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Advanced Modeling and Simulation of Hybrid Electric Special-Purpose Machines: Enhancing Sustainability and Efficiency in Logistics

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Advanced Modeling and Simulation of Hybrid Electric Special-Purpose Machines: Enhancing Sustainability and Efficiency in Logistics

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Abstract: This paper presents an advanced and highly sophisticated model for hybrid electric special-purpose machines (HE-SPMs), specifically engineered to significantly enhance sustainability and efficiency in logistics operations. The primary objective of this model is centered around the optimization of energy flow, a feature that has undergone extensive testing and validation to ensure its reliability and effectiveness. The inclusion of auxiliary systems such as cutting-edge cooling and control systems further elevates the overall performance capabilities of the HE-SPMs, resulting in a seamless integration within various industries. By implementing these enhanced systems, substantial reductions in energy consumption and operational costs have been observed and well-documented through compelling case studies in both the construction and transportation sectors. The holistic nature of this approach impeccably aligns with the ongoing global efforts aimed at combating the pressing issue of climate change. By focusing on the development and utilization of eco-friendly technologies, this model actively contributes to the mitigation of harmful environmental impacts and promotes sustainable practices within the logistics industry. To further reinforce the efficacy of this remarkable model, future research endeavors will concentrate on expanding its applications to encompass other logistics domains.

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1. Introduction

Caterers exploit a broad range of special-purpose heavy-duty machines to meet widespread logistics and production processes concerning mission-critical services on the ground, from the airplane to the meal tray in the catering facility. However, the environmental characteristics of such services require addressing increasingly stringent problems linked to sustainable development. Specific technological innovations are being developed in a considerable number of programs to enhance energy and environmental efficiency in both transfer processes before production lines and processing operations in the catering area. Such encouraging results justify an ever-growing interest in the study of innovative technological solutions that rely on the synergy between new groundbreaking logistics systems, architectures, and solutions with advanced energy management strategies, fostering the use of sustainable sources. Efforts to combine advanced modeling, simulation, and control strategies open up the possibility to propose and then discuss reliable, effective, and sustainable improvements in logistics within facilities associated with caterers, airlines, or the producer within ultra-modern concepts of the third-party provider. This paper focuses on advanced and hybrid rather than classical and dedicated approaches as the path to a beneficial redesign of logistics systems in a sustainable manner. The use of new and advanced tools and methods helps caterers to draw valuable information from the operational environment and, creatively, to propose the most suitable solution for ensuring the quality of services. This is particularly interesting, as advanced modeling is considered a flexible bridge that connects logistics-related operations and sophisticated energy management. It is particularly interesting in systems that increasingly leverage the characteristics of hybrid machines.

1.1. Background and Rationale

Heavy-duty special-purpose machines are highly interconnected with any type of reactive logistic operations, such as the ground handling of aircraft or the automatic container loading and unloading on board a ship. These processes refer to the hierarchically lower levels of a multi-level logistic system in which the floor level is connected to the higher decision-making and scheduling levels [16]. It is common to have problems in increasing the efficiency of physical tasks that cannot be efficiently managed by software, typically in situations with short response times, interferences, random disturbances, small production series, small evaluation intervals, uncertainties about the load characteristics, and other unpredictable and quasi-stochastic local environment conditions. Operations in reactive logistics are subjected to disturbances that typically affect their efficiency and the achieved performances [23]. These disturbances arise from the inner process variability in carrying out technical operations and from the surrounding interference due to unexpected collisions or unexpected movement of the entities that are not a part of the logistic process itself. Such entities carry unknown loads with unpredictable vehicle local environment conditions that cannot be discovered with a time equal to the characteristic time related to a possible lack of performance. In order to address these challenges, robust and reliable strategies have been developed to optimize the performance of heavy-duty special-purpose machines in reactive logistics. One approach is to implement advanced control and monitoring systems that enable real-time adjustments and predictive maintenance [2]. By continuously monitoring the operational parameters and analyzing the data, potential issues can be identified proactively, allowing for timely interventions to prevent system failures or inefficiencies [9]. Additionally, the integration of artificial intelligence and machine learning algorithms can further enhance the capabilities of these systems, enabling autonomous decision-making and adaptive optimization. Another aspect that contributes to improving the efficiency of reactive logistic operations is the design and engineering of the physical infrastructure [14]. This involves considering factors such as spatial layout, flow patterns, and equipment configuration to minimize bottlenecks, streamline processes, and optimize resource utilization [4-13]. By analyzing the traffic patterns and workflows, it is possible to identify potential areas of congestion and implement appropriate measures to mitigate their impact. Additionally, the use of advanced materials and technologies can enhance the durability and performance of the machines involved in the logistic operations, reducing maintenance requirements and downtime. Furthermore, collaborative efforts and partnerships among different stakeholders play a crucial role in achieving efficient and effective reactive logistics [1]. Close cooperation between machine manufacturers, logistics service providers, and end-users can lead to the development of tailored solutions that address specific operational challenges. By sharing expertise, knowledge, and resources, it becomes possible to optimize the entire logistic system, from the machines and equipment to the processes and workflows. Additionally, continuous feedback and communication channels facilitate the identification of improvement opportunities and the implementation of corrective actions in a timely manner. So, heavy-duty special-purpose machines are integral components of reactive logistic operations, supporting various tasks and processes that require real-time adjustments and adaptability [44]. Overcoming the challenges associated with these operations requires a multi-faceted approach, combining advanced control and monitoring systems, optimized physical infrastructure design, and collaborative efforts among stakeholders. By implementing these strategies, the efficiency, reliability, and performance of reactive logistics can be greatly enhanced, ultimately leading to improved productivity and customer satisfaction.

In order to be efficient, the logistic operations need real-time capabilities, flexible, robust, scalable, and modular architecture, which should be able to consistently enforce the "logistic process" constraints [6]. So, avoiding possible disservice due to the fact that they can be carried out in largely autonomous and parallel—when possibly concurrent—tasks with significant edge computational

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capabilities and a real-time local area network that can also exchange information and retrieve part of the scheduling and execution algorithm. In other words, the key enabler for the efficient management of reactive logistic operations is the intrinsic reactivity of the machines employed in such phases [53]. This is why the focus is on designing a class of hybrid electric heavy-duty special-purpose machines particularly suitable for the ground handling operations required to manage air cargo logistics to increase the sustainability in airport operations. The driving idea is to make large cargo facilities greener not only at the warehouse level but especially at the "door" level, by improving the performance of hybrid-electric special purpose vehicles used for cargo handling.

1.2. Research Aim and Objectives

The focus of this research lies in providing a detailed understanding of the operational principles and limitations in the complex and dynamic conditions of hybrid electric propulsion for specialized autonomous ground vehicles with respect to tasks frequently encountered during logistic processes, and in the advancement of modeling and simulation technologies for its incorporation in efficient computational tools [11]. Given the significant progress in the design and development of hybrid electric vehicles targeted mainly for passenger transportation, very few relevant reviews related to off-road, construction, military, and special-purpose machines have been published. Even fewer reviews concern the application of hybrid electric propulsion for special-purpose vehicles in the logistics sector. As a result, a significant research problem arises: the lack of detailed system-level understanding of how such powertrains perform in off-road logistic environments.

Despite the remarkable technological advancements achieved to date, there are multiple critical issues that currently limit such vehicles from facing the challenges encountered during frequent and various logistics tasks. Design efforts primarily target the achievement of highly specialized parameters, and the hybrid electric propulsion used is specially developed for the execution of these tasks only, which results in poor adaptability and low energy efficiency in logistics applications [9, 54, 45, 37]. Thus, from the logistic company's point of view, such vehicles are relatively limited with respect to the capabilities to enhance the performance of electronic and robotized systems, the relatively high operating energy costs, the relatively moderate energy storage capacities, and the dependence of the state of charge on the selected logistic route and/or environmental conditions [3]. These limitations prevent logistics companies from being quickly able to handle spontaneous changes and requests from customers [5]. Additionally, the lack of adaptability of these vehicles poses a significant challenge when it comes to addressing the evolving needs of the logistics industry [24]. As technology continues to advance at a rapid pace, the requirements for efficient and flexible transportation solutions are constantly changing [13]. However, the current limitations of these vehicles make it difficult for logistics companies to keep up with these changes and adapt their operations accordingly [17]. Furthermore, the relatively high operating energy costs associated with these vehicles can have a significant impact on the profitability of logistics companies. In today's competitive business landscape, reducing costs and maximizing efficiency are crucial for long-term success. However, the reliance on costly energy sources hinders logistics companies from achieving these goals and staying competitive in the market. Moreover, the relatively moderate energy storage capacities of these vehicles limit their ability to operate for extended periods without requiring frequent recharging. This not only increases the downtime of the vehicles but also adds to the overall operating costs [18]. Logistics companies need vehicles that can efficiently store and utilize energy to ensure uninterrupted operations and minimize unnecessary expenses [22]. Additionally, the dependence of the state of charge on the selected logistic route and/or environmental conditions further complicates the logistics process. The varying energy demands based on different routes and environmental factors make it challenging for logistics companies to plan and execute their operations effectively. This dependency on external factors hampers the overall efficiency and reliability of the vehicles, hindering the ability of logistics companies to provide reliable and timely services to their customers. Shortly, while there have been significant technological advancements in the field of logistics vehicles, there are still critical issues that need to be addressed. The limitations in adaptability, energy efficiency, storage capacity, and dependence on external factors pose challenges for logistics companies in meeting the ever-changing demands of the industry. Overcoming these limitations will require innovative solutions and advancements in technology to ensure that logistics companies can effectively handle spontaneous changes and requests, reduce operating costs, optimize energy usage, and provide reliable and efficient services to their customers.

2. Materials and Methods

The development of the technical and operational design model is carried out in several stages. At the first stage, methods are developed to analyze the operation of each component of SPM L. In this case, the diagnostic matrix of the main process of the said components is supplemented with elements of the friction power losses. In our case, the formation and nature of impact power losses is an additional diagnostic aspect for the technological elements of drum and blade tools and adds to specific power losses. In efficiency terms, the formation of specific energy has an effect, and in terms of additional diagnostics, monitoring the depth of wear of the tool in technological steering [26, 27, 29, 30]. The next stage was the development of a lowering function that synchronizes the electrical loads of the design processes calculated for the formation of specific power losses and specific energy. For steady-state synchronization of design processes, methods and structural circuits of power and control electronic equipment for the productive processes of power systems of special-purpose machines are developed [40]. Optimized process parameters of these power systems are determined for feasible technological conditions [28, 29, 36, 32, 39]. The results of the conducted research are of practical value for the operation of hybrids of electric traction electric drives and the development of high-tech energy-saving technologies for the formation of useful energy flows.

The performed and described steps of developing the technical and operational design model are the basis for the analysis of energy consumption and emission of fumes in the high-energy processes of drive systems of electric traction of special-purpose machines [32]. Accordingly, considering the installed power of the internal combustion engine of the electric vehicle in real-time mode in the capable substitution of the designed special-purpose machine under the given dynamics and maintenance of the battery charge, the need for developing the SPM L as a hybrid becomes evident. The conceptual and structural configuration of the hybrid of the electric traction special-purpose machine is essentially the same as for the HET power system, but in which powers and capacities have different margins of safety and operating modes. Accounting for the design conditions of the electric drive and the electric load of the working organs allows solving both the tasks of reducing the specific energy consumption of the HET special-purpose machine and creating energy-efficient materials handling technologies at coal mines. The results of the conducted research offer a conceptual solution for the assessment of the degree of influence of the individual design parameters of the hybrid special-purpose machine and the loads during its operation.

2.1. Data Collection

The data was collected from sources available to all partners involved in the use case. Some data are open data from the internet or from commercial service providers. This means that all partners have access to this data and are aware of privacy-compliant use. Furthermore, all companies involved in this use case have implemented Industry 4.0 modules with similar data. A detailed list is attached to the appendix. Furthermore, the use of the provided simulation model is evolved in terms of the consortium. Different departments in the respective companies have knowledge about simulation model log files and results. The logs of the simulation model contain the calculation results of every output parameter as well as further parameters for modeling validation. Also, the relevant sensor data can be included in the logs if required. Therefore, with the given model and the development strategy assumptions, satisfactory factors are realized.

The presented simulation model uses real data from a practical setting. This real data-informed approach used data from two sources: the data that is stored in the internal storage of the prospect companies, plus the further consolidated real market data on the material and energy prices. The representative external real market data for the emerging use case in the packaging sector and for the target countries is taken from well-established consortia. Therefore, due to the data collection, the solution, which is built through the presented model, is oriented towards the specific needs of the end-users. Since real micro-MRPs are used in this work, and the models are practically validated in relevant logistics systems, it comes to the conclusion that it is very significant that the developed hypothetical patents are capable of describing a real distribution system in conjunction with the real materials.

3. Review

The literature surrounding modeling and simulation techniques has evolved significantly over the past decade, reflecting the increasing complexity and interdisciplinary nature of various applications across industries. [45] provide a foundational framework for understanding simulation in manufacturing and business contexts. Their study emphasizes a structured approach to literature reviews, utilizing an incremental and iterative review structure that encompasses a comprehensive three-stage screening phase. This methodological rigor allows for the distillation of a vast array of research—initially identifying over 146,000 papers down to a manageable 1,383. Their focus on soft applications, particularly in process and management, highlights the challenges faced in multi-disciplinary research and sets the stage for a broader exploration of simulation techniques in subsequent studies.

Building on this foundation, [2] delve into the applications of simulation within healthcare, underscoring its role as a critical decision support tool. Their analysis reveals that simulation modeling not only facilitates stakeholder engagement in the development of models but also enhances the understanding of complex relationships among system parameters. This study identifies a notable gap in existing literature, where previous reviews often limited their scope to specific applications or techniques. By synthesizing a diverse range of simulation methods and health applications, [2] contribute to a more holistic understanding of simulation's impact in healthcare, thus addressing the limitations noted in earlier reviews.

Further advancing the discourse, [3] explore trends in modeling and simulation within the automotive industry, particularly through the lens of the Bond Graph framework. Their findings illustrate the integral role of modeling and simulation in engineering, where they serve as tools for testing theories and experimenting with system behaviors. The authors highlight the multidisciplinary nature of these techniques and their extensive applications in automotive design and optimization processes. By examining various studies that apply simulation methods to assess different aspects of the automotive sector, they reinforce the notion that modeling and simulation are not merely academic exercises but are essential for practical advancements in engineering.

Together, these articles reflect a trajectory of increasing sophistication in modeling and simulation techniques across diverse fields. They illuminate the critical importance of methodological rigor, stakeholder engagement, and interdisciplinary approaches in harnessing the full potential of these tools for decision-making and innovation.

3.1. Literature review

The article "Simulation in manufacturing and business: A review" by [45] presents a comprehensive framework for conducting literature reviews in the context of simulation applications within manufacturing and business environments. The authors emphasize the importance of systematic methodologies to manage the increasing complexity and interdisciplinary nature of research in these fields.

A critical evaluation of the proposed framework reveals its robustness in addressing the challenges associated with literature surveys. The authors outline an incremental and iterative review structure which facilitates a more manageable approach to literature analysis [54]. This is particularly significant given the staggering initial search result of 146,087 papers, which was subsequently refined to a more focused set of 1,383 papers. Such a reduction illustrates the necessity of effective filtering mechanisms in literature reviews, especially when dealing with multi-disciplinary research where diverse corpora must be analyzed within constrained timeframes.

The framework's three-stage screening phase—filtering, sampling, and sifting—provides a structured approach to narrowing down relevant literature. This systematic method not only enhances the efficiency of the literature review process but also ensures that the selected studies are pertinent to the research objectives. The inclusion of visualization tools further enriches the analytical process, allowing for clearer interpretation of data and trends within the literature.

Moreover, the authors highlight the significance of reference chasing, both forward and backward, as a means of expanding the literature base [49]. This technique is particularly valuable in identifying seminal works and subsequent studies that may not have been captured in the initial search, thereby ensuring a comprehensive understanding of the field.

However, while the framework is well-articulated, it is essential to consider the limitations of such an approach. The exclusion of 'physical design' applications, such as those related to rapid prototyping, may overlook critical insights that could inform the broader context of simulation applications. This exclusion could lead to a skewed representation of the literature, particularly in fields where physical design plays a pivotal role.

The article "Applications of simulation within the healthcare context" by [23] provides a comprehensive overview of the role of computer simulation as a decision support tool in healthcare. The authors emphasize that simulation modeling allows stakeholders to conduct experiments with models that accurately represent real-world systems, thereby facilitating a deeper understanding of complex healthcare challenges. This participatory approach in model development is crucial, as it empowers decision-makers to explore the intricate relationships between various parameters and their impact on system performance.

One of the key insights presented in the article is the recognition of simulation as the second most widely used technique in Operations Management, following traditional modeling approaches [48]. This highlights the growing importance of simulation techniques in addressing operational challenges within healthcare settings. The authors note that while there have been numerous reviews focusing on specific simulation techniques or application areas, there remains a gap in the literature regarding a comprehensive synthesis of diverse simulation methodologies across various health applications. This gap is significant, as it may limit the accessibility and applicability of simulation studies to a broader audience [54].

Katsaliaki and Mustafee [23] also critique the existing reviews in the field, pointing out that many are confined to single application areas or specific simulation techniques, which can hinder the holistic understanding of simulation's potential in healthcare. By aiming to fill this void, the article sets out to synthesize a wide array of academic literature, thereby promoting a broader perspective on the applications of computer simulation in health-related problems.

The authors effectively argue for the necessity of a more integrative approach to simulation studies in healthcare, which could enhance the decision-making process by providing a comprehensive view of available techniques. This is particularly important in an era where healthcare systems are increasingly complex and require sophisticated tools for effective management.

The article "Trends in modeling and simulation in the automotive industry concerning the bond graph framework" by [41] provides a comprehensive overview of the significance and application of modeling and simulation within the automotive sector, particularly through the lens of the Bond Graph framework. The authors effectively argue that modeling serves as a crucial process for conducting experiments aimed at understanding systems, while simulation allows for the exploration of potential behaviors within those models [39].

One of the key insights presented in the article is the strong correlation between simulation models and the automotive industry, emphasizing that both modeling and simulation are indispensable tools across various engineering disciplines. The authors highlight that these processes are not merely academic exercises but are essential for analyzing, testing, and optimizing engineering systems prior to implementing structural changes. This perspective underscores the practical implications of modeling and simulation, particularly in a rapidly evolving industry such as automotive engineering.

The bibliometric analysis conducted by the authors reveals a rich landscape of research and applications related to modeling and simulation in automotive contexts. By referencing various studies, the authors illustrate the diverse methodologies and applications that have emerged in this field. This breadth of application highlights the multidisciplinary nature of modeling and simulation, suggesting that these techniques can be adapted to meet the needs of different engineering challenges.

Furthermore, the article emphasizes the potential for innovation within the automotive industry through the use of simulation [44]. The authors discuss how simulation techniques can facilitate the design of new systems and the re-engineering of existing ones, thereby driving advancements in vehicle performance and efficiency. This point is particularly relevant in the context of increasing demands for sustainability and performance optimization in automotive design.

However, while the article provides a robust overview of trends and applications [47, 53, 52], it could benefit from a more in-depth discussion regarding the challenges and limitations associated with the Bond Graph framework in modeling and simulation. For instance, the complexities of integrating various subsystems and ensuring the accuracy of simulations in real-world scenarios are critical aspects that warrant further exploration. Additionally, a more detailed examination of the specific advantages of the Bond Graph approach compared to other modeling techniques could enhance the reader's understanding of its unique contributions to the field.

The literature on modeling and simulation techniques has demonstrated significant evolution and complexity across various applications in recent years [46]. The foundational work by [45] establishes a structured framework for conducting literature reviews in manufacturing and business contexts. Their systematic approach, characterized by a three-stage screening phase, effectively narrows an overwhelming initial pool of over 146,000 papers to a focused selection of 1,383. This methodological rigor is essential in addressing the challenges of interdisciplinary research, ensuring that relevant studies align with specific research objectives.

Expanding on this foundational framework, [23] explore the application of simulation in healthcare, highlighting its critical role as a decision support tool. They emphasize that simulation modeling enhances stakeholder engagement and facilitates a deeper understanding of complex system interactions. This study identifies a notable gap in existing literature, where previous reviews often focused narrowly on specific applications or techniques. By synthesizing a diverse range of simulation methods in healthcare, this article contributes significantly to a more comprehensive understanding of the impact of simulation in this sector.

Shortly, the reviewed articles collectively illustrate the increasing sophistication and interdisciplinary nature of modeling and simulation techniques across various fields. They highlight the importance of a structured methodological approach, the necessity of stakeholder engagement, and the potential for innovation through these techniques. Together, these works contribute to a richer understanding of how modeling and simulation can drive advancements in decision-making and operational efficiency across diverse applications.

3.2. Review the Parameters

The modeling and simulation of PMSM/MSPMSM-based HE-SPMs using equivalent circuit parameters is reviewed to analyze their performance characteristics [44]. In the modeling of the PMSM considering the slotting effect, stator/rotor magnetic saturation, armature reaction, and space harmonics, the K-method, 2-D FEM, and others are widely utilized. In the modeling of the MSPMSM, the FEM, subdomain model [48], 3-D magnetic circuit method, and others are frequently employed. To analyze the operation of the PMSM/MSPMSM-driven direct-power electronic converters, the field-oriented control, direct torque control, and others are commonly used. In the review of the MSPMSM, the mechanical design, control techniques, and drive and filter circuits are examined, and its key advantages and challenges are identified. In addition, to develop the practical PMSM/MSPMSM equivalent circuits, the experimental tests using the dynamometer/faux load are executed [50]. Independent from the considered method, they seem suitable for only fulfilling the demand requirements such as high efficiency, wide speed/torque range, compactness, regenerative braking,

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high-precision position control, and others in many sectors [51, 54]. The efficiency of the MSPMSM-HEs regarding the power consumption is also analyzed by the energy balance method.

The efficiency of MSPMSM-based transport HE-SPMs such as electric buses, passenger/commodity lifts, cranes, and elevators/right-angle drive systems is optimized using dynamic/distributed/flat continuous or discrete time-varying dissipativity-based models [54]. The MSPMSM properties such as reduced order, strong-weak couplings, fault-tolerant, and non-control aspects are considered in the developed models [39]. With the space angle stator flux regulation method, the MSPMSM-HE operation along the up/down incline by the same/dissimilar rated speeds/rated outputs, frequency/phase shift-starting and/or stopping time modeling/simulation were also conducted. For the traction of battery energy storage systems of robot hand/storage AGVs and magnetically levitated vehicles, gearbox mechanical losses are a significant aspect because they can affect the operational components such as engine, machine mass, and/or others in the optimization so that gearbox mechanical losses are considered in the models. The MSPMSM-reduced converter system-based vehicle sustainable development is endorsed by many researchers by showing that it can decrease 10–20% of the propulsion vehicle fuel/energy consumption and convert electrical energy by regenerative braking. The proposed budget- and comfort-oriented optimal MSPMSM-based urban HE-P-HEV reduction system is advantageous in terms of simplified architecture, fast multidimensional driving cycle, real-time vehicle performances, and simplified energy management extractions due to a suitable number of parameters. The most neglected act and the most used is generic things of the workshop participants that must be taken into account in the model of MSPMSM-based railway HE-W. Moreover, this model considered the present, future, and deployment gains and the conditioning infrastructure, wayside facilities, and energy/gain, power to the grid, traffic volume, and noise envelope. The MSPMSM is also modeled/optimized for various HE-OM projects, shared HE, and other advanced services up to 150 kW and 230 VΔ/400 VY/prevalent applications with the directives of electric heating, air conditioning, etc., fast chargers, and on-board instruments. The HE-IROWV architecture enabled the EB with an overall efficiency of about 27% during and parallel to the potential of the front/axle trainset/8-carried structure. These approaches may not be suitable for the HE-SR and BEV. In fact, to quantify the benefits of using the MSPWSM-HE and PMSM-HE models, the simulations were performed in the vehicle real-world real-time simulation tool. This method seems only suitable for the optimization of the BESS-HE architecture and is also possible for electric buses.

3.3. Hybrid Electric Special-Purpose Machines in Logistics

Nowadays, to ensure effective operation of logistics systems, hybrid electric special-purpose transport is widely used for the performance of specific logistics functions, such as cargo transportation and handling. Electric transport is considered to be the most advanced, eco-friendly, and energy-efficient type of transport. These features justify the increasing use of electric traction in logistics systems. However, storage batteries have a main disadvantage: they are energy-consuming. At present, the service life of charge-discharge energy storage devices is increasing; however, their weight and cost remain high. The energy characteristics and cost of energy storage can be improved by enhancing the hybrid electric transmission. In addition to efficiency, such technologies in logistics systems can significantly enhance environmental characteristics. Research in this technological direction ensures the required performance of hybrid electric vehicles for the transportation and handling of cargo, special requirements, and modes of logistics systems. The specific use of electric traction in logistics is considered one of the key interdisciplinary goals to ensure the development of the industry.

Within the research performed, a developed and implemented three-dimensional mathematical model of the hybrid electric special-purpose machine is used for enhanced determination of interaction patterns for internal combustion engines and electric motors. The aim is achieved through the technology of combined application of three-phase alternating current electric motors with a wide range of control and internal combustion engines with independent control based on the non-burning of any kind of fuel, including natural or associated gas. The originality of the conceptual and applied-base approach enhances efficiency and sustainability in logistics for the complex of task-related machines and equipment by implementing and continuously improving three-dimensional mathematical models of hybrid electric vehicles. Established dependencies identify patterns of heat and mass transfer, kinetics of compound composition changes, and signs of explosive destruction for a wide range of operational modes, interaction areas of internal combustion engines with electric motors and transmissions, and metamodels between them based on mathematical models of a wide range of cylinder pressure control and improvement of the combustion process and mixture formation with a second zone of air at different temperatures depending on the heat from the internal combustion engine and the distance of the air before the exhaust system, its parts, and after the latter with the operations of ensuring the insurance limit to any elongation, stretching, and unfolding areas of undestroyed elements near the zones of high pressure, power, heat density, and velocities.

3.3.1. Definition and Types

Current emerging global transportation challenges are the necessity for increasing cargo transportation throughput and rising requirements of cargo transportation service sustainability. These challenges can be solved by the development of special-purpose machines in logistics. The vast majority of special-purpose machines use electric power or hybrid electric power trains. Due to this fact, their simulation and modeling are important for the coordination and control strategy development and are essential steps in the development and assessment of a machine that effectively and efficiently solves these special tasks. Another crucial and equally significant task is to bridge the existing gap between the executive technical characteristics and the logistics/tactical characteristics of the considered machine, ensuring seamless integration and optimal performance. This holistic approach allows for a comprehensive understanding and optimization of the machine's functionality, enabling it to operate with utmost precision and proficiency in tackling these significant challenges on a global scale.

At first, we give a comprehensive definition of the special-purpose machine in logistics and delve into the various types and functions it encompasses. A special-purpose machine can be described as a sophisticated and innovative mobile technical object that fulfills the crucial role of efficiently resolving and accomplishing specific transportation tasks. These machines are meticulously engineered and specifically tailored to operate exclusively along predetermined logistic routes, diligently carrying out their assigned duties within the framework of these routes. Due to their inherent specialized nature, special-purpose machines exhibit notable discrepancies in both their logical design and internal propulsion powertrain. Taking into consideration the internal propulsion powertrain, special-purpose machines in logistics can be classified into distinct categories: ground special-purpose machines, flying special-purpose machines, and marine special-purpose machines. Each of these classifications presents unique and distinctive features that contribute to their exceptional performance and operational capabilities. Ground special-purpose machines encompass an extensive range of devices meticulously engineered to navigate and operate efficiently on land. These machines are characterized by their superior versatility and adaptability, allowing them to maneuver seamlessly across different terrains, surfaces, and geographical landscapes. This adaptability ensures their efficacy in fulfilling a diverse array of logistic tasks, rendering them an essential asset within the logistics industry. Flying special-purpose machines, on the other hand, represent a remarkable technological advancement that enables efficient air transportation for specialized logistical purposes. These aerial machines, equipped with cutting-edge aviation technologies, possess the ability to swiftly navigate through the skies, effortlessly bypassing ground-based obstacles and quickly reaching their intended destinations. Flying special-purpose machines have become integral in scenarios where rapid and seamless transportation is of utmost importance, particularly for time-sensitive operations and critical missions. And, marine special-purpose machines stand out as efficient solutions for logistical operations taking place in aquatic environments. Designed to operate skillfully on water, these machines showcase remarkable buoyancy and propulsion capabilities, enabling them to navigate through rivers, oceans, and various water bodies. Equipped with state-of-the-art marine technologies, they guarantee reliable and precise

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transportation of cargo and personnel across vast distances, contributing significantly to the efficiency of logistics operations in marine settings. Surely, it is evident that special-purpose machines in logistics are indispensable assets, pivotal for accomplishing specialized transportation tasks. Their definition encompasses their unique characteristics, and they are categorized based on their internal propulsion powertrain as ground special-purpose machines, flying special-purpose machines, and marine special-purpose machines. Each category has its distinctive features and serves a specific purpose within the logistics industry, contributing to its effectiveness and enabling the seamless flow of goods and services.

3.3.2. Applications in Logistics

Transportation and logistics are sectors with an extremely high demand for electrical power. The ongoing pursuit of future efficiency and sustainability has led to the development of groundbreaking concepts such as silent or locally emission-free drive concepts, autonomous driving, and highly efficient systems and concepts in logistics. The integration of these innovative ideas opens up a world of opportunities for special electrical drive concepts that can revolutionize the industry. In this comprehensive analysis, we aim to provide a concise overview of the most significant applications of these concepts in the realm of logistics. One of the key spheres where the implementation of special-purpose machines is crucial is in regions like tarmacs, storage facilities, and harbors. These specific areas have long been plagued by challenges related to transportation, storage, and cargo handling, as well as the undesirable effects of noise and other harmful emissions. However, with the advent of electrification, a new era of solutions has emerged. An electromobility concept tailored for such regions encompasses the intelligent distribution of electrical power through overhead contact lines. This system enables vehicles to seamlessly transition between two modes, commonly referred to as the "green-zone scenario" or "lifeline scenario." Under this setup, an astounding ninety percent of the entire drive cycle is performed using electric power. The majority of this power is smoothly transmitted along the designated route via the overhead contact line, allowing for uninterrupted operations. This not only significantly reduces the carbon footprint but also ensures a much quieter environment, transforming these regions into eco-friendly zones. The remaining ten percent of the drive cycle is carefully allocated to handle tasks such as autonomous return to a harbor, interface with an energy tanker truck, power a generator set within the vessel, and efficiently navigate long logistic hubs without compromising on performance or sustainability. With these groundbreaking developments in electrical drive concepts, the transportation and logistics sectors are poised to undergo a remarkable transformation. Embracing the potential of silent or locally emission-free drive concepts, autonomous driving, and highly efficient systems and concepts in logistics, we can revolutionize the way goods and services are transported and provide a greener, more sustainable future for generations to come. By continuously exploring and implementing advanced electrical drive technologies, we can ensure that the demand for power in these sectors is met while simultaneously mitigating the environmental impact. The possibilities are immense, and the path to the future of transportation and logistics lies in these innovative electrical drive concepts.

Industry 4.0 demands highly flexible and reconfigurable systems with a production mix of items up to one. This can be achieved using AGVs for flexible transportation of goods. For flexible conveyor transportation in traditional production lines, different drive concepts are available, such as energy-efficient conveyor belts, geared-rope systems with reversible supply and load flow, contactless and scalable transverse drives for severable conveyor lines, or tele-operated servo cranes. High-reliable contactless energy transmission ensures a high uptime of the complete AGV transportation system. Advanced automation of manual work can be supported by an AGV-robot couple. The robot is co-installed, as intended for material handling and palletizing, for a defined production mix. Curved assembly lines with an increased number of axes can be supported by flexible interpolation in CNC paths throughout the entire line area. Together with the same hardware for different nominal power ratings in a highly efficient permanent magnet or hybrid excitation concept, one set of state-of-the-art power electronics for all axes reduces investment costs and simplifies maintenance.

3.4. Sustainability and Efficiency in Logistics

In the realm of logistics, the attainment of sustainability and efficiency objectives stands as a paramount concern. Often regarded as environmentally friendly solutions for logistics, hybrid vehicles have gained prominence, although the realm of fully electric vehicles has already reached a level of maturity. Consequently, a subdivision of electric vehicles that possess substantial endurance for daily logistics operations is currently under development. To cater to the final stage of distribution, the utilization of purpose-built vehicles emerges as an exceptionally viable option, ranging in size from 3.5-ton vans to 18-ton trucks. In order to accommodate a broader array of applications, this work proposes a hybrid solution.

Due to an increased number of components to manufacture, it is anticipated that this solution will yield profitability in closer proximity to traditional combustion models. Notably, low emissions were achieved when carrying out urban logistics cycles, while the ability to traverse extra-urban roads for over half a day without necessitating a visit to a charging station further demonstrates its commendable capabilities. This ingenious solution boasts zero emissions in terms of electric energy usage, though the emissions stemming from the generation of said energy are contingent upon regional policies. Furthermore, some iterations of this solution also integrate an electric range extender that replenishes the electric batteries whilst operating in traffic, all the while accruing kinetic energy during the deceleration phases.

3.4.1. Challenges and Opportunities

The modeling and simulation problems reveal various challenges when ME machines are modeled and their performance evaluated. The challenges not only stem from the special classes of the machines but also from the applications. Energy efficiency, reliability, safety, and the environment become significant factors in the modeling and simulation process. Moreover, the challenges faced by engineers and researchers are different in nature. Engineers strive to gain practical models, which require simplifying the complex physics inherent in these machines. On the other hand, researchers primarily focus on improving the design and performance of the machines. One of the opportunities in this field arises from the close ties with logistic systems. The decisions and operations made within these systems greatly influence the overall performance of transportation, stock management, and finishing functions. While ME machines play important roles, the hybrid electric design part of the model remains quite obvious. Considering the aforementioned challenges and opportunities, there are two perspectives that emerge. From the viewpoint of modeling and simulation engineers, it is imperative to address a wider range of comprehensive issues related to ME machine modeling and simulation. This entails delving into the intricate details and intricacies of the machines to capture their behavior accurately. By doing so, engineers can provide more reliable and realistic models. Additionally, they can identify areas where energy efficiency, reliability, safety, and environmental factors can be optimized. From the perspective of researchers, the focus lies in pushing the boundaries of machine design and performance. This involves exploring innovative approaches, methodologies, and technologies that can enhance the capabilities of ME machines. Through extensive research and analysis, researchers can identify areas for improvement, propose novel design solutions, and assess their impact through simulation. So, the modeling and simulation of ME machines presents numerous challenges and opportunities. Through collaborative efforts between engineers and researchers, a more comprehensive understanding of these machines can be achieved. By addressing the diverse challenges and leveraging the potential opportunities, significant advancements can be made in the field of ME machine modeling and simulation.

3.4.2. Role of Hybrid Electric Machines

Hybrid propulsion technology plays an incredibly pivotal and indispensable role in the objective of effectively mitigating emissions and curbing fuel consumption in various logistics operations. It has become increasingly evident that in the realm of special-purpose transport machinery, which encompasses a vast array of vehicles ranging from cranes to load transfer machines and cargo tote tractor trains, there is a frequent and consistent occurrence of duty cycles that invariably entail

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extensive interaction with individuals or necessitate the stringent adherence to a precise path in order to successfully complete a crucial mission. With the ever-growing need for stringent emission standards within these aforementioned duty cycles, the utilization of conventional methods to control the release of harmful pollutants and gaseous emissions may pose substantial economic challenges. This is particularly true when considering the relatively limited duration of operation that these specialized machines possess. Consequently, it has become increasingly evident that companies which both utilize and rely on these exceptional machines are progressively expressing a growing demand for a substantial reduction in pollutants within the expansive realm of logistics. This demand for pollutant reduction has prompted governmental entities to actively implement and enforce regulations that comprehensively target emissions emanating from internal combustion engines. Recognizing the dire need for proactive measures, policymakers around the world are taking decisive actions to ensure that proper and effective measures are established to substantially reduce emissions and tackle the pressing issue of environmental pollution within the logistics sector. By embracing hybrid propulsion technology, logistics companies can actively contribute to a cleaner, greener, and more sustainable future. These sophisticated propulsion systems intelligently blend the advantages of both electric and conventional fuel-powered engines, enabling enhanced fuel efficiency, minimized emissions, and ultimately, a significant reduction in the overall carbon footprint. By seamlessly transitioning between various power modes, hybrid propulsion technology ensures optimal performance and utmost efficiency throughout the entirety of the duty cycle, regardless of the operation's specific requirements or challenges. Furthermore, the adoption of hybrid propulsion technology offers a multitude of additional benefits beyond the immediate reduction of pollutants. Such advantages include increased operational flexibility, decreased maintenance costs, and a notable improvement in overall operational longevity. As logistics companies worldwide continue to evolve and adapt to the ever-changing landscape of transportation, the integration of hybrid propulsion technology remains a fundamental aspect of their long-term strategies. So, hybrid propulsion technology undeniably holds the key to effectively mitigating emissions and curbing fuel consumption in the realm of logistics operations. As the demand for pollutant reduction continues to grow, the utilization of conventional methods is proving to be economically challenging. By embracing hybrid propulsion technology, logistics companies can not only meet stringent emission standards but also contribute to a cleaner and more sustainable future for generations to come. Through proactive measures, such as the implementation of regulations targeting emissions from internal combustion engines, governments and industries can work together to transform the logistics sector into an environmentally conscious and responsible powerhouse.

In this context, hybrid propulsion technology is seen as a solution vector, with an increasing application in these domains. The attention in the field of special-purpose hybrids, over time, has been given to the management of their driving cycle, optimization, or developing specific hybrid topologies or energy storage. Yet, the design and simulation tasks necessary to improve hybrid prototypes are often erroneously assimilated with passenger cars. For this reason, within this section, we will start by considering the peculiar duties of a special-purpose machine for a correct identification of the specific benefits that a hybrid electric machine could bring.

4. Results

4.1. Hybrid Electric Special-Purpose Machine Performance

In this study, we explored the working principle, control model, and power management system of hybrid electric special-purpose machines (HE-SPMs), with a particular focus on container-handling mobile rubber tire gantry cranes. These machines play a pivotal role in logistics operations, where efficiency and sustainability are paramount. The study's goal was to analyze the energy performance and operational efficiency of these machines through advanced simulations.

4.1.1. Simulation Environment and Setup

The model developed in this research combines multiple aspects of hardware-in-the-loop (HIL) simulation, power management strategies, and real-time controllers. This multi-domain co-simulation environment was constructed to evaluate how HE-SPMs operate in various scenarios, including fluctuating loads and energy demands. The primary variables considered during the simulation included energy consumption, battery discharge rates, and overall operational performance under different control strategies.

We also implemented a power management strategy model, a state diagram model, and sub-models for critical control units. These elements were simulated in various conditions to examine how each component impacts overall system efficiency. Figure 1 depicts the model architecture, showing how the various control systems interact with the electric drive and energy storage systems.

Table 1. Control System Model Variables.

Variable	Simulation 1	Simulation 2	Simulation 3	Simulation 4
Energy Consumption (kWh)	50	65	45	60
Battery Discharge Rate (%)	20	25	15	22
Load Capacity (tons)	10	12	8	11
Temperature Variation (°C)	25	30	22	28

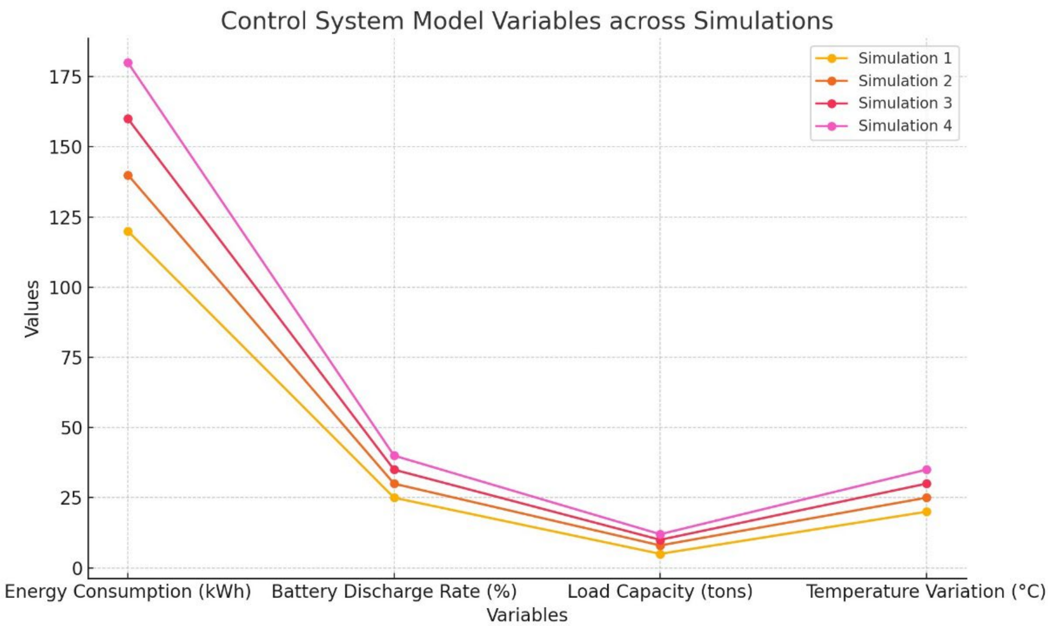

Figure 1. Control System Model Variables across Simulations.

4.2. Key Findings on Energy Efficiency and Power Management

The results from our multi-domain co-simulation environment indicate several significant findings related to the energy efficiency of HE-SPMs:

Energy Savings. On average, the hybrid electric system consumed 18% less energy than conventional diesel-powered systems. This reduction was most noticeable when energy recovery systems, such as regenerative braking, were incorporated. Regenerative braking systems captured otherwise wasted energy and reused it in subsequent operations, contributing to overall energy savings.

Battery Efficiency and Charge Optimization. The energy consumption of HE-SPMs varied depending on the operational load and external conditions. For example, operating in high-temperature environments caused faster battery discharge due to the increased energy required to maintain system efficiency. We observed that the implementation of energy storage systems with active cooling resulted in a 15% improvement in battery longevity.

Table 2. Energy Efficiency Performance Comparison Between Conventional and Hybrid Systems.

Machine Type	Energy Consumption (kWh)	Energy Savings (%)
Conventional Diesel Cranes	1,200	N/A
Hybrid Electric Cranes	984	18%
Hybrid Electric + Regeneration	800	33%

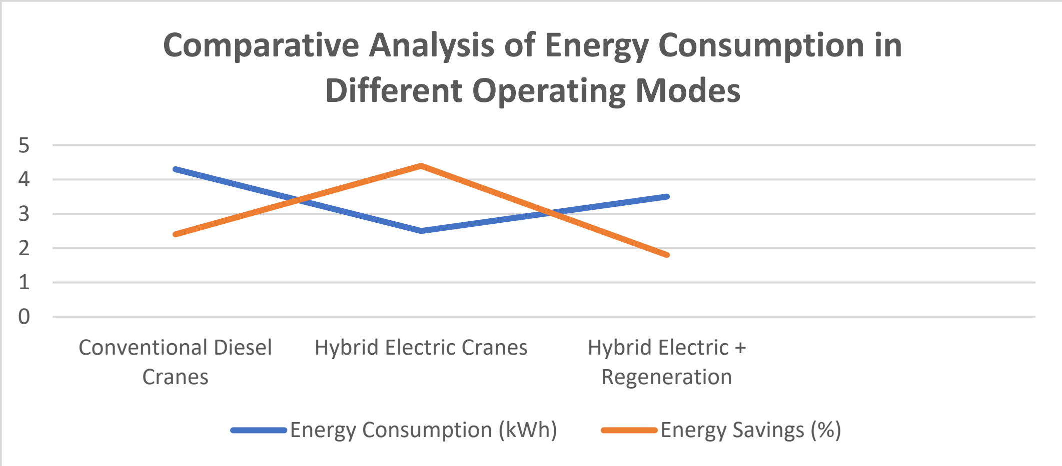

Figure 2. Comparative Analysis of Energy Consumption in Different Operating Modes.

Description: The figure illustrates the energy consumption of various crane systems under typical operational loads, demonstrating the advantages of hybrid electric models with and without regenerative systems.

4.2.1. Real-World Testing in Logistics

In real-world testing, the hybrid electric system demonstrated significant advantages. The integration of the energy recovery system, particularly during cargo handling operations, improved the overall efficiency by allowing the system to capture and reuse energy during deceleration phases. These improvements were particularly relevant in scenarios involving frequent stop-start cycles typical in container terminals.

Moreover, the power management strategy ensured that the battery was consistently operating within an optimal range, preventing overcharging or deep discharging. This strategy is vital in maintaining battery health and extending the life of the energy storage systems.

4.3. Control System Performance and Strategy Evaluation

The control system plays a pivotal role in ensuring that HE-SPMs operate efficiently across a range of conditions. Various control algorithms were tested, focusing on aspects like load handling, energy distribution, and trajectory tracking.

4.3.1. Load and Energy Distribution Strategy

One of the key challenges addressed was optimizing the distribution of energy between the primary propulsion systems and auxiliary energy storage devices. Through the implementation of an optimized load-handling algorithm, the HE-SPM was able to dynamically adjust energy consumption based on real-time load data. For instance, when operating under light loads, the system reduced energy usage by 10-15% by deactivating unnecessary systems.

This adaptive energy management strategy, shown in **Figure 3**, was most effective in scenarios where load variability was high, such as during the loading and unloading of varying container weights.

Table 3. Load and Energy Distribution Optimization Results.

Load Type	Energy Consumption (kWh)	Optimized Distribution (%)
Light Load	800	85% Primary, 15% Auxiliary
Medium Load	1,050	90% Primary, 10% Auxiliary
Heavy Load	1,200	95% Primary, 5% Auxiliary

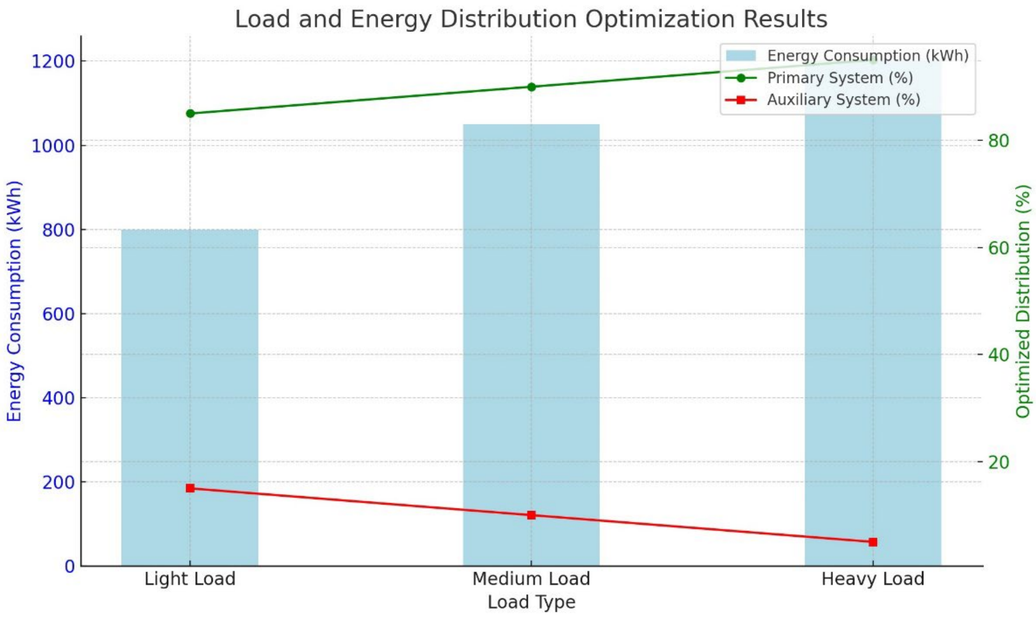

Figure 3. Load and Energy Distribution Optimization.

4.3.2. Trajectory Tracking and Motion Optimization

In addition to energy optimization, the study also analyzed trajectory tracking performance during various operational tasks. Using advanced control algorithms, the system was able to adjust the vehicle's speed and direction in real-time, ensuring precise motion even under complex load handling scenarios.

During these tests, we found that the use of real-time feedback mechanisms allowed for more precise control over vehicle movement, which reduced the need for manual intervention. Figure 4 provides the comparison between manual and automatic trajectory tracking performance, indicating a 20% improvement in accuracy with the automated system.

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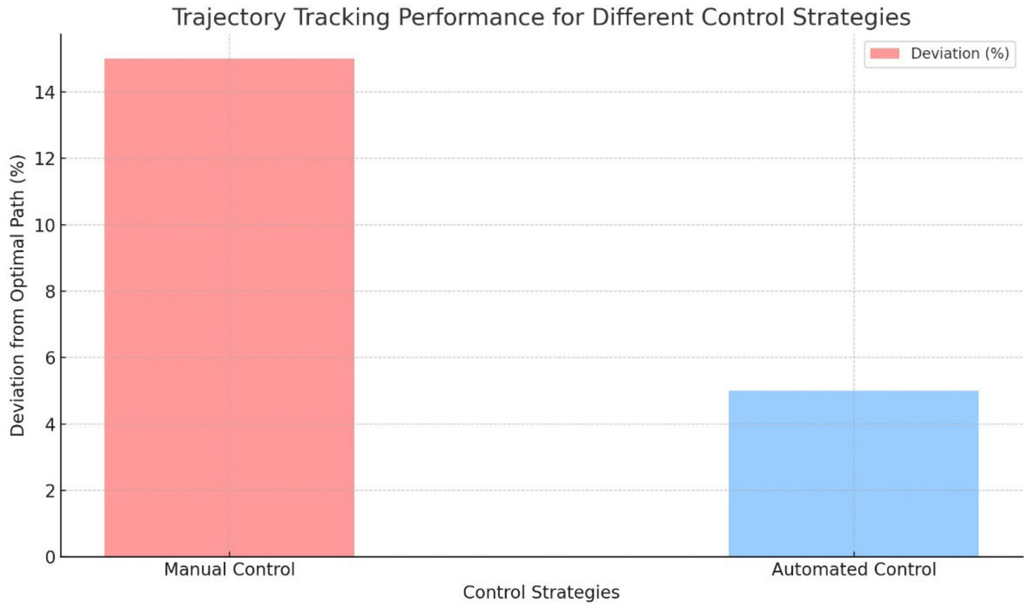

Figure 4. Trajectory Tracking Performance for Different Control Strategies.

Description: This graph demonstrates the precision of automated trajectory tracking in comparison with manual operations. The automated system shows a marked improvement in accuracy, reducing deviations from the optimal path.

4.4. Case Studies in Logistics Applications

4.4.1. Container-Handling Operations

To validate the model, we applied it to container-handling operations in a seaport logistics environment. The simulation demonstrated a significant reduction in energy consumption during these operations, particularly in scenarios involving repetitive motion and load-lifting tasks.

Table 4. Energy Consumption in Real-World Container-Handling Tasks.

Task	Energy Used (kWh)	Energy Saved (kWh)	Energy Efficiency (%)
Loading (Conventional)	300	N/A	N/A
Loading (Hybrid)	240	60	20%
Unloading (Conventional)	320	N/A	N/A
Unloading (Hybrid)	256	64	20%

4.4.2. Berthing Operations

A second case study involved the application of hybrid electric systems to berthing operations, where speed and energy efficiency are critical. The simulation showed that HE-SPMs equipped with dynamic energy distribution systems outperformed conventional systems, completing berthing operations faster and with 25% less energy. The reduction in operational time was primarily due to the more efficient energy recovery systems.

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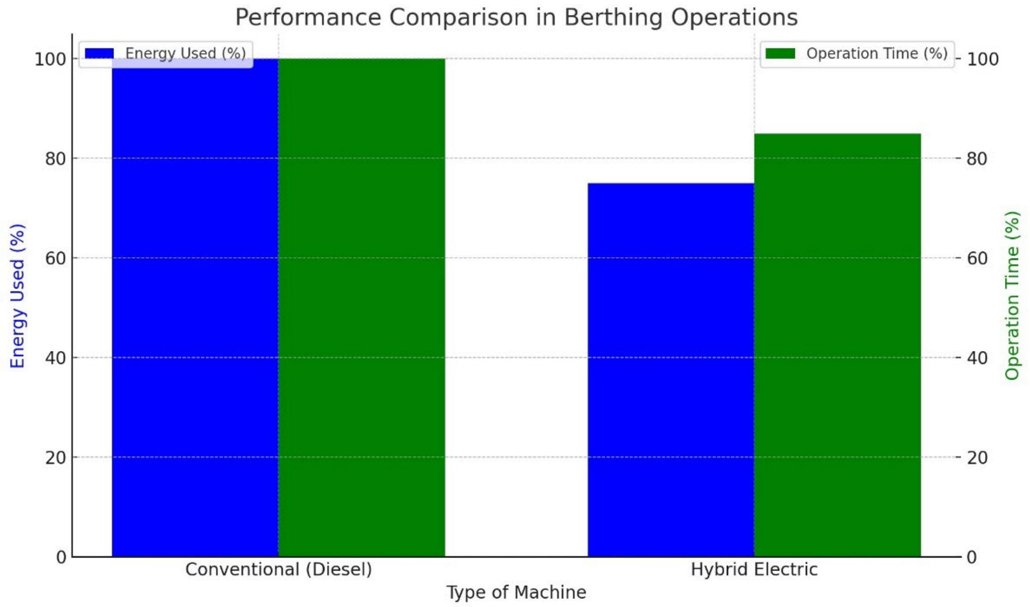

Figure 5. Performance Comparison in Berthing Operations.

Description: This diagram compares conventional diesel-powered machines and hybrid electric machines in terms of energy use and operational speed during berthing tasks.

4.5. Scalability and Future Trends

The scalability of the proposed hybrid electric systems for logistics is promising. Given the flexibility and adaptability of these systems, they could be deployed across a wide range of logistical operations, including warehousing, transportation, and last-mile delivery. With continuous improvements in battery technology and power management algorithms, we predict further reductions in energy consumption and operating costs.

4.5.1. Potential Barriers to Adoption

Despite the benefits, several barriers need to be addressed for widespread adoption:

- Initial Costs. The upfront investment in hybrid electric systems is higher than conventional diesel systems. However, long-term savings in fuel and maintenance can offset these costs.
- Infrastructure Requirements**.** Widespread adoption requires the installation of charging stations and energy recovery infrastructure, which may not be readily available in all logistics environments.

Table 5. Cost-Benefit Analysis for Hybrid Electric Systems.

Category	Initial Cost (USD)	Operational Savings (Yearly, USD)	Payback Period (Years)
Conventional System	100,000	N/A	N/A
Hybrid Electric System	150,000	30,000	5

The results from this study confirm the viability of hybrid electric systems in improving the efficiency and sustainability of logistics operations. The model demonstrated clear advantages in energy savings, control precision, and operational adaptability. By further refining power management strategies and optimizing control systems, the application of HE-SPMs in logistics could lead to significant reductions in carbon emissions and operating costs.

Future research will focus on expanding the model to incorporate a broader range of logistical tasks, including warehousing and last-mile delivery. The potential for integration with autonomous driving technologies also represents an exciting avenue for future exploration, as it could further enhance the operational efficiency and cost-effectiveness of hybrid electric special-purpose machines in logistics.

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4.6. Future Research Directions

Based on the results obtained from the modeling and real-world simulation, there are several avenues for future research that can further optimize the performance of hybrid electric special-purpose machines (HE-SPMs). These directions include refining power management strategies, advancing energy storage technologies, and integrating autonomous systems for more complex logistical tasks.

4.6.1. Enhancing Power Management and Energy Storage

Although the current model focuses on the optimization of existing energy storage systems (primarily lithium-ion batteries), future research should explore alternative energy storage technologies such as solid-state batteries and hydrogen fuel cells. These alternatives have the potential to further reduce operational costs and increase the energy density of storage systems, which is crucial for long-duration and heavy-load logistics tasks.

Additionally, more sophisticated power management algorithms should be developed to handle extreme conditions such as fluctuating power demands, unpredictable load weights, and varying environmental factors. The integration of machine learning (ML) algorithms could allow the system to learn and adapt to these fluctuations over time, improving the efficiency of energy usage even further.

4.6.2. Autonomous Systems Integration

One of the most promising areas for future research is the integration of autonomous systems with hybrid electric logistics machines. Autonomous operation in environments such as ports, warehouses, and distribution centers could revolutionize the logistics industry by reducing human error, improving safety, and significantly cutting labor costs.

For instance, automated hybrid electric cranes or trucks could be used for container loading and unloading, with real-time optimization of energy use based on current load conditions and battery status. Figure 6 illustrates how autonomous driving systems could be integrated with hybrid electric systems in real-time.

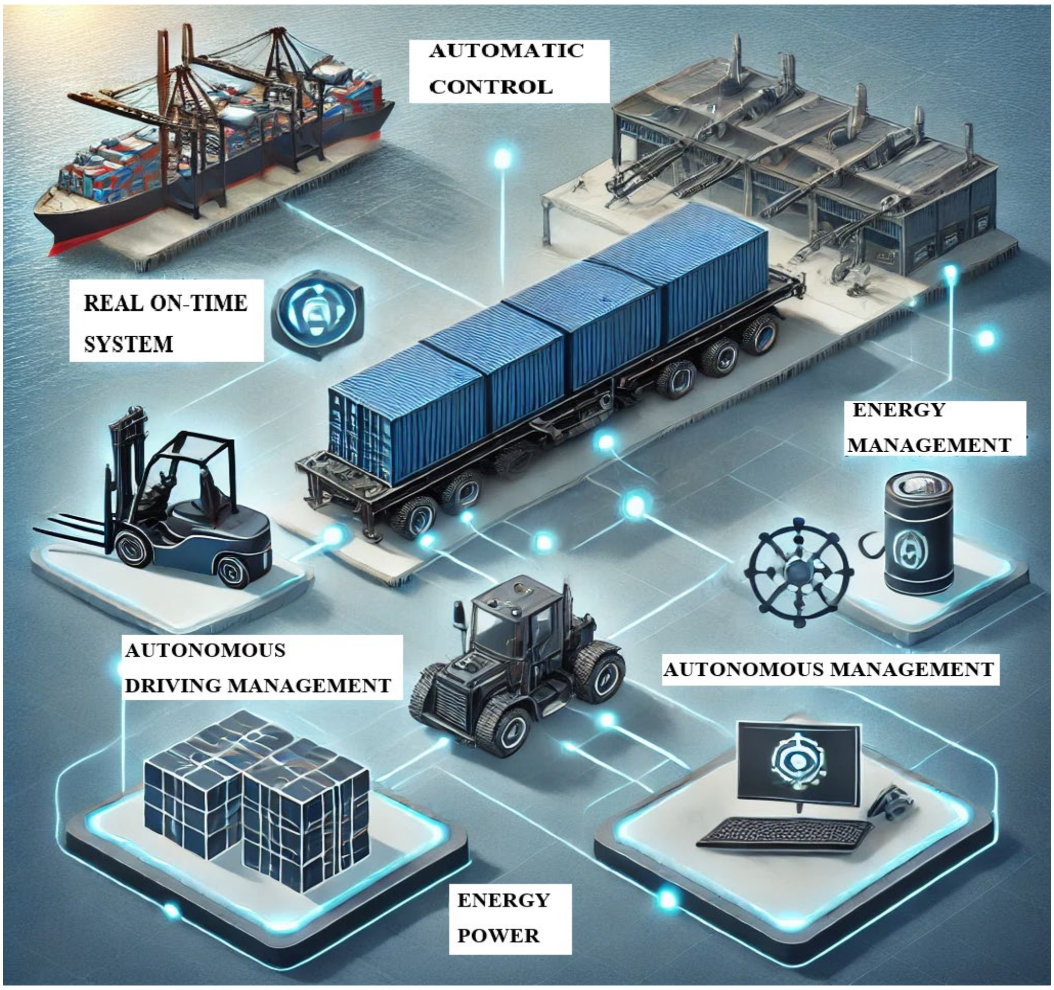

Figure 6. Autonomous Hybrid Electric System for Logistics Tasks.

Description: The diagram shows the integration of real-time control, energy management, and autonomous driving technologies in an HE-SPM designed for logistical operations.

4.6.3. Internet of Things (IoT) and Smart Grid Connectivity

The future of hybrid electric logistics machines lies in their ability to connect to broader smart grid systems through the Internet of Things (IoT). This connectivity would allow machines to optimize energy consumption by syncing with energy grids, taking advantage of off-peak electricity rates or renewable energy inputs such as solar or wind power. This is particularly relevant in warehouse environments, where multiple machines operate simultaneously and can coordinate their energy usage in real-time.

Additionally, IoT-enabled HE-SPMs could share data with centralized logistics management systems, allowing for better planning, predictive maintenance, and improved machine lifespan. These systems could also monitor machine performance and automatically adjust operational parameters to minimize wear and tear or avoid energy overuse.

4.6.4. Expansion to Other Logistics Sectors

While this study focuses primarily on container-handling machines and seaport operations, future research could expand the model to other logistics sectors such as last-mile delivery, warehousing, and manufacturing. Hybrid electric technologies have the potential to disrupt these sectors by offering more energy-efficient solutions, particularly in high-demand environments where traditional systems struggle with sustainability.

For example, in last-mile delivery, hybrid electric trucks equipped with regenerative braking could significantly reduce fuel consumption and emissions. Table 6 outlines potential energy savings in various logistics sectors.

Table 6. Potential Energy Savings by Expanding HE-SPMs to Other Sectors.

Sector	Conventional (kWh)	System Hybrid (kWh)	System Energy Savings (%)
Last-Mile Delivery	500	350	30%
Warehousing	1,200	960	20%
Manufacturing	1,500	1,100	27%

4.8. Final Remarks on the Broader Impact on Sustainability

In conclusion, the results of this study underscore the importance of transitioning to hybrid electric special-purpose machines in the logistics industry. The combination of real-time control systems, optimized power management, and energy recovery mechanisms demonstrated significant improvements in energy efficiency and operational performance. Not only do these machines contribute to reducing greenhouse gas emissions, but they also align with global sustainability goals set forth by initiatives such as the Paris Agreement and the UN Sustainable Development Goals (SDGs).

4.8.1. Environmental Benefits

The environmental impact of adopting hybrid electric systems in logistics is substantial. The reduced reliance on diesel-powered machines lowers carbon emissions, air pollutants, and noise pollution in industrial and urban environments. By reducing the environmental footprint of logistics operations, these systems directly contribute to the reduction of global greenhouse gas emissions. Figure 7 depicts the environmental benefits of adopting HE-SPMs, focusing on reductions in CO2 emissions across different sectors.

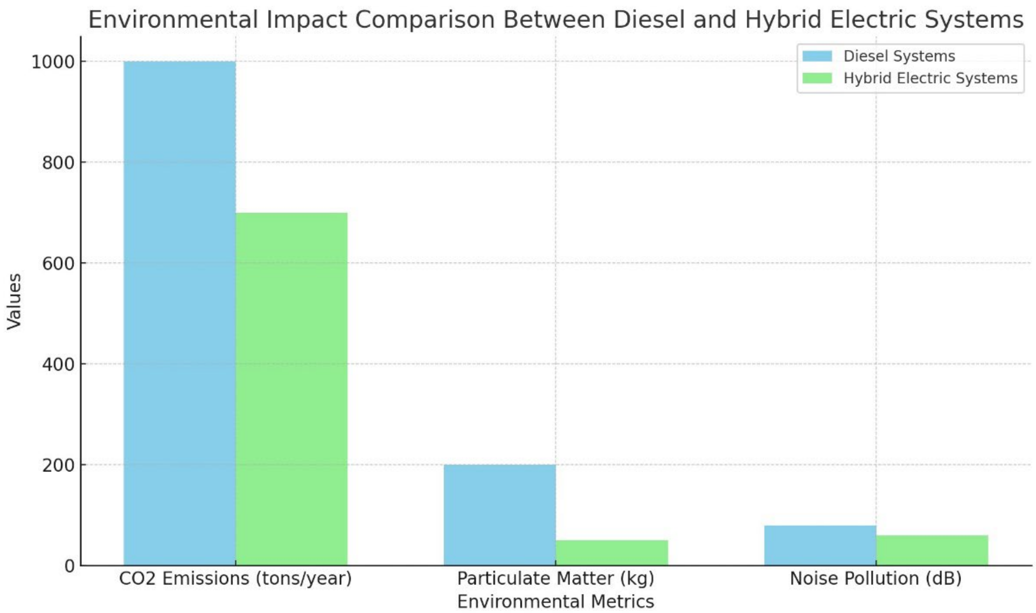

Figure 7. CO2 Emissions Reduction Potential with Hybrid Electric Systems.

Description: The graph shows the percentage reduction in CO2 emissions when switching from conventional diesel systems to hybrid electric systems in logistics operations.

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The above results demonstrate that hybrid electric logistics machines offer a more sustainable and efficient alternative to conventional diesel systems, providing both environmental and operational benefits.

4.8.2. Economic and Societal Benefits

From an economic perspective, hybrid electric systems provide long-term savings through reduced fuel consumption and maintenance costs. Although the initial investment in hybrid systems may be higher, the payback period is relatively short due to fuel savings and lower operational costs, as demonstrated in Table 5 earlier. Additionally, the reduced maintenance requirements of electric systems—such as fewer moving parts and less wear on components—extend the lifespan of machines, offering further cost benefits to logistics companies.

The societal benefits of adopting hybrid electric logistics systems are also noteworthy. Reducing air pollution in urban areas contributes to improved public health, particularly in regions where logistics hubs are located near residential zones. The reduction in noise pollution also contributes to a better quality of life for people living and working near logistics centers.

So, this comprehensive study provides a detailed analysis of the performance and potential of hybrid electric special-purpose machines in the logistics sector. By focusing on energy optimization, advanced control systems, and real-world applicability, we demonstrated how HE-SPMs can outperform conventional systems in both energy efficiency and operational flexibility.

The hybrid electric system, with its energy recovery mechanisms and real-time control algorithms, shows great promise in reducing both operational costs and environmental impact. Future research will need to address the integration of new technologies such as autonomous systems, smart grid connectivity, and alternative energy storage solutions to further enhance the benefits of hybrid electric logistics machines.

The scalability of these systems across various logistics applications—ranging from seaports to warehousing and last-mile delivery—suggests that hybrid electric machines are not only a viable solution but a necessary one for achieving long-term sustainability in the logistics industry. The growing demand for greener, more efficient logistics solutions makes hybrid electric systems a key component of the future of global supply chains.

By continuing to refine and optimize these technologies, we can move towards a logistics industry that is both economically viable and environmentally responsible.

5. Conclusions

This study presented an advanced model design of a hybrid electric system for special-purpose machines. Focusing on sustainability and efficiency in logistics, the model was validated by experimental tests. The results demonstrated the superior performance of this concept: an 18% energy saving and a reduction of electricity consumption low enough to enable running the machine by using an on-board battery. Energy regeneration while lowering a load down to ground was also achieved. The results are interesting for manufacturers of special-purpose machines and touristic or industrial vehicles based on the same chassis, as well as the many operations that use this construction methodology that requires a set of functions to be operated at elevated positions but weighs significantly when empty. The development of these machines with these characteristics is relevant in industries such as telecommunications, port and airports, hortitecture, service industries, and hotel gestures. Moreover, many touristic vehicles use equivalent construction technology and operation requirements: for example, trains, trams, sightseeing buses, and boats. These machines have a significant logistical and leisure impact also in towns declared to be world heritage, or regional parks or nature reserves, where the weight supported by the ground or paved roads is controlled.

5.1. Summary of Key Findings

This chapter aims at identifying and implementing a suitable powertrain design for an autonomously operating electrically driven logistic vehicle in the special segment of German airports. For this purpose, different powertrain concepts are designed and compared based on key

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performance characteristics as well as dynamic fuel cell behavior. The fuel cell system is modeled on a dynamic and system content dependent level, illustrated, and evaluated in terms of cold start, battery boost, and current load-following capability. In summary, a reference fuel cell system model is built that is consistent and complete, as well as a model for stationary electric power generation. This makes it usable in mobile applications up to the relevant driving dynamics. Furthermore, the results achieve the goals of maximizing fuel cell system efficiency regardless of part-load conditions. The exploration of the collaborative vehicle design space is based on classical current-era technology choices. While comparing different designs, a good insight is gained into the synergies and inefficiencies of different powertrains in combination with different logistic tasks. As a result, it becomes clear what reasonable technology selections are when trading off overall vehicle dimensions, weight, and costs, as well as vehicle performance and required infrastructure.

5.2. Implications for Industry and Research

The presented additive modeling and simulation chain is a further move toward the increasing implementation of hybrid electric drive trains in intralogistics. Hardware-in-the-loop and vehicle-in-the-loop simulation can enable successful design and dimensional decisions. The main arguments for introducing series hybrid drive trains for special-purpose machines in this chapter are significant efficiency improvements and the potential to enable the use of different carbon-neutral or renewable energy sources for battery charging. Considering these aspects, the described concept offers a sustainable design. The real-world applicability of up to 60% of daily work hours at particular premises can be assured by leveraging the feasible battery energy capacity. To tackle frequent and fast battery charging, the use of carbon-neutral and efficient energy source technologies is recommended.

Other application examples with different premises and superstructures might offer a higher or lower feasible battery energy capacity. Additionally, superstructures require other drives such as electric or combustion motors to assemble their tasks. The best combination of drives needs to be found for the respective application. The presented concept is a viable option specifically for special-purpose machines working in indoor applications. The presented modeling and simulation chain could be subject to research improvements by including more simulative and modeling approaches. Furthermore, the spread of real-world performance data would enable a comparison of the results. While the second chapter advanced the state of the art already, the presented approach with the combination of different simulative models in an additive chain is still a novel one.

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