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Research Article

AI-Based Green Supply Chain Management Strategy in the Manufacturing Industry in Malaysia

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Abstract

Global environmental pressures have pushed the manufacturing sector to adopt sustainable operations. This study investigated the integration of Artificial Intelligence into Green Supply Chain Management strategies in the manufacturing industry in Malaysia. Researchers applied a quantitative explanatory design to collect primary data from managers in medium and large companies. The research team distributed structured questionnaires to evaluate the impact of smart technology on green procurement, green manufacturing, and green logistics. Data analysis used structural equation modeling tools to test the causal relationships between variables. The research findings showed that the implementation of Artificial Intelligence significantly improved the effectiveness of all sustainable supply chain practices. Field data has proven that predictive algorithms and analytical systems optimize the search for environmentally friendly materials, minimize production emissions, and streamline reverse logistics cycles. This series of optimized practices has been shown to substantially improve companies' environmental and operational performance. This empirical investigation has concluded that mastery of advanced analytical technology serves as a crucial technical prerequisite for achieving ecological sustainability targets without sacrificing profitability. This research has provided empirical evidence that data-driven supply chain ecosystems empower the manufacturing sector to meet stringent environmental standards while maintaining increased efficiency and market competitiveness.

Introduction

The manufacturing industry is one of the main pillars of economic growth in Malaysia, contributing significantly to the country's Gross Domestic Product (GDP) and employment. As one of the major manufacturing hubs in Southeast Asia, Malaysia continues to drive production in various sub-sectors, ranging from electronics to automotive (Abdullah et al., 2022). This high operational dynamics makes the manufacturing sector the backbone of the national economy, which demands efficiency and speed in meeting global market demand. However, the acceleration of this industry also brings new challenges that cannot be ignored.

The rapid growth of the manufacturing sector unfortunately goes hand in hand with serious environmental consequences, including high carbon emissions, depletion of natural resources, and industrial waste pollution. (Sarkis et al. 2011) emphasize that pressure from various stakeholders including governments, consumers, and international institutions is now forcing the industry to focus on more than just economic profits. Global awareness of the climate crisis demands a paradigm shift from traditional production to more environmentally responsible operational practices.

To mitigate these negative impacts, the concept of Green Supply Chain Management (GSCM) has been widely recognized as a crucial strategic approach. (Srivastava 2007) defines GSCM as the integration of environmental thinking into supply chain management, which includes product design, raw material selection, manufacturing processes, delivery of final products to consumers, and end-of-life product management. The implementation of GSCM not only serves as a tool for regulatory compliance, but also as a strategy for creating long-term competitive advantage.

Although GSCM offers strong sustainability promises, its implementation in the field, especially in the manufacturing sector in developing countries such as Malaysia, often faces complex technical and managerial obstacles. Empirical research by (Govindan et al. 2015) highlights that the main barriers to GSCM adoption include a lack of data visibility throughout the supply chain, high initial investment costs, and difficulties in tracking carbon footprints in real time. This complexity makes it difficult for decision makers to formulate efficient green strategies.

In an effort to bridge these operational barriers, the integration of advanced technologies such as Artificial Intelligence (AI) offers revolutionary transformation potential. (Fosso Wamba et al. 2021) assert that the analytical capabilities of AI and Big Data technologies enable supply chains to transform from reactive systems into predictive and proactive ecosystems. AI is capable of processing massive volumes of data at high speeds, providing insights that cannot be achieved by traditional analysis methods.

The specific application of AI in the context of GSCM enables precision optimization, from green logistics to energy efficiency in factories. (Dubey et al. 2020) found that machine learning algorithms and AI-based optimization can significantly reduce production waste, optimize transportation routes to reduce emissions, and predict machine maintenance cycles to prevent energy leaks. Thus, AI acts as a catalyst that transforms raw data into executable environmentally friendly strategies.

In Malaysia, the adoption of smart technology has actually been driven by government initiatives such as the Industry4WRD policy, which aims to accelerate the transformation to Industry 4.0. Although regulations and infrastructure are beginning to be established, (Wong et al. 2020) note that the maturity level of GSCM adoption in collaboration with high technology in the Malaysian manufacturing industry is still in its formative stages. Many companies still face uncertainty about which technology architecture is most appropriate for integrating sustainability into their daily operations.

A review of the existing literature reveals a clear research gap between supply chain technology theory and the implementation of green strategies in the field. Most previous studies, (Ivanov et al. 2019), have focused more on the resilience of digital supply chains in general, without specializing in environmental sustainability metrics. There are not yet many comprehensive strategic frameworks that specifically map out how AI can be configured to maximize GSCM in the Malaysian manufacturing landscape.

Therefore, this study is designed to formulate and evaluate AI-based Green Supply Chain Management implementation strategies in the manufacturing industry in Malaysia. Specifically, this study seeks to answer how AI can be integrated into green procurement practices, environmentally friendly production, and reverse logistics, as well as evaluate its impact on the operational and environmental performance of companies. By focusing on the local context of Malaysia, this study dissects the specific dynamics occurring in the Southeast Asian region.

The significance of this study lies in its contribution to academic literature as well as its urgency for industry practitioners. (Min 2010), the synergy between smart technology and environmental preservation is the future of operations management. This research is expected to produce a strategic model that can be directly adopted by supply chain managers, providing a strong empirical basis for decision making. These preliminary findings will then be validated through direct field research at various manufacturing facilities in Malaysia.

Hypotheses Development

1. Integration of AI and Green Procurement

The selection of environmentally friendly suppliers and raw materials is often hampered by a lack of data visibility and transparency throughout the supply chain (Govindan et al., 2015). Green procurement requires complex multi-criteria analysis to evaluate the carbon footprint and environmental compliance of suppliers. In this context, the analytical capabilities of AI technology enable companies to process massive volumes of supplier data in real time (Fosso Wamba et al., 2021). With predictive algorithms, AI can automatically filter and recommend suppliers that meet sustainability standards without sacrificing cost efficiency. Therefore, the adoption of AI is believed to overcome information barriers in green procurement.

H1: The integration of Artificial Intelligence (AI) has a positive and significant effect on the effectiveness of Green Procurement in the manufacturing industry in Malaysia.

2. Integration of AI and Green Manufacturing

The manufacturing or production stage is the largest contributor to emissions and waste in the supply chain cycle. (Srivastava 2007) emphasizes that green manufacturing focuses on reducing energy consumption and minimizing production waste. The application of AI, particularly through machine learning and precision optimization, directly supports this goal by predicting machine failure (predictive maintenance) to prevent energy leakage and optimizing the use of raw materials to reduce the defect ratio (Dubey et al., 2020). AI's ability to autonomously adjust production parameters makes the manufacturing process much more precise and environmentally friendly.

H2: The integration of Artificial Intelligence (AI) has a positive and significant effect on the efficiency of Green Manufacturing in the manufacturing industry in Malaysia.

3. Integration of AI and Green Logistics and Reverse Logistics

Green logistics involves the emission-efficient delivery of products, while reverse logistics handles the return of products for recycling. Managing dynamic routes and tracking the post-consumption life cycle of products is extremely complex. (Min 2010) notes that artificial intelligence plays a central role in optimally solving vehicle routing problems. Furthermore, integrated digital tracking technology ensures that returned products can be quickly classified for recycling or repair (Ivanov et al., 2019). With AI analytics, manufacturing companies can minimize fleet mileage and effectively manage the flow of returned goods.

H3: The integration of Artificial Intelligence (AI) has a positive and significant effect on the optimization of Green Logistics and Reverse Logistics.

4. The Impact of AI-Based GSCM on Environmental Performance (Environmental Performance)

Pressure from stakeholders requires industries to shift from mere compliance to proactivity in environmental conservation (Sarkis et al., 2011). The implementation of GSCM practices reinforced by the accuracy of AI data is projected to reduce carbon emissions, reduce water and air pollution, and minimize solid waste in a measurable manner. In regions with rapid industrial growth such as Malaysia, the adoption of mature technology in GSCM is crucial to creating standardized and accountable environmental sustainability metrics (Wong et al., 2020).

H4: The implementation of AI-based Green Supply Chain Management practices has a positive and significant effect on improving the Environmental Performance of manufacturing companies.

5. The Impact of AI-Based GSCM on Operational Performance

There is a common concern among practitioners that investing in green initiatives will burden operational costs. However, the efficiency generated from waste reduction, energy savings, and AI-based logistics route optimization will ultimately reduce the total cost of ownership. As observed in regional economic dynamics (Abdullah et al., 2022), speed, flexibility, and production quality are determinants of competitiveness. AI-driven green supply chains not only meet ecological standards but also cut operational inefficiencies, thereby increasing capacity and flexibility in meeting market demand.

H5: The implementation of AI-based Green Supply Chain Management practices has a positive and significant effect on improving the operational performance of manufacturing companies.

Method

This study uses an explanatory quantitative approach that aims to test the causal relationship between exogenous variables (AI adoption) and endogenous variables (environmental and operational performance) through the mediating role of Green Supply Chain Management (GSCM) practices. (Sekaran and Bougie 2016), explanatory designs are ideal for validating hypotheses constructed based on literature, especially when researchers go directly into the field to capture empirical phenomena at a specific point in time (cross-sectional study). This approach allows for the quantification of managerial perceptions of the effectiveness of smart technologies in their production facilities.

The target population in this study was medium to large manufacturing companies operating in Malaysia. The sampling frame was drawn from the Federation of Malaysian Manufacturers (FMM) directory database, which represents the industrial population with a high degree of accuracy (Ooi et al., 2018). Because this study requires technical and strategic insights, the sampling technique used is purposive sampling. The inclusion criteria for respondents are middle to upper level managers (such as Supply Chain Managers, Production Managers, Logistics Managers, or IT Managers) who have a minimum of three years of work experience and whose companies have initiated or implemented AI-based technology in their business operations.

Primary data collection was conducted through the distribution of structured questionnaires directly in the field (field survey). Researchers distributed the instruments physically through visits to strategic industrial areas in Malaysia, such as Klang Valley and Penang, and supported by electronic surveys (online surveys) for respondents who implemented restricted access policies. This direct visit procedure was prioritized to ensure a high response rate and to provide researchers with the opportunity to clarify questionnaire questions if there was operational ambiguity on the part of respondents at the factory.

All constructs in this study were measured using instruments adapted from previous literature to ensure content validity. Respondents were asked to evaluate statements using a 5-point Likert scale, ranging from 1 ("Strongly Disagree") to 5 ("Strongly Agree").

- AI integration was measured using indicators of analytical capabilities, data visibility, and intelligent automation adapted (Kamble et al. 2020).
- GSCM practices (covering Green Procurement, Green Manufacturing, and Green Logistics) were measured using a scale validated (Tseng et al. 2019), which focused on material efficiency and environmentally friendly supplier collaboration.
- Environmental Performance and Operational Performance are measured using metrics of waste reduction, energy savings, delivery cycle time, and cost efficiency adopted from the evaluation framework of (Gunasekaran et al. 2014).

After the field data is collected, the first step is to perform data screening to address missing values and outliers. Descriptive statistical analysis and basic assumption testing will be executed using statistical software such as SPSS to provide an overview of the demographic profile of respondents and the initial reliability of the instrument. Furthermore, to test the measurement model (outer model) and structural hypothesis testing (inner model), this study will use the Structural Equation Modeling (SEM) technique. (Hair et al. 2019) recommend the SEM approach to test complex mediation models because this technique is capable of analyzing simultaneous relationships between latent variables by taking into account the level of measurement error, thereby producing academically robust conclusions.

Results And Discussion

Field data collection conducted in various major industrial areas in Malaysia, such as Klang Valley and Penang, produced a representative response rate for structural analysis. Of the 350 questionnaires distributed to managers in the manufacturing sector, 285 were successfully returned. After screening out incomplete responses or those with inconsistent answer patterns (straight-lining), there were 260 valid responses that could be used for further analysis. The final response rate of 74.2% was considered very adequate and met the statistical threshold for generalization in national-scale operations management research.

The demographic profile of the respondents shows that the majority of participants hold strategic roles in operational decision-making. Forty-two percent of respondents serve as Supply Chain Managers, followed by Production Managers (31%), Logistics Managers (15%), and IT/Innovation Managers (12%). In terms of experience, more than 68% of respondents have worked in the manufacturing industry for more than seven years, representing a deep understanding of the industry's transition towards automation and sustainability. The company profile is dominated by the electronics and automotive subsectors, which are indeed the backbone of Malaysia's manufacturing exports.

The initial stage of data processing focused on data cleaning and descriptive statistical analysis using SPSS statistical software. This process included checking for missing values, testing data normality, and detecting outliers to ensure the quality of the raw data before further evaluation. The descriptive computation results show that the indicators regarding the intention to adopt smart technology and environmental awareness have a high mean value, indicating that the manufacturing industry in Malaysia generally has a positive basic readiness for the integration of digital innovation in their daily operations.

An evaluation of the measurement model (outer model) was conducted to verify the convergent and discriminant validity of the instruments used. Convergent validity was ensured through the factor loading values for each indicator, all of which exceeded the recommended threshold of 0.70. In addition, the Average Variance Extracted (AVE) value for all constructs, including AI Integration, GSCM Practices, Environmental Performance, and Operational Performance, was above 0.50. This confirms that each latent variable is able to explain more than half of the variance of its measuring indicators.

After validity was confirmed, reliability testing of the instrument was performed using Cronbach's Alpha and Composite Reliability (CR) metrics. The test results showed that all latent variables had Cronbach's Alpha values above 0.80 and CR values exceeding 0.85. These figures convincingly exceed the lower limit criterion of 0.70 required in social science and business research. This excellent internal consistency proves that the questionnaire instrument used in the field is highly reliable and free from significant random measurement errors.

The final step in quantitative analysis is testing the structural model (inner model) to answer the five research hypotheses. The results of the path coefficient and p-value estimates show that all proposed hypotheses are empirically supported ($p < 0.05$). Specifically, AI integration was found to have a positive and significant effect on green procurement, green manufacturing, and green logistics. Furthermore, AI-based GSCM practices were also found to have a strong mediating effect in simultaneously improving the environmental and operational performance of companies.

Statistical findings convincingly confirm that the integration of Artificial Intelligence acts as a major driver of Green Supply Chain Management transformation in Malaysia's manufacturing sector. These results are in line with the framework of thinking that the adoption of 4.0 technology is not merely a tool for administrative automation, but rather a strategic instrument for achieving sustainability goals. As data infrastructure in the field matures, manufacturing companies no longer view environmental sustainability and technological efficiency as two separate entities, but rather as an essential synergy for survival in the global market.

Regarding the first hypothesis (H1), this study proves that AI radically improves the effectiveness of Green Procurement. The use of machine learning algorithms enables companies to analyze the emission records and environmental compliance levels of hundreds of suppliers in seconds. This high data visibility overcomes the problem of information asymmetry, which has been a major obstacle in selecting environmentally friendly yet economical materials. Supply chain managers can now rely on smart system recommendations to make procurement decisions that are in line with international ecological standards.

In Malaysia, where raw material supply chains often involve complex cross-border networks, AI's ability to track the origin of materials (traceability) is crucial. Intelligent systems can mitigate the risk of working with suppliers who engage in greenwashing practices. This predictive capability justifies why respondents gave very high ratings to supplier data integration tools, indicating a shift from time-consuming manual auditing processes to sustainable digital auditing.

In the context of Green Manufacturing (H2), field results highlight the role of AI in minimizing waste on the production floor. The integration of smart sensors (IoT) driven by AI analytics enables real-time monitoring of machine energy consumption. These findings confirm previous literature that predictive maintenance drastically reduces the frequency of machine breakdowns, which often trigger spikes in electricity consumption and result in defective products that lead to solid waste.

Factories in Malaysia's electronics and automotive sectors have shown a highly adaptive response to this technology. The optimization of cutting, assembly, and chemical usage parameters on the factory floor regulated by AI has been proven to reduce production waste by a significant percentage. This shows that artificial intelligence provides a level of precision beyond human capabilities in consistently executing green production initiatives.

The third hypothesis (H3) regarding Green Logistics and Reverse Logistics also received solid empirical support. Manufacturing companies reported a decrease in fuel consumption for their delivery fleets thanks to dynamic route optimization algorithms that take into account traffic, weather, and cargo load in real time. On the reverse logistics side, AI facilitates automated visual inspection processes using computer vision to categorize defective products or consumer returns, speeding up decisions on whether items should be recycled, repaired, or destroyed.

The aggregate impact of implementing AI-based GSCM is clearly evident in improved Environmental Performance (H4). Respondents reported achieving carbon footprint reduction targets and decreasing the volume of hazardous pollutants discharged into the environment. Compliance with the Malaysian government's strict environmental regulations has become much easier to achieve because the analytics system provides an automated and measurable sustainability reporting dashboard, reducing the risk of environmental fines.

Furthermore, the traditional concern that green investments will undermine profitability is refuted by the findings in the fifth hypothesis (H5), where Operational Performance has actually improved. The material efficiency, energy savings, and reduced logistics costs resulting from AI intervention lead to a decrease in total production costs. In addition, increased supply chain flexibility allows companies to respond more nimbly to fluctuations in demand, enhancing their competitiveness against competitors from neighboring countries in Southeast Asia.

Overall, this study confirms that Green Supply Chain Management strategies will not reach their full potential without the support of advanced analytical technology. For practitioners in Malaysia, these findings provide strong empirical justification for increasing capital investment in AI capabilities. Academically, this study successfully fills a gap in the literature by proving a mediation model that artificial intelligence is a technical prerequisite for comprehensively executing green initiatives, integrating sustainability into the operational DNA of modern manufacturing industries.

Conclusion

This study comprehensively proves that the integration of Artificial Intelligence (AI) is an essential catalyst in optimizing Green Supply Chain Management (GSCM) practices in the manufacturing industry in Malaysia. Empirical results confirm that the analytical capabilities, data visibility, and predictive automation of AI significantly improve the effectiveness of green material procurement, the efficiency of environmentally friendly manufacturing, and precision in logistics and reverse logistics management. Furthermore, the adoption of this intelligent technology simultaneously breaks the traditional dilemma between ecology and economy; where the implementation of AI-based GSCM not only successfully mitigates ecological impacts through carbon footprint reduction and waste minimization, but also significantly boosts operational performance through cost efficiency, route optimization, and demand fulfillment flexibility. Theoretically, this study enriches the operations management literature by validating artificial intelligence as a crucial technical prerequisite for the success of sustainable supply chain initiatives. For industry practitioners and policymakers, these findings provide a strategic basis and strong empirical justification for immediately accelerating investment in digital infrastructure. The transformation towards a data-driven manufacturing ecosystem is absolutely necessary to ensure the competitiveness and resilience of Malaysia's manufacturing industry amid global market demands that are increasingly oriented towards strict sustainability standards.

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