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Sustainability in Warehouse Design and Manufacturing by using Building Information Modeling & Simulation

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Abstract

The objective of this study is to assess sustainability in the design and management processes of a warehouse through a Simulation-based approach, emphasizing the integration of sustainable practices in design and logistical choices. The study created several warehouse models, incorporating mechanical, electrical, plumbing, and fire protection systems. The BIM (Building Information Modeling) methodology, which allows the inclusion of sustainability parameters and data, was integrated with Simulation to provide designers with immediate feedback on the economic and environmental impacts of their models. Additionally, the simulator was designed to optimize indoor logistics from a sustainability perspective, based on the BIM-derived model. This simulator identifies operational logistic parameters to achieve the most efficient and least impactful scenario. The study also explores the integration of BIM design with the Unity simulation environment. This paper contributes to the digitization of sustainability assessment processes through the integration of Modeling & Simulation and BIM methodology, offering a warehouse logistics simulator that opens avenues for future advancements in both design and management spheres.

Keywords: Sustainable Logistics, Modeling & Simulation, Building Information Modeling

1. Introduction

The increasing global awareness of environmental concerns and the pursuit of sustainable development have shifted focus towards integrating sustainability into various sectors, including logistics and warehouse management. Warehouses, as crucial nodes in supply chains, significantly contribute to energy consumption and emissions, making them a key area for implementing sustainable practices. It is estimated that the logistics sector accounts for a considerable share of global greenhouse gas (GHG) emissions, with internal logistics activities — such as warehousing, material handling, and transport — playing a critical role. In Europe, transport-related activities within logistics are responsible for about 25% of total CO2 emissions, and much of this stems from road freight and internal logistics operations (European Environment Agency).

Warehouse operations alone consume a vast amount of energy, contributing to both direct and indirect emissions. Studies have shown that internal logistics activities, including storage and product handling, accounts for up to 10-15% of total supply chain emissions (Perotti et al., 2022). Implementing sustainable practices such as optimizing warehouse layouts, adopting energy-efficient equipment, and integrating automation could help reducing the carbon footprint associated with these operations.

This paper focuses on the sustainability of warehouse operations and design, employing advanced tools such as Building Information Modeling (BIM) and simulation-based approaches. BIM has revolutionized architectural, engineering, and construction practices by incorporating sustainability parameters into design processes. The methodology enables the integration of detailed mechanical, electrical, plumbing, and fire protection systems into the warehouse models. By extending this to logistics management, it becomes possible to simulate and optimize warehouse operations, minimizing the environmental footprint and maximizing efficiency. As the role of warehouses continues to grow within supply chains, there is a need for digitized solutions that assess and enhance sustainability.

In response to these challenges, this study explores the integration of BIM with simulation technologies to optimize warehouse operations. The warehouse models created in BIM allow for a detailed evaluation of sustainability impacts at both the design and operational levels. Additionally, the use of a simulator aids in identifying logistical parameters that influence sustainability, offering insights into the most efficient configurations for warehouse management. The outcomes from this research provide a foundation for future advancements in sustainable logistics and warehouse design, contributing to the growing body of knowledge on sustainable industrial practices.

2. State of the Art

Climate Change represents a critical challenge for our future and commercial activities and logistics shows a deep impact on the environment. The growing interest in Sustainability has significantly influenced the design and management of warehouses which play a critical role in supply chains, and their operations have substantial environmental impacts due to energy consumption, material handling, and emissions associated with logistics activities (McKinnon et al., 2015). Sustainable warehouse design focuses on reducing environmental impacts through energy-efficient building designs, the use of renewable energy sources, and the incorporation of green building materials (Indrawati et al., 2018). The implementation of energy-efficient lighting, heating, ventilation, and air conditioning (HVAC) systems significantly reduces energy consumption in warehouse facilities (Park et al., 2018).

Moreover, sustainable management practices involve optimizing warehouse operations to reduce waste, improve resource utilization, and minimize emissions. Strategies such as cross-docking, inventory reduction, and the use of electric material handling equipment contribute to lowering the environmental footprint of warehousing activities (Gu et al., 2010). Building Information Modeling (BIM) has emerged as a transformative approach in the architecture, engineering, and construction (AEC) industry, enabling the creation of digital representations of physical and functional characteristics of facilities (Eastman, 2011). BIM facilitates sustainable design by allowing stakeholders to analyze energy performance, material usage, and environmental impacts during the early stages of the design process (Azhar et al., 2011).

Studies have demonstrated that integrating BIM in sustainable building design enhances collaboration among project participants, improves decision-making, and leads to better environmental outcomes (Succar, 2009). BIM tools enable simulations that assess energy consumption, daylighting, and thermal comfort, which are essential for designing energy-efficient warehouses (Ilhan & Yaman, 2016).

Simulation technologies have been widely used to optimize logistics and supply chain operations. Discrete event simulation (DES) and agent-based modeling (ABM) are common methodologies employed to model complex warehouse systems and assess the performance of different operational strategies (Bruzzone et al., 2003; Bruzzone et al. 2004).

Simulation allows for the evaluation of various scenarios without disrupting actual operations, enabling managers to identify bottlenecks, test process improvements, and quantify the impacts on efficiency and sustainability (Terzi & Cavalieri, 2004). The use of simulation in warehouse management supports decision-making in layout design, resource allocation, and process optimization, leading to reduced energy consumption and emissions (Bruzzone et al., 2012; Longo, 2011).

The integration of BIM with simulation tools represents a significant advancement in the pursuit of sustainable warehouse design and management. By linking BIM models with simulation software, it is possible to perform detailed analyses of building performance and operational efficiency (Lu & Olofsson, 2014).

Research has explored the coupling of BIM with energy simulation tools to assess the environmental performance of buildings throughout their lifecycle (Deng et al., 2019).

The combination of BIM and simulation provides a holistic platform for optimizing both the physical design and operational aspects of warehouses. This integrated approach facilitates the identification of sustainable solutions that encompass building construction, energy usage, and logistics processes (Sacks et al., 2018).

The integration of sustainable practices in warehouse design and management is crucial for reducing the environmental impacts of logistics operations. Building Information Modeling and simulation tools play pivotal roles in enabling the assessment and optimization of both the physical and operational aspects of warehouses. The convergence of these technologies facilitates a comprehensive approach to sustainability, addressing energy efficiency, material usage, and logistics optimization.

3. Conceptual Model

The conceptual model of this work integrates sustainability into both the design and management of warehouses through advanced simulation tools and Building Information Modeling (BIM). In the initial phase, crucial decisions were made regarding which variables to include in the model and which to exclude, aiming for a balance between completeness and complexity to ensure the model's manageability while providing relevant information. The model integrates a stochastic simulator to represent the operational processes involved in warehouse management, from receiving goods from suppliers to distributing them to points of sale or customers. The framework consists of two main components: sustainable warehouse design and operational logistics optimization.

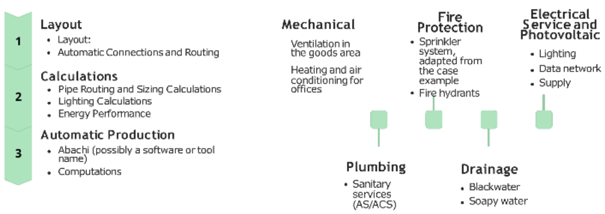

Fig.1 Generale Architecture

The model uses the BIM methodology to create detailed warehouse models that integrate mechanical, electrical, plumbing, and fire protection systems. These models are enhanced with sustainability-related parameters, such as energy consumption, material usage, and environmental impacts, providing a holistic view of the warehouse's sustainability performance. The BIM models allow for real-time feedback to designers, enabling them to evaluate the economic and environmental impacts of various design choices. BIM facilitates the analysis of energy efficiency, resource conservation, and sustainability metrics during the early design phase, ensuring that all sustainability criteria are incorporated into the project. The Simulation component focuses on optimizing indoor logistics operations within the warehouse using simulation tools like Unity. The BIM-derived warehouse models are transferred to a simulation environment where logistical processes, such as material handling, transport, and storage, are analyzed for efficiency and sustainability. The simulator identifies key logistical parameters — such as the layout of the warehouse, the flow of goods, and the use of resources — that impact sustainability. The goal is to minimize energy consumption, reduce emissions, and optimize the utilization of space and resources.

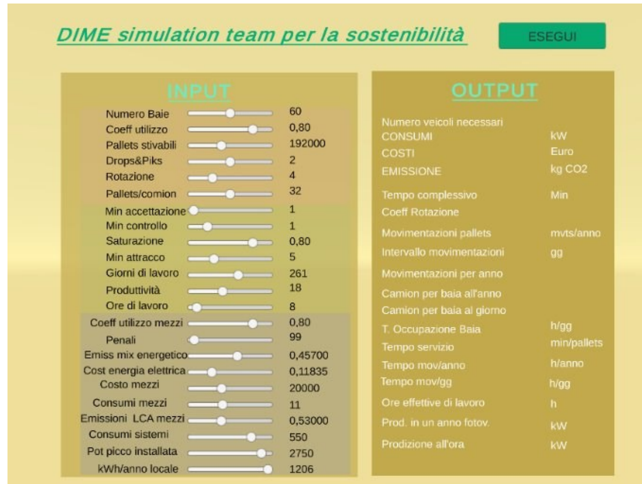

Fig.2 Simulator Dashboard

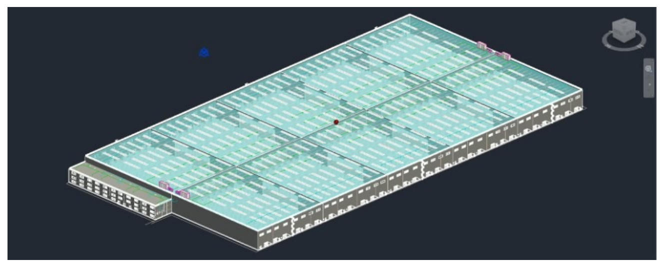

Fig.3 BIM Model

The operational flow starts with trucks delivering goods to the warehouse, where the unloading process takes place. The goods are moved to the reception area for registration and often verification in terms of quantity and quality. From there, the goods are transported by pallet movers to the storage area, where they are organized and stored on shelves or racks. Subsequently, goods are prepared for dispatch to loading bays based on the warehouse's needs. Material handling equipment, such as forklifts and reach trucks, are utilized to move goods from the storage area to the loading bays, from where they are then loaded onto trucks for delivery. These processes are modeled in various system configurations within the simulator, reflecting the layout and elements from the BIM (Building Information Modeling) design.

Key variables, such as the number of loading bays, pallet capacity, rotation frequency, and acceptance times, are factored into the model to analyze different warehouse configurations. These variables are defined with specific ranges, allowing for multiple scenarios to be tested in the simulation. The configuration of storage systems, such as the choice between LIFO (Last In, First Out) or FIFO (First In, First Out) storage logic, significantly affects the efficiency of the warehouse, although, for this particular study, the storage logic was excluded to maintain simplicity. Other operational factors, such as work shifts, directly impact the consumption of resources and the complexity of logistics. By extending working hours or increasing the number of shifts, the need for additional resources may decrease, but energy consumption and personnel costs rise.

Energy consumption data is drawn from the BIM model, which provides detailed information on electrical systems and energy loads. The simulation also takes into account the photovoltaic system integrated into the BIM model, which contributes renewable energy to the warehouse's overall consumption. The system's location is critical in determining the efficiency of solar energy production, as it influences the solar irradiance correction factor.

The simulator considers inputs such as the number of loading bays, warehouse occupancy rates, pallet capacity, vehicle utilization rates, and energy consumption. It outputs key metrics such as the number of vehicles required, total electrical consumption, costs, and CO2 emissions. These outputs allow for comprehensive analysis and help in optimizing the logistics configuration to achieve a balance between operational efficiency and sustainability.

The overall structure of the simulation allows the user to manipulate the input parameters to match the specific needs of a warehouse case study. This results in an analytical framework capable of assessing the impact of various logistical configurations on sustainability metrics like energy consumption and emissions. Furthermore, the simulator supports "what-if" scenarios that explore the consequences of different actions, tracking energy flow, cost variations, and time-related factors. Through mathematical formulas and logical constraints, the simulator enables a deep understanding of the relationship between operational decisions and sustainability outcomes.

4. Results and Discussion

The simulations were carried out to maintain all those values that represent the case study. In the work done the values coming from the BIM model were maintained, such as: number of bays, number storable pallets, the size, the consumption of the systems, and they were maintained as also characterizing all logistical times and commitments. In doing so we tried to maintain the part of the model that describes the physics of the building and the actions that take place is constant inside to be able to concentrate on the sensitivity of the three parameters: the working hours per day, days of work per year and productivity. To obtain information useful for the study from the simulations, a DOE was carried out. In the present study there are three factors of interest: hours of work, productivity and days of work. For convenience they are now called: A, B and C, each with the respective two resulting levels the ranges attributed in chapter six. From the analysis carried out, the results obtained after 150 were deemed sufficiently stable simulations.

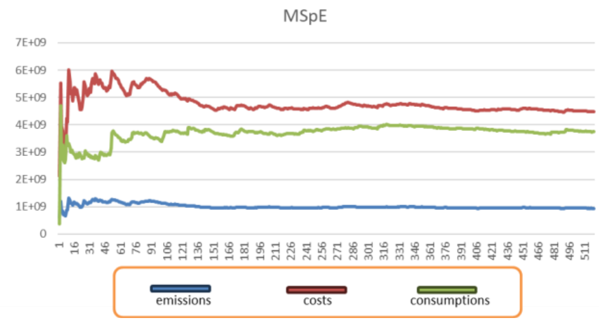

Fig. 2 Mean Square pure Error

The number of hours of work per day influences all four outputs. This positively influences emissions and costs. This is easily traced back to the relative costs of the services of the systems that must be active during the time of activity and to the increase in workers' wages. Although keeping the warehouse open longer hours has a negative effect on emissions a positive effect on consumption, this derives from the fact that as working hours increase two main effects correspond, one linked to the increase in the hours of system activity and services in operation, and the other linked to the reduced need for vehicles to manage the warehouse. In fact, there is a negative effect on consumption and the number of vehicles. This is two to the fact that by distributing the work over more hours, fewer resources are needed at the same time.

This second aspect again has two main effects, the first linked to emissions and the second to consumption. For both, as the number of vehicles decreases, there is a decrease in value. From this analysis it emerges that the advantage in terms of emissions linked to the lower number of means does not cover the increase linked to those resulting from the increase in consumption of the systems. Opposite discussion on consumption, where the advantage obtained from the reduction of vehicles exceeds those linked to warehouse systems.

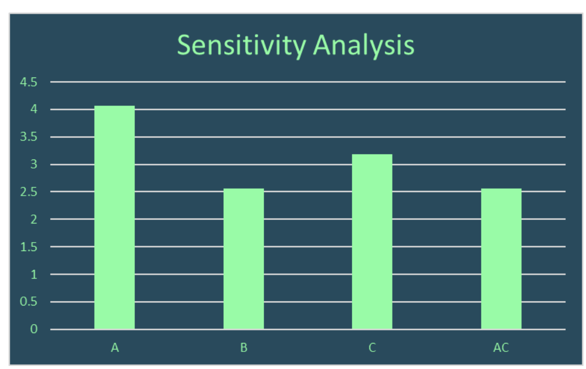

Fig. 3 Sensitivity Analysis: A is working hours, B is Productivity and C is Working days

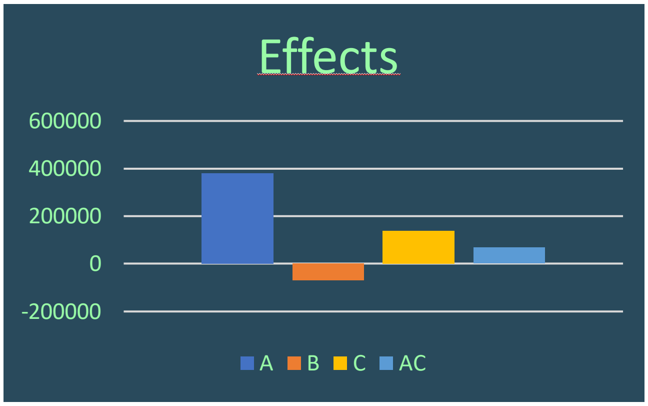

Fig. 3 Analysis of the Effects

5. Conclusions

In this study we had set two main objectives, the first related to digitalization of the processes and methodologies used to assess environmental impact and integrate them into the very promising BIM methodology. A large warehouse was designed on Revit, Autodesk's BIM program with all its associated systems. On this they went to insert for each element inserted into the model, values representing different parameters chosen for the evaluation of the environmental, economic and social impact. Taking advantage of the characteristics of the methodology BIM it was possible to create schedules capable of giving the designer an evaluation Real time impact of what you are creating on the Revit project. The second objective was aimed at the compatibility between the model produced in BIM and the environment of Unity simulation and from the mix of the two worlds create a simulator capable of optimize logistics and warehouse management in order to minimize costs, consumption and emissions. These two worlds were put in communication and the planned simulator was developed, but further developments are expected in the future to make them intimately integrated to have a unique and optimized package. For the simulator, you have created a simulation model that collects some input data from the BIM model and others that are made manageable by the user. Inside the simulator a user interface has been implemented that allows you to compose the model closest to the case study and to identify which combinations of input variables minimize costs consumption and emissions.

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