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Sustainability evaluation of material handling machines in intralogistics: a simulation-based approach

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Abstract: As sustainability becomes a strategic imperative in industrial operations, a comprehensive evaluation of material handling equipment's environmental, economic, and social impacts is essential. This study proposes a novel simulation-based framework to assess and compare the sustainability performance of forklifts and Automated Guided Vehicles (AGVs) in warehouse-to-assembly line operations. Leveraging the Triple Bottom Line (TBL) approach, we integrate technical, environmental (e.g., energy consumption, GHG emissions), economic (operational costs), and social (ergonomics) indicators into a unified evaluation model. Using Siemens Tecnomatix Plant Simulation, we model an automotive intralogistics scenario where components are transported from the warehouse to the assembly stations. Our results reveal that AGVs outperform forklifts in terms of energy efficiency (44% lower consumption) and scalability, but exhibit higher idle times (46.11%). In contrast, forklifts offer greater operational flexibility. The study presents a replicable methodology for dynamic sustainability assessment in intralogistics and provides actionable insights for technology selection, demonstrating how trade-offs between automation and social-centric systems influence sustainable outcomes in manufacturing environments.

1 Introduction

Intralogistics refers to the transportation, storage, and handling of materials within a facility, and is crucial for the efficiency of supply chain operations [1]. As global sustainability becomes increasingly important, the intra-logistics sector must adopt eco-friendly methods that optimize resource utilization while maintaining financial stability in the long run. Improving the sustainability of material handling helps companies meet their social responsibility goals while lowering costs, increasing efficiency, and gaining a competitive edge [2,3]. Moreover, the implementation of advanced technologies such as the Internet of Things (IoT), big data analytics, and artificial intelligence (AI) enables real-time oversight and enhancement of material handling procedures [4]. These technologies facilitate predictive maintenance, enhance inventory management, and improve the accuracy of route planning. This reduces unnecessary movement and energy consumption. IoT sensors can monitor the usage of material handling equipment, allowing for quick repairs, preventing equipment breakdowns, extending its lifespan, and reducing the need for replacements. This is good for the environment.

In the automotive sector, the transportation of supplies from warehouses to automobile assembly plants is a crucial component of the manufacturing process [5]. The efficacy of this procedure directly influences production flow, inventory precision, and system responsiveness [6]. Forklifts and Automated Guided Vehicles (AGVs) are integral to this process. When determining their placement, one should consider not just their mobility but also their influence on other sustainability metrics. A multitude of researchers and practitioners employ the Triple Bottom Line (TBL) framework to obtain a comprehensive understanding of sustainability. This concept categorizes sustainability into three primary components: economic, environmental, and social. Every component is equally vital for attaining equilibrium and enduring influence [7]. The economic aspect examines how long a system can remain financially stable. It focuses on aspects such as low startup costs, energy-efficient operations, and reduced maintenance costs for material handling equipment. The ecological or environmental aspect is about doing the least amount of damage to the planet. This includes reducing emissions when getting raw materials, making equipment easier to recycle, and making parts that are stronger

[8]. The social dimension examines how people utilize technology and systems, considering factors such as safety, comfort, and job satisfaction. In recent years, an increasing number of people have come to realize that protecting the environment often yields better social and economic outcomes. This illustrates the profound connection between these two areas and the crucial importance of being environmentally responsible in achieving full sustainability [9].

Sustainability in warehouse material handling is acknowledged as essential for enhancing operational efficiency and mitigating environmental damage [10]. Recent studies [11,12] mainly concentrate on general logistics performance or particular operational measures, frequently overlooking thorough sustainability assessments for specific material handling operations. This mismatch is especially apparent in contemporary warehouses, where automated technology, such as forklifts and AGVs, is increasingly prevalent. Despite the growing use of these devices, a rigorous framework for assessing them across various sustainability dimensions, technical, environmental, economic, and social, remains absent. Moreover, despite the extensive use of simulation tools for performance analysis, their full potential to enhance sustainability-focused decision-making in intralogistics has yet to be realized. This work presents a simulation-based evaluation system designed to assess the sustainability performance of material handling devices, specifically forklifts and AGVs, within the warehouse-to-assembly-line process. We utilize Siemens Tecnomatix Plant Simulation to construct the simulation model. This study examines the system outlined in section 5, namely the transportation of components from a warehouse (source) to an automotive assembly plant. This study presents a comparative analysis of forklifts and AGVs across various operational contexts, utilizing a comprehensive sustainability framework that encompasses technical, environmental, economic, and social factors. The findings offer actionable insights that support data-driven approaches to improve sustainability in various production settings.

2 Literature review

Intralogistics, which focuses on managing material flows within manufacturing facilities, has experienced remarkable changes with the rise of Industry 4.0 [13]. The introduction of digital technologies has led to the development of smart warehouses and factories, where interconnected systems work together to boost operational efficiency and adaptability [14]. This evolution is often referred to as "Warehouse 4.0," highlighting the utilization of innovations such as the Internet of Things (IoT), cyber-physical systems (CPS), and autonomous robots to enhance warehouse operations. These advancements enable real-time data collection, improve decision-making processes, and optimize resource use, ultimately streamlining intralogistics activities. However, despite these advancements, the integration of sustainability evaluation within such digitalized intralogistics environments remains limited, with most studies focusing primarily on productivity and automation performance rather than holistic sustainability outcomes. For example, a study by [15] focused on improving Automated Storage and Retrieval Systems (AS/RS) through the development of an innovative shuttle vehicle equipped with an integrated picking mechanism. While this system enhances operational efficiency and reduces manual labor, its broader sustainability implications, such as energy usage and life cycle impacts, remain underexplored. Similarly, Venkatadri and Murrenhoff [16] identified the need for a comprehensive framework that incorporates multiple decision-making layers and demonstrated how AI techniques, such as supervised learning and computer vision, can enhance operational efficiency. By emphasizing the value of human collaboration and aligning with the principles of Industry 5.0, the study highlights the role of AI in improving adaptability and innovation in modern logistics environments. Yet, such frameworks often lack explicit environmental or social evaluation metrics. Further studies by [13,17] explored the application of AI in managing internal material flows and echoed the call for structured frameworks that integrate intelligent technologies while maintaining a strong focus on socially centered design.

Material handling machinery is essential for enterprises and industries. Initially, they may appear markedly unlike; yet, a more thorough examination reveals numerous structural and functional commonalities. According to their structure and use, they can be categorized into approximately 15-20 principal varieties, including cranes. The precise quantity may vary according to expert categorizations of particular subtypes (for instance, the distinction between traveling and jib cranes). Figure 1 illustrates a method for assembling several types of material handling machinery**.** The method of material movement is a critical aspect that distinguishes material handling equipment. This is defined by the handling method, which fundamentally shapes the machine’s structure and function. There are four primary methods used in material handling systems [18]:

- Mobile handling units – Goods move on mobile machines; the machine itself defines movement characteristics like speed and route.
- Loading arms – Typically used for short distances, these fixed systems have rotating arms mounted to a wall or floor, equipped with grippers or hoists.
- Transport channels – These fixed or moving systems provide structured pathways for goods, often relying on gravity or other machines for loading/unloading.
- Tractive element systems – Goods are placed on transport carriers (e.g., plates, hangers) pulled along a line by chains, cables, or wheels.

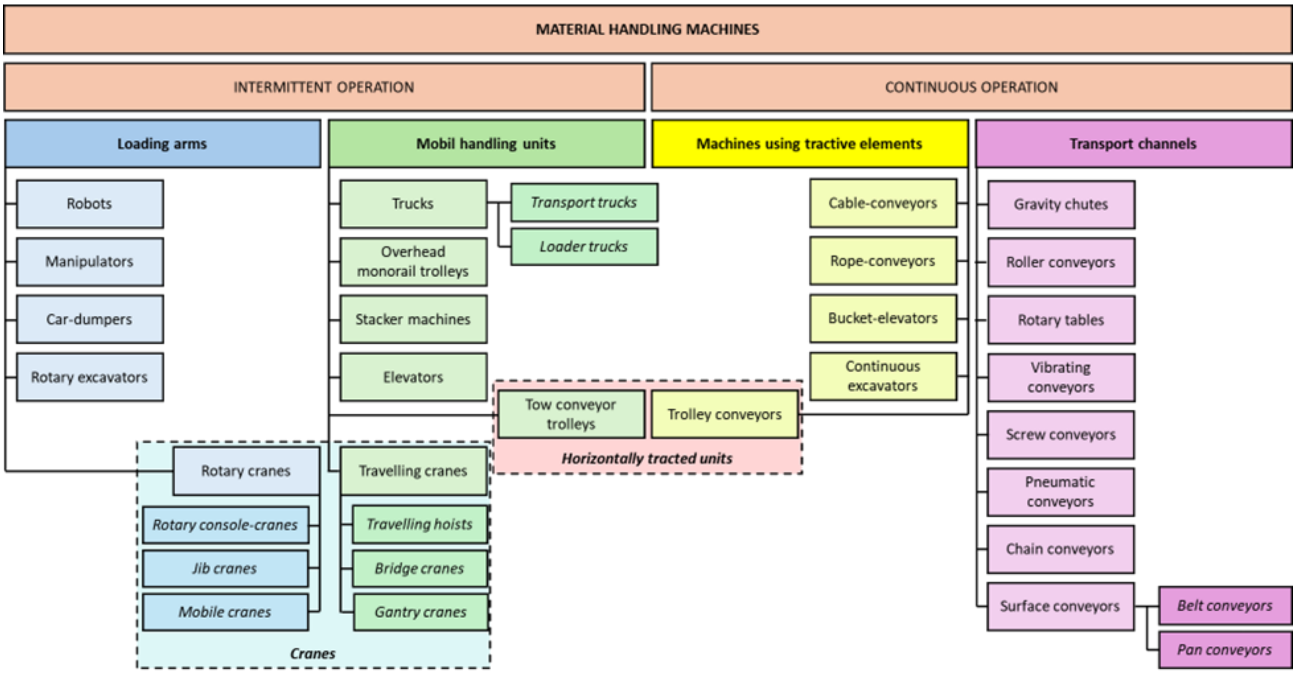


Figure 1 Overview of the main types of material handling machines

Mobile handling units and mobile cranes pose significant sustainability challenges. Mobile devices, on the other hand, require onboard power sources, such as batteries or internal combustion engines. This raises environmental concerns about emissions and resource use. Fixed systems, on the other hand, are usually powered by electricity and used indoors. Material Handling Equipment (MHE) is gaining more attention due to its environmental, economic, and social impacts, as well as its operational efficiency. This is because sustainability is becoming more important in industrial operations. People have used traditional methods, such as Life Cycle Assessment (LCA), to evaluate how these systems impact the environment. For instance, Vujicic [19] conducted a comparative study of diesel and electric cargo-handling machinery in port environments, demonstrating that electric alternatives significantly reduce greenhouse gas emissions, while Erkayaoğlu and Demirel [20] highlighted the context-dependent nature of sustainability assessments by showing that while belt conveyors had greater climate-related impacts, they also had lower acidification than mining trucks. These findings underscore the necessity of scenario-specific and system-oriented evaluation. Building on this, researchers have developed a structured framework that integrates multiple sustainability dimensions, typically organized in tabular or multi-criteria formats, to assess trade-offs across technical, environmental, economic, and social domains. A notable example is [21], who proposed a comprehensive framework for assessing the environmental and social sustainability of logistics halls. Their study addressed a critical gap in the application of Life Cycle Sustainability Assessment (LCSA) within the construction and logistics sectors by incorporating metrics such as worker safety and community impact alongside environmental considerations. This integrative approach offers a valuable foundation for extending sustainability evaluation into other domains of intralogistics.

Further [22] introduced a reverse logistics framework promoting modularity and reusability in MHE to minimize waste and extend equipment lifespan, while [23] advocated for holistic sustainability models that move beyond isolated environmental metrics by embedding social and economic indicators to support more balanced, long-term decision-making in logistics and manufacturing systems. Despite these contributions, current frameworks largely remain static and design-oriented, lacking applicability in dynamic operations where real-time factors, such as energy consumption, emissions, and ergonomic performance, fluctuate in response to process conditions. While Nantee and Sureeyatanapas [24] assessed the broader impacts of Logistics 4.0 technologies on corporate sustainability, their approach focuses mainly on static warehouse infrastructures. It lacks the methodological specificity needed to capture energy use, emissions, and ergonomic impacts in real-time, process-driven contexts. Addressing this methodological gap, the present study introduces a simulation-based, multi-criteria evaluation framework that operationalizes sustainability assessment in a discrete manufacturing environment. By comparing AGVs and forklifts within the warehouse to car assembly station, this research advances the practical evaluation of sustainability in the dynamic intralogistics context. Bridging the theoretical framework with measurable industrial applicability.

3 Methodology

3.1 Research design and approach

This study employs a simulation-based research design to evaluate the sustainability performance of material handling machines within intralogistics, with a particular emphasis on the material flow from warehouse operations to car assembly lines (referred to as Process 5). The methodology consists of four main stages: a comprehensive literature review to identify relevant sustainability indicators; schematic modeling of intralogistics operations; implementation of simulation models using Siemens Tecnomatix Plant Simulation 2404; and a structured sustainability assessment based on technical, environmental, economic, and social criteria.

3.2 Description of schematic

Figure 2 illustrates the step-by-step process of assembling a car and the tools used to transport the materials. Pre-assembly: This is the first step in assembling components, where parts and pieces are grouped together before being transferred to the main assembly line. Car Assembly: This is the first step in assembling a car from pre-existing parts and components. The final step is the inspection and quality control, which occurs when the car is assembled. This document provides a comprehensive overview of each step and the associated intralogistics processes. An automotive manufacturing facility's material handling system comprises numerous interconnected intralogistics operations that facilitate the smooth movement of parts and subassemblies from one stage of production to the next. To make things more efficient, reduce manual labor, and facilitate just-in-time manufacturing, each process utilizes a wide range of machines and automation technologies.

Process 1: Transporting raw sheet metal components from the Sheet Metal Factory to the warehouse requires transferring them to the Pre-assembly section. Automated storage and retrieval systems (AS/RS), conveyor systems, AGVs, and towing trucks enable this transfer. These systems ensure a consistent and dependable supply of raw materials to the pre-assembly line, indicating that upstream component preparation is disrupted only when necessary.

Process 2: The transfer of components and supplementary parts from the warehouse to the Pre-Assembly stage. This procedure employs material handling apparatus, including forklifts, automated storage and retrieval systems, and robotic manipulators. Forklifts are primarily used for the transportation of large and heavy objects. AS/RS and robotic arms enhance the storage and retrieval of diminutive components, hence improving inventory management and minimizing human error.

Process 3: Transporting from Sheet Metal Factory to Car Assembly Line: Specific sheet metal components can be transported directly from the mill to the assembly line, thereby bypassing the pre-assembly phase. This is particularly significant for larger components that do not necessitate assembly. Overhead cranes typically transport heavy components, while lightweight or medium-sized components are conveyed by AGVs or towing tractors. This adaptability enhances the modularity and efficiency of the manufacturing process.

Process 4: The transition from Pre-assembly to Car Assembly involves transferring pre-assembled components from the pre-assembly line to the final automobile assembly line. A mix of conveyor belts, robotic arms, automated AGVs, and forklifts is necessary to achieve this. These technologies work together to ensure a consistent supply of components in the primary assembly zone. This facilitates seamless and effective car assembly processes.

Process 5: The transfer of components or subassemblies from the warehouse to the Car assembly line is a pivotal phase in logistics. This procedure employs forklifts, AS/RS, and AGVs to guarantee the timely and accurate delivery of necessary components. This process must be exceptionally efficient to uphold the total manufacturing schedule. This is particularly crucial for punctual deliveries, as any delays can directly affect assembly line operations.

Intralogistics plays a crucial role in ensuring that materials and parts are moved efficiently between the different stages of the car assembly process. The use of various material handling machines, such as conveyor belts, AGVs, forklifts, and AS/RS systems, ensures that each stage is supplied with the necessary components without delay, thereby reducing downtime and increasing overall productivity. Proper synchronization of these intralogistics processes is essential for maintaining a smooth and continuous production flow, ultimately leading to the efficient assembly of the final product, the car.

This study exclusively examines Process 5, the internal material handling operation responsible for transporting components from the warehouse to the vehicle assembly line. The decision to segregate this procedure was grounded in both strategy and pragmatism. In automotive production, Process 5 is crucial since it represents the final stage in intralogistics, preceding the assembly of components in the final assembly process. Assembly lines rely on just-in-time (JIT) and just-in-sequence (JIS) systems; therefore, any inefficiencies or delays can directly impact the assembly line, leading to costly downtime and production losses. Concentrating on this phase enables the identification of critical operational bottlenecks where enhancements can yield considerable benefits. Moreover, Process 5 possesses a well-delineated and reproducible scope, rendering it optimal for high-fidelity simulation with Siemens Tecnomatix Plant Simulation. This regulated setting enables the precise measurement of sustainability metrics, including energy consumption, emissions, and temporal efficiency, particularly when evaluating the performance of AGVs and forklifts. This emphasis addresses a notable deficiency in the literature, as the majority of research examines intralogistics as a whole, rather than the distinct issues posed by each subprocess. From a pragmatic standpoint, Process 5 provides readily available data and operational transparency, enabling accurate modeling and real-world applicability. This paper provides theoretical insights and practical methods for enhancing sustainability in smart manufacturing, with a focus on this crucial link in the logistics chain.

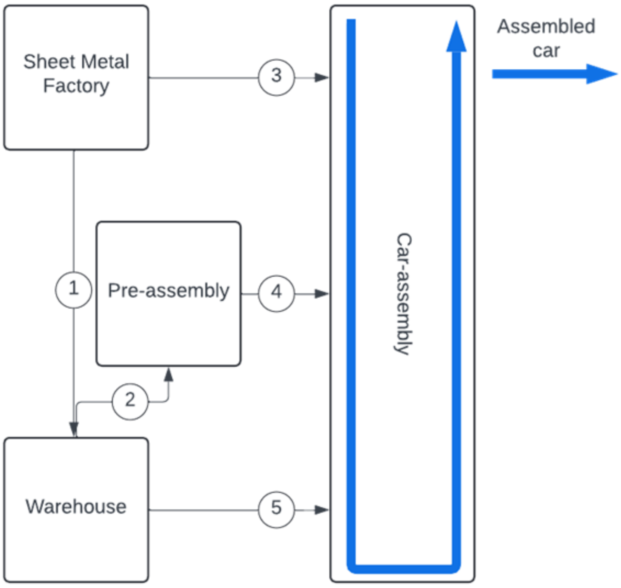


Figure 2 Schematic of car assembly plant

3.3 Simulation environment setup

The simulation environment was constructed using Siemens Tecnomatix Plant Simulation 2404, aligning with [25] methodology for modeling intralogistics in flexible manufacturing systems. Similar to their study, our model is a robust software platform for modeling and analyzing logistics systems and industrial processes, aligning with their research. The primary aim of the model is to replicate Process 5, which involves transferring materials from a Warehouse (source) to several Automobile Assembly Stations (Station 1–Station 4). The emphasis is on employing forklifts and AGVs as the principal intralogistics transporters. In the simulation, forklifts are programmed to retrieve components from a central loading location designated as “PartSequence,” representing the warehouse, and thereafter deposit them at designated unloading stations along the assembly line. Each station functions as a distinct auto assembly workplace, with forklifts adhering to a specified routing logic to guarantee prompt and equitable distribution. Key simulation parameters include vehicle routes, travel velocities, handling durations, and protocols governing the interaction between forklifts and workstations. Forklifts are programmed to traverse a circular route and halt at certain locations upon receiving a signal indicating their necessity. The model employs the Methods modules to incorporate control logic that manages task execution and component sequencing. The simulation output panel indicates that comprehensive statistics, including work time and waiting time, are gathered.

3.4 Sustainability evaluation

Sustainability evaluation in warehouse material handling is essential for enhancing operational efficiency while reducing environmental and societal impacts. This study introduces a systematic, simulation-driven evaluation approach that integrates technical, environmental, economic, and social aspects to assess the sustainability performance of material handling systems, particularly AGVs and forklifts. The methodology utilizes Siemens Tecnomatix Plant Simulation and is supplemented by three comprehensive assessment tables that facilitate multidimensional comparisons of handling operations across various production frameworks.

Although prior studies, such as [24] have assessed the impact of Logistics 4.0 on sustainability in automated warehouses, their frameworks primarily address static logistics infrastructures and broader corporate performance indicators. Similarly, previous research like [21] has contributed to the evaluation of environmental and social sustainability within logistics halls. However, these frameworks fall short of offering a directly applicable and operationalized methodology for assessing the real-time sustainability performance of automated material handling systems in dynamic, intralogistics environments.

To address this methodological gap, the present study extends the principles of LCSA into the operational domain of internal logistics. By incorporating a simulation-based, weighted multi-criteria decision-making approach, this research enables the evaluation of critical sustainability indicators, such as energy consumption, GHG emissions, ergonomics, and cost efficiency, based on actual operational performance. This methodological contribution bridges the gap between theoretical sustainability models and the practical needs of manufacturing systems, providing a robust and adaptable tool for sustainability-driven decision-making in material handling operations. Consistent with the methodology of Garbie [26], the relative weights between sustainability dimensions were treated as flexible parameters to analyze different scenarios and their impact on the overall integrated sustainability index.

Table 1 lists various evaluation types and assigns a score to each, reflecting their suitability and risk level. A score of 4 indicates that the equipment is appropriate, operates effectively, and presents no hazards. A score of 1 indicates that the equipment is unsuitable, costly, and poses a significant danger. This approach enables firms to prioritize enhancements to their material handling processes according to identified needs and risks. Table 2 offers a comprehensive examination of the characteristics and categories employed to assess sustainability. Technology, environment, economy, and society constitute these dimensions. The technology dimension examines the machinery utilized, whereas the environment dimension assesses energy consumption and its elasticity in relation to volume change. The economic aspect examines the expenses associated with operating a firm without energy, while the social aspect considers ergonomics, which is crucial for employee safety and comfort.

Table 1 Categories

Value	**Categories**					
	A	B	C	D	E	F
4	Well-suited Equipment	Excellent	very small	very low	Excellent	Zero Risk
3	Minor Modification	Good	Small	Low	Good	Low Risk
2	Major Modification	Fair	Medium	Medium	Fair	Medium Risk
1	Not Suitable	worst	High	High	worst	High Risk

Table 2 Categories and criteria

Dimensions	**Categories**
Technology	A. Machine types
Environmental	B. Energy Consumption
	C. Greenhouse Gas Emission
	D. Elasticity of Energy on Volume Change
Economic	E. Operational Cost without energy consumption
Social	F. Ergonomics

Table 3 categorizes transportation-type material handling equipment into four performance tiers, ranging from Level 1 (Worst) to Level 4 (Excellent). These values are determined by daily energy use (measured in joules) and operational expenses, excluding energy expenditures. The emphasis is on labor and maintenance expenditures. This methodology enables a comprehensive evaluation of the equipment's efficiency, economic implications, and potential avenues for improving environmental sustainability. The data in the table is based on hypothetical operational scenarios and standard specifications prevalent in the industry, including typical power ratings, duty cycles, manpower demands, and maintenance schedules. These assumptions aim to delineate realistic operational parameters for prevalent transportation equipment, including forklifts, tow trucks, and AGVs. The specific values may fluctuate based on the context, but the levels provide a systematic and comparable method for evaluating equipment performance in sustainability-oriented decision-making. Organizations can perform a thorough examination of their material handling procedures by integrating these tables into the evaluation framework. This systematic method not only identifies avenues for enhancing performance but also ensures that daily operations align with overarching sustainability objectives. Processes that consume excessive energy or generate elevated greenhouse gas emissions can be enhanced or altered, for instance, by transitioning to machinery that utilizes reduced energy. Moreover, social factors, especially ergonomics, are essential for ensuring worker safety and well-being. By emphasizing ergonomic design in material handling equipment, organizations can reduce the risk of injuries, increase productivity, and create a more favorable work environment.

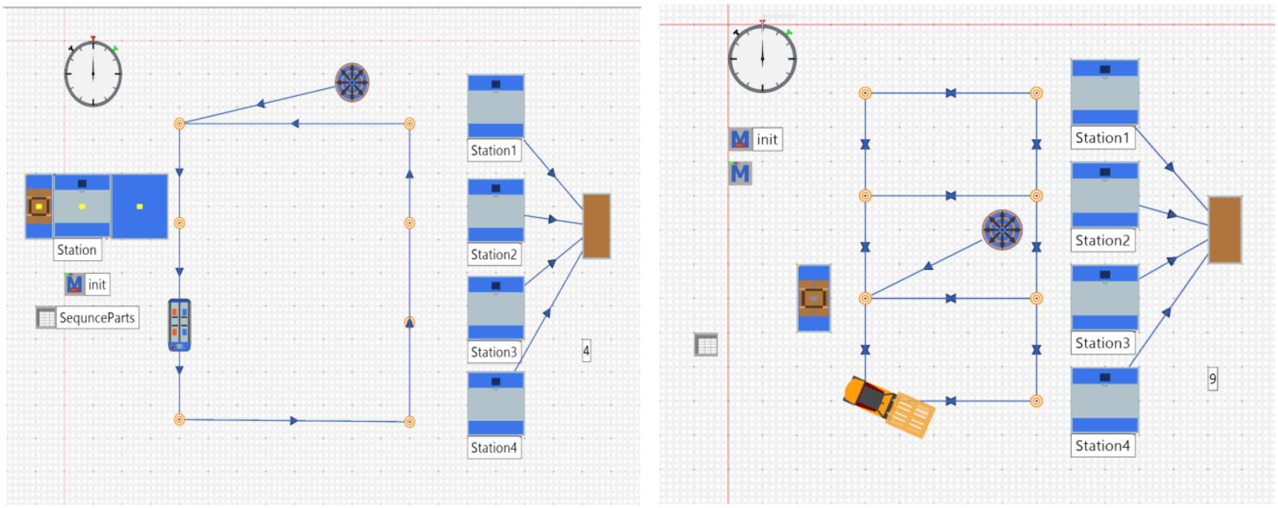
Table 3 Evaluation of Energy Consumption and Operational Cost, excluding energy consumption

Performance Level	Energy (J/day)	Labor (€)	Maintenance (€)	Op. Cost excl. Energy (€)
Level 1 (Worst)	more than 9.75×10^6	220	70	201-290
Level 2 (Average)	6.26×10^6 - 9.75×10^6	150	50	126-200
Level 3 (Good)	3.26×10^6 - 6.25×10^6	95	30	71-125
Level 4 (Excellent)	0-3.25×10^6	55	15	0-70

4 Results and discussion

4.1 Simulation

Process 5 in this study models the material handling operations between the warehouse (source station) and four car assembly stations, using two different transport methods: AGV and forklifts. Both scenarios are built using Siemens Tecnomatix Plant Simulation to evaluate their performance and sustainability under identical layout conditions. This modelling approach enables a direct performance and sustainability comparison within a controlled intralogistics environment, aligning with methodologies applied in prior works such [24] those who emphasize simulation-driven sustainability evaluation for logistics 4.0 systems. Figure 3a illustrates that the vehicle in the AGV scenario operates within a closed-loop system, commencing at the buffer zone. It can load a maximum of four items from a source station via a regulated loop, ensuring optimal load efficiency. Upon completion, the AGV adheres to a designated route marked by virtual checkpoints to transport the components to its station. Following each delivery, it momentarily halts before emptying, subsequently retracing a new route to initiate the next cycle. This method aims to be ongoing, enabling us to continually evaluate the AGV's efficiency in terms of travel duration, load capacity, idle time, and energy consumption. Conversely, the forklift scenario (Figure 3b) employs the identical material flow but adopts a more adaptable and dynamic handling methodology. The forklift retrieves one component at a time from the source and determines its destination according to the component type (A, B, C, or D). The destinations are Stations 1 to 4. This decision-making process resembles the manner in which a human would react to diverse commands. Upon arrival at the designated station, the forklift discharges the component and autonomously proceeds to the subsequent component. Forklifts tend to consume more energy and exhibit prolonged idle periods compared to AGV, particularly during manual operation. This simulation directly contrasts the merits and drawbacks of both methodologies by replicating them inside an identical context. AGV provides efficient and reliable pathways with minimal human intervention, resulting in uniform performance and reduced labor requirements for personnel. Conversely, forklifts exhibit greater adaptability and short-term cost efficiency, although they may consume more energy and necessitate a larger workforce in the long run. AGV, particularly electric variants, are typically more sustainable and environmentally benign. Conversely, forklifts may present challenges related to pollution, ergonomics, and safety.



(a) (b)

Figure 3 Simulation layout (a). AGV (b). Forklift

The simulation results from Tecnomatix Plant Simulation reveal critical insights into the performance of the AGV-based transport system. The AGV exhibited 44.02% occupancy and 46.11% idle time, indicating underutilization despite completing 316 transports over a distance of 2649 meters. Meanwhile, the Drain station showed a 72.96% waiting rate, suggesting inefficiencies in material flow, with an average exit interval of 11.29 seconds and a total throughput of 316 units. The high idle time at the Drain contrasts with the AGV's availability, highlighting a bottleneck in upstream processes, likely due to unbalanced task allocation or delays in workstation operations. Prior work has demonstrated that AGV idle times can be reduced through adaptive scheduling and real-time dispatch algorithms that account for production variability and congestion. When such strategies are applied, AGVs substantially reduce non-value travel and energy consumption [27]. However, the simulation results demonstrate the performance limitations of a single-item forklift system. The forklift spent nearly equal time empty (50.14%) and occupied (49.86%), completing 144 transports over a distance of 2,736 meters. The Drain station processed only 143 units with 52.44% waiting time, indicating significant idle periods between deliveries. The average exit interval of 24.98 seconds and throughput of 2.38 units/minute reveal constrained material flow due to the forklift's single-item capacity.

4.2 Sustainability evaluation

This study develops a comprehensive framework for a comparative sustainability assessment of material handling systems, specifically AGV and forklift. The evaluation is structured around six criteria: machine types, energy consumption, greenhouse gas emissions, energy elasticity in response to volume changes, operating costs, and ergonomics. These criteria are selected to capture the technical, economic, environmental, and social dimensions of sustainability. A systematic scoring framework (1-4), grounded in empirical and simulation data, was employed to assess each criterion. Reflecting established Multi-Criteria Decision-Making (MCDM) principles, each criterion was assigned an importance weight to articulate its relative priority within a sustainable intralogistics context, a methodological approach aligned with contemporary research practices [28]. The weighting scheme is justified as follows: GHG emissions received the highest weight (4), a priority consistent with the emphasis in sustainability literature on their critical environmental impact and escalating regulatory significance [29]. Energy consumption and operating costs were assigned a weight of 3, acknowledging their substantial combined pressure on both economic viability and environmental performance, where optimization is crucial for long-term operational resilience. Machine type and ergonomics each carried a moderate weight of 2. The former dictates process efficiency and system adaptability, while the latter incorporates the social dimension by evaluating operator safety and physical strain, particularly in manual systems [28]. Finally, energy elasticity, which measures the responsiveness of energy use to production volatility, was assigned a weight of 1, recognizing its role as a secondary but relevant factor in dynamic operational environments. By integrating these weighted criteria, this holistic framework facilitates data-driven decision-making, enabling a balanced evaluation that enhances the resilience and sustainability of intralogistics networks.

The total scores for AGVs and forklifts are 48 and 43, respectively, indicating that AGVs are slightly better. Based on 24-hour simulations of journey distance and throughput, AGVs use less energy (Good vs. Fair) and have less energy elasticity (Low vs. High). Both technologies perform similarly in key areas, such as greenhouse gas emissions (Very Low) and ergonomics (Low Risk). This means that they adhere to safety and environmental regulations. Both systems have high operational costs (for both Fair), which means they could be improved. The findings indicate that AGVs are optimal for energy-sensitive tasks, whereas forklifts are preferable when emissions and ergonomics take precedence. This study highlights the need for further optimizations to enhance cost efficiency and scalability in sustainable material handling solutions for industrial settings. Subsequent research may explore hybrid models or empirical case studies to validate these findings across various operational situations. Table 4 presents the outcomes of the sustainability evaluations for AGVs and forklifts. The evaluation is based on six sustainability criteria, each of which is assigned a weight to indicate its importance. When given a weight of 4, both AGVs and forklifts release the same amount of greenhouse gases. This means they each get 4 points, for a total of 16 points. AGVs get a score of 3 (9 points) for energy use, while forklifts get a score of 2 (6 points). This means that AGVs are better at saving energy. For both categories, the costs of running a business, excluding energy use, are assigned a weight of 3. Each category receives 2 points, totaling 6 points. Machine types and ergonomics, both weighted at 2, produced comparable outcomes for the AGV and forklift, scoring 4 (8 points) and 3 (6 points), respectively. Nevertheless, the AGV demonstrated superior adaptability to fluctuations in volume, a factor of lesser significance with a weighting of 1, achieving a score of 3 (3 points) in contrast to the forklift's score of 1 (1 point). The AGV got a score of 48 points, which was better than the forklift's score of 43 points. This means that the AGV is more sustainable, particularly in terms of energy efficiency and scalability. Both types of vehicles excel in key areas such as emissions and comfort. Still, AGVs may be better suited for projects that aim to conserve energy and remain flexible in their operations.

The comparative sustainability evaluation results reveal that, consistent with [1,30] AGVs achieve superior energy efficiency under repetitive, high-volume scenarios; however, they suffer from high idle times and utilization losses unless dispatching and load management are optimized. Meanwhile, forklifts maintain high flexibility in handling variable tasks but achieve lower throughput and higher energy per unit moved, aligned with findings from [30]. These trade-offs underscore that automation alone does not guarantee sustainability superiority; rather, system utilisation, volume profiles, cost structure, and human-machine interaction must all be optimised.

Table 4 Sustainability evaluation

Category	Weight factor	AGV		Forklift	
		value	Weighted value	value	Weighted value
A. Machine types	2	4	8	4	8
B. Energy Consumption	3	3	9	2	6
C. Greenhouse Gas Emission	4	4	16	4	16
D. Elasticity of Energy on Volume Change	1	3	3	1	1
E. Operational Cost without energy consumption	3	2	6	2	6
F. Ergonomics	2	3	6	3	6
			48		**43**

5 Conclusions

This study developed a simulation-based framework to evaluate the sustainability of material handling machines in intralogistics, specifically comparing AGVs and forklifts in an automotive warehouse-to-assembly line process. By employing a TBL approach that incorporated technology, environmental, economic, and social indicators, the research provided a comprehensive assessment of these technologies under realistic operating conditions. The results demonstrated that AGVs achieved superior performance in terms of energy efficiency and scalability, making them particularly suitable for operations that prioritize environmental sustainability and high throughput. However, the analysis also revealed that AGVs exhibited significant idle time (46.11%), indicating potential underutilization that could offset their energy advantages in specific scenarios. Forklifts, although less energy-efficient, offer greater flexibility and lower upfront costs, suggesting their continued relevance in operations that require adaptability or face capital constraints. Both technologies performed comparably in terms of greenhouse gas emissions and ergonomic considerations, meeting baseline sustainability standards.

Methodologically, the study advances sustainability evaluation through dynamic simulation, enabling the capture of real-time performance data beyond conventional static assessments. Nonetheless, the limitations include reliance on a single layout configuration and simulation-derived data, which may restrict generalizability. Future research should extend this framework using empirical validation and LSCA to incorporate broader boundaries. The integration of AI-driven predictive modelling and digital twin technologies offers potential for adaptive fleet management, real-time optimization, and predictive maintenance. Moreover, exploring hybrid fleets and the social dimension of sustainability aligned with Industry 5.0's human-centric principles can yield deeper insights into resilient, intelligent, and sustainable intralogistics design.

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Review process

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