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The Future of Smart Campuses: Combining Digital Twin and Green Metrics

Akıllı Kampüslerin Geleceği: Dijital İkiz ve Yeşil Metriklerin Birleştirilmesi

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ABSTRACT

The "Smart Campus" concept combines environmental sustainability and technological innovation and plays an important role in educational institutions. In this context the contribution of "Digital Twins" and "Green metrics (GM)" to smart campus is one of the important areas of research. In this study, a digital twin architecture is proposed, including energy and climate change, waste and water issues, which account for 48% in GM criteria. Digital simulation and communication protocols, predictive analysis and dynamic decision support can be synthesized between the physical world and the sensor-based framework. This synthesis reveals the potential to reduce environmental damage through effective waste management, efficient use of water resources, identification of efficiency gaps through real-time analysis of energy consumption, and reduction of carbon footprint through energy savings. This study aims that the combined approach presented with the proposed framework according to GM criteria will contribute to future educational environments by ensuring smart campus sustainability.

Keywords: Digital twin, green metrics, smart campus

ÖZ

Çevresel sürdürülebilirlik ile teknolojik yeniliğin birleşimini temsil eden "Akıllı Kampüs" kavramı, geleceğin eğitim kurumlarında önemli bir rol oynamaktadır. Bu açıdan, "Dijital İkiz" teknolojisinin ve "Green Metrics (GM)" ölçümlerinin akıllı kampüslere nasıl katkı sağlayacağı önemli araştırma alanlarından biridir. Bu çalışma kapsamında, GM kriterleri arasında etki değeri %48 olan enerji ve iklim değişikliği, atık ve su konuları dikkate alınarak bir dijital ikiz mimarisi önerilmiştir. Bu kriterler kullanılarak oluşturulan sensör tabanlı çerçeve ile dijital simülasyon ve fiziksel dünya arası iletişim protokolü, tahmine dayalı analiz ve dinamik karar desteği sentezlenebilmektedir. Bu sentez ile kampüslerdeki atıkların etkili bir şekilde yönetilerek çevresel zararın azaltılması, su kaynaklarının verimli kullanımı, enerji tüketiminin gerçek zamanlı analizi ile verimlilik açıklarının belirlenmesi, enerji tasarrufu sağlayarak karbon ayak izinin azaltılması potansiyelleri ortaya çıkmaktadır. Bu çalışmada GM kriterleri doğrultusunda önerilen çerçeve ile birlikte sunulan birleşik yaklaşımla beraber, akıllı kampüslerin sürdürülebilir olması sağlanarak geleceğin eğitim ortamlarına katkıda sağlanması amaçlanmaktadır.

Anahtar Kelimeler: Akıllı kampüs, dijital ikiz, yeşil metrikler

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1. INTRODUCTION

In recent years of rapid technological developments, the concept of "Digital Twin", which is created as a copy of the physical world, has attracted great attention in various sectors from manufacturing to urban planning. Digital twin technology, which aims to improve business processes and increase efficiency, has gained importance primarily for organizations operating in areas where test and defective product costs are quite high by using real-time data from the physical world (Kumaş & Erol, 2021). However, digital twin technology, which is used to support digital transformation and decision-making processes in many sectors and based on data for desired results, is a concept that expands and continues to develop according to the areas in which it is used (VanDerHorn & Mahadevan, 2021). Three features stand out for the success of the digital twin concept, which creates a virtual mirror by modeling the behavior of the physical world. These are the design of the digital twin as a dynamic representation of the physical world, the bidirectional data flow between them, and the connection of the digital twin to include all processes in the physical world (Trauer, Schweigert-Recksiek, Engel, Spreitzer & Zimmermann, 2020). The conceptual diagram for digital twin technology is presented in Figure 1.

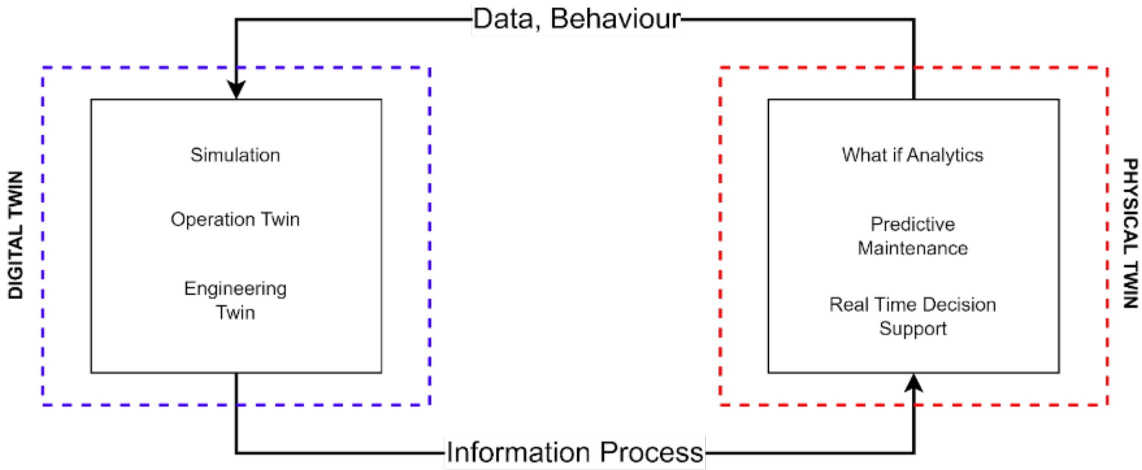

Figure 1. The Conceptual Diagram for Digital Twin

The Internet of Things (IoT), which is among the technologies that have gained importance with the Industry 4.0 revolution, is considered as a dynamic structure that connects the physical world and the digital world using any network or service (Georgios, Kerstin & Theofylaktos, 2019). Today, the concept of IoT has an important place in the design and acquisition of smart structures designed with data flow from physical structures. IoT-based technologies can be used to create smart campuses aimed at improving service quality and improving campus business operations. In this way, an infrastructure can be created for the presentation of applications in which variables such as people, spaces, vehicles, etc. in the campus ecosystem are in connection with each other (Abuarqoub et al., 2017).

The smart campus concept, which has an important place within the scope of digitalization in educational institutions, can be designed not only to improve campus activities, but also to optimize corporate business processes and prioritize sustainability. The driving force behind this formation is the adoption of "GreenMetric" (GM) measurements. GreenMetric is a sustainability ranking launched by the University of Indonesia in 2010 to see the green space rating on campuses using 6 criteria and 39 indicators. These criteria are indicated in Figure 2 as Setting and Infrastructure (SI), Energy and Climate Change (EC), Waste (WS), Water (WR), Transport (TR) and Education and Research (ED) (UI GreenMetric, 2023). These measurements are used to assess the environmental impact of campus activities, from energy consumption and waste generation to transport modes and water use.

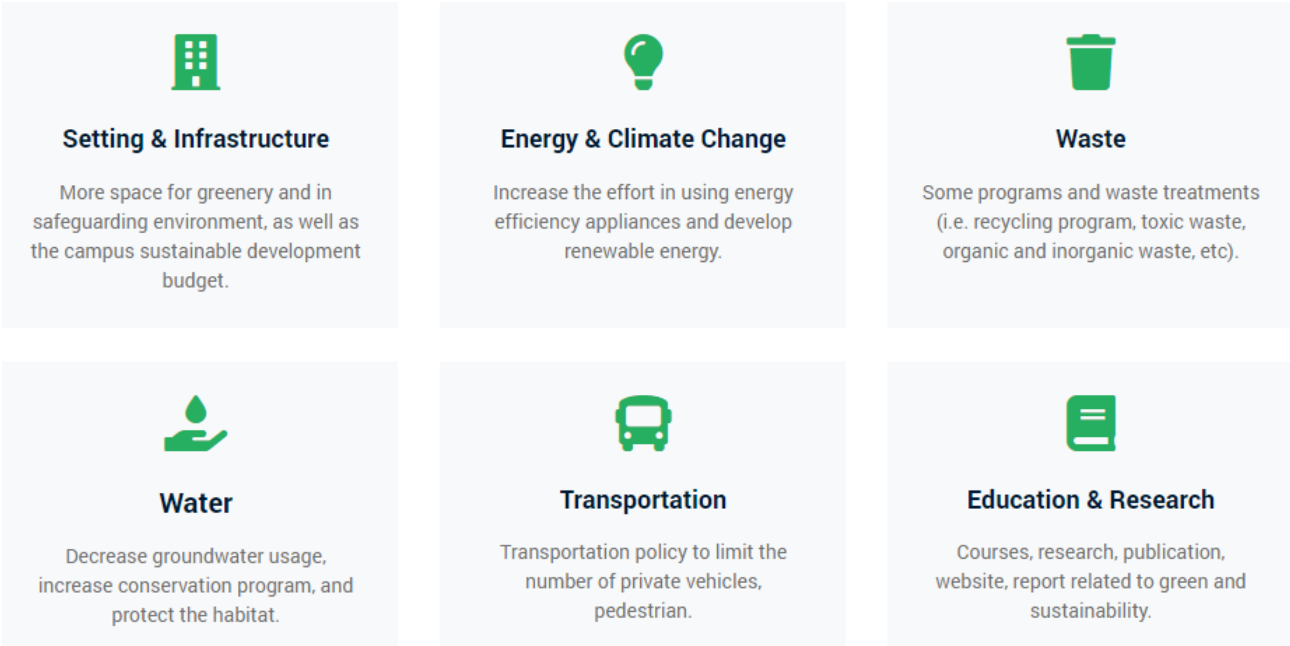

Figure 2. GreenMetric Criteria

The conceptual framework presented within the scope of digital twin in this study is based on the application of digital twin technology to the smart campus concept by blending it with GreenMetric criteria. The study focused on three GM criteria: energy and climate change, waste and water. The digital twin concept, created with the data obtained from the IoT-based smart campus structure, has been prepared to obtain real-time information about the GM criteria and to support the decision-making processes of this information. In addition, the other aim of the study is to estimate the sustainability plan of the University by combining the digital twin concept and GM measurements, which are created using the data flow from the smart campus system. Using smart campus formation and digital twin and GreenMetric criteria, this study is expected to contribute the way in promoting a culture of sustainability through campus communities, reducing ecological footprints and encouraging "eco-conscious" behaviors.

2. LITERATURE REVIEW

Within the scope of GreenMetric (GM), digital twin and smart campuses, many studies are found in the literature. In particular, GM evaluation criteria, which are used to understand and develop the sustainability potential of smart campuses, can be used in smart campuses since they can produce predictive simulations when considered together with digital twin architectures. In this direction, GM criteria such as energy and climate change, waste and water categories were evaluated and discussed for the digital twin architecture created in the smart campus by conducting literature research.

First of all, in the study of Corrado, DeLong, Holt, Hua & Tolk, in 2022, a model proposal is presented by examining the existing research in the field of GreenMetric and digital twin on smart cities. The model proposal, which evaluates a city as a sociotechnical complex system based on current research, enables sustainability planning at various levels related to city planning and governance and provides computational decision support for complex challenges (Corrado et al., 2022). In another study by Pexyean, Saraubon, and Nilsook in 2022, the use of digital twins obtained with IoT output data is discussed in order to better understand the energy management potential in campuses. One of the highlights of the study is the emphasis on new energy models and management that can solve future emergencies by externally controlling the virtual energy data obtained with the digital twin in smart campuses (Pexyean et al., 2022). Considered from this aspect, the architecture proposed in this study is similar to the results obtained by the authors in this direction.

Han et al. in 2022, it is recommended to use digital twin technology to digitally create the physical campus environment at the university, detect the physical campus in real time, accurately map the virtual campus to the virtual campus, and provide reverse control of the twin virtual campus to the physical campus. The results obtained within the scope of the study show that the virtual-real campus system can improve school management and teaching, and important implications can be obtained by promoting campus smart systems within the scope of the implementation of development processes (Han et al., 2022). Wang's research in 2022 highlights that traditional campus management faces problems such as cost, maintenance, low efficiency and energy waste. With the findings obtained in this direction, a control cloud platform was created in order to reduce costs, reduce energy consumption, and improve the use of assets and equipment by using smart IoT research, and a dynamic campus management was provided (Wang, 2022).

In another study conducted by Suwartha and Sari in 2013, the ranking and application results of GreenMetric, which provides the development of the current situation and policies regarding green campus and sustainability in universities all over the world, were evaluated. In the study, it is emphasized that the most important criteria achieved by many universities are energy and climate change (Suwartha & Sari, 2013). With this aspect, in the study carried out on the axis of digital twin, smart campuses and GreenMetric; energy and climate change, waste and water criteria were discussed, and the data set and digital twin architecture design were carried out based on the relevant criteria.

Celebi et al. in 2020, campuses defined as a component of cities were discussed and a study was conducted in the example of Aksaray University. In the study, which was carried out using the "Smart City Circle" proposed by Boyd Cohen, sustainable environment-oriented approaches were discussed through university examples (Celebi et al., 2020). Finally, Zaballos et al. in 2020, a smart campus concept is proposed to explore the integration of building information modeling tools with IoT-based wireless sensor networks in the fields of environmental monitoring and emotion sensing and to give an idea about the level of comfort. The preliminary results obtained highlight the importance of monitoring workspaces as it has been proven that productivity is directly affected by environmental parameters. Comfort monitoring infrastructure can also be used to monitor physical parameters in educational buildings to improve energy efficiency (Zaballos et al., 2020). For this reason, since energy and climate change are in the first place within the scope of GreenMetric criteria, campus building and facility data are also included in the data layer within the scope of architecture.

Within the model proposed within the scope of the study, machine learning techniques to be selected according to the data size will also differ. As the data size increases and the number of features increases, different and more complex machine learning methods may be needed. Three important perspectives emerge here; model simplification to reduce computational complexity, optimization approach to increase computational efficiency, and computational parallelism to increase computational capacity (Wang et al. 2020). Regarding the choice of algorithms, Sala et al. 2018, emphasizes that statistics and simple ML models are useful and sufficient for low-dimensional data sets, while for complex data and high-dimensional data sets, tree-based algorithms and advanced artificial neural networks are recommended. As for another important step, hyperparameter optimization, Gambella et al. 2018, stated that an important part of most machine learning approaches is the selection of the hyperparameters of the learning model. They emphasized that Hyperparameter Optimization is usually driven by the experience of the data scientist and the characteristics of the dataset and typically follows heuristic rules or cross-validation approaches. Furthermore, Li's research in 2017 stated that gradient descent algorithms are the most important and popular techniques for optimization of models related to deep learning. Also, that study emphasized that "adagrad" converges faster than "adam" and other optimization methods on various tasks in different neural network structures.

Looking at the literature review, it is seen that the GreenMetric evaluation criteria used to understand and develop the sustainability potential of smart campuses, when combined with digital twin architectures, have the potential to enable the development of predictive simulations in smart campuses. In this context, a conceptual framework is presented in the study and the layers in this proposal are detailed in the following sections.

3. CONCEPTUAL FRAMEWORK

A conclusion may review the main points of the paper, do not replicate the abstract as the conclusion. A conclusion might elaborate on the importance of the work or suggest applications and extensions.

In this study, a conceptual framework that combines the digital twin concept with the data obtained from the smart campus formation using IoT technology is presented. A conceptual framework is a visual or written representation of the relationships between key concepts or variables in a study. It is used to guide the research process and help the researcher make sense of the data and set of relationships. The conceptual framework approach establishes a link between the facts describing the subject under investigation and research practice (Leshem & Trafford, 2007). The conceptual framework approach, which can be specific to the research topic and present the study as a logical master plan, encompasses the theoretical framework concept, which can be summarized as the interpretation of other researchers' ideas about the study (Kivunja, 2018). Within the scope of this study a diagram representing the conceptual framework is created and presented in Figure 3.

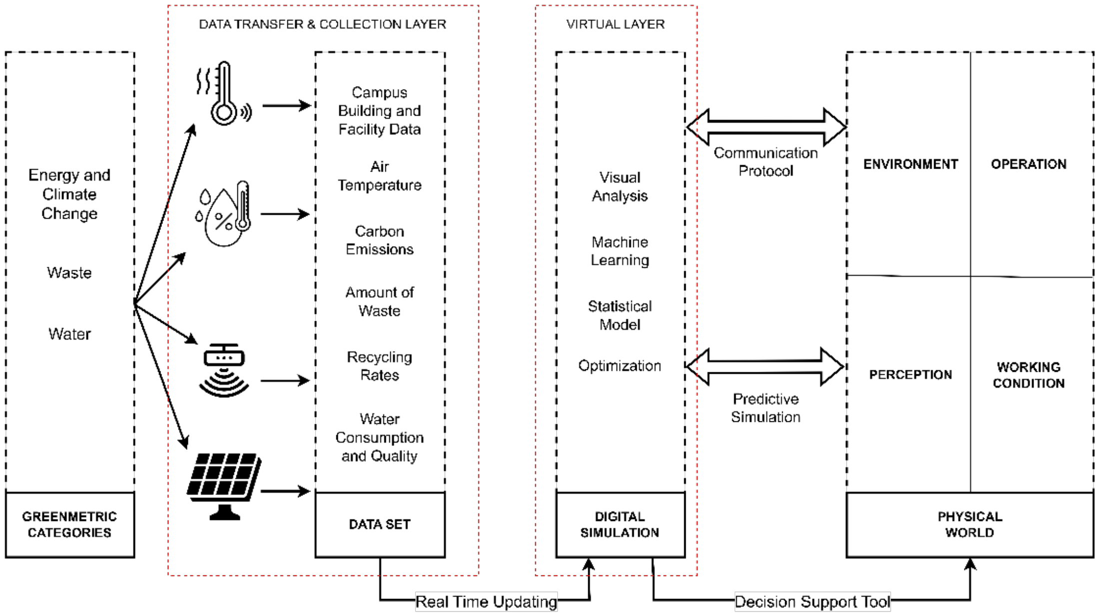

Figure 3. Conceptual Framework Design of Digital Twin for GM Criteria in Smart Campuses

In the architecture presented in Figure 3, it is aimed to integrate the data collected continuously and in real time from the physical world with various simulation models for the GM criteria. With this integration, a real-time model is obtained by creating a data-driven digital twin that represents the physical process. This aims to allow the digital twin to simulate the behavior of the physical object and predict how it performs or will perform under different conditions. Detailed explanations of the structures in the conceptual framework created are presented in the following sections.

3.1. GreenMetric Criteria

The UI GreenMetric World Universities Ranking is a ranking of universities' environmental commitments and initiatives, launched by Universitas Indonesia in 2010. The ranking is based on 39 indicators across 6 criteria, including campus infrastructure, energy and climate change actions, water management, waste management, transport, green education and research. The distributions of the criteria, which have the degree of importance in percentages, affect the ranking in different degrees. The percentage distributions of the impacts of the criteria on the ranking are presented in Table 1 (Lauder et al., 2015; UI GreenMetric, 2023).

Table 1. *Impact of GM criteria on ranking*

Framework	Criteria	Weighting (%)
UI GreenMetric	Setting and Infrastructure	15
	Energy and Climate Change	21
	Waste	18
	Water	10
	Transportation	18
	Education and Research	18

Universities can carry out studies for all criteria at the same time or give priority to studies for criteria with higher importance. One of the important parameters here is to make a planning according to the criteria that can be solved in the short term and to take beneficial actions.

Sonetti et al. in the study they carried out in 2016, they conducted an analysis study by examining the GreenMetric criteria of different universities. In this study, it was revealed that the need for improvement was most intense in the 3 areas selected in the study (Sonetti et al., 2016). Demiroğlu et al., in their study in 2017, examined 5 campuses in Turkey on the basis of Green Campus approaches. In the findings of the study, it was seen that the investments in the selected campuses focused on the use of renewable energy in the campus, improving waste management, reducing the carbon footprint and using water resources more efficiently (Demiroğlu et al., 2017).

Lukman et al. in 2009, they conducted a study based on the use and functioning (construction and maintenance, heating, lighting and water consumption) and daily consumption of various items (paper and plastic bottles). In the improvements presented in this study, it has been revealed that improvements such as heating-cooling, changing energy habits, making waste management more sustainable contribute much more than construction improvements and are the right approach for campuses (Lukman et al., 2009). Finley et al., 2012 and Register, 2006 determined that the "Eco City" concept, which was developed by integrating smart energy, waste management and water management with new building construction, is the best method for university campuses (Finlay & Massey, 2012; Register, 2005).

Massuco and others. with a study carried out by Genoa University in 2023, the energy performance of the campus was improved. Various measures have been taken, including the implementation of a system for real-time monitoring of the electricity consumption of the buildings that consume the most energy. The results allowed the reduction of energy consumption and provided important and practical guidelines for energy saving, highlighting the domino effect of the changes made in this chapter (Massucco et al., 2023).

In this study, not all GreenMetric criteria are chosen based on research objectives and focus. A strategic decision-making process is carried out. Based on the findings of the literature review, "Energy and Climate Change, Waste and Water" criteria were selected for resource management and cost efficiency, easier to measure, quickly implementable, increasing public awareness and perception by appealing to large audiences, open to innovation and technology, integrating interdisciplinary features and maximizing the contribution of staff. Basically, one of the most important reasons for selecting these criteria is that they are in line with the United Nations Sustainable Development Objectives, especially Objective 7 "Affordable Clean Energy", Objective 12 "Responsible Consumption and Production" and Objective 13 "Climate Action".

These criteria correspond to 49% in order of importance, that is, almost half of the total criteria, and the improvements to be made at this stage will be stimulating and exemplary for other categories as well. Another prospective goal of the study will be a holistic approach that includes all criteria.

3.2. Dataset Collection with IoT

Collecting data with IoT-based sensors for measurements in the field of "Energy and Climate Change, Waste and Water" in smart campuses plays a very important role in understanding and improving the sustainability performance of the campus. Sensor-based data collection provides real-time and accurate information on energy production, energy consumption, waste generation and water use, if available, enabling data-based decision making and targeted sustainability initiatives. Considering the criteria used in this study, it is aimed to ensure that the measurements are taken as instant and fluent data by using sensors with different skills in different ways for each criterion (Table 2).

Table 2. *Data collected from sensors according to GM criteria*

GM Criteria	Sensor	Data Collected
Energy and Climate Change	- Air Conditioning System Related Sensors (Temperature, Humidity, Carbon Dioxide, Movement, etc.) - Energy Meters and Submeters - Lighting Sensors	- Building and facility data on campus - Heat - Carbon Emission Amount - Energy Consumption
Waste	- Weight Sensors (Load Cell) - Occupancy Sensors - RFID Tags - Image Sensors	- Waste Amount - Recycle Rate
Water	- Water Flow Sensors (Flowmeter etc.) - Water Quality Sensors - Sensors for rainwater harvesting (If equipped) - pH Sensors	- Water Consumption - Water Quality

By connecting a collection of sensors or devices to a cloud-based platform and processing the data collected by these devices, data collected by simply framed IoT systems trigger processes that may require user input or automated system responses. A holistic IoT system consists of four main components: sensors or devices, data transmission, data processing, and user interface.

Sensors/Devices collect data from the environment. A device can have multiple sensors; For example, a smartphone has many features such as GPS, camera, accelerometer. Basically, the sensor or sensors collect data from the environment for a specific purpose.

In the Data Transmission Phase, after data is collected from the devices, this data must be transmitted to the cloud. This can be accomplished with a variety of technologies; these technologies may include connecting to the Internet via Wi-Fi, Bluetooth, satellite, low-power wide area networks (LPWAN), or direct Ethernet. The type of connection to use depends on the respective IoT application.

In the Data Processing Phase, when the data reaches the cloud, the related software processes this data and decides to apply the most accurate data preprocessing methods. This may include sending an alert or automatically adjusting sensors or device without requiring user input. However, in some cases user input may be required and that's where the UI comes in.

The User Interface is actually the part where the software communicates with the user. All operations performed by the user are carried out in the opposite direction through the system. In other words, actions are sent from the UI to the cloud and then back to the sensors or devices to make the necessary change.

The exact connectivity, networking, and communication protocols used by web-enabled devices will vary depending on specific IoT applications. IoT is increasingly using artificial intelligence (AI) and machine learning technologies to make data collection processes both simpler and faster. This significantly increases the IoT's ability to collect, analyze and transform data into meaningful information.

The Internet of Things (IoT) represents a network of embedded, interconnected and communicating devices containing sensors and software to collect, exchange and process data. In the context of smart campus sustainability covering selected GM criteria, IoT provides a powerful data collection platform to collect high-resolution, real-time data for in-depth analysis and informed decision-making in the digital twin creation process.

Sharma and Suryakanthi conducted a field study on IoT applications for university campuses in their study in 2015. In this study, the development of a Smart System that optimizes power consumption by analyzing the use of all electrical and electronic devices for the campus is discussed. The proposed system has been developed using a combination of IoT, Wireless Sensors, Network Security, Green information technologies, Big Data Analysis (Sharma & Suryakanthi, 2015). In a study by Khan and Naseer in 2020, a solution was proposed to improve wastebasket management, which is a small and important component of the university waste management system. The basic idea of this project is to provide a healthier and cleaner university environment by using the Internet of Things (IoT) protocol (Khan & Naseer, 2020). Anh Khoa et al. in 2020, a new method is proposed that performs waste management powerfully and efficiently by estimating the probability of filling the waste levels in the bins (Anh Khoa et al., 2020). With the smart green campus vision proposed in the study conducted by Abdulmouti et al., it is aimed to provide people with different innovative systems and to support the development of the country. It has been observed that 63.7% of electricity is saved when electrical energy is obtained from solar energy and innovative applications are applied in the smart green campus, and 0.02 percent of the emissions released into the air and carbon dioxide (Abdulmouti et al., 2022).

3.3. Data Collection for Energy and Climate Change Criteria

Within the scope of Energy and Climate Change criteria, the campus needs to be transformed in areas such as adaptation to climate change, reduction of carbon footprint and smart energy consumption. Some materials are also needed to collect the data set required for transformation in this area. Sensors or devices that provide important data for this criterion are mainly energy meters and sub-meters, heating, ventilation and air conditioning (HVAC) and lighting sensors, SCADA tools and climate sensors (Temperature, humidity and other air parameters).

Energy meters and sub-meters are specified as key components of the energy monitoring infrastructure of the smart campus. By providing precise measurement and monitoring of electricity consumption at various levels, they provide valuable insight into energy usage patterns and identifies opportunities for energy optimization. Energy meters are devices used to measure the total electrical energy consumption of a particular area or the entire building. They are typically installed at the main electrical supply point of the campus or individual buildings. Energy meters provide cumulative energy consumption data, usually measured in kilowatt-hours (kWh) or megawatt-hours (MWh) over a period such as daily, weekly, or monthly. Submeters, also known as branch circuit meters or individual meters, are devices installed below energy meters to monitor energy consumption in more detail. They measure energy use for specific areas, sections, floors or individual equipment within a building. Like energy meters, sub-meters can be integrated with data communication networks for real-time data transmission and analysis.

HVAC and lighting sensors, another source of monitoring and instantaneous data, are an important element of a smart campus' energy monitoring and management system. These sensors enable real-time data collection and analysis from heating, ventilation, air conditioning and lighting systems, providing valuable insight into energy use patterns and opportunities to optimize energy efficiency. Sensors such as "temperature sensor, humidity sensor, occupancy and motion sensors, carbon dioxide sensors" are used in this system, which presents the flowing data to the user with the cooperation of different sensor groups. Thus, in order to keep it in the desired comfort range, operations such as arranging the operation of the instruments according to the indoor temperature, humidity level in the interior, occupancy or movement in the rooms and evaluating the indoor air quality can be performed. In addition to the sensors in this group, which can also be called Climate Sensors, special sensors such as solar radiation sensors and precipitation sensors can be added. These sensors can help campuses adapt their HVAC systems to prepare for extreme weather events and maintain indoor comfort and safety in extreme temperatures, laying the groundwork for applications such as mold prevention, better control of HVAC systems, energy demand forecasts, and climate resilience.

Recently, clean energy investments created by universities on campus have become very popular. It is aimed to build cleaner and more sustainable campuses for the future, both with educational presentations to students and with studies carried out within the scope of sustainable campus goals. By integrating sensors to measure power output from renewable energy sources such as solar panels or wind turbines, universities can gain valuable insight into the performance of these renewable energy systems and their contribution to the overall energy mix of the campus. Thus, added value is provided in areas such as data-driven decision making, reduction of carbon footprint, resource planning and energy management with maximum efficiency.

3.4. Data Collection Water Criteria

Water is getting more and more important in today’s world. With the effect of global climate change, it becomes imperative to take precautions against possible problems in access to clean water. In this context, university campuses can contribute to the goal of sustainability and a more accessible future by making water management smarter and more efficient. At this stage, more efficient taps for water use and sinks with sensitive sensors can be preferred in university campuses. In addition, data providers and water flow sensors, rainwater harvesting sensors and water quality sensors can be used to measure how well the measures taken are working.

Detailed monitoring of water flow is crucial for early detection of potential leaks and excessive water consumption. Also, the management of water distribution and allocation between campus buildings and facilities can be done more efficiently based on this data. Detection of sudden changes in water flow is critical for monitoring leaks in the plumbing system. Real-time water flow data enables campus managers to make informed decisions about water usage, budgeting and sustainability initiatives and facilitates resource tracking. Such practices not only provide significant added value, but also help the campus move up the Green Metric rankings. Therefore, it is of critical importance that the data obtained as a result of measurement and monitoring practices is collected in a healthy and regular manner.

3.5. Data Collection Waste Criteria

In smart waste management systems, various sensors are used to optimize waste collection, encourage recycling and reduce waste in a smart campus, and the data from these sensors provide important outputs for decision support systems.

Smart waste bins can be equipped with fill level sensors that continuously monitor the amount of waste in the bin. These sensors use various technologies such as ultrasonic, infrared or weight-based sensors to measure the fill level. Real-time fill level data allows waste collection teams to optimize their routes and prioritize bins that need to be emptied, reducing unnecessary trips and fuel consumption. Smart waste bins provide more efficient waste collection practices, resulting in cost savings in labor, fuel and vehicle maintenance. Ensuring that the trash cans are emptied at the right time reduces the possibility of overflow.

Separation and recycling sensors are used to analyze waste streams and identify recyclable materials in waste. These sensors can also help identify and remove non-recyclable materials or contaminants that may hinder the recycling process.

Waste generation tracking with weight sensors contributes to waste reduction initiatives by helping to measure the amount of waste produced by specific buildings or areas. It can also evaluate the effectiveness of recycling programs by comparing the weights of recyclable and non-recyclable waste.

3.6. Digital Simulation

Using the data collected from the sensors mentioned in the data set collection section, it is aimed to create insightful and interactive visualizations with the help of visual analytical techniques. This step of the approach plays an important role in creating a closer to the original digital twin, providing important ideas for next steps, and making the right decisions by making data-related transactions healthier.

3.7. Visual Analysis

Data visualization is an important step to give insight into the data collected and to make the preprocessing of various data healthier and better for decision processes.

The purpose of visual analysis for the energy and climate change criterion is to gain insight into energy consumption patterns and their relationship to climate factors. It is aimed to follow the trend with the visualizations, to help identify the peak energy demand periods as well as potential opportunities for energy efficiency and renewable energy integration. The main purpose is to enable decision support mechanisms to work properly by being informed about energy consumption patterns and their relationship with climate factors. Data visualization tools such as different types of graphs, heat maps and scatter plots will be used to show energy consumption trends over time. In order to understand how weather affects energy demand, performing correlation analyzes with climate parameters such as temperature and humidity will help create a healthy digital twin by facilitating the system's response to current and possible extreme situations. In addition, markings on the map to display the distribution of renewable energy sources such as solar panels and wind turbines throughout the campus play an important role in the analysis of data in order to follow these mini power plants and make their future forecasts more reliable.

Visualizations will provide a comprehensive understanding of water consumption patterns in campus buildings and facilities. Visualizations help identify high water use areas, detect leaks and optimize water conservation efforts. We use a variety of graphical and data visualization techniques, such as water flow maps, to show water use patterns over time and spatially. Interactive visualizations allow users to explore water consumption trends in different campus areas and buildings. Comparative visualizations of water use before and after the implementation of conservation measures help evaluate the effectiveness of water conservation initiatives.

As for waste, which is one of the GreenMetric criteria, added value can be provided in understanding waste accumulation patterns, optimizing waste collection routes, and encouraging waste reduction and recycling efforts. Visualization of waste composition and recycling rates is important to give an idea about the effectiveness of recycling programs. Interactive waste collection route maps help optimize collection schedules and visualize data is essential to reduce unnecessary travel and associated emissions.

Visualizations enable data-driven decisions to improve energy efficiency, water conservation and waste reduction strategies, while resource optimization and understanding of consumption and production patterns enable campuses to allocate resources more efficiently, resulting in cost savings and environmental benefits. Additionally, Interactive visualizations will engage the campus community in sustainability efforts, foster awareness and participation, and enable stakeholder engagement.

3.8. Physical World

The definition of the Physical World refers to the campus area where data for all criteria specified in the above sections are collected. Within the scope of the study, it refers to the tangible, observable and measurable aspects of a campus that can be characterized as smart, especially in relation to energy and climate change, water management and waste management. The physical world, which includes the real infrastructure, resources and behaviors in the campus environment, which is subjected to data collection, analysis and optimization through smart technologies, sensors and similar tools, is a real-world representation of the digital twin created.

In order to create a healthy digital twin in this area and to offer more accurate solutions, the infrastructure that will provide the most appropriate data collection should be established. A communication protocol that will contribute to decision support processes between processes such as data analysis and machine learning in the operation processes within the created environment will enable the digital twin process to sit on a stronger infrastructure.

One of the most important purposes of the digital twin within the scope of predictive simulation is to imitate the main system, to bring the perceived results with the analysis of the created working conditions to the system integration and to ensure that the physical world is fully complete. For the physical world, which represents all the physical components of the existing infrastructure in the campuses, and the targeted digital twin, creating the most suitable working conditions for the hardware integrated for data collection and monitoring is a necessity for the healthy functioning of the proposed approach.

4. DISCUSSION AND CONCLUSIONS

Contribution to environmental sustainability requires a more comprehensive and detailed understanding of the ecological impacts of various activities, especially within large institutional structures such as universities. Given their scope, the diversity of their activities and their overall impact, universities have a critical role to play in promoting and implementing sustainable practices. However, the complexity and scale of activities on a university campus make it difficult to monitor and manage the environmental footprint. In addition, the specific focus of this study on blending digital twin technology with GM metrics is a crucial step towards assessing and improving sustainability practices on university campuses. It also creates an opportunity for world universities to be ranked and gain prestige. In other words, the university gains environmental, economic and social benefits by contributing to environmental sustainability policies while at the same time increasing its own prestige.

Establishing such a framework will also have a full benefit-oriented and value-adding effect, given the global focus on achieving the United Nations' Sustainable Development Goals and the Green Deal. With universities, which are very important institutions in society, leading these initiatives, a data-driven, technologically advanced approach can serve as a guide for other institutions and sectors seeking sustainability.

In order for the proposed model to be sustainable and efficient, it should be taken into consideration that the machine learning and optimization techniques to be used in the model should be selected according to the type and size of the collected data. For low-dimensional data studies, statistical models (regression, etc.), which are more efficient in terms of both time and cost, are foreseen to be used. For more complex and larger data sets, depending on the problem, decision tree-based algorithms (XGBosst etc.) or classical artificial neural networks, which have been proven to work well in the literature, can be used. In order to obtain more differentiated and advanced results, advanced models of these networks (LSTM etc.) can be selected depending on the problem content. In addition, scalability and efficiency should be considered in case the size of the data collected in line with GM criteria increases by using IoT technologies. In this case, it is foreseen to use cloud solutions that provide fast and secure access to data, storage of high-dimensional data sets, better management of risks and synchronization advantages.

In conclusion, this study proposes a digital twin architecture to be built within the smart campus concept, combining GM criteria with selected energy and climate change, waste and water issues. It makes a valuable contribution to the growing literature on the application of digital twin technology and IoT in university campuses, with a particular focus on sustainability. This integrated approach has significant potential in the sustainability context by providing universities with the opportunity to assess, plan and monitor their sustainability efforts in a more effective and data-driven manner. The proposed architecture aims to improve the environmental performance of campuses by combining a sensor-based framework and digital simulation with predictive analysis and dynamic decision support protocols, including communication with the physical world. In this context, the potentials of making waste management more efficient, ensuring efficient use of water resources, and identifying efficiency gaps by analyzing energy consumption in real time are highlighted. The proposed framework provides a holistic and data-driven approach to assessing the environmental performance of smart campuses. With its effective solutions on critical issues such as energy and climate change, waste and water management, it is thought to provide an important step towards the construction of environmentally friendly and sustainable educational environments in future educational institutions. The combination of "Digital Twin" technology and the concept of "Green Metrics" will allow smart campuses to make significant progress in environmental sustainability and green consensus. With the spread of such smart campuses in educational institutions in the future, it will be possible to build an environmentally friendly, efficient and innovative educational environment. This study should be considered as an important step in shaping the educational environments of the future.

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