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Research Article

Selection of electric motors for automated guided vehicles within the framework of technology management

Kamil Bircan [1]

[1] Asst. Prof., Department of Logistics Management, Söke Faculty of Management, Adnan Menderes University, Aydın, Türkiye

Abstract

This study examines the electric motor selection process of a research and development (R&D)-focused automatic guided vehicle (AGV) manufacturer within the framework of the Technology Management Model, evaluating the impact of technological decision-making on strategic competitiveness. As one of the core activities of technology management, technology selection was analyzed using multi-criteria decision-making (MCDM) methods. The technical and sustainability-based criteria identified in the study were weighted using the FUCOM (Full Consistency Method), and alternative motor manufacturers were evaluated through the PROMETHEE (Preference Ranking Organization Method for Enrichment Evaluations) approach. The findings indicate that sustainability-oriented criteria play a decisive role in technology selection, revealing that companies prioritize not only technical performance but also social and environmental sustainability dimensions. The results show that suppliers with strong sustainability practices and high technical competence achieve higher competitive positions, demonstrating the growing importance of integrating sustainability into technological choices. Overall, the study emphasizes that technology selection should not be limited to technical compatibility but should also incorporate sustainability, governance, and integration factors within a holistic technology management perspective. By highlighting the strategic value of combining sustainability with technological capability, this research contributes to the literature by underlining that integrating sustainability principles into technology management enhances long-term competitiveness and organizational adaptability.

Keywords Technology management, Sustainability in production, FUCOM, PROMETHEE

Jel Codes M10, M11, L23

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Correspondence

K. Bircan
kamilbircan@adu.edu.tr

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ORCID

K. Bircan 0000-0003-1367-4189

1. Introduction

The effective management of technology forms an important foundation for achieving competitive advantage. The fact that the word "technology" is derived from the Greek words "technicos" and "logia" indicates that technology must be approached through systematic, planned and disciplined processes (Teece, 2018). Technology should not be perceived solely as physical tools or elements. Although electronic devices, transistors, or gears are often cited as examples of technology in daily life, the knowledge and design processes behind them are equally important. This perspective highlights that technology can produce both tangible and intangible outputs (Mikalef et al., 2019). It is emphasised that technology is a dynamic structure that continuously evolves with the accumulation of knowledge. This continuous evolution requires companies to manage their technological processes well, thereby gaining a competitive advantage. Porter & Heppelmann (2015) also state that technology creates new competitive strategies by integrating both physical and digital components. Approaching technology not merely as a tool, but also considering the underlying knowledge, processes, and management strategies is indispensable for competitive superiority. This situation supports the necessity for companies to develop innovative and adaptive approaches in today's digital age (Kraus et al., 2021).

Technology enables products and services to be produced with fewer resources and lower costs, while achieving higher efficiency, quality, and benefits (Porter & Heppelmann, 2015). This demonstrates that technology contributes to economic growth by optimising production processes. However, the view that technologies arise solely from economic needs is being questioned. Individuals with the ability to discover and guide within limited means develop significant technological innovations. This reveals that technology is also fuelled by creative and innovative processes (Kraus et al., 2021). When society embraces technology as a tool for competition and development, technology spreads, is learned, and continuously evolves with new knowledge (Mikalef et al., 2019). This process supports the dynamic nature and constantly evolving structure of technology. Economic value is defined as the difference between the production cost of a product or service and the value the customer is willing to pay. The greater this difference, the more economic value the firm creates, and technology emerges as a critical resource in increasing this economic value.

Developing knowledge and decision-making processes is crucial for making technology a strategic resource (Kraus et al., 2021). The intense competition and high quality expectations brought about by globalisation are directing business leaders towards the development of product and process technologies. This situation highlights the need to adapt quickly to technological innovations (Porter & Heppelmann, 2015). Companies and institutions are restructuring to keep pace with changes in technology. This restructuring is made possible by developing dynamic capabilities and gaining strategic flexibility (Teece, 2018). Planning technology development activities to adapt to changes in the market and customer needs is fundamental to remaining competitive globally. Thus, technology stands out as both a competitive advantage and a means of sustainable growth for organisations.

High costs and time are significant factors in the technology development process. The proper management of finance and human resources is critical for the effective development of technology (Teece, 2018). Being able to predict the future in the strategic decision-making process requires taking steps at the right time and in the right direction. However, today, the accumulation of knowledge and the speed at which technology is updated complicate management mechanisms

(Kraus et al., 2021). This situation makes it difficult to control companies' actions with the strategies developed. In addition, three fundamental questions arise that companies must answer in this challenging environment,

1. Which technologies will enable which jobs today and in the future?
2. Which technologies should we develop, and which should we source from external providers?
3. Which technologies should be specifically protected, and which can be commercialised?

These questions have led to the emergence of the discipline of Technology Management, which lies at the intersection of engineering, science, and management. Technology Management is a field that evaluates the potential of technologies and seeks ways to use them for the benefit of the organisation (Mikalef et al., 2019).

The environment in which the company operates and the objectives it sets based on this environment play an important role in strategic management. Objectives such as customer satisfaction, profitability, competitive advantage, sales growth and quality are shaped within the framework of market dynamics, competitors, financing sources, partnerships, legal regulations, workforce and existing capabilities (Kraus et al., 2021). Technology emerges as an important resource in achieving these objectives. This is because technology can assist the company in developing strategies in harmony with environmental factors and implementing these strategies (Porter & Heppelmann, 2015). In this context, technology management explores how technology can be directed and integrated in line with the company's objectives (Teece, 2018).

The channelling of technological capabilities in line with the firm's objectives is determined by different decisions, strategies and methods. Companies formulate their strategies by considering factors such as customer expectations, the competitive environment and legal regulations, in line with influences from their internal and external environments (Kraus et al., 2021). This differentiation is one of the key elements that determine competitive advantage. The technology management approach does not suggest a single method or strategy. Instead, it provides businesses with a practical framework for managing their technological capabilities (Teece, 2018). This framework can be applied to any type of organisation, regardless of the company's size, experience, or routine operations. When each firm adopts and implements the technology management framework in accordance with its own conditions, it can differentiate itself in the competitive environment and gain an advantage.

2. Techonology Management Process and Actions

Today, challenges such as rising costs, the pace of technological developments, and products incorporating different technologies have led businesses to use technology as a strategic resource in order to gain a competitive advantage (Özdemir, 2017). The company's technology strategy must be aligned with operational activities such as marketing, human resources, production, and investments. Thus, the economic value of technology can be maximised (Büyüközkan & Göçer, 2016). Five key actions stand out within the scope of technology management, as defined primarily by Gregory (1995). These actions can be summarised as follows:

Monitoring and Identifying Current Technologies: SMEs identify and analyse emerging or existing technologies to determine critical technologies. Daily customer–supplier relationships and marketing activities also contribute to this monitoring process (Büyüközkan & Göçer, 2016).

Selecting Technologies that will Provide a Competitive Advantage: Among the identified technologies, those that are compatible with the SME's strategic objectives must be determined. The integration of business strategy and technology strategy becomes important at this stage (Yıldırım et al., 2021).

Acquiring Technology: The process of acquiring selected technologies through purchase, collaboration, or development using the SME's own resources involves elements such as financing, human resources planning, and business partnerships (Akçay, 2018).

Utilising Acquired Technology: The acquired technology must be integrated into the company's product or service production processes to deliver the expected benefits. Marketing, production, and human resources planning play a critical role at this stage (Seyidoğlu, 2017).

Protection: Commercialised technology or technology with commercialisation potential must be protected through means such as intellectual property rights or human resources planning. This is a significant step in creating a sustainable competitive advantage for the technology (Güngör, 2021).

Technology management plays a key role in channelling SMEs' technological capabilities towards strategic objectives appropriate to the firm. This approach aims to create a competitive advantage by integrating technology with operational activities. In today's competitive environment, the proper planning and implementation of a technology strategy is essential for success.

Technology management activities are not a linear sequence of steps, but rather consist of actions that interact with and complement each other. How these activities are implemented and how they are aligned with company activities is of critical importance (Özdemir, 2017). Furthermore, the technology management process consists of flexible actions that are input-output related, rather than independent steps that follow one another. The literature indicates that some activities may be implemented more intensively during certain time periods, while others may be implemented less frequently or not at all (Büyüközkan & Göçer, 2016). For example, in the technology selection process, it is stated that the action of protecting technology may not be a priority at first, but may later gain strategic importance. Therefore, when selecting technology, consideration must also be given to how the selected technology will be protected (Yıldırım et al., 2021). Ensuring coordination among technology management activities is possible by first understanding each action individually and then evaluating them holistically. Thus, the company will be able to implement a flexible technology management process that is consistent with its strategic objectives (Akçay, 2018). These activities form a dynamic and interactive structure rather than a sequential order, enabling companies to adapt to environmental and strategic changes (Güngör, 2021).

It is crucial to conduct systematic activities to closely monitor technological developments and assess their impacts. In the literature, these activities are referred to as 'Technology Intelligence' (Asikhia et al., 2019). The primary objective of technology intelligence is to detect the signals emitted by industry leaders, i.e., technological clues, at an early stage. These early signals are analysed and interpreted to determine the direction of future technological developments. This process is not limited to merely gathering information. The information obtained is used to make strategic decisions based on the speed and impact of technological trends. This allows companies to develop policies appropriate to changing conditions and seize opportunities to gain a competitive advantage. Technology intelligence is a process that directly influences how organisations and managers respond to changing market conditions. When accurate analyses are conducted, businesses can both minimise risks and evaluate opportunities more quickly.

Technology monitoring begins with a company identifying its needs, deciding which technologies to monitor and how, and determining who will carry out this process. For the process to be successful, task distribution and work planning must be carried out meticulously. Suppliers are an important source during the information gathering phase. Their investment trends, strategies for new technologies, and the latest developments in the sector can provide valuable concrete and factual information for SMEs. Trade fairs and conferences are ideal venues for seeing innovations in the sector and establishing business connections. At these events, companies can closely examine new products and gain concrete information about technological trends. Customers are a critical source for understanding which technologies in products and services will meet their expectations. Consumer demands provide important clues about which technologies companies should invest in for the future. Digital platforms are highly accessible resources for keeping up with current developments. Industry news, technology forums, and social media channels provide companies with the latest trends in real time. Scientific studies play an important role in understanding the fundamental dynamics behind technological developments. Academic publications, seminars, and conferences contain innovative ideas directly linked to the sector. Finally, professional organisations and associations are valuable sources of information where the latest developments in the sector are shared. Workshops, newsletters, and special reports can serve as guides for businesses. The effective use of these resources plays a critical role in SMEs gaining a competitive advantage and making strategic decisions for the future.

One of the most critical stages of technology monitoring is how the collected data will be analysed and integrated into strategic decision-making processes. Various analysis methods are used at this stage. Tools such as Quality Function Deployment (QFD), trend analysis, patent analysis, and technology foresight provide important information about the direction and speed of technological developments. This information can be disseminated throughout the organisation to directly contribute to strategic decisions. For example, technology monitoring data integrated into quality management processes can be turned into targets that all employees should monitor. Similarly, changes can be made to the organisational structure in this direction. The advantages of technology monitoring for SMEs are presented below.

Gaining a competitive advantage: Technology monitoring helps to make timely and accurate decisions against small or large competitors.

Customer-focused innovation: It becomes easier to identify current customer needs and develop innovative solutions to meet those needs.

Developing proactive strategies: It becomes possible to take swift and pre-emptive measures against major technological changes.

SMEs' flexibility advantage makes them more agile than large-scale companies. An SME equipped with technology intelligence activities can adapt more quickly to changes in the market and rapidly update its strategic decisions.

Choosing the right technology for SMEs is a critical process in terms of gaining a competitive advantage. A wrong decision or a delayed choice can result in serious costs. Therefore, technology intelligence activities must be carried out continuously and correctly. The points to consider in technology selection are presented below.

Alignment with Organisational Capabilities: The selected technology should be compatible with the SME's learning and implementation capabilities. This ensures that the technology can be rapidly converted into a product or service. Integration into Business Areas: The technology should be usable in different areas of the company and easy to adapt. This can minimise technology costs.

Alignment with Acquisition Alternatives: Options for acquiring the technology through purchase, R&D development or partnership should be appropriate for the SME's financial and infrastructural conditions.

Alignment with Strategic Goals: Technology should be compatible with the company's current production, marketing, and growth strategies. Thus, technology management processes can be carried out more efficiently and effectively.

Technology selection is not merely a technical decision, but also a strategic step. For SMEs to secure a sustainable competitive advantage, it is crucial that they integrate technology into their strategic plans.

SMEs may adopt different strategies for technology acquisition. This choice is determined by the company's resources, technical capacity, and long-term objectives.

Technology Development through R&D: Companies that conduct their own R&D activities internalise the technologies they develop and gain a competitive advantage. However, challenges such as high costs, the need for expertise, and lengthy processes can be a major obstacle for SMEs.

Technology Transfer: Acquiring existing technologies through licensing agreements is less costly than R&D. However, SMEs must carefully evaluate factors such as licence duration, technical support requirements, and the organisational learning process.

Joint R&D Activities: Companies can participate in joint technology development projects to reduce costs and risks. Expertise and resource sharing can be achieved through joint ventures or consortia.

Innovation Networks: National and international innovation networks bring together actors from different sectors, offering opportunities for knowledge sharing, cost reduction, and collaboration. Supported by government incentives, this system can provide significant advantages for SMEs.

There is no single correct method for acquiring technology. SMEs should select the most appropriate method, such as R&D, transfer, joint ventures or innovation networks, according to their financial and technical capacities.

The conversion of acquired technology into economic gain is directly related to effective marketing strategies. The presentation of technology as a product or service involves critical decisions such as market entry timing, pricing, and presentation method. Launching a product early or late can affect competitive advantage. Competitors' strategies and market conditions must be taken into account. For a successful marketing process, customer profiles, demand, and competitive conditions must be analysed. The pricing of the product or service should also be based on these analyses.

Customer reactions and feedback provide important inputs for the development of technological products. Continuous improvement is necessary for long-term success. Technology should not only be developed but also brought to market with the right strategies. Market research, timing, pricing, and customer feedback should be considered for a successful launch.

The protection of intellectual property rights is crucial to prevent technological innovations from being imitated by competitors and to ensure sustainable economic gains. Developed technology can be protected through various methods. Patents, utility models, copyrights, trademarks, industrial designs, and trade secrets are the most commonly used protection tools. Patent protection, in particular, is among the most effective methods for gaining a competitive advantage. Patents ensure that innovative products or processes cannot be used by others for a certain period of time. This provides companies with the opportunity to strengthen their position in the market. Protecting technological innovation is a critical strategy for gaining a competitive advantage and securing long-term economic gains. Therefore, companies must effectively manage their intellectual property rights and properly plan legal processes.

3. Research Methodology

The study addresses the problem of selecting an AGV motor based on 13 motor selection criteria from 10 alternative brushless electric motor manufacturers for an automatic guided vehicle (AGV) manufacturer that develops technology through R&D. In the research, the weights of the motor selection criteria were calculated using the FUCOM Method, and the best alternative was selected within the framework of the criteria determined by the PROMETHEE Method.

3.1. The FUCOM Method

The FUCOM method enables weight calculation by performing fewer pairwise comparisons compared to the AHP method, which is based on pairwise comparisons. The FUCOM method aims to minimise inconsistencies that may arise in pairwise comparisons while calculating criterion weights with n-1 pairwise comparisons. The advantages of the FUCOM method are that it is not overly complex and can be used in situations where there are multiple decision-makers (Ayçin & Aşan, 2021). In the FUCOM method, the deviation value from full consistency is found when determining weights. FUCOM ensures the validation of the model by determining the deviation from full consistency and calculating the error value for the weight vectors (Pamučar et al., 2018).

The application steps of the FUCOM method are as follows (Pamučar et al., 2018):

Step 1. The criteria are ranked by the decision-makers from the most important to the least important. Thus, as seen in Eq. 1, the criteria are ranked according to the expected values of the weight coefficients. K represents the degree of the observed criterion.

$$C_{j(1)} > C_{j(2)} > \dots > C_{j(k)} \tag{1}$$

Step 2. Based on the decision maker's preferences, the comparative priorities (ϕ k/k+1) of the criteria are determined by establishing their importance rankings, and the comparative priority vector of the criteria is obtained. The comparative priority vector of the evaluation criteria is as shown in Eq. 2.

$$\varphi = \left(\phi_{1/2}, \phi_{2/3}, \phi_{3/4}, \dots, \phi_{k/k+1}\right) \tag{2}$$

Step 3. The final values of the weight coefficients of the evaluation criteria $(w_1, w_2, ..., w_n)^T$ are calculated. The final values of the weight coefficients must satisfy the following two conditions. Condition 1. The ratio of the weight coefficients is equal to the comparative priority values of the criteria determined in Step 2.

$$\frac{W_k}{W_{k+1}} = \phi_{k/k+1} \tag{3}$$

Condition 2. The final values of the weight coefficients must ensure mathematical consistency.

$\varphi_{k/k+1} \otimes \varphi_{k+1/k+2} = \varphi_{k/k+2}$ must hold. Similarly, since $\varphi_{k/k+1} = \frac{W_k}{W_{k+1}}$ and $\varphi_{k+1/k+2} = \frac{W_{k+1}}{W_{k+2}}$, we obtain the equality $\frac{W_k}{W_{k+1}} \otimes \frac{W_{k+1}}{W_{k+2}} = \frac{W_k}{W_{k+2}}$. The necessary condition for the final values of the evaluation criteria weights is shown in Eq. 4.

$$\frac{W_k}{W_{k+2}} = \varphi_{k/k+1} \otimes \varphi_{k+1/k+2} \tag{4}$$

When these two conditions are met, a state of full consistency, or in other words, a deviation from minimum full consistency (DFC) X, is achieved. The final importance weights of the criteria are obtained by solving the linear programming model in Eq. 5.

$$\begin{aligned} &\text{Min } X \\ &\quad s.t. \\ &\qquad \left| \frac{w_{j(k)}}{w_{j(k+1)}} - \phi_{k/k+1} \right| \leq x, \forall j \\ &\qquad \left| \frac{w_{j(k)}}{\left(w_{j(k+2)}\right)} - \phi_{k/k+1} \otimes \phi_{k+1/k+2} \right| \leq \chi, \forall j \\ &\qquad \sum_{j=1}^{n} w_j = 1, \forall j \\ &\qquad w_j \geq 0, \forall j \end{aligned} \tag{5}$$

3.2. The PROMETHEE Method

PROMETHEE (Preference Ranking Organisation Method for Enrichment of Evaluations) was first developed by Brans in 1982 and expanded by Brans & Vincke in 1985 (Behzadian et al., 2010). The method was developed to select the best alternative within the framework of specified criteria and has an approach that offers decision-makers the opportunity to view all data related to the problem in an easy-to-understand table (Ergün Bülbül & Köse, 2016). It was developed based on the difficulties encountered in the application phase of existing prioritisation methods in the literature (Dağdeviren & Eraslan, 2008). The fundamental characteristics of the PROMETHEE method are simplicity, transparency, and balance (Genç, 2013). The method is based on the notion of a generalised criterion, establishing a valued outranking relation (Brans et al., 1986). The PROMETHEE method allows for both partial ranking (PROMETHEE I) and full ranking (PROMETHEE II) on a set of possible actions (alternatives) (Brans & Vincke, 1985). PROMETHEE I is based on the positive and negative outranking flows for each alternative. A positive outranking flow (Φ+) indicates how much an alternative outperforms all other alternatives and demonstrates the strength of that alternative.

The negative superiority flow (Φ-) indicates how far behind an alternative is compared to all other alternatives and demonstrates its weakness. The PROMETHEE II full ranking is obtained by calculating the net superiority flow (Φ), which is the balance between positive and negative flows. The net superiority flow is calculated by taking the difference between the positive and negative superiority flows (Coquelet et al., 2025). The fundamental difference between this method and other multi-criteria decision-making methods is that a separate preference function can be defined for each criterion, and the method also takes into account the internal relationship of each evaluation criterion (Kalender & Aygün, 2019). These functions convert the performance difference between alternatives into a preference degree between 0 and 1. In the PROMETHEE method, the superiority of two alternatives being compared is determined by considering the numerical magnitude of the difference between their performance values, using the indifference threshold and preference threshold set for the preference functions. The indifference threshold is the largest deviation considered negligible by the decision-maker; the preference threshold is the smallest deviation considered sufficient to constitute a complete preference (Brans & De Smet, 2016).

The following steps are followed in applying the method based on the pairwise comparison of alternatives' performance according to the fundamental criteria.

1. First, a table is prepared in which each alternative is evaluated according to each criterion (Murat et al., 2015). This table contains the performance values of m alternatives for n criteria. $f_j(i)$ represents the performance value of the i^{th} alternative according to the j^{th} criterion. The data table analysed is as follows.

Table 1. Performance values of alternatives according to criteria

	Criterion 1	Criterion 2	...	Criterion n
Alternative 1	$f_1(1)$	$f_2(1)$	...	$f_n(1)$
Alternative 2	$f_1(2)$	$f_2(2)$	...	$f_n(2)$
⋮	⋮	⋮	⋱	⋮
Alternative m	$f_1(m)$	$f_2(m)$	...	$f_n(m)$

2. The w_j, value (weight of criterion j), which indicates the importance level of each criterion, is determined. The sum of the weights of the criteria must be 1. When determining criterion weights, objective or subjective criterion weighting multi-criteria decision-making methods can be applied. PROMETHEE does not provide specific guidelines for determining these weights; however, it assumes that the decision-maker can evaluate the criteria appropriately, at least when the number of criteria is not excessive (Macharis et al., 2004).

3. Once the weights have been determined, alternatives are compared in pairs for each criterion and deviation values are calculated. To denote two separate alternatives, a and b, the deviation value for criterion j is calculated using the following Eq. 6 (Behzadian et al., 2010).

$$d_j(a,b) = f_j(a) - f_j(b) \tag{6}$$

4. According to the assessments given in Table 1, a specific P_j preference function must be determined to convert the deviation between the two alternatives into a preference scale ranging from 0 to 1 (Murat et al. 2015:731). The six types of preference functions used in the literature are

given in Table 2 (Brans & Vincke, 1985). The degree of preference of alternative a over alternative b on criterion j is expressed as follows (Brans & Mareschal, 2005).

5. The preference scores calculated for each alternative pair are multiplied by the weight values specified for the criteria and summed for each criterion to calculate a general preference index denoted by $\pi(a,b)$. Where n denotes the number of criteria, $\pi(a,b)$ is calculated using the following equation (Behzadian et al., 2010).

$$\pi(a,b) = \sum_{j=1}^{n} P_j(a,b).w_j \tag{7}$$

6. After calculating the overall preference indices, the next step is to calculate the positive ($\Phi+$) and negative ($\Phi-$) superiority flows for each alternative. Let x be an element of the set of alternatives A. The negative and positive superiority flows for $a \in A$ are calculated as follows. (Brans and Vincke 1985:653). The superiority flows are normalised by dividing the total values given in the equations by $m-1$. PROMETHEE I provides a partial ranking based on the positive ($\Phi+$) and negative ($\Phi-$) superiority flows for the alternatives. This ranking reveals the definite superiority, indifference, and incomparability of one alternative over another (Brans & Mareschal, 2005).

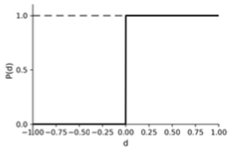
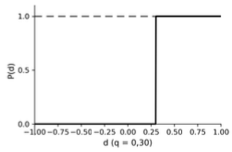
$$\Phi^{+}(a) = \frac{1}{m-1} \sum_{x \in A} \pi(a,x) \tag{8}$$

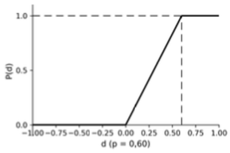
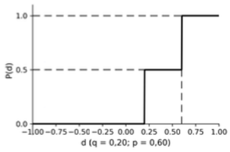
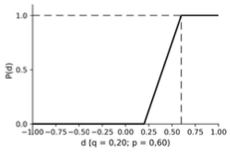
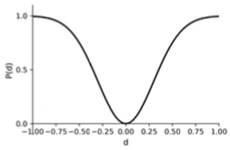
$$\Phi^{-}(a) = \frac{1}{m-1} \sum_{x \in A} \pi(x,a) \tag{9}$$

Using PROMETHEE II, the net flow score (Φ) is calculated by taking the difference between the positive and negative superiority of alternatives. For alternative a in set A, where a∈A, the net flow score $\Phi(a)$ is found as $\Phi^{+}(a) - \Phi^{-}(a)$ (Ergün Bülbül & Köse, 2016). The net flow score determines the final ranking of alternatives, and the alternative with the highest net flow score is considered the best. The net flow score is included in PROMETHEE II, which does not include cases where alternatives are incomparable (Genç, 2013).

$$P_j(a,b) = F_j\left[d_j(a,b)\right] \tag{10}$$

Table 2. PROMETHEE preference functions

Function type	Parameters	Function	Graph
Type I Usual criterion	-	$P(d) = \begin{cases} 0.0, & d \leq 0 \\ 1.0, & d > 0 \end{cases}$	
Type II U-Shape criterion (Indifference threshold)	q indifference threshold	$P(d) = \begin{cases} 0.0, & \lvert d \rvert \leq q \\ 1.0, & \lvert d \rvert > q \end{cases}$	

Function type	Parameters	Function	Graph
Type III V-Shape criterion (linear preference)	p preference threshold	$P(d) = \begin{cases} 0.0, & d \le q \\ \frac{d}{p}, & 0 < d \le p \\ 1.0, & d > p \end{cases}$	
Type IV Level criterion (step preference)	q indifference threshold p preference threshold	$P(d) = \begin{cases} 0.0, & d \le q \\ 0.5, & q < d \le p \\ 1.0, & d > p \end{cases}$	
Type V V-Shape criterion (Indifference criterion)	q indifference threshold p preference threshold	$P(d) = \begin{cases} 0.0, & d \le q \\ \frac{d-q}{p-q}, & q < d \le p \\ 1.0, & d > p \end{cases}$	
Type VI Gaussian criterion (soft preference)	s spread parameter (std dev)	$P(d) = 1 - \exp\left(-\frac{d^2}{2s^2}\right)$	

Source: Brans & Vincke (1985)

4. Application

The following criteria have been established to facilitate the decision-making process for an AGV manufacturer developing technology through R&D, focusing on technical and sustainability aspects, when selecting from 10 alternative brushless DC/AC motor suppliers.

- Power: The electrical/shaft power (W or kW) that the motor can deliver continuously and at peak. The AGV's load capacity, acceleration, and gradient capability are directly related to motor power. Insufficient power can lead to operational inefficiency or overheating risks.
- Torque: The motor's capacity to generate rotational force (Nm) — both continuous and starting/peak torque. AGVs require high torque for lifting loads, starting, and moving on ramps. Low torque means loss of traction and reduced performance.
- Speed (Speed / RPM): The motor's rotational speed range (rpm) and speed-dependent torque characteristics. The AGV's maximum cruising speed, precise positioning, and speed control dynamics depend on this criterion. Speed-torque matching must be appropriate for the requirements.
- Integrated Driver / Inverter: The presence and capabilities of an integrated driver/electronics within the motor or supplied with its assembly. Integrated drivers reduce space, cabling, and development time; prevent motor-driver incompatibilities; and can offer telemetry and control functions (CAN, EtherCAT, etc.). Provides the advantage of rapid prototyping for R&D.
- Lead Time / Supply Speed: The time from order to delivery and the supplier's production/supply capacity. R&D cycles, prototyping, and transition to production times are dependent on lead time. Short and predictable lead times are critical for digital transformation and ramp-up to series production.

- Reliability: The motor's fault-free operating time, MTBF (Mean Time Between Failures) and field performance history. AGVs typically perform critical tasks on production/logistics lines; high reliability reduces operational downtime, maintenance costs and labour loss.
- Environmental Sustainability: Environmental impacts during production, materials and use (energy efficiency, recyclability, absence of hazardous substances). Corporate sustainability goals, supply chain regulations and customer demands make this essential. Energy efficiency reduces long-term operating costs.
- Social Sustainability: The supplier's working conditions, compliance with human rights, supply chain transparency, and social impacts. This is important for corporate reputation, supply chain risk management, and sustainability reporting; ethical supplier selection facilitates long-term business relationships.
- Governance / Supplier Management: The supplier's corporate governance quality, quality management systems (ISO9001), supplier sustainability commitments, and contract management competence. Working with stable, transparent and well-managed suppliers reduces contract enforceability, continuous improvement and risks. IP management and contract terms are critical in R&D collaborations.
- Ease of Integration/Assembly: The ease of mechanical and electrical integration of the motor; assembly tolerances, connector types, assembly accessories, and documentation quality. Quick assembly and maintenance equate to production line efficiency. Integration costs are important when transitioning from R&D prototypes to series production.
- Durability / Robustness: The motor's physical and environmental resistance: IP rating, thermal resistance, vibration/shock tolerance, operating temperature range. AGVs operate in harsh production/logistics environments — dust, moisture, impact and continuous operation require durability. A durable motor means fewer breakdowns and less maintenance.
- Functionality / Features: Additional functions offered by the motor: encoder/position sensor, brake integration, torque control, regenerative braking, telemetry, diagnostic features. Advanced functions improve AGV control and energy management; system cost and complexity decrease with fewer additional components. Provides flexibility for R&D.
- User-Friendliness / Maintainability: Ease of working with the motor and driver: documentation, fault detection tools, driver software interfaces, training materials. Ensures easy maintenance, quick training, fewer installation errors and shorter repair times; reduces field maintenance costs. Facilitates field testing for R&D.

These 13 criteria have been selected around three main objectives:

- Performance & Safety: (Power, Torque, Speed, Durability, Reliability) Ensures that the AGV performs its tasks safely and efficiently.
- Integration & Operational Efficiency: (Integrated Driver, Ease of Assembly, Functionality, User-Friendliness) Accelerates both R&D prototyping and mass production phases, reducing total cost of ownership.
- Sustainability & Management: (Environmental, Social, Management, Supply Speed) Ensures corporate responsibility, regulatory compliance, and supply chain reliability.

4.1. Calculation of Criterion Weights Using FUCOM

In this study, the FUCOM (Full Consistency Method) approach was selected to determine criterion weights. Compared to traditional pairwise comparison methods such as AHP, FUCOM offers significant advantages, including requiring fewer comparisons (n-1) and aiming to minimise inconsistencies in subjective judgements. Furthermore, the method's ability to confirm the accuracy of the model by calculating the deviation from full consistency (DFC) value was also influential in this choice. The necessary subjective assessments are based on the judgements of the chief engineer of design-manufacturing-production. In accordance with the FUCOM methodology, the chief engineer first ranked the criteria from most important to least important, then determined the importance ratios (comparison coefficients) between successive criteria according to this ranking. This ranking and coefficients determined by the decision maker are summarised in Table 3. The final criterion weights obtained from the calculations performed using the Python programming language based on these inputs in Table 3 are presented in Table 4.

Table 3. FUCOM criterion comparison coefficients (ϕk/(k+1))

Criterion	Social Sustainability	Environmental Sustainability	Power (Watt)	Torque (Nm)	Integrated Driver (Inverter)	Lead Time (Supply Speed)	Reliability	Speed (rpm)	Governance	Durability	Functionality	Ease of Integration	User Friendliness
Rank (k)	1	2	3	4	5	6	7	8	9	10	11	12	13
Coefficient (φk/k+1)	2	2	2	2	2	2	2	1	1	1	1	1	-

According to the comparison coefficients given in Table 3, social sustainability ranks first in the criteria ranking, while user-friendliness ranks last. The values in Table 3 show how many times more important criterion i is than criterion i+1. In determining the weights, FUCOM's proportional consistency structure was not limited to neighbouring comparisons (i,i"+" 1) but also included triple transition constraints (i,i"+" 3) in the model. Thus, the triple transition constraints ensure a high degree of consistency that neighbouring ratios alone cannot impose; they contribute to obtaining a singular and more stable FUCOM weight vector by tightening the feasibility region. The final FUCOM weights, which are the input to the PROMETHEE method, are given in Table 4.

Table 4. Criterion weights found using the FUCOM method

Criterion	Weight
Power (Watt)	0.12307692
Torque (Nm)	0.06153846
Speed (rpm)	0.00384615
Integrated Driver / Inverter	0.03076923
Lead Time / Supply Speed	0.01538462
Reliability	0.00769231
Environmental Sustainability	0.24615385
Social Sustainability	0.49230769
Governance / Supplier Management	0.00384615
Ease of Integration/Assembly	0.00384615

Criterion	Weight
Durability / Robustness	0.00384615
Functionality / Features	0.00384615
User-Friendliness / Maintainability	0.00384615

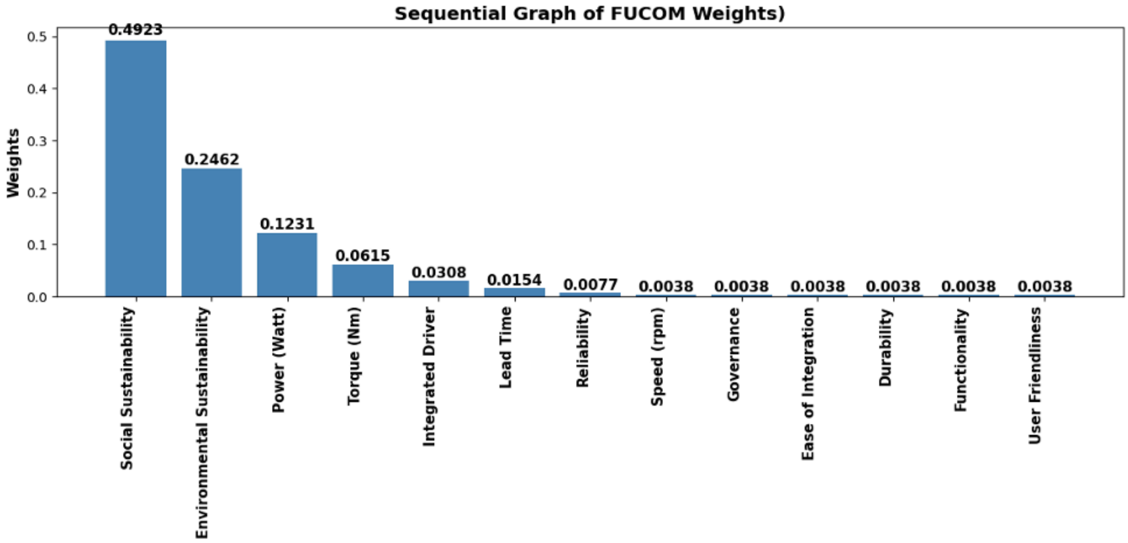


Figure 1. Sequential Graph of FUCOM Weights

Figure 1 shows that the highest weight is assigned to the social sustainability criterion (0.492). Environmental sustainability (0.246) ranks second, followed by power (0.123) in third place. In last place are the criteria of speed, governance sustainability, ease of assembly, durability, functionality, and user-friendliness (0.003). The criterion weights obtained using the FUCOM method were transferred to the model to be used in the evaluation of alternatives in the PROMETHEE analysis. Thus, the relative importance levels of the criteria were weighted based on the decision-makers' judgements, and in the PROMETHEE method, the performance balances of the alternatives were analysed under these weights.

4.2. Application of the PROMETHEE Method

In this section, the problem of selecting the most suitable industrial electric motor for an AGV vehicle from among various suppliers has been solved using the PROMETHEE multi-criteria decision-making method. PROMETHEE was chosen because it provides both partial (PROMETHEE I) and full ranking (PROMETHEE II) among alternatives and can effectively manage conflicting criteria. The criterion weights used in the analysis were determined using the FUCOM method, based on the subjective judgements of the chief engineer of design-manufacturing-production department, who was responsible for the decision-making process. The analysis performed using this weight set first provides a partial ranking using PROMETHEE I, revealing the superiority (S), indifference (I), and incomparability (I) relationships between the alternatives. Subsequently, a PROMETHEE II full ranking based on net flow scores was created to provide the decision-maker with a definitive ranking. Table 5 shows the evaluation matrix created for the criteria and alternatives used in the PROMETHEE method. The bottom row shows the criterion direction (max/min) and the row above it shows the criterion weights.

Table 5. PROMETHEE Evaluation Matrix

	Power (Watt)	Torque (Nm)	Speed (rpm)	Integrated Driver	Supply Speed (Day)	Reliability	Environmental Sustainability	Social Sustainability	Governance	Ease of Integration	Durability	Functionality	User-Friendliness
Maxon Motor (Switzerland)	500	120	4200	1	7	10	9	9	9	8	8	8	8
DunkerMotoren (Germany)	200	100	4500	1	7	9	8	8	9	8	9	8	7
Faulhaber (Germany)	500	130	4100	1	7	9	8	8	9	8	8	8	7
Nidec Corporation (Japan)	600	130	3700	0	9	8	9	8	9	8	9	8	7
Oriental Motor (Japan)	600	150	3000	0	9	9	8	8	9	7	9	8	7
Mabuchi Motor (Japan)	700	180	3200	0	9	9	8	8	9	7	8	8	7
Kollmorgen (USA)	800	200	4200	0	5	7	7	6	7	7	8	8	8
Schaefer Inc. (USA)	800	180	1500	1	5	8	7	5	7	7	7	8	8
Shenzhen Lianyi Motor (China)	300	150	1500	1	3	6	5	4	6	6	6	8	7
MRC (China)	300	120	3500	0	3	5	4	3	6	6	6	8	7
Weights	0.1238	0.0615	0.0039	0.0308	0.0154	0.0077	0.2462	0.4923	0.0038	0.0038	0.0038	0.0038	0.0038
Criterion Direction	max	max	max	max	min	max	max	max	max	max	max	max	max
Preference Function	V-shape	V-shape	V-shape	Usual	V-shape with indifference	V-shape	V-shape	V-shape	V-shape	V-shape	V-shape	V-shape	V-shape

Table 5 shows the area preference functions, determined by considering the variable type (scale) of each criterion. Since the quantitative criteria of power (W), torque (Nm) and speed (rpm) are performance indicators, the V-shape function has been used, which ensures that preference increases linearly as the difference between alternatives increases. This function enables the differences between the technical characteristics of the engines to be proportionally converted into preference strength, providing a structure that is sensitive and consistent with the scale in terms of performance criteria. As the integrated driver presence criterion is binary in nature, the Usual function was chosen, which allows the difference to be evaluated only in terms of 'present/absent'. The supply speed criterion is a cost-oriented (minimisation type) criterion; therefore, the V-shape with indifference function was selected, where small differences are considered insignificant and large differences create a significant preference difference. In contrast, for criteria based on subjective or semi-qualitative assessments (reliability, environmental, social and governance sustainability, ease of assembly, durability, functionality and user-friendliness), the V-shape function, which increases the degree of preference in parallel with the magnitude of the difference, was deemed appropriate by the decision-maker. Through these selections, an attempt has been made to establish a balanced and realistic preference structure, taking into account the decision-maker's perceptual threshold in subjective evaluations. Table 6 provides the numerical values of the criteria used in the study and the q and p parameters required in the preference functions.

Table 6. Criterion-Based Parameter Values For PROMETHEE Preference Functions

Criterion	Min	Max	Range (max–min)	Function Type	q (0.1*range)	p (0.5*range)
Power (Watt)	200	800	600	V-shape	–	300
Torque (Nm)	100	200	100	V-shape	–	50
Speed (rpm)	1500	4500	3000	V-shape	–	1500
Integrated Driver/Inverter	0	1	1	Usual	–	–
Lead Time/Supply Speed	3	10	7	V-shape with indifference	0.7	3.5
Reliability	5	10	5	V-shape	–	2.5
Environmental Sustainability	4	9	5	V-shape	–	2.5
Social Sustainability	3	9	6	V-shape	–	3
Governance/Supplier Management	3	9	6	V-shape	–	3
Ease of Integration/Assembly	6	9	3	V-shape	–	1.5
Durability/Robustness	6	9	3	V-shape	–	1.5
Functionality/Features	6	8	2	V-shape	–	1
User-Friendliness/ Maintainability	7	8	1	V-shape	–	0.5

In this study, the parametric threshold values of the preference functions in the PROMETHEE method were determined proportionally according to the observed value ranges of the criteria. Taking into account the ranges suggested in the literature (e.g., Behzadian et al. (2010); Macharis et al. (2004)), the fixed coefficients α=0.10 and β=0.50, representing the decision maker's medium level of sensitivity, were preferred. These values ensure that small differences remain in the indifference region and that significant differences are evaluated as definite preferences. Accordingly, the threshold values are defined proportionally as follows for each criterion based on the observed value range $(x_{\max} - x_{\min})$

$$q = \alpha \times (x_{\max} - x_{\min}), p = \beta \times (x_{\max} - x_{\min}) \tag{11}$$

Using this formulation, indifference (q) and preference (p) threshold values were determined for each criterion, and these values were applied to the preference functions used in comparing alternatives. Thus, the decision-maker's sensitivity can be proportionally included in the analysis based on the observed range of each criterion. Using this parametric structure, PROMETHEE I and II analyses were conducted, resulting in the calculation of the positive (φ^+), negative (φ^-), and net flow (φ) values for the alternatives. The obtained values reveal the overall performance levels and relative superiorities of the alternatives. These results are presented in Table 7.

Table 7. PROMETHEE II Flow Values and Full Ranking of Alternatives

Alternative	Pozitive Flow (φ^+)	Negative Flow (φ^-)	Net Flow (φ)	Order
Maxon Motor (Switzerland)	0.522	0.083	0.439	1
Nidec Corporation (Japan)	0.41	0.098	0.312	2
Mabuchi Motor (Japan)	0.396	0.085	0.311	3
Oriental Motor (Japan)	0.357	0.11	0.247	4
Faulhaber (Germany)	0.346	0.12	0.226	5

Alternative	Pozitive Flow (φ⁺)	Negative Flow (φ⁻)	Net Flow (φ)	Order
Dunker Motoren (Germany)	0.309	0.2	0.11	6
Kollmorgen (USA)	0.32	0.353	−0.033	7
Schaefer Inc. (USA)	0.27	0.451	−0.181	8
Shenzhen Lianyi Motor (China)	0.084	0.713	−0.629	9
MRC (China)	0.021	0.822	−0.801	10

The PROMETHEE results presented in Table 7 show the overall performance levels of the alternatives and their relative superiority rankings. Positive flow (φ^+) represents an alternative's dominance ratio over others; negative flow (φ^-) represents the extent to which it is not preferred by other alternatives; net flow (φ) represents the difference between these two effects. These values have been calculated taking into account the performance scores and criterion weights of the alternatives in the decision matrix. Therefore, alternatives with high net flow values represent options that generally perform better in terms of weighted criteria.

As a result of the analysis, Maxon Motor (Switzerland) achieved the highest positive flow (0.522) and lowest negative flow (0.083) values, ranking first with a net flow score of 0.439. This result stems from the fact that the alternative in question scored highly in the decision matrix's technical performance (power, torque, speed) and sustainability (environmental, social, governance) criteria.

Nidec Corporation (Japan) and Mabuchi Motor (Japan) ranked second and third respectively, with net flow values of 0.312 and 0.311, demonstrating high performance particularly in terms of reliability and social sustainability criteria. The position of Japanese manufacturers in this ranking is consistent with the high evaluation scores observed in the decision matrix.

Oriental Motor (Japan) and Faulhaber (Germany) have been identified as moderately strong alternatives with net flow scores of 0.247 and 0.226 respectively. Although these manufacturers are competitive in terms of technical capacity, they have relatively lower scores in terms of supply speed and integration features.

Dunker Motoren (Germany) ranks sixth in the ranking despite its moderate positive flow (0.309), due to the relatively high level of its negative flow (0.200). This situation stems from its strong performance in some criteria (e.g. durability) and weak performance in others (e.g. delivery time).

Ranked lower down the list, Kollmorgen (USA) and Schaefer Inc. (USA) have limited competitive advantages, with net flow values of −0.033 and −0.181 respectively. These alternatives' relatively low scores on environmental and social sustainability criteria have negatively impacted their position in the ranking. The alternatives ranked last, Shenzhen Lianyi Motor (China) (−0.629) and MRC (China) (−0.801), are clearly at a disadvantage in terms of overall performance, as they have the lowest scores in the decision matrix for technical capacity and reliability indicators.

In general, the PROMETHEE II ranking shows that European and Japanese manufacturers have optimised the technical and sustainability dimensions in a balanced manner, achieving high scores; in contrast, Chinese manufacturers lag behind in these criteria despite their low-cost strategies.

As a result, it was observed that the parametric threshold coefficients $\alpha = 0.10$ and $\beta = 0.50$ used in the model sufficiently distinguished the differences between the alternatives. These values ensured that small differences remained in the indifference region and large differences remained in the certainty preference region, thereby enabling the differentiation of alternatives in the decision problem. The flow values obtained from the PROMETHEE II analysis only show the general performance ranking of the alternatives; they do not directly reveal the underlying pairwise preference relationships behind this ranking. Therefore, the PROMETHEE I partial ranking was also performed in the study, and the superiority (S), indifference (I), and incomparability (I) relationships between the alternatives were determined. The PROMETHEE I approach clearly reveals which alternatives are dominant, equivalent, or indistinguishable by showing the decision-maker's preference direction for each alternative pair.

Table 8. PROMETHEE I Superiority Relations Matrix

Alternatives	Maxon Motor (Switzerland)	Nidec Corp. (Japan)	Mabuchi Motor (Japan)	Oriental Motor (Japan)	Faulhaber (Germany)	Dunker Motoren (Germany)	Kollmorgen (USA)	Schaefer Inc. (USA)	Shenzhen Lianyi Motor (China)	MRC (China)
Maxon Motor (Switzerland)	-	P	P	P	P	P	P	P	P	P
Nidec Corp. (Japan)	-	-	R	P	P	P	P	P	P	P
Mabuchi Motor (Japan)	-	R	-	P	P	P	P	P	P	P
Oriental Motor (Japan)	-	-	-	-	P	P	P	P	P	P
Faulhaber (Germany)	-	-	-	-	-	P	P	P	P	P
Dunker Motoren (Germany)	-	-	-	-	-	-	R	P	P	P
Kollmorgen (USA)	-	-	-	-	-	R	-	P	P	P
Schaefer Inc. (USA)	-	-	-	-	-	-	-	-	P	P
Shenzhen Lianyi Motor (China)	-	-	-	-	-	-	-	-	-	I
MRC (China)	-	-	-	-	-	-	-	-	I	-

Note:
P = Preference (Superiority of the row alternative over the column),
I = Indifference (No significant difference),
R = Incomparability (Alternatives cannot be compared directly due to conflicting criteria)

The results obtained from the PROMETHEE I analysis are generally consistent with the PROMETHEE II ranking. Maxon Motor (Switzerland) is dominant over all alternatives and is not dominated by any alternative. Nidec Corporation (Japan) and Mabuchi Motor (Japan) exhibit conflicting flow characteristics; while Nidec has a higher positive flow, Mabuchi possesses a better (lower) negative flow. Consequently, an incomparability (R) relationship was observed between them. Furthermore, Oriental Motor (Japan) demonstrates a clear superiority (P) over Faulhaber (Germany), as it outperforms Faulhaber in both positive and negative flow indicators. The alternatives Kollmorgen (USA) and Schaefer Inc. (USA), which are ranked lower, have only been able to demonstrate superiority over Chinese manufacturers, while Shenzhen Lianyi Motor (China) and MRC (China) are in an incomparable or weak position against almost all alternatives. These results structurally support the net flow ranking in PROMETHEE II and provide the decision-maker with the opportunity to examine the relative differences between alternatives in greater detail.

The joint evaluation of PROMETHEE I and PROMETHEE II results demonstrates the consistency of the decision model in terms of both partial and full ranking. The superiority, indifference, and incomparability relationships determined by the PROMETHEE I method are consistent with the net flow values obtained in the PROMETHEE II analysis. In other words, the alternatives ranked at the top in PROMETHEE II also occupy a dominant (P) position relative to other alternatives in the PROMETHEE I matrix. This supports the consistency of the decision-maker's preference structure and the model's discrimination power. Thus, the complete ranking provided by PROMETHEE II can be considered a numerical synthesis of the preference relationships determined by PROMETHEE I.

5. Conclusion

In this study, integrated multi-criteria decision-making methods were applied to support the motor selection process of an AGV (Automatic Guided Vehicle) manufacturer within the framework of technology management. Focusing on the technology selection stage—one of the key actions of technology management—the study provided a comprehensive evaluation that integrates technical performance indicators with sustainability-based criteria.

The criterion weights determined by the FUCOM method revealed that the decision-maker assigned greater importance to social and environmental sustainability, reflecting the shift in contemporary technology management from a purely efficiency-oriented perspective toward a strategic sustainability-oriented approach. This finding reveals that sustainability factors are positioned as a strategic priority by the company in the selection of technical components. It can be assessed that the corporate orientation towards strategic goals such as compliance with the European Union's Green Deal framework, reduction of the carbon footprint, and strengthening of sustainable supply chain management is directly reflected in the aforementioned weighting structure. Furthermore, the high importance given to social sustainability demonstrates that the company has adopted a management approach that focuses on enhancing its corporate reputation, meeting stakeholder expectations, and prioritising occupational health and safety and employee well-being. Therefore, the weighting distribution can be interpreted not only as a technical preference but also as evidence that the company's long-term sustainability vision is strongly integrated into its decision-making mechanisms. The PROMETHEE analysis results demonstrated that suppliers with strong sustainability performance, such as Maxon Motor (Switzerland) and Nidec Corporation (Japan), also achieved superior technical outcomes in terms of power and torque. This finding underscores the fact that competitiveness in technology-intensive industries increasingly depends on the balanced integration of performance, innovation, and sustainability.

Accordingly, the findings indicate that technology selection should not be limited to evaluating technical adequacy alone but should also encompass governance, sustainability, and integration capabilities within the supply chain. Emphasising sustainability-oriented criteria in the selection of strategic components such as AGV motors represents a long-term competitive strategy within the broader context of technology management. Ultimately, integrating sustainability-focused decision models into corporate technology strategies strengthens technological resilience and enhances firms' capacity for sustainable competitive advantage.

Declarations

Conflict of interest The author(s) have no competing interests to declare that are relevant to the content of this article.

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