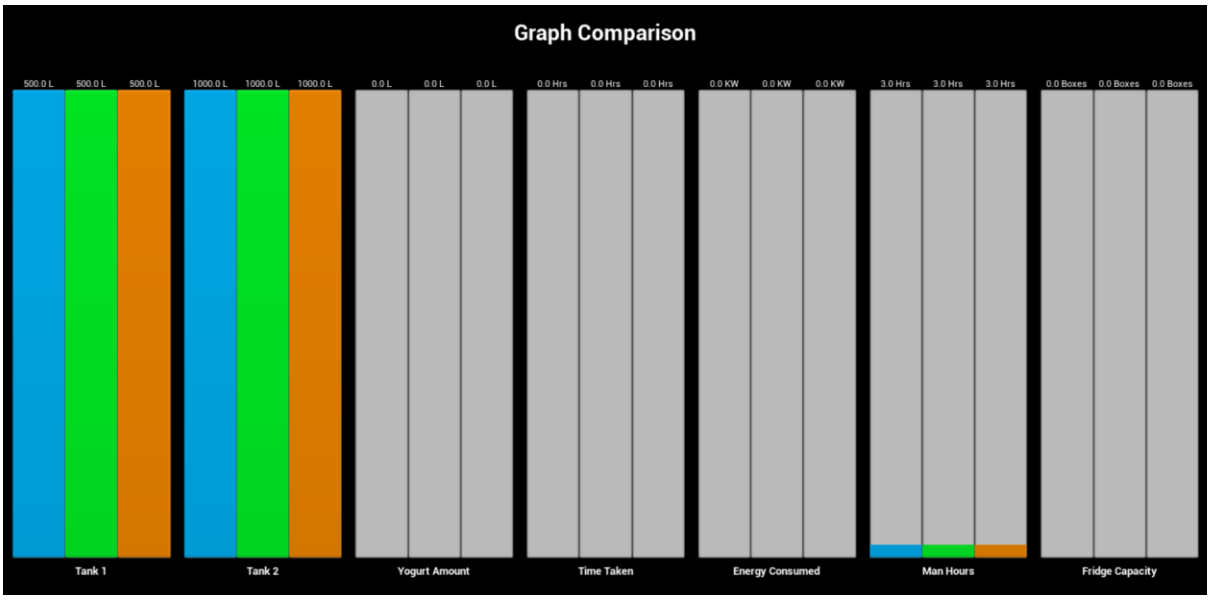

Figure 17*: Hybrid Approach showing the graphical representations of the attributes.*

5.5. User tasks:

The user tasks designed for this study aim to evaluate the effectiveness, efficiency, and user satisfaction of the Digital Twin (DT) in facilitating decision-making for farm managers. By engaging users in specific tasks, we can assess how well the DT's text-based and hybrid data representation approaches support various operational scenarios on a soy farm that produces yogurt. These tasks can aid in real-life decision-making processes, providing valuable insights into the usability and functionality of the DT.

The primary objectives of the user tasks are to assess data representation, evaluate decision-making support, and compare different scenarios. This involves determining how the text-based and hybrid approaches convey critical information, evaluating how the DT aids in making informed decisions regarding production, storage, and resource management, and comparing different operational scenarios to understand their impacts on attributes such as time, energy consumption, and storage capacity.

The tasks are designed with specific goals in mind. Task 01 involves locating the farmer’s house within the DT environment to familiarize users with navigating the interface. This initial task ensures users are comfortable with the DT and can easily find essential elements. Task 02 requires users to locate the filling machine and the two tanks, acquainting them with the core components involved in the yogurt production process. Understanding the location and function of key machinery is crucial for performing subsequent tasks effectively. (See Appendix B)

In Task 03 users were made to focus on the text and hybrid approaches, where users had to report the time required for a specific yogurt packaging order. This task evaluates how well the text-based and hybrid-based approach supports detailed operational planning and time estimation, addressing the research question regarding the usability of different data representation methods. Task 04 involves scenario analysis using both textual and hybrid approaches, where users compare different scenarios based on fridge capacity, yogurt production, energy consumption, and man hours. This helps determine which scenario fits within the available storage capacity, maximizes yogurt availability for future production, optimizes energy consumption during a subsidy period, and can be completed within the available man hours.

These tasks are designed to reflect real-world challenges faced by farm managers, such as balancing production demands with storage constraints, optimizing energy usage, and managing man-hours effectively. By performing these tasks, users can experience firsthand how the DT facilitates informed decision-making, addressing the core research question of how different data representation approaches impact the usability and functionality of a Digital Twin for a soy farm.

The user tasks help achieve several outcomes: validation of data representation methods, enhanced decision-making, and improved scenario planning. By comparing user performance and preferences between text-based and hybrid approaches, it can validate the best method for representing farm data. Insights gained from user interactions with the DT can lead to improved decision-making processes on the farm, highlighting the practical benefits of the DT. Additionally, the ability to compare different scenarios allows for better strategic planning and resource allocation, demonstrating the DT's capability to support complex operational decisions. These outcomes directly contribute to answering the research questions by providing empirical evidence on the effectiveness, efficiency, and user satisfaction of various data representation strategies within a Digital Twin framework.

5.6. Usability testing:

The major component of this research involves conducting a usability analysis to assess the effectiveness, efficiency, and satisfaction of the different approaches to data representation within the digital twin. This analysis aims to provide insights into the practical utility of the DT for farm management and decision-making. The tasks created in the previous step of the methodology serve as the basis for the usability testing (ISO 9241-11:1998).

Effectiveness of the DT is the accuracy with which users complete assigned tasks. This involves assessing the precision of their decisions and actions, considering the data representation method used in each version of the DT. Effectiveness serves as a key indicator of how well the DT supports farm management processes.

Efficiency is measured in terms of the time taken by users to complete the tasks. Comparing the efficiency of users across different versions of the DT determines if one representation method leads to faster and more efficient decision-making and task execution. This analysis provides insights into the practicality of each approach.

User satisfaction is evaluated through surveys and feedback forms. Participants provide feedback on their overall experience using the DT, including the ease of use, visual appeal, and realism of the representation. Additionally, qualitative feedback is gathered to understand user preferences and any specific advantages or disadvantages they perceive in the various versions of the DT.

5.6.1. Users:

The usability analysis involved a diverse group of participants, including the farm owner and colleagues at ITC. The inclusion of colleagues from ITC is justified by their familiarity with technology, despite their lack of farming knowledge. This provides a unique perspective on the usability of the DT from a technological standpoint. On the other hand, the farm owner or manager bring in-depth farming knowledge, although they may not be as familiar with advanced technological tools. This combination ensures an evaluation of the DT, incorporating both technological usability and practical farming applicability. Their feedback and performance data are analyzed to conclude the most effective, efficient, and user-friendly approach to data representation in the digital twin of the soy farm.

The usability testing was conducted with a group of 10 participants, comprising 9 individuals from ITC and 1 farmer. Although the sample size may seem small, it is considered adequate for usability testing according to several usability experts. Jakob Nielsen, a prominent usability consultant, argues that testing with just 5 users can uncover up to 85% of usability issues (Usability Study, 2018). Nielsen's research suggests that the first few users are likely to encounter most problems, making larger groups less efficient for initial testing phases. Including a participant from the target user group (a farmer) ensured that the DT system was evaluated from the perspective of its primary end-users, adding practical insights to the more technical perspectives provided by ITC professionals.

5.6.2. Usability Methods:

To evaluate the DT system multiple usability testing methods were employed. The primary methods included the talk-aloud protocol, survey forms, and eye-tracking. Each method provided different insights into aspects of user interaction with the system.

At the start of the usability test, each user was briefed about the research and its objectives. This included a brief explanation of the digital twin and the importance of their participation in the study. Additionally, the concept of the talk-aloud method was explained thoroughly to ensure users understood how to articulate their thoughts during the test. Necessary information about how to interact with the DT, including navigation and task completion, was provided. A consistent script was used for all participants to maintain uniformity and minimize bias in the instructions given. This script included explanations to ensure all participants had the same understanding and could perform the tasks effectively.

The talk-aloud protocol allowed participants to verbalize their thoughts and reactions while using the DT system, revealing immediate usability issues and cognitive processes. Survey forms were designed to gather structured feedback on user satisfaction, ease of use, and perceived utility, helping to quantify their preferences. Eye-tracking technology, specifically Tobii Pro Fusion, was used to analyze gaze patterns and visual attention, providing objective data on how users interact with the text-based and hybrid visualizations.

By integrating these diverse methods, an understanding of the DT system's usability was achieved, addressing both user feedback and performance. This approach ensures a thorough assessment of the system which would aid in determining the more user centric approach of visualization.

5.6.3. Survey:

A survey form was designed which aligned with the research questions. The primary goal of the survey was to gather qualitative and quantitative data from users to address specific aspects of the research, such as the effectiveness of text-based versus hybrid data visualizations and overall user experience with the DT system.

The survey form was crafted to ensure it covered all critical areas relevant to the study. It included a range of question types such as choice, scale (1-10), and open-ended questions. These questions were designed to extract feedback on various aspects of the DT, including ease of use, clarity of information, and overall satisfaction with both the text-based and hybrid visualization methods.

To facilitate easy access and efficient data collection, the survey was created using Microsoft Forms. Additionally, it provided the capability to visualize responses through built-in analytics tools, aiding in the initial stages of data analysis.

No personally identifiable information was collected except for the farmer because he is the main user. The respondents were assured that their answers would be used solely for research purposes. This was crucial in obtaining candid responses, particularly regarding any potential criticisms or suggestions for improvement.

In addition to the standard questions, the survey included sections for participants to provide open-ended feedback. This allowed users to express their thoughts in more detail and offer insights that might not have been captured through structured questions. The collected survey data was analyzed using Microsoft Excel. Graphs and Charts were made in Excel to further visualize the information.

5.6.4. Talk Aloud:

Observing users as they interact with the Digital Twin provides direct feedback on user interactions, task completion times, errors, and user satisfaction, offering insights into the system's usability. To complement the usability testing, the talk-aloud method is employed. This involves observing users as they interact with the digital twin while verbalizing their thoughts, actions, and decision-making processes. This method provides valuable insights into users' cognitive processes, revealing their expectations, frustrations, and understanding of the system. It helps vocalize the short-term memory of the user and provides qualitative data for analysis (Fox, 2015). The talk-aloud method is selected because it does not require probing users to answer questions by accessing their long-term memory (Fox, 2015). By articulating their thoughts, usability issues can be identified, such as confusing interfaces or unclear instructions, and users can provide feedback on their overall experience.

5.6.5. Eye-tracking

To assess user interactions of data visualization methods in the DT of the soy farm, we employed eye-tracking technology using Tobii Pro Fusion. This state-of-the-art eye tracker provides precise and comprehensive eye movement data, allowing us to understand how users interact with the DT and compare the effectiveness of text-based and hybrid data representations.

Tobii Pro Fusion is a high-performance, lightweight, and compact eye tracker designed for behavioural research and usability testing. This eye tracker was chosen because of its availability and because it offers a high sampling rate, capable of up to 250 Hz, ensuring detailed capture of eye movements. Its portability and compact design make it easy to transport and set up in the farmer's office. Additionally, it provides highly accurate and precise tracking data, essential for in-depth analysis of gaze patterns and user interactions.

Key Specifications of the hardware include:

- Sampling Rate: Up to 250 Hz.
- Accuracy: High precision in tracking gaze points.
- Portability: Lightweight and compact, easy to transport and set up.
- Calibration: Quick and user-friendly calibration process.
- Binocular Tracking: Simultaneous tracking of both eyes.
- Compatibility: Integration with Tobii Pro Lab for comprehensive analysis and visualization.

The eye-tracking procedure began with designing the project in Tobii Vision Pro. The objective was to create an experimental setup for testing user interactions with the DT. Tobii Pro Lab is an advanced software platform specifically designed for eye-tracking studies. It facilitates the design, execution, and analysis of eye-tracking experiments. Pro Lab allows researchers to efficiently capture and interpret eye movement data. It supports a variety of study designs, from simple gaze tracking to complex behavioral experiments. The software's capabilities include stimulus presentation, gaze mapping, and the generation of comprehensive visualizations such as heat maps and gaze plots. The integration of Tobii Pro Lab with Tobii Pro Fusion provides a seamless workflow for eye-tracking research. After collecting eye-tracking data with Pro Fusion, Pro Lab was used to process and analyze the data. The software offers powerful visualization tools, allowing for the creation of heat maps, which highlight areas of high visual attention. Gaze plots illustrate the sequence of fixations and saccades, providing insights into how users navigate through visual information. These visualizations are crucial for comparing different data representation methods in the DT and for understanding user behavior.

Tobii Pro Fusion recorded the users' eye movements throughout these sessions, capturing data on where and for how long they focused on different parts of the screen. The collected eye-tracking data was then analyzed to generate heat maps, visually representing the areas where users' gaze was most concentrated. Separate heat maps were created for text-based and hybrid visualizations. In addition to heat maps, gaze patterns were analyzed to understand the sequence and duration of users' eye movements across different elements of the DT interface. This analysis helped identify which areas drew the most attention and how users navigated through the information.

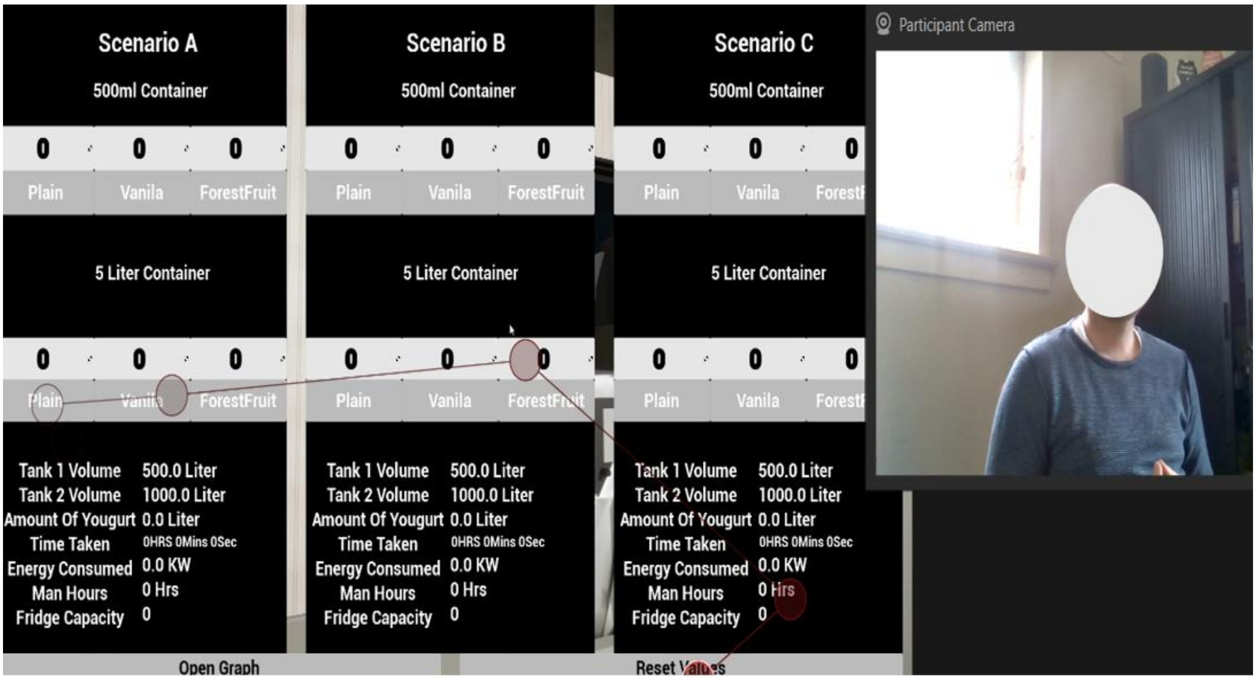

***Figure 18**: Gaze movement of farmers during usability testing.*

By integrating these diverse methods, the usability analysis provides an evaluation of the DT's effectiveness, efficiency, and user satisfaction, contributing to the optimization of digital twin technologies in agricultural settings.

5.7. Analysis of the results:

Upon completing the usability study, three types of data were gathered: eye-tracking data, talk-aloud sessions, and survey responses. For the eye-tracking component, ten videos were recorded for each participant as they interacted with the dashboard, segmented into intervals based on specific tasks. Intervals, marked by start and end events, were crucial for tracking and analyzing user interactions accurately (Tullis & Albert, 2008)

These intervals were used to create Times of Interest (TOI) in Tobii Pro Lab, which filtered the data to relevant segments. These TOI helped in making efficiency graphs for every task. Heat maps and other visualizations like scan paths were generated to observe user focus and interaction patterns. This method provided information on where users directed their attention during tasks.

Survey data, collected and analyzed using Excel, complemented the eye-tracking data. Charts and tables focused on usability, comparing performance between text-based and hybrid approaches. Survey results evaluated the dashboard's effectiveness in conveying information and recorded task completion times to assess efficiency.

Talk-aloud sessions provided qualitative insights, highlighting common themes such as challenges and suggestions for improvement. Notes from the talk-aloud session were made during the testing and from the recorded sessions. These qualitative data points were cross-referenced with eye-tracking and survey results to identify consistent user behaviors and preferences, thus validating the findings.

The combined use of eye-tracking, talk-aloud, and survey data offered an analysis of the dashboard's usability. Eye-tracking provided measures of user focus, while talk-aloud sessions offered qualitative feedback and surveys offered quantitative feedback. This multi-faceted approach confirmed user behaviors and preferences, enhancing the reliability of the study's conclusions.

6. Results and Discussion:

6.1. Efficiency results:

In this study, we aimed to evaluate the efficiency of users in completing tasks within a DT environment. The first two tasks were designed to test basic navigation and object identification skills. Task 01 required participants to locate the farmer's house, while Task 02 involved locating the filling machine and two tanks within the farmer’s house. Everyone started at the same location in the 3D environment.

The results of these tasks, as illustrated in the "Farm Exploration" graph in Figure 19, reveal notable variations in the time taken by each participant to complete the tasks. For Task 01, the time taken by users varied from 1.28 to 1.4 minutes, with the farmer completing the task in approximately 1.35 minutes. User 7 took the longest time (1.4 minutes) to locate the farmer's house, while the farmer was the quickest, taking just 1.25 minutes.

In Task 02, the time required to locate the filling machine and the two tanks showed a similar range, but with generally shorter completion times. User 1 took the longest time (1.5 minutes), while user 5 completed the task in the shortest time (1.28 minutes). Notably, the farmer completed this task in about 1.25 minutes, slightly quicker than the average participant.

Overall, the data indicates that while there is some variability in task completion times among different users, most participants were able to complete both tasks in a relatively short amount of time, demonstrating a reasonable level of efficiency in navigating and identifying key components within the 3D DT environment.

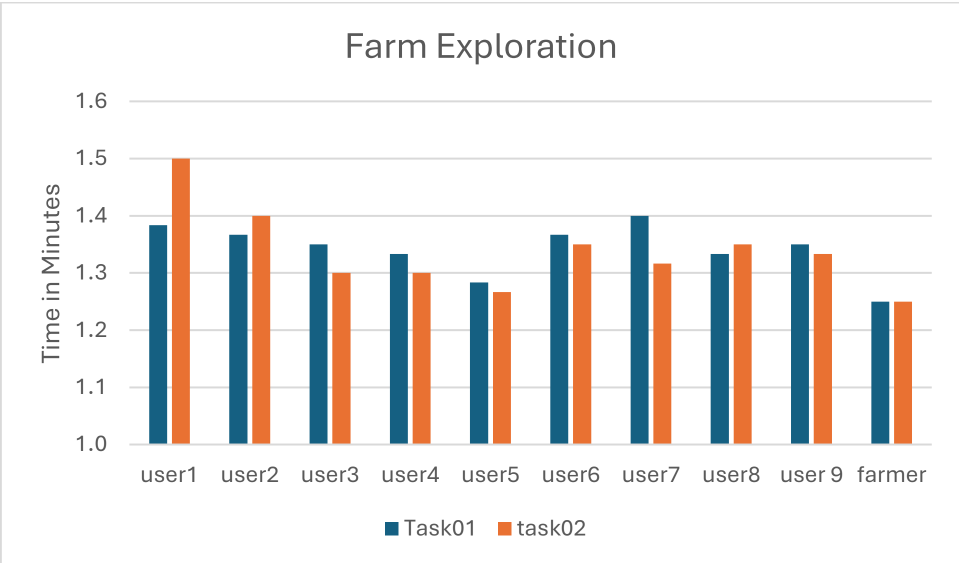

Figure 19*: Efficiency graph of farm exploration tasks (task 01 and task 02).*

The efficiency results show a clear pattern: participants, including the farmer, were able to navigate the DT environment and locate specific objects with relative ease. The farmer's performance, in particular, was slightly faster than most other participants for both tasks, likely due to his prior knowledge and familiarity with the farm layout. This prior knowledge likely contributed to the farmer's ability to quickly identify and locate the necessary items, thereby completing the tasks more efficiently.

For other users, the variability in task completion times can be attributed to several factors, including their individual familiarity with digital environments, their ability to quickly interpret and navigate the DT interface, and their general spatial awareness. The fact that users were able to complete these tasks in a relatively short time frame suggests that the DT environment is designed in a user-friendly manner, facilitating efficient exploration and task completion.

These findings underscore the importance of user familiarity with the environment in determining task efficiency. While the farmer's innate knowledge of the farm provided him with an advantage, other users' performance indicates that the DT system is accessible and intuitive enough to support effective navigation and task execution even for those less familiar with the physical farm layout.

The analysis of the efficiency of users interacting with text-based and hybrid approaches as shown in Figure 20 reveals several insights. For the task requiring participants to determine the time taken for the task using textual information (Text a) (Available in Appendix), ITC users took an average of approx. 2.0 minutes, whereas the farmer took longer, approx. 2.5 minutes. This indicates a challenge for the farmer in processing textual data as efficiently as ITC users. In the hybrid approach (Hybrid a), participants needed to determine the time taken for the task using a combination of text and visual aids. ITC users completed the task in an average of 1.5 minutes, while the farmer took 1.6 minutes, demonstrating that the hybrid method aids in faster comprehension for both groups.

When selecting a suitable scenario given a fridge capacity of 150 boxes with 25 boxes already present (Text b), ITC users completed the task in an average of 1.2 minutes, while the farmer took 1.45 minutes, highlighting the farmer’s slower performance with information technology. For the task requiring the selection of a scenario where 500L of yogurt would be produced the next day, ensuring maximum yogurt remains in the tank (Text c), ITC users took an average of 1.48 minutes, while the farmer took 1.5 minutes, indicating a similar level of difficulty for both groups with textual information.

For the task with a government subsidy on energy, requiring the selection of a scenario with maximum energy consumption using the hybrid approach (Hybrid b), ITC users completed the task in 1.5 minutes on average, while the farmer took 1.3 minutes. This again demonstrated that the hybrid method facilitated quicker decision-making for both groups, with the farmer showing significant improvement. Lastly, for the task requiring the selection of a scenario where two employees could finish within 7 hours using the hybrid approach (Hybrid c), ITC users took an average of 1.8 minutes, while the farmer took 2.1 minutes, suggesting some complexity in this task even with the hybrid method.

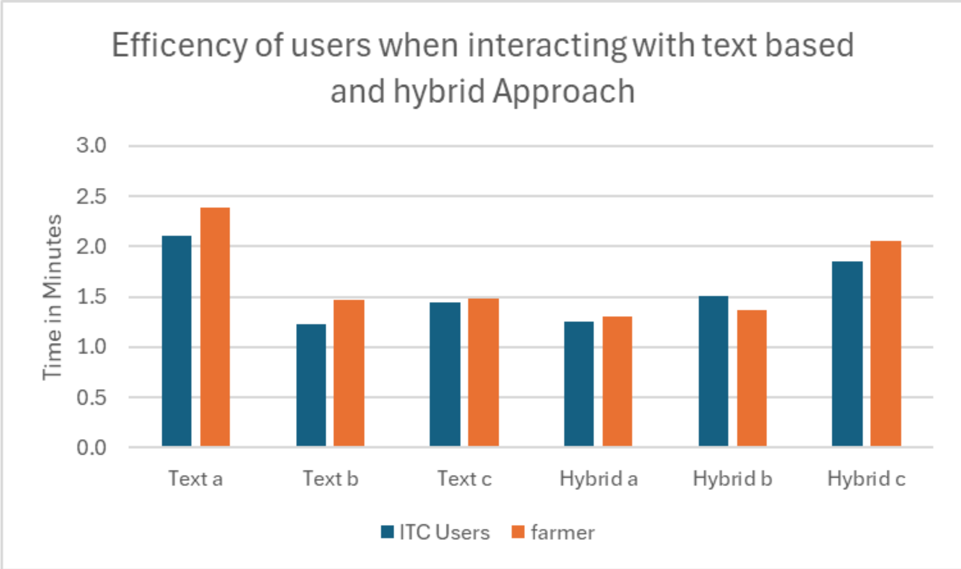

***Figure 20**: Efficiency graph of a user across each task related to text and hybrid approach.*

The hybrid approach consistently resulted in faster or similar task completion times compared to the text-based method, indicating that the visual aids provided by the hybrid approach enhanced the comprehensibility and accessibility of the information. The farmer took noticeably longer with the text-based approach in tasks such as determining suitable scenarios based on the time taken (Text a), fridge capacity (Text b), and maximum yogurt production (Text c). However, the performance gap narrowed with the hybrid method, as seen in tasks Hybrid b and Hybrid c, where the time taken by the farmer was closer to that of the ITC users.

The farmer's familiarity with the farm layout and processes could explain some of the observed performance patterns. The farmer's prior knowledge likely contributed to relatively better performance in farm-related decisions. Nevertheless, the design and data presentation of digital tools play a crucial role in efficiency. The hybrid approach's combination of text and visual aids appears to mitigate the limitations posed by purely textual data, particularly for users less experienced with digital data interpretation.

While the hybrid approach offers a clear advantage in terms of user efficiency and ease of understanding, it is also important to note the need for intuitive design and clear labelling within these tools. The missing elements, such as legends or titles for bars, were noted as limitations in the hybrid approach by the ITC users, suggesting areas for improvement. This suggests that optimizing digital twin systems with a focus on user-friendly hybrid visualizations can significantly enhance their usability and effectiveness in various agricultural settings.

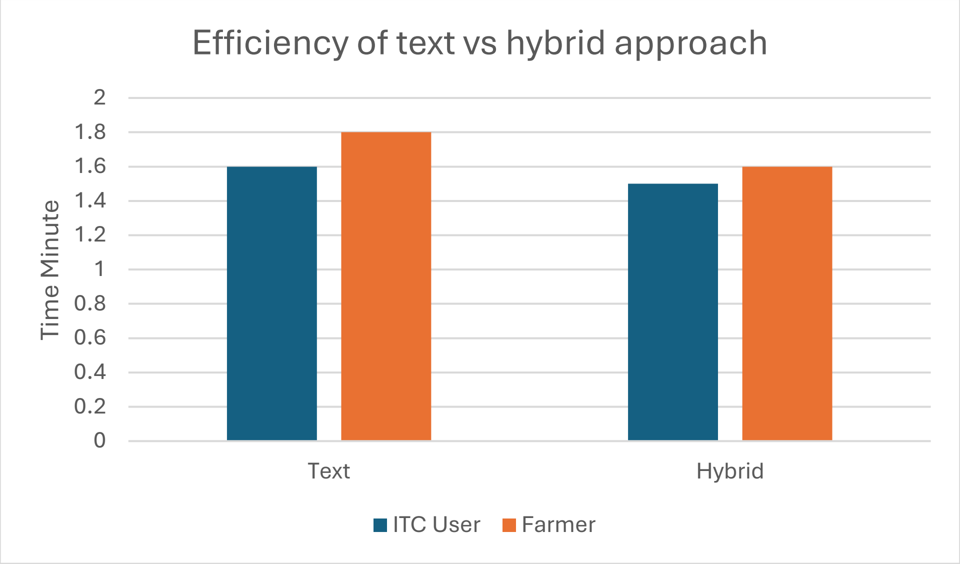

Figure 21: *Efficiency of text vs hybrid graph for farmer and ITC users (average across all tasks).*

The comparison of efficiency between text-based and hybrid approaches for ITC users and the farmer reveals notable differences (see Figure 21). For tasks using the text-based approach, ITC users took an average of 1.6 minutes, while the farmer took longer, with an average of 1.8 minutes. This indicates a slower performance by the farmer when interpreting textual information alone. On the other hand, the hybrid approach showed improved efficiency for both groups. ITC users completed tasks in an average of 1.4 minutes, and the farmer took 1.5 minutes. The reduction in time required for the hybrid approach suggests that the inclusion of visual aids significantly enhances the understanding and speed of task completion for both groups. Furthermore, it can be noted that the difference in efficiency between the ITC user and farmer also decreased from 0.2 minutes in textual information to 0.1 minutes in the hybrid approach.

The results indicate that the hybrid approach is more efficient than the text-based approach for both ITC users and the farmer. The hybrid method, which combines text with visual aids, seems to facilitate quicker comprehension and decision-making. The farmer's slower performance with the text-based approach can be attributed to several factors. Firstly, the farmer may not be as accustomed to processing purely textual data compared to ITC users who are likely more experienced with such formats due to their background.

The visual aids in the hybrid approach appear to bridge this gap by providing an intuitive way to interpret data. This is evident from the reduced time taken by the farmer in the hybrid approach compared to the text-based approach. The graphical elements likely help in quickly identifying key information and trends, which can be more challenging to discern from text alone.

Furthermore, the farmer's familiarity with the farm layout and processes could also play a role in the efficiency observed with the hybrid approach. Visual representations of familiar contexts may resonate better with the farmer's practical experience, allowing for faster and more accurate interpretations.

The slight efficiency gap between ITC users and the farmer even with the hybrid approach suggests that while visual aids significantly improve comprehension, there might still be a need for additional training or more intuitive design elements tailored specifically for users with varying levels of digital interaction. Ensuring that graphs and visual aids are clearly labeled and easy to understand can further enhance the effectiveness of the hybrid approach.

The think-aloud protocol and user feedback collected after the tests provided additional insights into the user experience with the different visualization approaches. Out of 10, eight users expressed that the hybrid approach allowed them to compare different data points quickly and easily. They mentioned that the visual nature of the hybrid method enabled them to grasp the information immediately, without having to read through extensive text.

In contrast, users reported that the text-based approach required them to spend more time looking at and reading the information. They found it more challenging to compare different data points efficiently, as they had to read through each piece of text carefully to understand the data.

In conclusion, the hybrid approach proves to be a more efficient method for representing complex information, particularly for individuals who may not be as proficient with text-based data. This finding underscores the importance of integrating visual aids in digital tools designed for diverse user groups, ensuring that all users can access and interpret information effectively.

6.2. Effectiveness:

The graph in Figure 22 illustrates the effectiveness of text versus hybrid visualization approaches among users, including ITC users and a farmer. All participants accurately performed all the tasks assigned to them, indicating a certain level of effectiveness. However, to understand the extent of the effectiveness, survey forms were analyzed. Participants rated the effectiveness of each visualization method on a scale from 1 to 10. For the text visualization approach, most users scored it between 7 and 9, indicating a high level of effectiveness. However, there was notable variation, with some users rating it as low as 6. This variation suggests that while the text approach is generally effective, it may not be equally effective to all users.

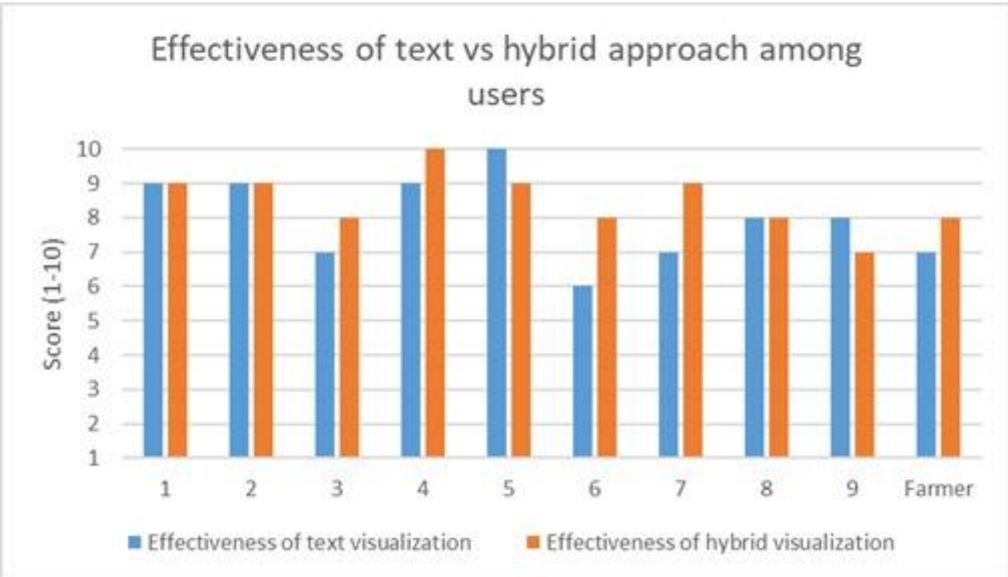

Figure 22: *Effectiveness rating of users across.*

On the other hand, the hybrid visualization approach received consistently higher scores. Most participants rated it between 8 and 10, highlighting its higher effectiveness in conveying information. Notably, the farmer also rated the hybrid approach higher than the text approach, reflecting a broader trend among users. Specifically, the farmer rated the hybrid approach with a score of 9, compared to a score of 7 for the text-based method.

Among the ITC users, the scores for the text approach varied slightly, with some users rating it as low as 6 and others as high as 10. In contrast, the scores for the hybrid approach were consistently high, with several ITC users rating it a perfect 10. This consistency indicates a strong preference for the hybrid method among ITC users, likely due to its enhanced clarity and ease of use.

Overall, the average effectiveness score for the text approach was around 8, while the hybrid approach averaged approximately 8.5. This difference underscores the perceived advantages of combining text with visual aids, which help users better understand and interpret complex data.

However, it is noteworthy that in some cases, the user satisfaction scores for the text-based approach were higher. For instance, User 5 showed a higher satisfaction with the text-based visualization compared to the hybrid method. According to User 5's feedback on the survey form, they found reading the text-based information easier and simpler, which contributed to their higher rating for this approach. Despite these individual variations, the overall trend indicates a strong preference for the hybrid approach.

Interestingly, Users 1 and 2 rated both visualization approaches equally in terms of effectiveness. This indicates that for these users, both the text-based and hybrid methods provided a similar level of usability and efficiency. Their neutral stance suggests that they found both approaches equally beneficial for different reasons, possibly appreciating the detailed information in the text-based approach and the intuitive visual comparisons in the hybrid approach.

The results suggest that users generally find the hybrid visualization approach more effective than the text-based approach. The higher scores for the hybrid method can be attributed to several factors. Firstly, the hybrid approach combines textual data with visual aids, making it easier for users to comprehend complex information quickly. Visual aids, such as graphs and charts, help in identifying patterns and trends that might be less obvious in text-based data.

The slight variation in the effectiveness ratings for the text approach highlights individual differences in data interpretation skills. ITC users showed a clear preference for the hybrid approach. This preference indicates that while text-based data is useful, the addition of visual elements significantly enhances understanding and usability.

For the farmer, the difference in scores between the text and hybrid approaches is interesting. As the farmer rated the hybrid approach significantly higher, reflecting the increased accessibility and ease of use provided by visual aids. This supports the idea that users with less experience in handling text-based data can benefit greatly from hybrid visualizations. The overall trend of higher effectiveness ratings for the hybrid approach underscores the importance of using diverse data representation methods in digital tools.

The results indicate that the hybrid approach is particularly beneficial in contexts where quick comprehension and decision-making are crucial. The visual elements help users to quickly grasp key information without having to read through extensive text. This is particularly advantageous in high-pressure environments or situations where time is of the essence.

6.2.1.Eye Tracking:

The gaze fixation heat map in Figure 23 illustrates where users concentrated their attention while interacting with the three different scenarios (A, B, and C) within the DT environment. All the gaze fixation heat maps for the study were generated as an aggregate for all the users. In Scenario A, there is a high concentration of fixations, particularly around the areas displaying "Tank 1 Volume," "Tank 2 Volume," and "Man Hours." This suggests that users spent more time interpreting information in Scenario A compared to the other scenarios. Scenario B shows a moderate level of fixation, with users focusing on similar elements but with less intensity than in Scenario A. Scenario C, on the other hand, has the least concentration of fixations, indicating that users found that every scenario was indicating the same information. This heat map was generated when the user first viewed the 3 scenarios. The heat map for gaze fixation was generated as an aggregate for all the users.

__Figure 23__: Gaze fixation results when the users first saw the 3 scenarios.

It is also important to note that all three scenarios presented the same information. This could explain why users focused heavily on Scenario A initially, spending more time to understand the data. Once they grasped the structure and content of Scenario A, they likely found it easier to interpret Scenarios B and C with less attention, leading to fewer fixations in those scenarios. This behaviour suggests that once users become familiar with the format and content, their efficiency in processing similar information increases, reducing the need for prolonged focus on subsequent scenarios.

The gaze fixation heat map in Figure 24 demonstrates how users interacted with the three different scenarios (A, B, and C) when tasked with determining the fridge capacity. In Scenario A, the users' focus is highly concentrated around the "Fridge Capacity" value, which is 140. This indicates that users spent significant time verifying the fridge capacity in this scenario. In contrast, Scenario B and Scenario C show more spread-out eye fixations. The fridge capacity in both these scenarios is 119, and users' attention was not only focused on this value but also spread out across other parts of the display.

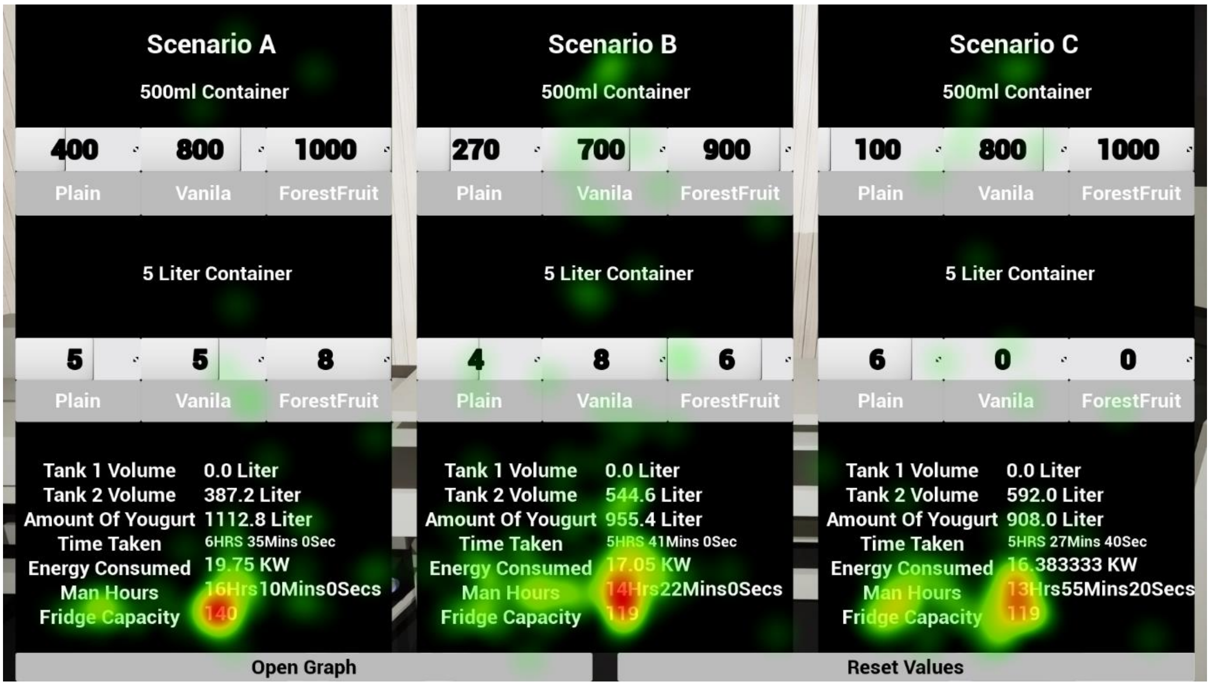

Figure 24*: Gaze fixation of users when performing task related to fridge capacity.*

This spread of fixation in Scenarios B and C suggests that users were checking additional information to ensure they were answering the task correctly. Given that the correct answer to the task was found in both Scenario B and C, users were likely verifying multiple data points to confirm their decision, leading to a broader distribution of their attention. This indicates that while users concentrated heavily on the fridge capacity in Scenario A, they engaged with more elements in Scenarios B and C to arrive at the correct answer.

The heat map analysis provides valuable insights into the effectiveness of the visual presentation of fridge capacity across the three scenarios. The intense focus on Scenario A indicates that users primarily concentrated on the fridge capacity value, which was incorrect for the given task. This could be due to the users quickly identifying that the fridge capacity in Scenario A was not the correct option and therefore not needing to check additional information.

In Scenarios B and C, the more spread-out fixation patterns suggest that users were engaging with multiple pieces of information. This broader distribution of attention likely reflects the users' efforts to ensure accuracy in their responses, given that the correct answer to the fridge capacity task was in these scenarios. Users were not only looking at the fridge capacity value but also comparing it with other relevant data points to confirm their answers. This behaviour highlights how users interact with data sets, validating their decisions by cross-referencing multiple information sources.

The overall pattern of gaze fixations suggests that users were more thorough in Scenarios B and C, as they needed to confirm the correct fridge capacity and verify their decision with other related information. This approach in Scenarios B and C indicates a more effective engagement with the data, leading to the correct answers.

Furthermore, the heat map reveals that while the fridge capacity information was quickly accessed in Scenario A, it was not the correct answer, leading users to spend less time on other elements. Scenarios B and C, with their correct fridge capacities, prompted users to spread their attention more evenly across the information provided, ensuring a more accurate and well-informed decision. These findings highlight the importance of clear and intuitive information presentation in digital twin systems to enhance user effectiveness and reduce cognitive load.

Moreover, the heat map shows the areas of user attention within a certain time period which is defined by the length of the task. This information is helpful, but the sequence of fixations can only be guessed and not told with certainty. The gaze sequence map in Figure 25 shows the exact sequence of one user's gaze. The image shows the user's gaze starting from number 1 in scenario B then going to scenario A fridge capacity and moving to scenario B and then scenario C fridge capacity. Since the right answer to this task is either scenario B or C user's gaze returns to scenario B. This method tells the exact sequence of gaze movement but fails to tell the whole story because it is within a very short time and the gaze can go back to scenario A or scenario C. Hence it is important to note the limitations of using gaze sequence and gaze fixation heat map. This study utilizes the use of gaze fixation heat map as it can be analyzed for the complete duration of the task.

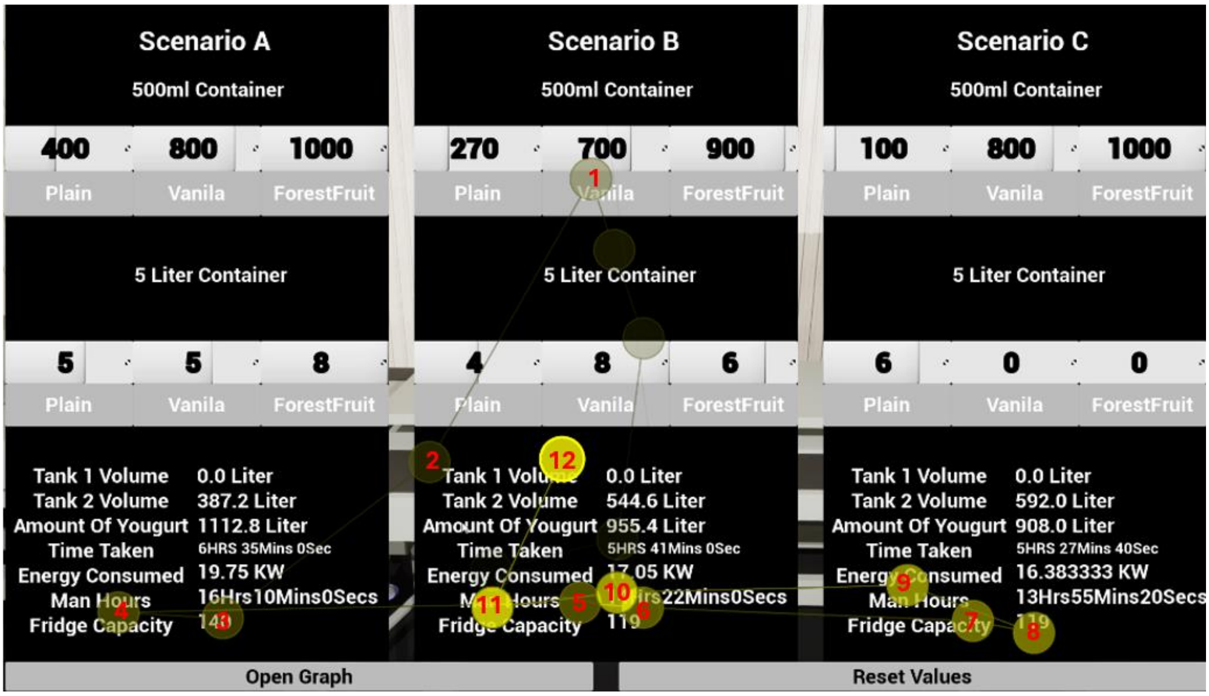

Figure 25: Gaze sequence of a single user for fridge capacity task.

Similar to the previous results, the eye fixation heat map in Figure 26 for this task shows how users interacted with the three different scenarios (A, B, and C) when tasked with determining the maximum amount of yogurt left for packaging. The correct answer to this task was Scenario C. The heat map reveals that users have focused on "Tank 2 Volume" and "Amount of Yoghurt" to determine the amount of yogurt left for packaging.

Figure 26*: Gaze fixation of users when performing task related to Tank 02 volume.*

In Scenario A, the users' focus is highly concentrated around "Tank 2 Volume" and “Amount of yoghurt” suggesting that users correctly identified two variables which were relevant but did so by first going through the names of all the attributes and determining which attribute would answer their question. In Scenario B and C users' fixations are more spread out, showing attention to multiple elements, including "Tank 2 Volume" and "Amount of Yogurt." This spread of fixation suggests users were checking additional information, likely due to confusion about the task requirements or they were confused as to which of this attribute was the correct one.

The intense focus on "Tank 2 Volume" and “Amount of yoghurt” indicates that users identified a key data point but failed to use it effectively, potentially due to misinterpretation of the task requirements or confusion between "Amount of Yogurt" and the actual yogurt left in the tank.

In Scenario B and C, the more spread-out fixation patterns suggest users were engaging with multiple pieces of information, including "Tank 2 Volume" and "Amount of Yogurt." This broader distribution of attention likely reflects the users' efforts to ensure accuracy in their responses, despite some confusion about the task.

The users' confusion about the "Amount of Yogurt" field indicates a limitation in the design, as the attribute descriptions were not included in the visualization. This lack of clarity could have led users to misinterpret the field as the amount of yogurt left in the tank rather than the total amount of yoghurt produced.

The confusion observed highlights the need for clearer attribute descriptions in the visualization design to enhance user understanding and effectiveness. These findings underscore the importance of clear and intuitive information presentation in digital twin systems to reduce cognitive load and improve decision-making accuracy.

The gaze fixation heat map in Figure 27 shows how users interacted with the hybrid approach interface when tasked with determining the maximum energy consumption scenario. The heat map indicates that users first directed their attention to the bottom of the graph to read the attribute names. This initial step is evident from the gaze fixations concentrated at the lower part of the graph. However, it is important to note that the heatmap doesn't tell us when fixations happened.

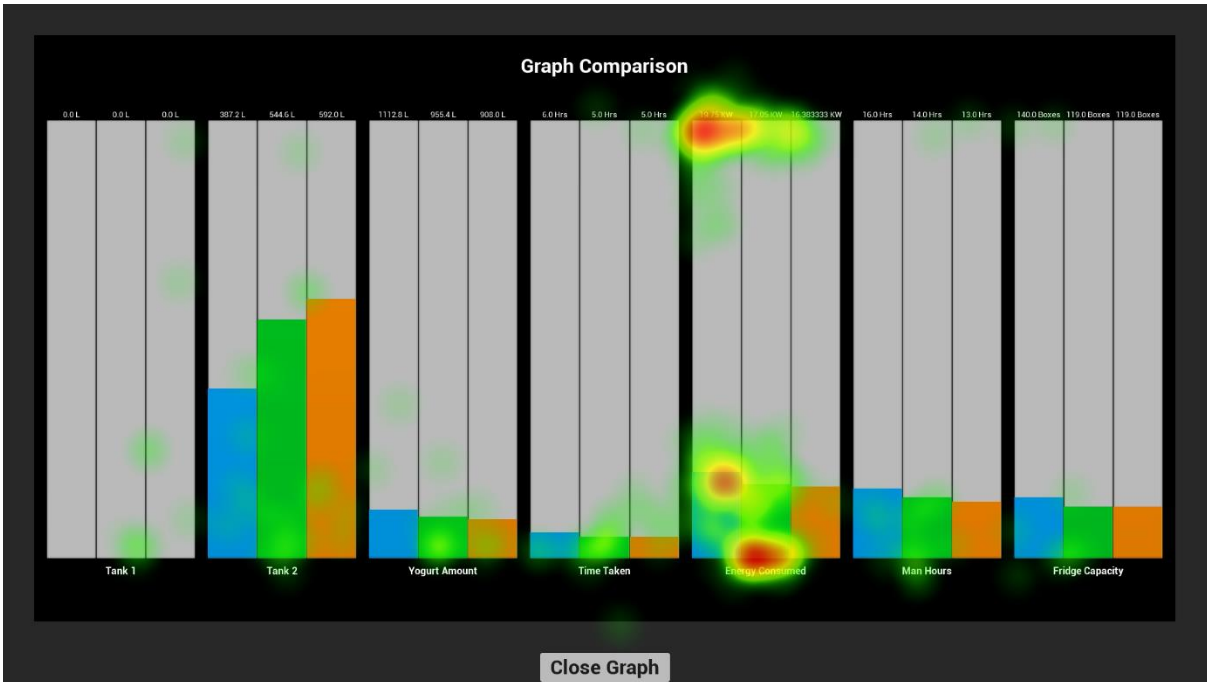

Figure 27*: Gaze fixation of users when performing task related to Energy consumption.*

Once users identified the "Energy Consumed" attribute, their attention shifted to the corresponding bars. The heat map shows intense fixations around the bars representing energy consumption, with a particular focus on the highest bar, which corresponded to Scenario A. Users then read the value at the top of the bar to confirm that Scenario A had the maximum energy consumption. This sequence of actions allowed users to identify the scenario effectively and efficiently with the highest energy consumption. Another possible reason for the focus on the values at the top might be due that the user's found the font size to be small.

The users' initial focus on the attribute names at the bottom of the graph indicates that they were methodically identifying the relevant data points. This behaviour suggests that the users were effectively using the interface to locate the information needed to complete the task. The concentrated fixations on the highest bar indicate that users quickly and accurately identified. The subsequent fixations at the top of the bar, where the value is displayed, confirm that users were verifying their findings to ensure accuracy.

The users' ability to quickly identify and verify the highest energy consumption scenario highlights the interface's effectiveness in presenting complex data in an accessible and user-friendly manner. However, the users also indicated through survey form and talk aloud that they were initially confused as to what did the colours in the graph represented, which were the scenarios. This posed a limitation in the approach which could be made better with inclusion of legend depicting what each colour showed or the bars can be labelled (A, B, C).

The gaze fixation heat map in Figure 28 for this task shows how users interacted with the graph comparison interface when tasked with determining the scenario that would complete within the given time based on man hours. The correct answer for this task was Scenario B. The heat map indicates that users initially directed their attention to the bottom of the graph to read the attribute name "Man hours", as seen from the eye fixations concentrated at the lower part of the graph.

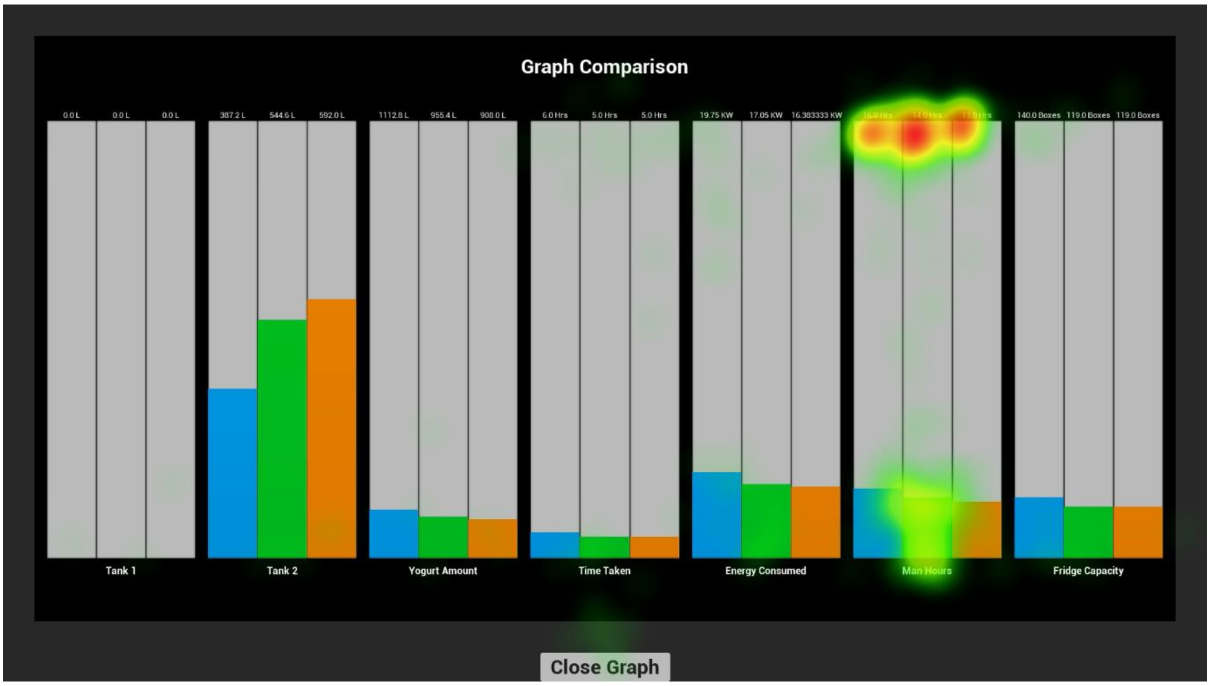

Figure 28*: Gaze fixation of users when performing task related to Man hours.*

Once users identified the "Man Hours" attribute, their attention shifted to the corresponding bars. The heat map shows intense fixations around the bars representing man hours, with a particular focus on the bar for Scenario B. Users then read the value at the top of the bar to confirm that Scenario B had the appropriate man hours that met the task's requirements. This sequence of actions allowed users to identify Scenario B as the scenario that would complete within the given time.

The eye tracking tests for both the text-based and hybrid/graph comparison methods provide insights into the effectiveness and efficiency of each visualization approach. The heat maps and eye fixation patterns help us compare how users interacted with the different interfaces and how effectively they could complete the tasks.

In the text-based visualization tasks, users primarily relied on reading and interpreting textual information. The eye fixation heat maps showed concentrated attention on specific textual data points, indicating that users needed to spend more time reading and understanding the text to complete the tasks. This method often resulted in longer times to identify the correct answers and higher cognitive load, as users had to process large amounts of text.

In contrast, the hybrid/graph comparison visualization tasks demonstrated a different pattern. Users first scanned the attribute names at the bottom of the graphs and then focused on the relevant bars corresponding to the task requirements. The eye fixation heat maps showed that users could quickly identify and compare the visual data, leading to faster and accurate task completion. The visual representation of data in graphs allowed users to grasp the information more intuitively and make decisions more efficiently.

6.3. User satisfaction:

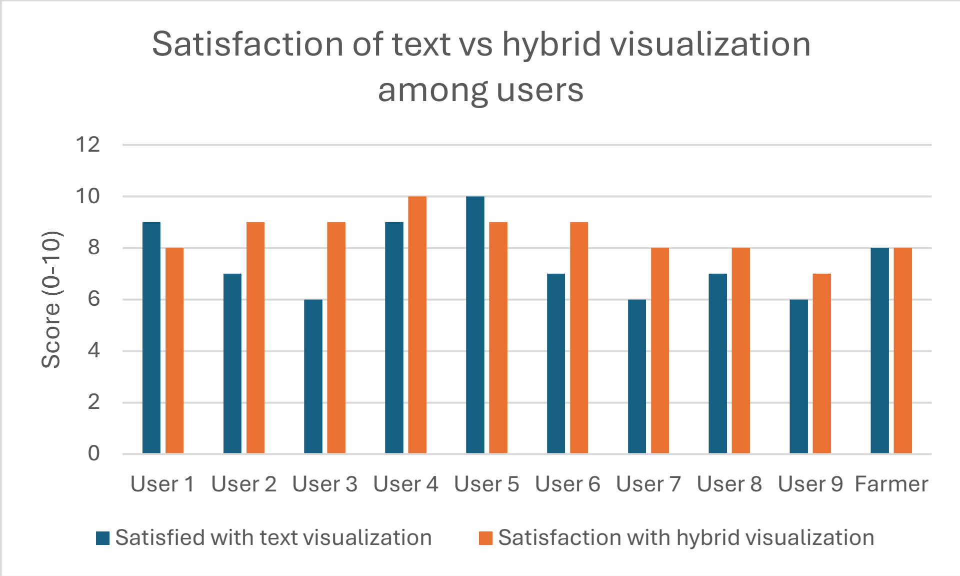

Figure 29*: Graph of user satisfaction for text and hybrid approach.*

The user satisfaction graph in Figure 29 showed that the majority of the users were more satisfied while using the hybrid approach, whereas User 1 and User 5 tended to differ and were more satisfied with the text-based approach. For User 5, the results are verified as User 5 had a higher effectiveness rating for the text-based approach. According to User 5's feedback on the survey form, they found reading the text-based information easier and simpler, which contributed to their higher rating for this approach.

Interestingly, Users 1 and 2 rated both visualization approaches equally in terms of effectiveness. This indicates that for these users, both the text-based and hybrid methods provided a similar level of effectiveness. But their satisfaction scores are different for each approach which may be due to user preference.

Moreover, the farmer (User 10) rated both the text-based and hybrid approaches equally in terms of satisfaction. This suggests that, for the farmer, both visualization methods provided a similar level of usability. The farmer's neutral stance indicates that both approaches were equally beneficial for different reasons.

From the think-aloud protocol and survey forms, several users, including User 1 and User 2, suggested that the hybrid approach would benefit from the inclusion of a legend. Initially, these users were confused about what the different colours represented. This confusion is reflected in the eye-tracking data, where there was noticeable hesitation and scattered fixations at the start of the tasks. However, after some time, users were able to understand the colour coding and proceed with the tasks effectively.

In summary, the hybrid visualization approach generally received higher satisfaction scores, indicating a preference for its ability to present data in a more intuitive and accessible manner. Most users showed a clear preference for the hybrid visualization. Meanwhile, the farmer demonstrated equal satisfaction with both approaches, indicating a neutral stance.

When users were asked which visualization method, they preferred for managing the storage and packaging of soy yogurt, the majority expressed a clear preference for the hybrid approach. Nine out of ten users including the farmer favoured the hybrid approach over the text-based approach. This preference generally aligns with the satisfaction scores previously discussed, where the hybrid visualization method received consistently higher satisfaction ratings from most users.

However, it is noteworthy that in some cases, the user satisfaction scores for the text-based approach were higher. For instance, Users 1 and 5 showed a higher satisfaction with the text-based visualization compared to the hybrid method. Despite these individual variations, the overall trend indicates a strong preference for the hybrid approach.

The visual nature of the hybrid approach helps reduce cognitive load and enhances user efficiency, making it easier for users to comprehend and compare information quickly. This is further supported by the farmer's higher satisfaction with the hybrid approach, emphasizing its practical benefits in real-world applications.

This feedback aligns with the effectiveness scores from the user. The hybrid approach not only received higher satisfaction ratings but was also reported to be more user-friendly and effective during the think-aloud sessions. Users consistently noted the ease and speed with which they could interpret and compare data using the hybrid method, highlighting its effectiveness in enhancing user experience and decision-making processes.

The table 2 summarizes user views on both text-based and hybrid visualization approaches. The text-based approach is praised for its clarity and direct visibility of details, making it easy to interpret single scenarios and compare values. Users appreciated the clear interpretation of attributes and the exact quantity of parameters involved in the process, highlighting its straightforward and understandable nature. However, the hybrid approach was favored for its ability to simplify comparisons between several scenarios, making decision-making more intuitive. Users found it easier to understand with visual aids, quickly noting changes and differences side by side. The combination of an easy-to-understand layout with exact and necessary numbers in the hybrid approach facilitated a more interactive and comprehensive understanding of the data. Critically, while the text-based approach excelled in presenting detailed information clearly, the hybrid approach offered a more effective and user-friendly way to compare multiple scenarios, enhancing overall satisfaction by reducing cognitive load and improving efficiency in decision-making. Moreover, the users found the text-based approach to be “too wordy” and they were confused as to which color represented which scenario in the hybrid visualization approach. This preference aligns with the higher satisfaction ratings observed for the hybrid approach, indicating its superiority in providing a comprehensive and intuitive visualization experience.

Table 2: *Summarized user views on visualization approaches.*

Text-Based Visualization Approach	Hybrid Visualization Approach
All details are clearly visible and understandable directly.	Easier to select between several scenarios for comparison.
Clear interpretation of attributes.	Good for comparing all scenarios easily and understanding them.
Easy to interpret and understand the overall scenario if we are viewing a single scenario.	Makes the comparison of scenarios much easier and intuitive.
Easy to compare values.	Graphs help in getting an idea of the portion of tanks empty or full.
Shows the exact quantity of parameters involved in the process.	Changes are very easy to note, scenarios can be seen side by side, quickly seeing differences to make decisions.
Easy to understand.	Combines easy to understand layout with exact and necessary numbers.
Too many information to see, or too wordy.	Bar for each scenario was not titled so takes time to understand which colour represents which scenario.

In conclusion, while there are some instances where the text-based approach received higher satisfaction scores, the overall user preference strongly favours the hybrid visualization method. This preference reinforces the earlier findings on effectiveness and efficiency. The hybrid visualization method is more efficient, effective and user-friendly, making it the preferred choice for most users. These results highlight the importance of incorporating intuitive visual elements in digital twin systems to improve user experience and decision-making processes.

6.4. Discussion on Aid of 3D Environment:

Based on the survey form results, it is evident that all users found the 3D environment helpful in understanding the processes occurring at the farm. This unanimous positive feedback indicates a clear preference for the presence of a 3D environment. The 3D environment likely provides a more immersive and intuitive way for users to interact with and comprehend complex farm operations.

However, a notable limitation of the survey was that it did not ask users to specify how the 3D environment was useful or the reasons behind their positive feedback. This omission means that while we know the 3D environment was well-received, we lack detailed insights into the specific aspects that users found most beneficial. Furthermore, the research didn't compare the 3D version with a 2D version so the need of a 3D environment can't be answered with surety. Despite these limitation, several potential benefits of the 3D environment can be inferred based on general principles of spatial visualization and user interaction.

The 3D environment likely helped users better understand the layout and spatial relationships of the farm. This understanding is essential for tasks such as locating equipment, navigating between different areas, and comprehending the workflow of processes. However, the 3D view isn't in the actual yoghurt simulations, it may be beneficial in orienting people (e.g. new employees) to the farm and equipment. Additionally, a 3D environment can make the interaction more engaging by allowing users to explore the farm virtually. This interactivity can lead to a deeper understanding of the processes as users can see and manipulate elements in a more natural and intuitive way. By visualizing the processes in a 3D environment, users can observe the dynamics of the farm operations in a more realistic manner. This can help in identifying bottlenecks, inefficiencies, and areas for improvement that might not be as apparent in a 2D representation. Furthermore, the 3D environment can provide a clearer and more comprehensive view of the farm operations, aiding users in making informed decisions. The ability to visualize the impact of different scenarios in a realistic setting can enhance the decision-making process.

To address the limitation of the current survey, future surveys should include questions that ask users to specify how the 3D environment was useful to them. Questions could include: "What specific aspects of the 3D environment did you find most helpful?" "How did the 3D environment improve your understanding of the farm processes?" "Can you provide examples of how the 3D visualization aided your decision-making or problem-solving?" "How long could the 3D information be beneficial?" By including these questions, future research can gain more detailed insights into the benefits of the 3D environment and further validate its effectiveness in aiding user understanding of complex processes. Furthermore, a comparison with a 2D version of the DT will also aid in answering this question. This additional information will be valuable for refining the 3D environment and making it even more effective as a tool for farm management and process optimization.

6.5. Discussion on Scalability and Adaptability:

To optimize the DT for scalability and adaptability, several strategies can be implemented. One key aspect involves enhancing the input scenarios that users can compare. Currently, the DT allows for the comparison of up to three scenarios. However, to make the system more adaptable, it is crucial to solicit user input on how many scenarios they would like to compare. By gathering this feedback, the DT can be adjusted to meet the varying needs of different users, allowing for a more flexible and user-centric approach.

Moreover, the current attributes in the DT are hardcoded, which poses a limitation in terms of adaptability. For instance, if there is a change in container size or the introduction of new container types, the hardcoded attributes would need to be manually updated. To overcome this limitation, the DT should be designed with dynamic data handling capabilities. This can be done by allowing users to make changes in container size when interacting with the scenarios and subsequent changes in the formulas can be adjusted through a pop-up window which ask's questions to the user about time etc and integrates them into the formulas for calculating the attributes. Furthermore, to reflect these changes in the hybrid visualization there is a need to intergrade a flexible data visualization framework that automatically adjusts the graphs and visual elements based on real-time input data. Such a framework would ensure that any changes in the farm's infrastructure, such as new machinery, container sizes, or operational processes, are seamlessly reflected in the DT without requiring extensive manual reconfiguration. This can be done by adding a separate user interface where these changes can be done and would reflect in the actual DT.

Moreover, this study incorporated the use of the direct connection between Revit and Unreal Engine through Twin Motion, due to which modifications made in the Revit model are immediately reflected in the Unreal Engine environment which makes the 3D model scalable.

User feedback is also crucial for optimizing the DT. Regularly soliciting feedback from farm managers, and workers can provide valuable insights into how the system is being used and where improvements can be made. This iterative feedback loop ensures that the DT evolves in line with the actual needs and challenges faced by the users, making it a more effective tool for managing farm operations.

Optimizing the Digital Twin for scalability and adaptability involves several key strategies. These include enhancing user input capabilities, integrating dynamic data handling, adopting modular design principles, and maintaining a regular feedback loop with users. By implementing these strategies, the DT can be made more flexible, robust, and capable of evolving in response to future modifications or expansions of the soy farm infrastructure.

7. Conclusion:

7.1. Answers to Research questions:

This study set out to evaluate the usability of different visualization methods for visualizing constituent parts in Digital Twins (DTs) in agricultural contexts specifically the storage and packaging processes of soy yogurt within a soy farm context. By comparing text-based and hybrid visualization approaches, we aimed to determine the most effective method for conveying complex agricultural data to users, particularly farmers. The research was guided by several key questions, which we addressed through a combination of detailed 3D modeling, usability testing, and user feedback.

RQ1: What specific data inputs and parameters are necessary to represent the packaging and storage processes of soy yogurt within the DT system?

Through requirement analysis and discussions with the farmer, we identified seven critical attributes: Tank 1 volume, Tank 2 volume, amount of yogurt, time taken, energy consumed, man hours, and fridge capacity. These parameters were essential in accurately simulating the operations of the packaging and storage machinery within the DT.

RQ2: How can the DT be enhanced to ensure scalability and adaptability for potential future modifications or expansions of the soy farm infrastructure?

To enhance scalability and adaptability, the DT should incorporate dynamic data handling and modular design principles. Feedback from users indicated the need for a flexible system that can easily accommodate changes in container sizes or the addition of new machinery. By integrating these features, the DT can evolve alongside the farm's infrastructure, ensuring long-term usability and relevance.

RQ3: Does the 3D environment aid the user in better understanding the processes happening at the farm?

Survey results and user feedback unanimously indicated that the 3D environment significantly aids in understanding farm processes. Users found the 3D representation immersive and intuitive, which facilitated better spatial and operational comprehension. This aligns with previous studies suggesting that 3D environments enhance user engagement and understanding (Jones et al., 2020). While the 3D environment gave insights to both farmers and ITC users, they were not equally useful to both. For non-farmers, the 3D environment was primarily an educational tool, bridging their knowledge gap to some level and getting to know the farm's area. However, for the farmer who already knew the farm's environment like the back of their hand, it was useful as a tool which can be used to train new employees, present to stakeholders, etc. However, it was noted that the survey did not specifically ask how the 3D environment was useful, indicating a need for more detailed future investigations. Moreover, no comparison was done with a non-3D version, thus this research question can't be answered with a surety within the scope of this study.

RQ4: In the context of usability evaluation for Efficiency, how efficient are the different visualizations in conveying information to the users to perform tasks related to the packaging and storage of soy yogurt using the different digital twins?

Efficiency results showed that users completed tasks more quickly and accurately using the hybrid visualization approach compared to the text-based method. The visual aids in the hybrid approach facilitated faster data interpretation and decision-making, demonstrating its superior efficiency.

RQ5: In the context of usability evaluation for Effectiveness, to what extent do different digital twin visualizations prove effective to convey information for users in making informed decisions related to the packaging and storage of soy yogurt using the different digital twins?

Effectiveness was also higher with the hybrid approach, as users found it easier to comprehend and compare information. The eye-tracking data revealed that users could quickly identify and verify key data points using the hybrid method, resulting in more accurate decision-making.

RQ6: In the context of usability evaluation for Satisfaction, what is the level of satisfaction among users when interacting with the different digital twins?

User satisfaction ratings favored the hybrid approach, with users reporting a more intuitive and engaging experience. The farmer, in particular, appreciated the hybrid method's ability to present data in a more accessible format, highlighting its practical benefits.

RQ7: How does the usability of a text-based digital twin compare to that of a hybrid digital twin, when focusing on the packaging and storage of produced soy yogurt?

Overall, the hybrid digital twin outperformed the text-based version in terms of usability. Both the farmers and non-farmers found the hybrid approach more efficient, effective, and satisfying, underscoring the importance of incorporating visual aids in DT systems to enhance user experience.

In conclusion, this study demonstrates the significant advantages of hybrid visualization approaches in digital twin systems for agriculture. By integrating textual data with visual variables and leveraging 3D environments, we can create more effective, efficient, and user-friendly tools for farm management. These findings contribute to the advancement of digital twin technologies in agriculture, promoting sustainable and efficient farming practices.

7.2. Implications:

The findings of this research have several important implications for the future development and application of Digital Twin (DT) technologies in agriculture, particularly in enhancing the storage and packaging processes of soy yogurt on farms. By implying this methodology, there is potential for farmer's decision making ability to be better. By integrating advanced visualization techniques and leveraging user feedback, this study underscores the potential for DTs to revolutionize agricultural management practices, improve operational efficiency, and support sustainable farming.

Efficiency

One of the key implications of this study is the demonstrated ability of DTs to enhance operational efficiency on farms. The hybrid visualization approach, which combines textual and graphical representations, was found to be significantly more effective and user-friendly than text-based methods alone. This suggests that integrating visual aids can help farm managers and workers quickly comprehend complex data, leading to faster decision-making and reduced cognitive load. This is consistent with findings in other sectors where visual analytics improve task performance and decision-making (S. Few., 2006)

Scalability and Adaptability

The research identifies the need for DT systems to be scalable and adaptable to accommodate future changes in farm infrastructure. The implementation of dynamic data handling capabilities and modular design principles can make DTs more flexible, allowing them to evolve alongside the farm's needs. This adaptability is crucial for ensuring that DTs remain relevant and useful as new technologies and farming practices emerge (Boschert & Rosen, 2016). By continuously integrating user feedback and updating the system based on real-time data, DTs can provide ongoing support for farm management.

User Satisfaction

User satisfaction is a critical factor in the successful adoption of DT technologies. The study's findings indicate that users, including farmers and ITC professionals, generally preferred the hybrid approach due to its intuitive and accessible nature. This preference highlights the importance of designing DT systems that are user-centric and cater to the needs of diverse user groups. Incorporating features such as clear labelling, legends, and user-friendly interfaces can further enhance user engagement and satisfaction (Don Norman, 2013).

Addressing Research Gaps

This research also addresses significant gaps in the literature by providing a comparative analysis of text-based and hybrid visualization approaches within DTs, specifically in an agricultural context. While previous studies have explored the use of DTs in various domains, there has been limited focus on their application in agriculture, particularly regarding the visualization of processes like storage and packaging (Grieves, 2014.; Tao et al., 2019). This study contributes to filling this gap and sets the stage for future research to explore additional visualization techniques and their impact on agricultural management.

Improving Effectiveness

The effectiveness of the DT system was significantly enhanced by incorporating visual aids into the hybrid approach. The eye-tracking data and user feedback indicated that users were able to quickly identify key information and make informed decisions more efficiently with the hybrid approach. The visual representation of data, such as bar graphs and color-coded scenarios, allowed users to grasp complex information at a glance, reducing the time and effort required to interpret text-based data. This aligns with existing research on the benefits of visual aids in improving data comprehension and decision-making (Ware, 2014). The hybrid approach not only facilitated quicker information retrieval but also minimized errors and misunderstandings, thereby increasing the overall effectiveness of the DT system.

3D Environment Aids

The inclusion of a 3D environment in the DT was found to be particularly beneficial in helping users understand the processes occurring at the farm. The immersive nature of the 3D model allowed the non-farmers to visualize the spatial relationships and workflow of the farm operations more intuitively. Survey results indicated that all users found the 3D environment helpful, which is likely due to its ability to provide a realistic and engaging representation of the farm. However, the survey's limitation was that it did not ask for specific reasons why users found the 3D environment useful. Despite this, it can be inferred that the 3D environment aided users in comprehending complex processes, such as the flow of materials and the layout of equipment, which would be more challenging to understand through 2D representations alone. This finding is supported by research indicating that 3D visualizations can enhance understanding of spatial relationships and improve task performance in complex environments (Billinghurst & Kato, 2002).

Additionally, the use of 3D environments within DTs has been questioned within the DT community. Some argue that the added complexity of 3D models may not always justify their use, especially if the same information can be effectively conveyed through simpler means (Grieves, 2014.) However, this study provides evidence supporting the inclusion of 3D environments as they can significantly enhance the user's understanding of spatial and process-related information, making complex operations more intuitive and easier to manage.

To address the limitation of the current survey, future surveys should include questions that ask users to specify how the 3D environment was useful to them. Questions could include: "What specific aspects of the 3D environment did you find most helpful?" "How did the 3D environment improve your understanding of the farm processes?" "Can you provide examples of how the 3D visualization aided your decision-making or problem-solving?" "How long could the 3D information be beneficial?" By including these questions, future research can gain more detailed insights into the benefits of the 3D environment and further validate its effectiveness in aiding user understanding of complex processes. This additional information will be valuable for refining the 3D environment and making it even more effective as a tool for farm management and process optimization.

7.3. Future Work:

This study has provided valuable insights into the usability of different visualization approaches within a Digital Twin (DT) for agricultural settings, specifically focusing on the storage and packaging processes of soy yogurt. However, several avenues for future research and development can further enhance the scalability, adaptability, and overall utility of DTs in agriculture.

One significant area for future work is the incorporation of more dynamic data handling capabilities. Currently, the DT uses hardcoded attributes, which limits its adaptability to changes in the farm's infrastructure, such as the introduction of new machinery or changes in container sizes. Developing a more flexible data visualization framework that can automatically adjust based on real-time input data would ensure that the DT remains up to date without requiring extensive manual reconfiguration. This dynamic framework could be integrated with a user-friendly interface, allowing farm managers to easily input changes and immediately see their effects in the DT.

Additionally, the scalability of the DT can be enhanced by adopting modular design principles. By treating each component of the farm as an independent module, new elements can be added or existing ones modified without disrupting the entire system. This modular approach would facilitate easier updates and expansions, making the DT more robust and capable of evolving alongside the farm's needs.

User feedback has proven invaluable in this study and will continue to be a critical component of future development. Regularly soliciting feedback from a diverse group of users, including farm managers and workers, will provide ongoing insights into the practical challenges and needs of those interacting with the DT. This iterative feedback loop will help ensure that the DT evolves in alignment with user requirements, enhancing its effectiveness as a tool for farm management.

Another promising direction for future research is the exploration of advanced visualization techniques. While this study compared text-based and hybrid approaches, future work could investigate the integration of other visual aids, such as augmented reality (AR) or virtual reality (VR), to create even more immersive and intuitive interfaces. These technologies could provide users with a more interactive and engaging way to understand and manage farm operations, potentially leading to greater efficiency and accuracy.

Additionally, user-suggested inputs or parameters that could enhance the Digital Twin (DT) system for representing the packaging and storage processes of soy yogurt. Users have highlighted the potential value of adding sub-attributes related to the distribution of yogurt post-production, which would help in differentiating orders for customers. Incorporating variables such as the amount of flavour available and used could provide a more comprehensive view of the production process. Furthermore, introducing a user demand variable, along with tracking the remaining empty containers based on orders, would enable more precise inventory management. Users also suggested the inclusion of a help button to assist in understanding the scenarios better, which could later be utilized by the farm manager for marketing purposes to showcase operational processes. Additionally, integrating financial parameters such as packaging carton costs could offer insights into the economic aspects of the packaging process. These enhancements would make the DT system more robust, user-friendly, and aligned with real-world operational needs.

***Table 3**: User suggestions on additional input or parameters that could be added to the DT.*

What additional inputs or parameters do you think can be added for the DT system to effectively represent the packaging and storage processes of soy yogurt?
Addition of sub attributes in distribution of yoghurt after production.
To differentiate order for the customer.
I think the amount of flavour available and how much flavour is used could be a nice input.
User demand variable. Amount of flavour. Remaining empty containers based on order.
Maybe a help button to understand the scenarios a bit better, and later the farm manager can use it for marketing to show how he operates.
Finances involved could be added such as the packaging cartons etc.

Finally, expanding the scope of the DT to include other aspects of farm management, such as soy yoghurt production, soil health, irrigation scheduling, and crop yield predictions, could provide a more comprehensive tool for farmers. By integrating a wider range of data sources, the DT could offer even more valuable insights, helping farmers optimize all aspects of their operations and contribute to more sustainable agricultural practices.

7.4. Ethical Considerations:

All participants in this study were provided with a consent form (Appendix A), detailing the nature of the research, and any potential risks associated with participation. This form emphasized the voluntary nature of participation, ensuring participants understand they have the right to withdraw from the study at any point without any repercussions. Additionally, all data collected from participants, including usability metrics were anonymized to ensure privacy. Any personal identifiers, such as names or contact details, were removed, and replaced with an Id number.

Interacting with a complex DT interface can be cognitively demanding, leading to feelings of frustration, inadequacy, or stress. To mitigate these risks, participants were told that they can take breaks during the usability tests. Moreover, participants were briefed ahead of time of the potential frustrations. Additionally, participants were debriefed post-interaction, allowing them to share their experiences, voice any concerns, and receive reassurance.

Given the digital nature of the research, there's a risk of technical failures, such as software crashes or hardware malfunctions. Backup systems will be in place to ensure minimal disruption, and participants will be rescheduled if necessary. These backup systems will include additional PCs or Laptops with the different versions of DT on them, providing an extra layer of redundancy to safeguard against technical failures. Moreover, data loss, whether due to technical failures or human error, can be detrimental to the research. Regular data backups will be conducted, and data will be stored in multiple secure locations.

Additionally, while making the DT all the confidential information e.g., certain machinery, and the yoghurt production etc., were not modelled in the DT so as to preserve the confidentiality of some part of the process as discussed with the farm owner.

7.5. Cooperation with other groups:

Cooperation with the soy farm owner and managers was fundamental for gaining access to the farm, its facilities, and the necessary resources for data collection and testing. Their insights into the daily operations, challenges, and goals of the farm were invaluable in designing a user-friendly and effective digital twin system. Communication with the farm's management team was maintained to address their concerns, gather feedback, and ensure the usability testing aligns with their objectives.

7.6. Use of AI:

The author has employed ChatGPT to validate information against reliable sources, ensuring the accuracy and credibility of the content presented. After this, the author used Grammarly to further correct any remaining grammatical issues, thus enhancing the overall quality of the thesis. This combination of tools has streamlined the research and writing process, making it a crucial component in the completion of this academic work.

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9. Appendices

9.1. Appendix A

Consent Form

Project Title: **Evaluating the Usability of Different Methods for Visualizing Constituent Parts in a Digital Twin of a Livestock Farm**

Faculty of ITC, Geoinformation science and Earth Observation science.

Introduction:

You are being invited to participate in a user testing session for the Soy Farm Digital Twin project. The purpose of this study is to evaluate the usability and effectiveness of different visualization methods within the digital twin framework for soy farm management, with a focus on processes related to storing and packaging of soy yogurt. Your participation in this study will involve interacting with various visualization tools and providing feedback on your experience.

Participant Consent:

By agreeing to participate in this study, you acknowledge that:

1. You have read and understood the information provided in this consent form.
2. You voluntarily agree to participate in the user testing session for the Soy Farm Digital Twin project.
3. You understand that your participation is entirely voluntary, and you may withdraw from the study at any time.
4. You understand that your participation will involve interacting with digital visualization tools and providing feedback on your experience.
5. You understand that your participation may involve the recording of audio, video, or screen activity for research purposes, and you consent to the use of such recordings for data analysis and reporting.
6. You understand that any information collected during the study will be kept confidential and will only be used for research purposes.
7. You understand that your identity will be kept anonymous in any reports or publications resulting from this study, and only aggregate data will be presented.

Participant Rights:

1. Your participation in this study is entirely voluntary, and you may withdraw at any time without penalty.
2. You have the right to refuse to answer any questions or perform any tasks that make you feel uncomfortable.
3. You have the right to ask questions about the study before, during, or after your participation, and these will be answered to the best of the researchers' ability.

Consent:

By providing your signature below, you indicate that you have read and understood the information provided in this consent form, and voluntarily agree to participate in the user testing session for the Soy Farm Digital Twin project.

Participant Signature:

9.2. Appendix B

User tasks

Task 01:

Locate the farmer:

Task 02:

Locate the filling machine and the two tanks.

Task 03:

You are the farm manager; you have an order of

Container size	Plain	Vanilla	Forest Fruit
5ooml	480	250	1000
5L	6	8	6

Text a: What is the time taken for the task, tell from the textual information?

Hybrid a: Also tell the time taken from Hybrid approach.

Task 04:

Reset everything. (From the rest button)

Add the following values:

Scenario A:

Container size	Plain	Vanilla	Forest Fruit
5ooml	400	800	1000
5L	5	5	0

Scenario B:

Container size	Plain	Vanilla	Forest Fruit
5ooml	270	700	900
5L	4	8	6

Scenario C:

Container size	Plain	Vanilla	Forest Fruit
5ooml	100	800	1000
5L	6	0	0

Text b: Your fridge capacity is 150 boxes you already have 25 boxes in the fridge which scenario is suitable.

Text c: You must produce 500L of yoghurt tomorrow so pick a scenario with maximum yoghurt left in the tank.

Hybrid b: Government has subsidised on energy today, pick a scenario with maximum energy consumption.

Hybrid c: Man, hours is an attribute that gives the time taken for one person to run the whole simulation. Suppose you have two employees working. Pick a scenario where you would finish within 7 hours.

9.3. Appendix C

***Table 4**: User efficiency across tasks.*

Users	Task01	task02	Text a	Text b	Text c	Hybrid a	Hybrid b	Hybrid c
user1	1.4	1.5	2.3	1.3	1.6	1.7	1.7	1.8
user2	1.4	1.4	2.1	1.2	1.4	1.2	1.3	1.9
user3	1.4	1.3	1.9	1.2	1.4	1.2	1.6	1.6
user4	1.3	1.3	2.3	1.2	1.5	1.2	1.6	2.1
user5	1.3	1.3	2.3	1.2	1.5	1.2	1.2	2.0
user6	1.4	1.4	2.0	1.3	1.4	1.2	1.6	1.8
user7	1.4	1.3	2.1	1.2	1.5	1.3	1.5	1.9
user8	1.3	1.4	2.0	1.2	1.4	1.2	1.5	1.8
user 9	1.4	1.3	2.0	1.2	1.4	1.2	1.5	1.8
farmer	1.3	1.3	2.4	1.5	1.5	1.3	1.4	2.1

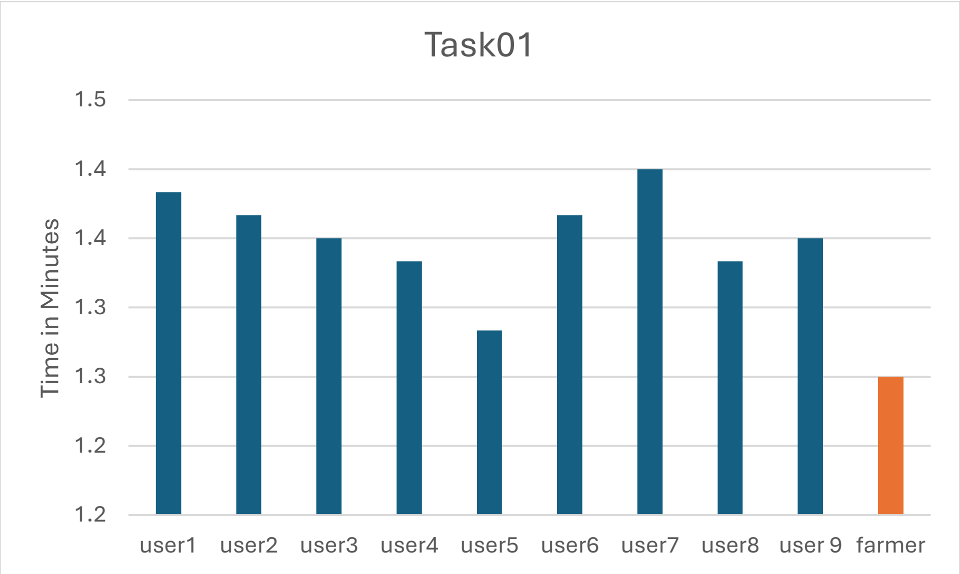

***Figure 30**: Task 01 efficiency graph.*

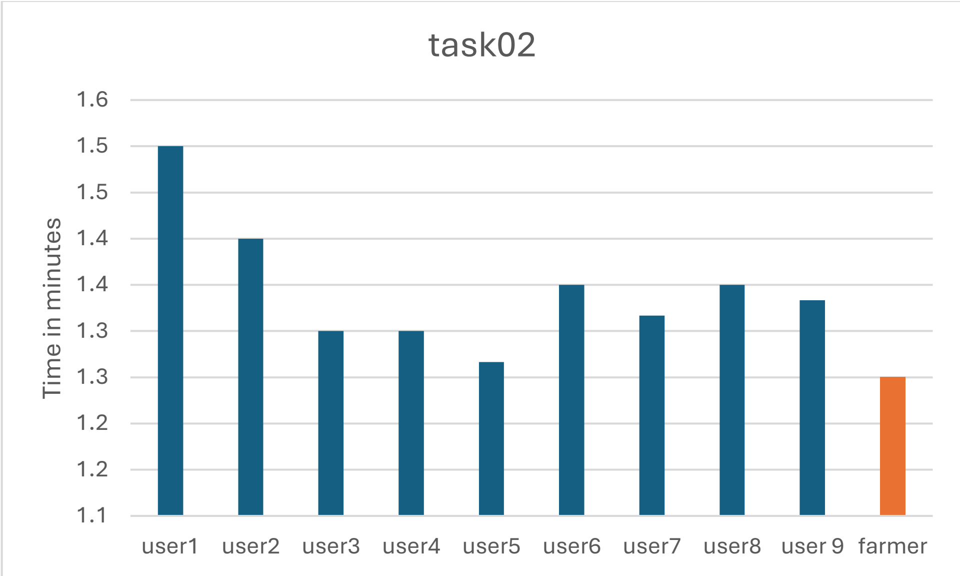

Figure 31*: Task 02 efficiency graph.*

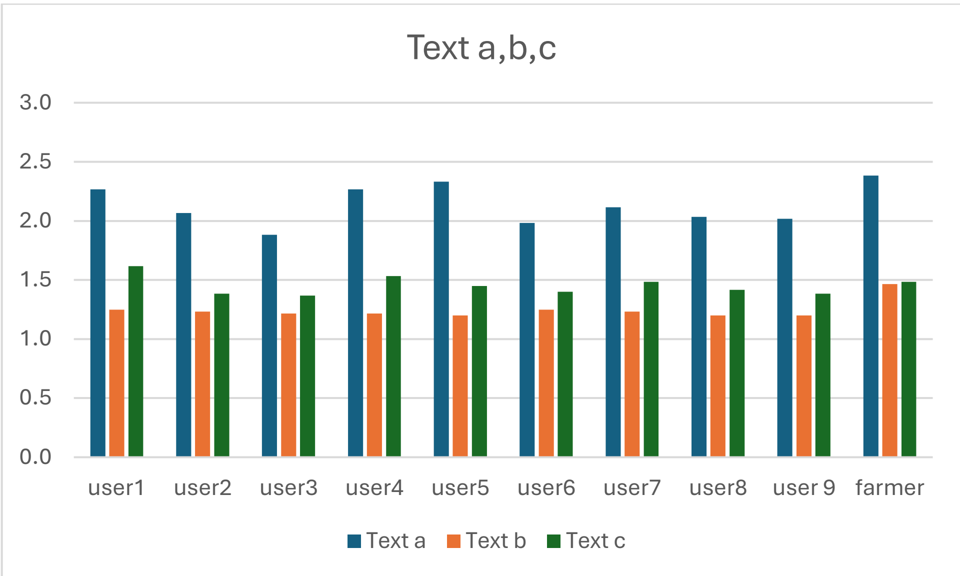

Figure 32*: Efficiency graph of tasks using text representation a, b, c.*

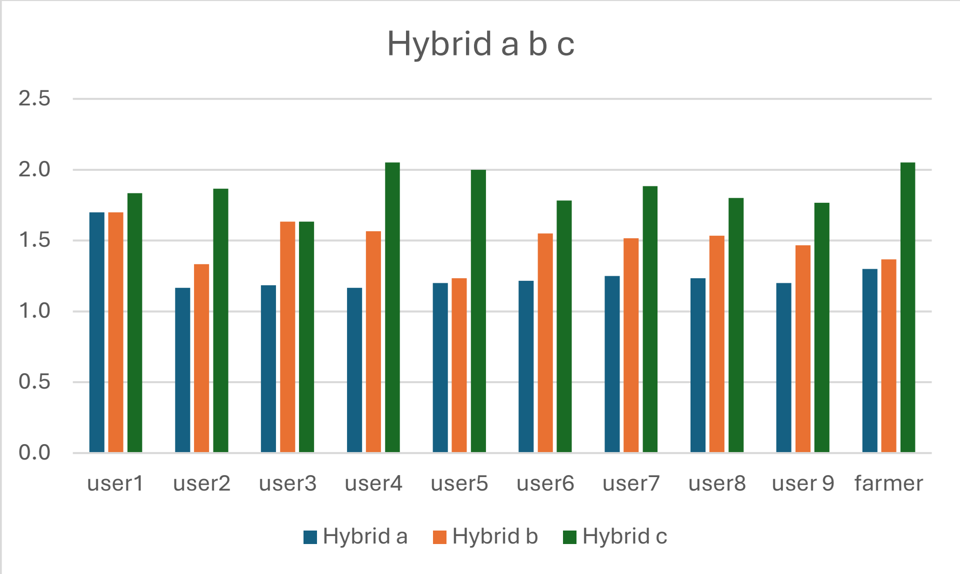

Figure 33*: Efficiency graph of tasks using hybrid representation a, b, c.*

Table 5*: Time taken to perform task by Farmer and an average of time taken by ITC users.*

Users	Text a	Text b	Text c	Hybrid a	Hybrid b	Hybrid c
ITC Users	2.1	1.2	1.4	1.3	1.5	1.8
farmer	2.4	1.5	1.5	1.3	1.4	2.1

Table 6*: Effectiveness rating.*

id	Effectiveness of text visualization	Effectiveness of hybrid visualization
1	9	9
2	9	9
3	7	8
4	9	10
5	10	9
6	6	8
7	7	9
8	8	8
9	8	7
Farmer	7	8