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TOWARDS INTELLIGENT WAREHOUSING: INTEGRATING LEAN AND INDUSTRY 4.0 TOOLS TO ENHANCE AUTOMOTIVE LOGISTICS PERFORMANCE

PhD Thesis - Abstract

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The automotive industry today is more than ever characterized by intricate supply chains and increasing demand for efficiency, responsiveness (agility) and resilience to adapt to constant disruptions as those in recent years, which also drives a similar paradigm shift in warehouse logistics. This thesis addresses the critical need for intelligent warehousing by exploring the synergistic integration of Lean management principles and Industry 4.0 technologies within the automotive sector, by providing insights into the research study of implementing one of the first automatic storage systems in Romania. Lean methodologies, with their focus on waste reduction and process optimization, provide a foundational framework for streamlining warehouse operations, whereas Industry 4.0 tools, encompassing automation, data analytics, and interconnected systems, offer innovative opportunities to enhance visibility, agility, and decision-making within warehouse operations (internal logistics) and flow management (inbound-storage-outbound). This research outlines actual results after successful implementation of these tools and proves modern management tools and mindsets can unlock significant improvements in automotive logistics performance, in both production and warehouse areas. By leveraging Lean's emphasis on flow and value stream mapping alongside Industry 4.0's capabilities for real-time data acquisition, predictive analytics and faster operations (cobots and automatic storage systems), warehouses can evolve from traditional storage facilities into intelligent, adaptive nodes within the broader supply chain. This thesis delves into the process of achieving such an ambitious and important integration, exploring practical applications through own research studies and analysis, and proposes an innovative framework for automotive companies and their managers who are eager to seeking to transform their warehouse operations into intelligent, agile and adaptive assets that drive enhanced efficiency, resilience, and competitive advantage in today's dynamic automotive business background and setting.

Chapter 1 introduces the automotive industry’s overall setting: major drivers of competitiveness, international supplier network, car groups and alliances as well as recent worldwide sales dynamics to have an overview of its complex, resilient and very competitive supply chain. The chapter provides pertinent empirical data about production volumes, sales figures and the main worldwide car manufacturers from the automotive industry for manufacturers, OEMs and their supplier networks, as well as the dynamics of the industry in recent years, along with the most important challenges faced by the carmakers in today’s interconnected environment, as well as its development perspectives in light of the ongoing and accelerating transition towards electric vehicle technologies. The first chapter is divided into 4 subchapters (*General overview, Automotive suppliers' network characteristics, Automobile manufacturers' groups and alliances and Worldwide sales and perspectives on main markets*), each dealing with its specific area.

The United States, China, Japan, and Germany are the benchmark countries for automotive industry (production, sales, jobs, innovation, research). The current shift towards more sustainable forms of transportation (hybrid and full electric cars) has slowed down in the last year, but petrol and diesel cars are expected to see more and more competition from these alternative mobility options, as the industry is adapting to changing times and regulations. China is the world's largest and fastest-growing automotive market and is increasing its global presence (even in Europe), an unexpected change of scenario, showing it has developed a lot in the last 20 years. The United States is the world's second-largest market and an important automotive benchmark with some of the most important car brands (General Motors, Ford), as well as innovators such as Tesla. Japan is the third-largest automotive market in the world and has set the pace for high quality and reliability standards for the industry across all its major brands (Toyota, Honda, and Nissan), being a resilient competitor for the United States and China. Germany is no longer the fourth-largest world automotive market (overtaken by India, South Korea and Mexico, as of 2024), but is still a major player with a range of premium brands (BMW, Mercedes-Benz, Porsche) in addition to its high volume brand, Volkswagen. In Europe there is little space for growth, as the industry seems to have already reached its peak. Moreover high cost of labor, workforce shortage, complex regulatory environment of the EU, low birth rate and aging population are reducing the demand for new vehicles. Nevertheless the European automotive industry is still a major driver of economic growth, will continue to grow (with lower margins) and adapt in these times towards electric transition to remain competitive on the global market.

Analysis of the top 20 global automotive suppliers reveals a geographical concentration, with the United States accounting for the largest share (five entities: Cummins, Lear, Goodyear, Tenneco, BorgWarner). Following closely are Japanese suppliers (four companies including Denso, Aisin, Bridgestone, and Sumitomo Electric). German and French suppliers each contribute three major players to this ranking, with Bosch, ZF Friedrichshafen, and Continental consistently positioned among the top four worldwide, and Michelin, Forvia, and Valeo representing France, respectively.

Most carmakers are part of groups or alliances and own several other brands in order to take advantage of common cost structures, extend their market presence and have a wider range of models offered within their portfolio. The most prominent examples are the Volkswagen and Stellantis Groups, the Renault-Nissan-Mitsubishi Alliance or the Chinese business model with joint-venture foreign brands producing their models locally. Volkswagen's portfolio also includes premium (Audi, Porsche), luxury (Bugatti, Bentley, Lamborgini) and sports brands (Cupra), in addition to its own range (Volkswagen, SEAT, Skoda). The Renault-Nissan-Mitsubishi Alliance also owns Dacia and Alpine (Renault) or Infiniti and Venucia (Nissan) brands and is one of the world's leading electric vehicle manufacturing groups due to its already famous models (Nissan Leaf and Renault Zoe). The Stellantis Group includes 16 brands (Italian, American, French, German/British) as a mix of the portfolio of Fiat Chrysler Automobiles (Alfa Romeo, Fiat, Maserati, Chrysler, Dodge, Jeep) and PSA Group (Peugeot, Citroën, DS Automobiles, Opel/Vauxhall). SAIC Motor, FAW Group, Dongfeng Motor Corporation and Changan Automobile are part of the largest 4 state-owned car manufacturers of China. All of these Chinese brands manufacture vehicles under foreign-branded joint ventures, in addition to their own brands. GAC Group, ZGH (commonly known as Geely), BYD Auto and BAIC are other important Chinese automakers.

General Motors currently has 4 brands (Chevrolet, GMC, Buick and Cadillac) and leads sales figure in the United States.

In terms of sales, as of 2024 Toyota is still leading with sales of over 10 million units (5th consecutive year), despite a 3.7% decrease in sales dynamics, followed by the Volkswagen Group (9.03 million units and 2.3% contraction) with Hyundai Motor Group coming in third with over 7 million units sold (7.23 million cars, but a 1% dip in dynamics in 2024). GM came close to reaching the 6 million unit milestone (5,998,000 vehicles and 3.04% decline in dynamics) with Stellantis achieving 5.415 million units (12.2% drop compared to 2023). The Renault-Nissan Alliance is likely to reach around 6.5 million vehicles (Renault Group 2,264,815 vehicles and Nissan 3,348,687 vehicles), with official data (around 940,000 units in sales, estimate) for Mitsubishi not yet available. BYD Auto and SAIC are also in the top 10 sales with over 4 million units sold, followed by Ford and Honda, both carmakers close to reaching the same mark. Geely and Suzuki both sold over 3 million units, whilst sales for German brands (BMW Group and Mercedes-Benz Group) were around 2.5 million units (2024).

Chapter 2 dives into the role and importance of the automotive industry in the European Union (EU) with an overview of its top 10 most relevant manufacturing countries. The subsequent subchapters then shift towards the automotive industry's specifics in Romania, both in terms of manufacturing, as well as the supplier network (especially multinational companies), before integrating these insights into a broader perspective (contribution of Eastern Europe to the automotive industry in view of the high supplier density in the Western region of Romania. This second chapter is divided into 5 subchapters (*General overview, Automotive industry in Romania, Romania's automotive industry supplier network, Perspectives in Romania and Eastern Europe and Automotive industry in the Western Region of Romania*), each dealing with its specific subtopic, issues, challenges and perspectives.

Globalization and cost-competitiveness have challenged traditional carmakers to become more efficient and also brought about partial shifting of production volumes from their home countries (Germany, France, Spain, Italy, UK) to other group owned manufacturing sites in lower-cost countries, from both the EU and outside the EU. Central European countries (Czech Republic and Slovakia) are benefiting from their automotive industry activity, both in terms of car manufacturing, as well as supplier network growth since Czech brand Skoda was bought by Volkswagen 30 years ago. The Czech Republic has the highest share of direct automotive employment in the EU (13.8%) and since 2007 Slovakia is the world's largest producer of cars per capita. Poland (Stellantis, Volkswagen, Toyota), Hungary (Audi, Mercedes-Benz, Suzuki) and Romania (Dacia, Ford) have also increased their relevance in the top 10 manufacturers in the EU and share similar growth patterns when it comes to the automotive industry. Building upon its established position, the European Union stands as a significant global player in vehicle exports, holding the second-largest share worldwide, closely following China's dominant performance. Within the EU, Germany maintains its status as the preeminent automotive manufacturing hub, contributing a substantial 29% to the region's total vehicle production output. An analysis of production volumes in 2022 reveals a concentration among a few key member states (Germany, Spain, France, the Czech Republic and Slovakia), each achieving an output exceeding 1 million vehicles annually. This highlights their critical role in the continent's overall automotive landscape, whilst their collective output significantly shapes the EU's position in the global automotive market.

Romania is the fastest-growing automotive market in the EU, with an annual growth rate of 10%. Automotive industry in Romania is developed around the 2 major car manufacturing plants in the country (Dacia and Ford), as well as an extensive network of multinational automotive suppliers. Automotive industry turnover in Romania exceeded 30 billion euros (2022), contributing to 12% of GDP and 30% of exports (70% increase in the last 10 years), whilst more than 60% of these sales were generated by its network of domestic suppliers. Overall, the growth of the automotive industry (more than 630 companies and 230,000 employees) has increased 25 times since 20 years ago and was marked by its third consecutive year with production output of over half a million vehicles (560,102 vehicles in 2024 and a 9.1% year-on-year increase). Dacia's factory in Romania averages 90-95% productivity levels at its factory in Mioveni (maximum capacity: 350,000 vehicles), above industry standards. The Ford Otosan factory in Craiova had a slower start to its operations before transitioning to more models in recent years, but has matched the output of the Dacia factory in 2024, with over 90% of production being exported by train towards the maritime port of Constanta. After a slight 10% decrease in 2021, but 2022 marked another increase (195,237 units), before the absolute production output for the manufacturing plant (5,893 employees): 250,670 units (2024) for production capacity of close to 272,000 vehicles (92.15% productivity) and 45% of all cars made in Romania, reducing the gap to Dacia.

Romania's impressive automotive industry growth was sourced by traditional carmakers (Germany, France and Italy) needs to have, in addition to Asian suppliers, closer alternatives to their home factories. The cost competitiveness of the Romanian market was thus seen as an opportunity for expansion and further growth in an emerging market (Mercedes-Benz Group's gearbox suppliers Star Assembly and Star Transmission, Michelin, Pirelli, Continental, Hella, Autoliv, Bosch) in addition to Renault's research center in Bucharest (Renault Technologie Roumanie), technical center in Titu or Dacia Logistics center in Mioveni, due to highly skilled, young and motivated workforce. Continental is the country's main industry employer (with factories and research centers across all major regions) with over 20,000 employees as of 2024. Favorable investment factors were the general local economic conditions (former factories, specialized workforce was already available and willing to work, good quality infrastructure, support of local authorities), but also proximity of the chosen factory sites to motorway access (mainly A1) and nearby airport options in every major region (Banat-Crisana, Transylvania, Moldova, Oltenia and/or Dobrogea). Some of the multinational companies have also invested and is partnering in local dual education projects in their established regions to further develop their current and future workforce. Multinational companies represent around 85% of the first 100 companies in Romania in terms of sales and profits (2022). The 10 most important automotive suppliers in Romania are multinational groups account for almost 10 billion euros worth of sales (more than 25% of all suppliers' contribution to the automotive sector's turnover) and are multinational groups. Romania's network of automotive part suppliers includes, in addition to international/multinational groups, former state-owned traditional Romanian companies or ventures initiated by Romanian shareholders. The recent expansion of Romania's supplier network has brought about the fact that almost any car manufactured or sold in Europe has at least 1 component which is manufactured here, thereby highlighting its role in today's automotive setting.

Compared to Poland and Hungary, Romania presents a nuanced automotive landscape. Its two primary car manufacturers, Dacia and Ford, are complemented by a developed supplier network, particularly strong in regions like the West, which benefits from robust logistics and competitive economic conditions. However, infrastructure limitations in areas such as Moldavia and the northern regions, coupled with incomplete motorway networks (notably the A1 sections and congested routes from Bucharest), pose significant disadvantages. Furthermore, while Romania joined the Schengen Area on January 1, 2025, the prior non-membership and ongoing workforce migration towards major urban centers continue to challenge a more evenly distributed and sustainable supplier ecosystem across the country. Hungary has 4 main car manufacturers based on its premises (Suzuki Esztergom, Audi Gyor, Mercedes Kecskemet and BMW Debrecen) in Northern, Northwest, Central and Eastern Hungary. The automotive industry is Hungary’s most important industrial sector (5% of GDP and 21% of exports) with more than 740 companies and around 175,000 direct and indirect employees. Poland's automotive sector features four major car producers: Fiat, Volkswagen, Opel/Stellantis, and Toyota, with Toyota operating 6 hybrid production lines. The country also manufactures MAN, Volvo, and Scania buses and is a significant automotive hub, contributing 8% to its GDP and 21% of its export value in 2019. Employing over 187,000 people across 2,500 companies, including major suppliers, Poland exports 80% of its automotive output, primarily to EU neighbors, demonstrating rapid growth and a commitment to a 50% carbon footprint reduction by 2030, with Polish suppliers delivering components to all major brands (Volkswagen Group, Ford or Mercedes-Benz and BMW). Romania attracts higher automotive investments compared to other CEE nations, with complex component production (advanced electronics) by companies like Bosch, Fujikura, and Continental, alongside increasing automation and Industry 4.0 adoption (interconnected machines, smart data management, automated warehousing solutions). Non-car automotive components constitute around 70% of the country's automotive exports, primarily destined for the EU and other global manufacturing hubs. While Poland and Hungary pose strong competition with superior infrastructure and Western European proximity, Romania benefits from cost-competitiveness, a skilled workforce, and a strong customer value reputation in key automotive regions like Sibiu and Timisoara. Ford Otosan's accelerated shift towards hybrid and electric vehicle production in Craiova and Dacia's plan to produce hybrid engines in Mioveni post-diesel engine cessation demonstrate this transition. For sustained growth, Romania needs to attract investments in electric battery and electronic component manufacturing.

The Western Region of Romania stands as a pivotal automotive hub, characterized by extensive activity and a diverse ecosystem of automotive suppliers concentrated around Timișoara, Arad, and Oradea. This attractiveness stems significantly from its strategic geographical positioning along the Hungarian border, providing unparalleled access to robust infrastructure encompassing motorways connecting to Hungary's M43 via Nădlac-Csanadpalota (Arad being a 45-minute drive away), well-developed airport facilities in Timișoara (the 4th largest nationally in 2022 with over 1 million passengers and a DHL logistics center), Oradea (the 9th largest with approximately 200,000 passengers), and a smaller airport in Arad, alongside a comprehensive railway network and the strategically important international rail port intermodal terminal at Curtici, the largest and most modern inland container terminal in Romania and a key facility in Central and Eastern Europe. Notably, Arad and Timișoara benefit from bypasses, streamlining heavy cargo traffic flow, a feature less common in other major Romanian cities. Further bolstering the region's appeal is the presence of the Politehnica University in Timișoara, a highly regarded institution and the primary source of technically skilled graduates across various engineering disciplines. The city's robust academic infrastructure, comprising four major universities with a combined student population exceeding 40,000, ensures a consistently well-qualified talent pool readily available for the automotive sector. The Banat region's inherent multiculturalism, with significant Hungarian, Serbian, and German native minorities, fosters a multilingual environment where a substantial portion of the populace possesses fluency in at least two to three languages, representing a considerable asset for international business operations. The first Automotive Forum (2014) was held in Timisoara 10 years ago, with 100 companies being represented, and at the time the main topic was how to prepare engineers for the future needs of the automotive industry’s development perspectives. The export of high-value-added automotive products directly contributes to the economic prosperity and enhanced quality of life observed in the areas where these companies are located. Despite these considerable advantages, the Western Region faces challenges. The exceptionally low unemployment rate, consistently below 1% (with Sânnicolau Mare famously reporting 0% unemployment), creates significant difficulties in recruiting and retaining personnel. Even larger urban centers like Arad and Timișoara grapple with competitive headhunting and a job market favoring employees. To mitigate these workforce challenges, companies often provide extensive transportation and shuttle services for employees commuting from distances of 50-100 kilometers or even from neighboring countries (including non-EU workers within quota), while simultaneously striving to maintain employee loyalty amidst intense competition for talent. The Western Region's strategic importance is further amplified by the significant presence of top-tier global automotive suppliers. In 2022, three out of the top four worldwide automotive suppliers had a strong operational base in this region (Bosch, Continental, ZF). The confluence of excellent road (A1 motorway), rail (Railport Arad – Curtici Cargo Center for intermodal shipments), and air infrastructure (Timisoara, Oradea and Arad airports), coupled with the presence of dedicated industrial parks and a competitive landscape of logistics service providers (including 3PL and warehousing), has firmly established the Western Region as the largest logistics hub in Romania, attracting significant transportation companies. The Romanian automotive industry's remarkable growth trajectory over the past two decades, from approximately 3.8 billion euros before EU accession in 2007 to nearly 20 billion euros in 2015 and roughly 30 billion euros in 2022, underscores the region's and the nation's increasing significance in the global automotive landscape, with major players like Continental expanding their presence alongside established manufacturers Dacia and Ford.

Chapter 3 introduces mathematical models and methods that can be used to understand some of the underlying principles used in warehousing and logistics management. The subsequent subchapters handle some of the most commonly used mathematical tools that enable an easier understanding and modeling of warehouse operations, before designing scenarios than can then be fully analyzed and simulated through proper software tools and optimization programs and packages. This chapter enables a logistics manager to better assess his operational flows and gain improved and deeper understanding of the overall warehouse performance, as well as its individual and more area metrics. This third chapter is divided into 4 subchapters (*Data-Driven Tools for Accurate Logistics Decisions, Limits for Scaling Logistics Operations, Modeling Dynamic Processes to Approach Logistics Optimization* and *Data Analytics for Effective Logistics*), each dealing with its specific set of mathematical tools.

While mathematical modeling could describe much of our internal warehouse logistics, frequent and rapid changes in layout, operations, and constraints hinder the practical application and validation of operations research models, often rendering results quickly outdated (inapplicable in our real life conditions). Therefore, this section presents simpler, more directly relevant methods employed to varying degrees, acknowledging their limited complexity due to these dynamic operational shifts. Linear interpolation, a fundamental estimation technique, generates approximations by connecting existing data points, thereby enhancing data granularity. Mathematically, it's a curve-fitting method employing linear polynomials to predict values within a known dataset's range. This tool proves valuable in logistics and warehouse operations for informing decisions, as demonstrated in our applications for warehouse space and equipment utilization analysis (internal performance), storage handling volume predictions (demand and inventory forecasting), and inbound-outbound transportation cost estimations. Several practical applications of linear interpolation to enhance warehouse operations were explored (optimizing warehouse space allocation, equipment utilization, particularly forklifts during peak handling times, proactive maintenance scheduling, bottleneck identification, enhanced equipment allocation for anticipated volume increases, demand and inventory forecasting). Finally, linear interpolation assisted in transportation cost estimation across various distances and service providers (analyzing costs for known distances from different forwarders, estimating costs for intermediate routes, more effective route planning and selection of the most cost-efficient transportation options).

To formalize and validate our analysis, results, and the progression of improvements within the warehouse, we also employed the logistic function. This mathematical tool is valuable for modeling capacity constraints and projecting both the growth trajectory and eventual saturation points of our operational changes. Our initial and primary utilization of this function involved modeling the adoption rate of novel technologies, a subject explored in greater detail in a subsequent chapter. Specifically, we applied the logistic function to address the complexities associated with implementing a new warehouse management and storage system, the AutoStore. Given its novelty within Romania and the limited precedent for large-scale adoption, particularly in Eastern Europe at the time, our objective was to forecast the technology's assimilation rate within our plant by drawing comparisons with established implementation cases across the broader industry. The logistic function proved particularly suitable for modeling such adoption curves, effectively illustrating to the Supply Chain Management team the anticipated progression over time. Notably, the function accurately estimated productivity metric levels for each critical implementation stage – launch, growth, and maturity – at various temporal points, demonstrating remarkable precision despite our initial unfamiliarity with the system. This insightful outcome played a pivotal role in our decision-making process regarding the potential expansion of the AutoStore solution to new storage areas versus reverting to a more conventional rack and forklift approach. Beyond technology adoption, the logistic function also provided valuable insights in optimizing our warehouse layout, with a specific focus on minimizing travel time for order-picking personnel within the pre-automated storage section. By employing the logistic function to model the relationship between the distance traversed by workers and the corresponding number of orders picked, we were able to calculate both value-added and non-value-added time components. This analysis facilitated the identification of optimal placement strategies for frequently requested items, enabling a clearer understanding of the warehouse's theoretical and actual carrying capacity.

Addressing challenges beyond warehouse space optimization, we encountered significant issues in vehicle routing, particularly for inbound truck arrivals, and queuing system analysis concerning the prioritization of both raw material deliveries and finished goods dispatches. Explicit analytical methods directly project a system's future state from its present condition. Conversely, implicit methods involve solving equations that incorporate both current and future states, offering a potentially more accurate but also more complex representation of system dynamics. The selection of an appropriate numerical method is problem-dependent. The Euler method, an iterative, stepwise technique, enables the calculation of trajectories and offers forecasting capabilities. When employing implicit methods, the operator splitting method often presents advantages by decomposing the differential operator into distinct linear and nonlinear components. The Euler method, a foundational numerical approach of first order, offers a straightforward approximation for solving ordinary differential equations over a specified interval. Both the forward and backward implementations of the Euler method yield a generally acceptable estimation of the solution's trajectory and magnitude, exhibiting a reasonable resemblance to the true solution even when juxtaposed with more intricate numerical methods. The Euler method offers a practical approach for evaluating various warehousing and operational challenges. In the context of space optimization, this method can predict future storage space requirements when goods arrive at fluctuating rates. By modeling the accumulation of goods based on the potentially time-varying rate of incoming items, the Euler method provides a useful initial estimate of the necessary storage capacity at different points in time, facilitating proactive planning to prevent both storage overflow and stockout scenarios. A recurring logistical challenge involves simplifying vehicle routing. Delivery trucks navigating multiple locations face variable arrival times at our plant gates due to priorities and unforeseen delays. By modeling the change in queue length over time, we can obtain a rough estimate of queue dynamics. This basic queuing analysis (distinct from the more sophisticated techniques of queuing theory) offers a quick and straightforward assessment of arrival volumes and potential scheduling strategies to proactively mitigate bottlenecks at our loading docks.

The operational management of a warehouse environment inherently necessitates a focus on continuous improvement or optimization, encompassing both the enhancement of internal process efficiency and the comprehensive analysis of overall performance. Network optimization algorithms offer powerful tools for streamlining the movement of goods and information both within the warehouse and throughout the broader supply chain. For instance, shortest path algorithms, such as Dijkstra's, excel at identifying the most efficient routes between any two points in a network. This capability can be directly applied to optimize order picking sequences or the pathways for material handling equipment within the warehouse. Another category of valuable algorithms is minimum spanning tree algorithms, exemplified by Prim's algorithm. These algorithms determine the minimal set of connections required to link all nodes within a network. In a warehousing context, this can be leveraged to optimize the physical layout of storage areas and workstations or to design the most cost-effective transportation network for inbound and outbound logistics. Statistical analysis provides quantitative metrics to evaluate operational performance and quantify deviations from established targets. These methods enable the examination of warehouse operation data to discern underlying trends, recurring patterns, and areas necessitating improvement. Common statistical techniques employed include regression analysis, time series analysis, and hypothesis testing. The integration of these mathematical tools and techniques into our analytical framework has increased the level of detail in understanding our warehouse operations and facilitated identifying areas suitable for performance optimization projects.

Chapter 4 presents some of the most important concepts and principles (lean management and operations management) used within our every-day activity in the warehouse, but that are also typical for our communication with the colleagues from production and shop floor area, as well as the overall internal logistics team. This fourth chapter is divided into 4 subchapters (*Warehouse layout management, JIT production flow principles, Globalization's Impact on Production Management and Visual Management*) and addresses some very common language for a typical automotive industry plant.

Lean warehouse layout management centers on optimizing flow and minimizing waste, a continuous effort achieved through incremental improvements to the warehouse and storage area, where handling, internal logistics, and material flows frequently intersect. The layout should support efficient, value-added activities and accommodate performance-enhancing adaptations. A streamlined layout fosters process understanding and reveals opportunities for cost reduction and waste elimination, often identified by engaged employees (improvements are frequently readily apparent and often originate from employees and workers themselves), empowering informed management decisions. Contemporary supply chain management in this industry emphasizes the value chain perspective and global optimization principles, necessitating a holistic view of the entire network of both vertical and horizontal suppliers to ensure the effective delivery of value to the end consumer. The automotive industry operates within a highly competitive environment, driven by rapid technological advancements and the continuous challenges of managing growth and adapting to evolving regulatory frameworks.

The Just-In-Time (JIT) system minimizes inventory by delivering materials precisely when needed for production, a demand-driven approach focused on waste reduction through "produce only when necessary." In warehouse management, JIT principles optimize storage capacity and enhance goods movement. We have adopted a 5-step practical methodology to cut inventory holding costs and boost warehouse productivity: Optimize Storage Space, Improve Goods Flow, Reduce Waste, Clear Visualization, Flexibility/Adaptability. Adopting Just-In-Time (JIT) within warehouse management offers substantial potential for boosting operational efficiency, lowering costs, and enhancing customer satisfaction. The Japanese automotive production system, while drawing inspiration from Ford's mass production, diverged to prioritize flexibility in response to changing market needs. Key figures like Taiichi Ohno, Shigeo Shingo, and Kaoru Ishikawa advocated for optimizing internal material flow, continuous improvement, and waste elimination, captured by the "Less is more" philosophy. The intense competition within the automotive sector is also demonstrated by the increasing number of collaborations and alliances. These partnerships aim to share costs and leverage combined resources, expertise, and profits. As a result, the number of independent automotive suppliers has significantly decreased over the last half-century, along with a reduction in direct suppliers. These complex, multi-layered relationships, alliances, and business partnerships among car manufacturers thoroughly define ownership structures (majority or minority control) and the extent of collaboration (joint ventures, shared production plants, and the integration of specific brands, models, and engines across different brands and models within the group or alliance) for major global car brands.

The globalization of automotive production has forged a complex landscape, balancing expanding markets with intricate operational and logistical hurdles that demand robust management for sustained cost efficiency and performance. Global disruptions have challenged traditional cost-focused, dispersed supplier networks, highlighting vulnerabilities and prioritizing supply chain resilience. Sustainable automotive supply chains require fostering innovation, adopting technology, and maintaining financial strength. Automotive firms must excel in supplier quality (balancing excellence, cost, and reliability), integrating advanced vehicle technologies, and adapting to technological shifts in the supply base, especially battery technology. Effective business strategy is crucial, significantly impacting short- and long-term performance and competitiveness, influencing finances, supply chains (OEM-supplier relationships), and overall success. A resilient strategic approach is vital in today's dynamic environment, surpassing historical advantages, as seen in industry mergers. The automotive sector's cyclical evolution, with continuous market shifts, necessitates rapid adaptation, stringent cost competitiveness, and operational resilience for all suppliers. Increasing customer demands, stricter regulations, vehicle complexity, and shorter product lifecycles amplify operational and logistical challenges, fueling intense industry competition.

Visual management is paramount in a warehouse handling electronic automotive industry products due to the sector's stringent requirements for precision, traceability, and quality. Clear visual cues streamline complex processes, ensuring the correct components reach the right assembly lines at the exact time. Color-coded labeling, designated storage locations, and visual aids for part identification minimize errors in handling diverse and often delicate electronic components. Lean constantly seeks to find the optimal balance between maximizing the quantity of output and the smoothness of the workflow on one hand, and rigorously ensuring the quality of products or services while proactively preventing defects on the other. Visual work instructions and process flow diagrams displayed at workstations guide employees through intricate handling procedures, ensuring adherence to quality standards and minimizing damage to fragile electronics. By systematically identifying the root causes of these wastes and implementing targeted elimination strategies, Lean streamlines operational processes, significantly reduces associated costs, and accelerates delivery times. Furthermore, visual management tools like Kanban boards or electronic displays can provide real-time inventory status, preventing shortages that could halt production or overstocking of rapidly evolving electronic parts. Performance metrics displayed visually, such as pick rates and error counts, foster a culture of continuous improvement and accountability among warehouse personnel. This intense focus on waste reduction directly translates into the ability to produce greater quantities more efficiently and ensures a smoother, more predictable flow of work throughout the entire production or service delivery system. Ultimately, in the high-stakes environment of electronic automotive component warehousing, effective visual management translates to enhanced efficiency, reduced errors, improved quality control, and a more streamlined and responsive supply chain. This can only be upheld by employees who know and have the correct routine for both Kaizen and visual management, as complementary techniques.

Chapter 5 presents the comprehensive analysis that was done in order to implement the first automatic storage system (AutoStore) within a manufacturing plant outside of the multinational company's home country. This fifth chapter is divided into 7 subchapters (*A Case Study of Warehouse Automation, Material flow analysis (current demand), Demand Planning for Material flow (future demand), Implementation of aAGV in shop floor (case study), Warehouse layout and material storage processes, Optimizing warehouse performance with AutoStore and Modernizing Warehouse Logistics Operations*) and presents the case study with only the data that the author could present within a delivered external document without being subject to NDA legal and contractual breaches.

The analysis first considered the plant area, both outside and inside, to see how flexible the design would be and if the automatic storage could be increased (in case of a positive ROI and increased warehousing performance) on the outside level, as well as on the inside (more density). This part also included some sales projections and forecasting future demand to better estimate for an actual optimum utilization level for when the project would be operational and running to full capacity.

The next step was related to the plant's material flow analysis (current demand), including the warehousing area. This was in order to see how much volumes could still be shifted inside the plant from warehouse to production (shop floor) in order to gain in added value space, as well as to consider the minimum requirements for the automatic storage area. This was done with lots of sets of data, both quantitative and qualitative, scenarios simulations and inputs from several management levels to make sure the right decision and choices were made before starting the implementation phase.

Once the setting was agreed upon, a new round of estimates, projections and calculations was made in terms of demand planning for material flow (this time for future demand). This also meant updating layout, recalculating operations flows and calculating what kind of robots and machinery could be used, in both the production area, as well as the warehouse. These calculations were also very important, because they should match the reality of the new production and warehouse areas once AutoStore would be operational.

Meanwhile a previous innovative project was being evaluated: the implementation of aAGV in shop floor (case study), so we could use these results and lessons learned in order to better design the AutoStore area. Regarding the aAGV's in the production area the experience was positive as most of the expected outcomes were matched or even delivered superior results, with some minor adjustments to make for the future implementation of such projects in production (HMI and PSS) – hansei from JIT.

Since this was the first time we did the automatic storage project, we had to document everything in terms of project progress: warehouse layout and material storage processes were marked, updated, changed, written down, then corrected, until the end version corresponded to the actual expected layout and configuration needs. This was very intense and it taught us the value of fully understanding our flows and knowing where to look in case of some technical issues, allowing for all team members to contribute and source ideas and improvement proposals, similar to an obeya meeting from JIT.

Optimizing warehouse performance with AutoStore, or the actual implementation, was very easy, as the system worked flawless from the beginning. The only challenge was related to the way we needed to carefully repack the components that needed to go into AutoStore (special ESD pallets) before entering the production area. Since these were also very high value materials, this required extra care, but once in the automatic storage system, the level of productivity was very high, with very few minor errors from our part during testing and the first 6 months of working with the system.

Modernizing warehouse logistics operations also brought about a more connected operations team from production (megalift storage and e-kanban ordering) and warehouse (repack, AutoStore and dispatch), as now both teams would be facing similar challenges and their work would influence or would be influenced by the others. In addition, some external yard projects were implemented for better truck arrival scheduling, as well as time delivery windows and registration systems for a better tracking of our incoming materials and trucks.

Chapter 6 presents the author’s research contributions throughout his PhD studies (research papers presented at scientific events under coordination of his PhD supervisor and his Doctoral Advisory Commitee) and his personal contributions to the field after over 20 years of experience in logistics and supply chain management. This sixth chapter is divided into 4 subchapters (*Warehouse Redesign Challenges – Adapting Layout and Improving Process Flow, Innovation in Warehouse Logistics – Industry 4.0 Operational and Productivity Gains, Bottlenecks in Automotive Industry: Lead Time, Excess Inventory and Production Organization Challenges and Driving Operational Excellence: Agile Lean Approach to Optimize Warehouse Performance Management*) and outlines intermediate results presented at scientific events and conferences I attended in these years.

The strong competitiveness of automotive suppliers in Western Romania has generated significant business growth, with the Timișoara plant consistently securing new projects that validate its high performance. This increased activity, however, necessitates higher output for both existing and new projects within the same spatial limitations, requiring a careful balancing of production lines to maintain optimal productivity. Rising customer demands, complex technical specifications, customized requirements, and shorter project lifecycles place additional pressure on the plant to sustain its quality and cost-effectiveness. Leveraging innovative reorganization concepts and Industry 4.0 principles, the plant has successfully redesigned its layout to accommodate increased volumes and optimize process and material flows. Initial results indicate a doubling of location occupancy rates, reaching 95% (nearly 20% above target), efficient traffic flow despite increased activity (higher output, speed, and safety), and consistent process flow within the new layout (with an initial 7% overall improvement, and some areas showing 15-20% gains). These encouraging outcomes demonstrate the plant's capacity to handle the anticipated medium-term launch of new projects with their associated volumes and complexities. The plant's business development prospects and competitive standing within the group are projected to remain strong, provided it continues to adapt its operations to challenges through innovation and a comprehensive continuous improvement strategy, aligning its achievements with the company's overarching objectives.

A pioneering initiative by a German automotive supplier in Western Romania to enhance its warehouse capacity and logistics efficiency yielded significant advancements. Driven by regional workforce dynamics (high skills, low unemployment, salary pressures, and fluctuation), substantial project scales with projected five-year growth (inbound logistics increases of roughly 15% by 2021, over 30% by 2022, and exceeding 60% by 2024), and spatial limitations (precluding expansion while production area grew, reducing warehouse space), the company adopted an innovative solution previously implemented in its German facilities: an Industry 4.0-aligned automatic storage (AutoStore) system designed to address operational and productivity targets. Implemented in April 2019, the AutoStore system demonstrated its effectiveness within six months. Repackaging processes achieved 30% greater stability through optimized work cells favored by employees. Material storage transitioned to ESD pallet levels, reducing forklift traffic and accelerating internal movements. Storage capacity surpassed initial estimates by over 20%, despite a 50% improvement in the warehouse-to-production floor space ratio, exceeding company benchmarks by nearly 10%. The AutoStore's features (compact ESD box storage, full automation, and Industry 4.0 integration) more than doubled location occupancy to around 95%, a 20% improvement over targets. Picking performance also increased significantly, with interoperation issues dropping by 70% below the target rate. Overall, the AutoStore system achieved approximately four times higher productivity for regular orders (80% of the total) and up to ten times better responsiveness for urgent orders (20%). This reduced the projected need for external storage to a manageable 10-20% for 2019-2021 within the existing layout, allowing for further optimization to accommodate future growth. The rapid success of the AutoStore project underscores the substantial operational and productivity gains achievable through innovative Industry 4.0 storage concepts in warehouse logistics. It also reinforces technology's crucial role in enhancing process flow, logistics effectiveness, added value, and cost competitiveness. While Industry 4.0 improves plant operations and quality, it necessitates a skilled workforce to effectively implement its principles and enhance customer value. In the dynamic automotive sector, long-term success hinges on the adaptability of manufacturers and their supply chain partners to market shifts and technological advancements.

Our data did not establish a clear correlation between travel distance and inventory levels across the analyzed suppliers due to numerous specific influencing factors. While longer distances might intuitively increase the likelihood of disruptions and thus necessitate higher inventory to buffer against shortages (a partial correlation was observed), contradictory findings within our dataset prevented a definitive confirmation. However, our results consistently showed a positive correlation between excess inventory and scrap rates for both German and European supplier processes. A significant reduction in excess inventory (71.14% for German, 68.29% for European suppliers) corresponded with a substantial decrease in scrap rates (71.22% and 57.01%, respectively). While a direct positive correlation between excess inventory and scrap across both supplier groups was only partially supported by our findings, an intermediate conclusion suggests that higher excess inventory levels increase the probability of higher scrap rates in associated production. The implementation of the EOQ model resulted in a substantial reduction in excess inventory (71.14% for German suppliers, 68.29% for European suppliers). This decrease in inventory levels in the second semester coincided with improved production performance. German suppliers saw a 71.22% reduction in overall scrap rate and a 1.55 percentage point decrease in the scrap rate range between frontend and backend processes. European suppliers experienced a 57.02% scrap rate improvement, although the frontend-backend scrap rate range slightly increased. Overall, output performance improved by over 50% in frontend processes and just above 70% in backend processes within approximately 26 weeks. The analyzed data underscores the value of continuous improvement initiatives, demonstrating that consistent and regular efforts can significantly enhance performance metrics and overall company outcomes. In our case, applying the EOQ model reduced inventory levels by 3.31 times to 10.69%, with a corresponding 65.25% reduction in the overall scrap rate across all 14 suppliers after implementing the Kanban method. These results represent the culmination of a complex improvement project that significantly enhanced operational performance, working conditions, and fostered a more balanced work environment. Sustaining these changes is crucial for maintaining a positive dynamic for the workforce, encouraging innovation and problem-solving, and ensuring sustainable performance levels within the company.

The final part is dedicated towards how to approach several of the issues encountered in the warehouse or any logistics setting in the automotive industry, such as the correct balance between quantity and quality (Operational performance analysis (balanced lean flow)) and the subsequent operations overview (Balanced workplace management (efficient flow)), as well as the most relevant KPI monitoring methods (Designing warehouse performance metrics), before being able to standardize and document everything for new or improved technical procedures which could be replicated in other sites (Agile Lean management routine approach). The final figure is more about an overview and is best understood after having already experienced the previous 4 steps as this part is basically a summary of the previous approaches and adds-on the whole picture view (Integrated lean cycle for automotive warehouse logistics).

Drawing upon the author's extensive experience in production, logistics, and manufacturing plant management, the following additional research topics are proposed to further deepen the understanding of performance drivers within the automotive industry and to validate the pertinence of the findings presented in this work:

1) **impact of advanced automation (like AutoStore and increased use of aAGVs) on workforce transformation and skill development** in automotive industry: this research study could investigate the long-term effects of deploying sophisticated automation technologies on the roles and required skill sets of warehouse personnel within the automotive industry. This is particularly relevant as automation becomes more prevalent, necessitating a deeper understanding of its societal and organizational impact;
2) **applying digital twin technology for proactive warehouse optimization and risk mitigation in the automotive industry**: this research could explore the development and implementation of digital twin models for automotive warehouses. Investigating how these virtual representations can be used for real-time monitoring, predictive maintenance of automated systems, simulation of layout changes, and proactive identification of potential disruptions (bottlenecks, equipment and/or failures, peaks of demand) would be valuable for optimizing efficiency and mitigating risks;
3) **developing a dynamic and adaptive framework for balancing quantity and quality in highly variable warehouse operations**: expanding on the proposed trade-off management method (within this thesis), future research could focus on creating a more dynamic and adaptive framework that automatically adjusts the balance between quantity and quality based on real-time operational data and fluctuating demands in automotive warehouses;
4) **studying the role of integrated lean and agile methodologies in enhancing resilience and adaptability in automotive supply chains** post-disruption: this research could examine the synergistic effects of combining lean principles with agile methodologies in bolstering the resilience and adaptability of automotive supply chains in the aftermath of recent global disruptions (Covid-19 pandemic, chip shortage, high inflation, energy crisis, war in Ukraine, etc.);
5) **optimizing warehouse performance metrics design for holistic operational**

visibility and predictive analytics: future research could delve into the design of more comprehensive and predictive warehouse performance metrics tailored to the specific needs of the automotive industry (exploring the integration of data analytics and machine learning to move beyond traditional KPIs and develop metrics that provide a holistic view of operational efficiency, identify potential bottlenecks proactively, and forecast future performance trends);

6) **assessing the impact of Industry 4.0 technologies on the agility and responsiveness of inbound and outbound logistics in the automotive industry**: this research could specifically investigate how the adoption of various Industry 4.0 technologies (e.g., IoT sensors, AI-powered analytics, autonomous vehicles) affects the agility and responsiveness of inbound (supplier-to-plant) and outbound (plant-to-customer) logistics within the automotive industry (impact on lead times, transportation efficiency, inventory management, and the ability to adapt to fluctuating market demands, optimizing end-to-end supply chain performance);
7) **developing a maturity model for lean implementation in automotive industry-specific warehousing operations**: assessing adoption, impact, and sustainability: future research could focus on creating a maturity model to assess the level of Lean implementation within automotive warehouses (practical tool for benchmarking and guiding continuous improvement efforts);
8) **analyzing the results and role of data-driven network optimization in enhancing the efficiency and sustainability of automotive parts distribution networks**: this research could explore the application of advanced network optimization algorithms and data analytics to improve the efficiency and sustainability of automotive parts distribution networks.

When discussing the **limitations of the current thesis and suggesting future research topics**, it is important to consider the following aspects: The current research has focused on a specific type of warehouse, a particular segment of the automotive supply chain, which may be typical of a limited geographical region, like Romania or Eastern Europe (or not). Future research could broaden this scope to provide more generalizable findings. For example, the study might have focused on a tier-one supplier; future research could explore tier-two or aftermarket logistics (**scope of the study**). The findings might be specific to the context of the specific organizational culture in the company I worked for or how this organizational culture is applied in the Romanian automotive industry. Future research could investigate the transferability of these findings and proposed frameworks to other geographical regions or different sectors within the automotive industry (**generalizability of findings**). The analysis was constrained by the availability or granularity of specific data (this is not necessarily true 100%, but the extent to which I could use all the data I gathered was indeed considerably limited). Future research could aim to gather more detailed or longitudinal data to enable more robust analysis and the application of more sophisticated statistical techniques. Access to proprietary data from multiple companies could also be a limitation, as most companies do not allow for disclosure of their data, or if they do it is usually for generic datasets which are rarely relevant for significant research purposes (**data availability and specificity**). The research findings reflect a specific period (my PhD studies with intermittent working sprees). Future research could examine the long-term impact of the implemented changes and the evolution of the identified trends over a more extended timeframe or not, as it could consider a smaller time period for analysis, like 6-12 months, for a more targeted research question (**time constraints**). The thesis might have employed specific methodologies (case studies, partial and limited use of specific mathematical models). Future research could explore the application of alternative or mixed methodologies to provide different perspectives or validate the findings. For instance, simulation modeling could be used to test the robustness of proposed solutions under various scenarios and attempt using optimization models or software (**methodological choices**). The research might have primarily focused on quantitative analysis. Future research could incorporate more in-depth qualitative data collection (conducting interviews and/or focus groups) to gain a richer understanding of the human and organizational factors influencing warehouse operations (**qualitative aspects**).

As of April 2025, the author has written, presented and published a number of **4 research papers** (2 of which are indexed WoS, 1 is indexed Scopus and 1 is pending indexation – see separate document for details). The final version of the PhD thesis contains 304 pages, including 42 tables and 172 figures, with a total number of 193 references.

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