Journal of Manufacturing Systems 82 (2025) 319–332

Contents lists available at ScienceDirect

Journal of Manufacturing Systems

journal homepage: www.elsevier.com/locate/jmansys

Technical Paper

From cost to capability: Technology Multiplier in EV manufacturing strategy

Roman Girke [a], Louis Schäfer [a,*], Tanja Maier [a], Florian Stamer [a], Shun Yang [b], Jung-Hoon Chun [c], Gisela Lanza [a]

[a] wbk Institute of Production Science, Karlsruhe Institute of Technology (KIT), 76131, Karlsruhe, Germany
[b] Faculty of Engineering Technology (ET), University of Twente, 7522, Enschede, Netherlands
[c] Laboratory for Manufacturing and Productivity, Massachusetts Institute of Technology (MIT), Cambridge, MA, 02139, USA

ARTICLE INFO

Keywords:
Production planning
Manufacturing network
Distributed manufacturing
Integration

ABSTRACT

In an increasingly dynamic and uncertain global environment, companies face significant challenges in aligning production strategies with long-term competitiveness and innovation. Many firms focus on short-term cost savings through outsourcing and relocation, which can negatively impact internal knowledge, capabilities, and long-term growth. This study explores the strategic decision-making process of production segment allocation, emphasizing the need for a systematic and holistic approach. Using the Analytical Hierarchy Process (AHP), key decision factors are introduced, including cost, innovation capability, and social impact. The qualitative study is applied to the case of electric vehicle (EV) battery production, where in-house production, outsourcing, and joint ventures are evaluated. The results reveal key drivers such as design capabilities and customer centricity, highlighting the strategic importance of maintaining core technological capabilities in-house. The study provides a foundation for the concept of a "Technology Multiplier" to quantify the long-term value of in-house production in terms of innovation, adaptability, and competitive advantage, offering a new framework for strategic manufacturing decisions.

1. Introduction

For many years, the manufacturing industry has been characterized by an increasing number of companies systematically reducing their production depth by relocating sites or outsourcing production volumes to suppliers [1]. Current efforts to stay competitive are decided based on gut feeling and aimed at rapidly reducing fixed costs, implementing cost leadership strategies, and copying successful concepts for short-term benefits [1–3]. Thus, manufacturing companies are more than ever faced with the challenge of ensuring not just short but long-term competitiveness in a dynamic and global environment [4]. These industry-defining changes have been particularly evident in the automotive industry in recent years, where combustion engine technology that has dominated since the beginning is increasingly being replaced by battery electric drives and battery technologies [5].

The configuration of production systems, including their production segment allocation and their supply networks, has a significant impact on a company's competitiveness [6]. Moreover, based on the increased complexity resulting from globalization, cost constraints, and market volatility, conventional metrics, especially those influenced by immediate cost considerations, often fail to comprehensively address the broader implications for the competitiveness of production systems [1].

Therefore, the complexities associated with determining the appropriate production segment allocation are multifaceted and require careful consideration of a wide range of qualitative and often quantitative factors [7]. Production segment allocation involves the strategic decision of determining which specific segments or components of the overall production process will be handled by the company itself and which will be outsourced or obtained from external sources. The determination of production segment allocation can also have far-reaching implications for an organization's set-up of its production system [8]. Deciding which components and assemblies to produce in-house or outsource determines the extent to which existing internal or external capabilities should be used and how capabilities should be developed in the long term [9]. With regard to the automotive industry, in which manufacturers typically account for a high proportion of the added value of the drive system in combustion engine technology, the important strategic question therefore arises as to the extent to which they want to position themselves with regard to the drive technology of a battery electric vehicle consisting of the motors and the battery [10].

It is evident that an integrated approach that considers not only immediate financial factors, but also the long-term strategic consequences of decisions about production segment allocation and the configuration

* Corresponding author.
E-mail address: louis.schaefer@kit.edu (L. Schäfer).

https://doi.org/10.1016/j.jmsy.2025.06.008
Received 25 November 2024; Received in revised form 26 May 2025; Accepted 5 June 2025
Available online 25 June 2025

of production systems is needed. Within that context, the concept of a "Technology Multiplier" could provide an understanding of the real long-term value that in-house production could bring in terms of technological innovation, adaptation to changing market requirements, and overall competitiveness [11]. Furthermore, it indicates the immense value of internal knowledge, expertise, and capabilities, which may serve as a basis for organizations to create advanced products, increase the efficiency of their innovative processes, or improve their innovative workflows to boost the competitiveness of their production system.

1.1. Research motivation and objective

This study is part of a systematic and iterative research approach to create a robust and applicable "Technology Multiplier" that improves manufacturing segment allocation decisions by quantitatively measuring long-term value rather than short-term benefits. In manufacturing, the allocation of production segments, the decision to produce in-house, outsource, or engage in other contractual forms, is a strategic decision with profound implications for a firm's competitiveness and innovation trajectory [12].

While previous research has established a comprehensive model to understand what may be relevant determinants for a more holistic approach with a "Technology Multiplier" analysis [11], the characteristics and nuances associated with specific assemblies require a deeper understanding. It is necessary to evaluate each assembly individually, taking into account the importance of cost aspects and the value of innovation. In order to formulate a differentiated "Technology Multiplier" that takes into account those product and assembly-specific circumstances, we extend the previous preliminary study with an industry and assembly-specific evaluation of relevant aspects.

The objective of this research is to extend and deepen a preliminary model that supports enhancing the understanding of strategic choices of the production segment allocation. In previous research [11], a preliminary model is introduced. A limitation of the preliminary model was the heterogeneity of the case studies. While this heterogeneity had the advantage of providing diverse insights into the motivation behind production segment allocation decisions, it also resulted in a lack of comparability and the ability to derive more in-depth decision-making patterns. To address these limitations, it is necessary to increase the number of case studies and to focus the selection of companies even more strongly on one industry and one assembly. In this paper the model is applied to the specific case of electric vehicle (EV) battery production as an example of an assembly, which has a high strategic relevance and could be considered an important core competence in the EV value chain [5]. This assembly is not only technologically complex but also central to the EV value proposition [10]. We aim to uncover the specific factors that are most influential in the decision to produce EV batteries in-house, outsource, or pursue a joint venture. This detailed understanding will provide researchers and manufacturers with actionable insights tailored to the specific challenges and opportunities of EV battery production, thereby enhancing their strategic decision-making capabilities in this rapidly evolving landscape. The insights gained from this analysis are expected to extend the understanding of the key determinants of the "Technology Multiplier" concept, which aims to quantify the long-term value of in-house production in terms of technological innovation and adaptation.

1.2. Structure of work

The remainder of this article is structured as follows: Section 2 outlines the theoretical background necessary to understand and derive the research questions, approach, and method, which are defined in Section 3 and are further explored afterwards. Section 4 presents the concept and the results of several case studies that were conducted. The concluding Sections 5 and 6 provide a discussion and outlook of the study.

2. Related work

This section presents an overview of the theoretical aspects that are relevant to the research objective. The intention is to provide an understanding of the interlinkages between the fields of action and the ways in which they can be combined to develop a holistic approach.

The initial segment of this section focuses on the pivotal role of production segment allocation in manufacturing. Subsequently, the role of innovation capability for manufacturing companies is elucidated. These two subjects are then integrated through the technology multiplier, a concept that holds particular significance for the transformation of industries such as the automotive sector. To offer a more precise definition of the technology multiplier, the utilization of a decision support model is proposed.

2.1. Importance of production segment allocation

Decisions related to the question of which components or products a company should manufacture with its own resources or buy on the market are called "make-or-buy"-decisions and are fundamentally important for a company as a whole [13]. More generally, it is the strategic decision on the production depth of a company. Production depth, in this context, is characterized by the extent of value-added content that the company generates itself [13]. While production depth deals with the overall vertical integration of production processes, production segment allocation specifically addresses the strategic decisions regarding which parts or segments of the production process are managed internally and which are sourced externally. They are interconnected concepts as decisions regarding production depth influence production segment allocation, and vice versa, in shaping an organization's manufacturing strategy [14]. As the focus in this paper is not based on "how much" of the value creation is produced in-house but rather "which" components and technologies are strategically done in-house, the term "production segment allocation" is used in the following.

In the quest for short-term financial gain, many firms have turned to offshoring or outsourcing their production to regions that offer immediate cost advantages [15]. Although literature offers numerous good arguments for outsourcing, it is widely recognized that as the connection between product and production becomes more important, it becomes increasingly challenging to achieve the optimal balance in terms of quality performance [16], innovation speed, or time-to-market [17]. This underscores the necessity for models that accurately reflect the multifaceted nature of contemporary decision-making processes.

2.2. Role of innovation in manufacturing strategy

Innovation plays a pivotal role in shaping manufacturing strategy by driving improvements in both operational processes and product development, which are essential for enhancing competitiveness. The integration of innovative technologies, such as automation, advanced robotics, and artificial intelligence, into manufacturing processes can significantly reduce production costs and lead times while enhancing precision and flexibility [18]. These advancements enable manufacturers to streamline operations, increase production capacity, and improve quality control, leading to greater overall efficiency and productivity.

An organization's existing resources shape its innovation capabilities, which can be considered valuable, unique, and inimitable [19]. Lawson and Samson [20] define innovation capabilities as "the ability to continuously transform knowledge and ideas into new products, processes, and systems for the benefit of the firm and its stakeholders". Moreover, ownership of R&D and manufacturing systems can enhance technological innovation [21]. By fostering a culture of continuous improvement and leveraging cutting-edge technological advancements, manufacturers can optimize their operations and develop innovative products that resonate with consumers. This dual focus on process and product innovation not only enhances efficiency and quality but also ensures that manufacturers remain agile and responsive to market fluctuations and disruptions. As markets become increasingly volatile, and consumer preferences shift rapidly, the ability to innovate becomes a critical determinant of success [22].

Innovation is not just an operational aspect; it is a strategic necessity that secures long-term success and sustainability for manufacturing companies in a rapidly evolving global market. Investment in both process and product innovation allows manufacturers to build resilient operations capable of adapting to and capitalizing on new opportunities, ultimately securing a competitive edge in their respective industries.

2.3. Technology Multiplier

The concept of a "Technology Multiplier" underscores the long-term, knowledge-based advantages that firms can gain through investments in internal production systems [11].

By retaining a greater share of value creation in-house, companies expedite learning processes, reduce time-to-market, and improve their capacity to innovate. This emphasis on internal manufacturing also enhances in-depth expertise in complex production, enabling precision and cost efficiency. The "Technology Multiplier" framework is designed to quantify these benefits, including enhanced innovation workflows and intellectual capital, extending beyond the immediate goods output. Consequently, it provides a strategic metric to measure the incremental value derived from in-house capabilities relative to their acquisition and operational costs, offering clear insight into how domestic manufacturing investments can drive long-term competitiveness [11].

A key challenge in establishing such an approach is a deep understanding of decision drivers, which is addressed in this work.

2.4. Positioning of the research in the industry context

An illustrative example of the pivotal role of production segment allocation in the context of new innovations can be observed in the automotive industry. The automotive industry has undergone a profound transformation in recent years. This is being driven by various technological innovations such as electric vehicles (EVs), autonomous vehicles (AVs), connected cars, and personal mobility services [10].

From a manufacturing perspective, the shift to EVs is particularly important, as battery production is a potential new core competency for companies. As a result, automakers are increasingly integrating battery production and management into their operations. The main reason for this important role of the battery is that the battery is a major determinant of the cost and performance of the vehicle [5]. The battery represents a significant portion of the cost of an EV, comprising up to one-third of the total. Furthermore, it plays a pivotal role in determining the vehicle's range and efficiency. Consequently, the production and continuous innovation of EV batteries have emerged as a crucial core competence for numerous manufacturers. Manufacturers can leverage this expertise to differentiate themselves from competitors by producing their own batteries. As the example of Tesla demonstrates, a high degree of vertical integration, encompassing the production of the battery, the assembly of the car, and the charging infrastructure, can be employed to secure a competitive advantage [5]. Furthermore, the shift to electric vehicles represents a significant technological and strategic shift in the automotive industry. The traditional competencies centered around the internal combustion engine are becoming less relevant, while new competencies in battery technology and electric power-trains are becoming more critical [10]. This transition underscores the need for established automakers to adapt by developing in-house battery production capabilities or forming strategic partnerships to remain competitive [23]. In consideration of this transition, decision-making models have the potential to facilitate the meticulous evaluation of various factors and possible courses of action.

2.5. Decision support model for production segment allocation

Decisions about the optimal production segment allocation are highly complex and require careful consideration of various qualitative and quantitative aspects. Such decision problems consisting of different, often conflicting, criteria and a given set of alternatives to choose from can be classified as multi-attribute decision-making (MADM) problems. A widely used method in MADM is the Analytical Hierarchy Process (AHP), which is based on pairwise comparisons of criteria and alternatives [24]. The AHP was first introduced by Saaty [25] and further developed in his subsequent work. In the AHP, the decision problem is initially structured into a hierarchy, featuring an overarching objective. Criteria are then derived from the objective and further broken down into sub-criteria. Various alternatives representing the lowest hierarchy level are identified for the decision problem. Priority comparisons are made among objects at each hierarchy level, evaluating criteria, sub-criteria, and alternatives. The AHP as an established method of the MADM [26] allows high adaptability and quantification of qualitative data in the decision-making process and is therefore well suited to obtain an indication of relevant metrics [11].

A critical factor in the decision-making process is the management of uncertainty to ensure consistency and independence. Various techniques can be employed to address uncertainties, including fuzzy logic approaches, integration with the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), and conducting sensitivity analyses [26]. Given the inherent uncertainty of input data in decision scenarios, and to ensure accessibility for participants in the case studies who may not be familiar with advanced methods such as fuzzy logic, we opted to implement a sensitivity analysis. This method enables the exploration of how variations in input parameters affect the decision outcomes, thereby offering insights into the robustness of the derived conclusions. By adopting this approach, a balance is struck between rigorously addressing uncertainty and ensuring that the methodology remains practical and accessible to practitioners.

3. Research approach, method and model

3.1. Preliminary overall research approach to establish a "Technology Multiplier"

The preliminary research approach, as illustrated in Fig. 1, for establishing the "Technology Multiplier" framework is a structured, multi-stage process designed to progressively refine and validate relevant metrics that can quantitatively measure long-term value in production segment allocation decisions. The methodology is comprised of two principal phases. The initial pre-studies and the "Technology Multiplier" definition each comprise a number of discrete stages.

The general initialization is stated in a previous paper [11] with the goal of driving metrics and testing with different firms of various industries. The study investigates the applicability and benefits of the methodology, as well as the relevance of the "Technology Multiplier" research topic. The product-specific initialization, which is the focus of this study, applies the initial metrics to a specific component within the same industry. Using qualitative case study research allows for a more detailed examination of the applicability of the metrics. Moreover, an investigation is pursued into the extent to which the weighting of the sub-criteria may diverge, with a particular focus on the strategic significance of the component in the context of the industry. The high relevance of the application strengths of our decision model was decisive for the selection of the case study industry and component. Accordingly, it must be a production segment allocation decision that revolves around current or future strategically highly relevant core competencies, a market-defining innovation is present and a number of quantitative and qualitative factors must be carefully weighed against each other [11]. The global automotive industry is undergoing an unprecedented transformation, driven by the shift in technology towards

	Focus of previous study	**Focus of this study**	Subsequent stages will be addressed in future research		
Stage	General Initialization	Product Specific Initialization	Model Development	Quantification with Data Training	Validation and Refinement
Goal	Initial research of driving metrics and testing with manufacturing firms of different industries	Application of initial metrics to one specific product with firms of the same industry	Transformation of quantitative metrics and set-up of a quantified model for the calculation of a Technology Multiplier	Quantification of the model metrics based on large scale industry data	Validation of Technology Multiplier model with industry partners and potential refinement of metrics and weights
Method	Literature Research, Case Studies	Case Studies	e. g. Multivariate Regression	e. g. Multivariate Regression	e. g. Multivariate Regression, Case Studies
Data focus	Qualitative, Semi-Quantitative	Qualitative, Semi-Quantitative	Quantitative	Quantitative	Quantitative
Sample size	low	low	n.a.	high	low
	Initial Pre-Studies		Technology Multiplier Definition		

Fig. 1. Overview of research approach.

battery electric vehicles [5]. Companies that have benefited from their expertise in building internal combustion engines are now facing new competition and the need to adapt their development and production to a new technology [27]. Deciding whether to produce the associated assemblies and components, most importantly the battery, in-house or with a supplier, requires the consideration of a wide range of company-specific factors. Because of the fitting circumstances, the automotive industry was selected to further evaluate our model at this stage.

The second phase, the “Technology Multiplier” Definition, consists of the three stages of model development, quantification, as well as validation, and refinement. Those subsequent stages all follow the overall objective of generating a quantifiable model suitable for calculating the “Technology Multiplier” by transforming the refined metrics through more quantitative research with statistical methods.

This research approach guarantees a comprehensive and incremental development process, from the initial identification of metrics to the concluding validation of the model. It integrates both qualitative and quantitative approaches, progressively refining the metrics and model through real-world application and industry collaboration. The objective of this structured approach is to develop a robust and applicable -“Technology Multiplier” that enhances the precision of manufacturing segment allocation decisions by quantitatively measuring long-term value.

3.2. Research questions

In order to address the challenges outlined before, it is important to successfully address the following research questions in the subsequent sections of this article.

- What are the primary factors influencing strategic production segment allocation decisions within the EV battery industry, and how do these factors contribute to long-term innovation and cost competitiveness?
- How do different companies prioritize these factors, and what variations in strategic emphasis can influence the metrics and structure of the “Technology Multiplier”?

In the following, insights from the analysis will be used to develop a quantifiable “Technology Multiplier” concept that measures the additional long-term value gained from in-house production, particularly in innovation capability and competitive advantage.

3.3. Decision model

In the development of our framework for the Product Specific Initialization, a qualitative research approach is used. The research methodology is based on a combination of the already developed AHP and a validating case study approach. The AHP model is employed due to its efficacy in addressing complex decision-making processes, enabling a systematic assessment and prioritization of the factors influencing production segment allocation in a manner analogous to reverse engineering. Furthermore, the approach was validated through a case study that applied these principles in real-world scenarios and compared the outcomes with the current decision-making practices in companies. The application of the framework in the case studies offers insights into the relevance of specific factors for the development of a “Technology Multiplier”, as indicated by the scores within the AHP. The assigned scores permit an initial semi-quantitative estimation of the relative importance of the various metrics.

The AHP model, developed in our previous pre-study, is employed in a slightly modified manner. As in this research, the objective is not to test its general applicability but to generate insights into the weighting of the factors between different companies while focusing on one specific object. Consequently, Phase 1 of Fig. 2 in the AHP framework can be excluded. The traditional AHP is expanded by including a sensitivity analysis to consider uncertainties.

The relevant criteria utilized in the AHP model were initially identified during the general initialization stage through comprehensive literature research and subsequently validated through case studies in our previous study. As the results demonstrated that the model contains the most relevant criteria and sub-criteria, no modifications have been made [11]. For purposes of clarity, the individual factors are presented once more in the subsequent Fig. 3.

In evaluating the production segment allocation in our recent work [11], three primary criteria emerged as pivotal: social impact, innovation capability, and costs. Each of these criteria encompasses various sub-criteria that provide a comprehensive understanding of different facets of the company’s operations, impacts, and strategies. The social impact criterion includes job security, ecological impact, company reputation, workforce training, and employer attractiveness. Job security refers to the level of confidence employees have in the continuity and stability of their employment, thereby minimizing the risk of job loss or insecurity. Ecological impact examines the consequences of a company’s activities on the ecological environment, assessing the sustainability practices implemented to minimize environmental harm. Company reputation considers the consequences of

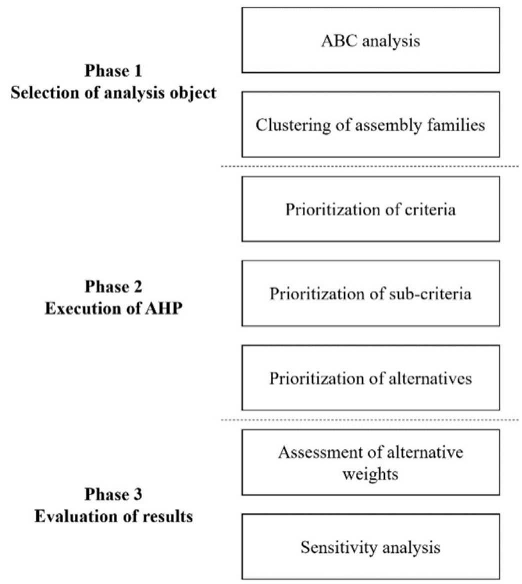

Fig. 2. Structure of the general AHP decision-making framework.

a company's actions on its public image, including perceptions of integrity, social responsibility, and trustworthiness. Workforce training evaluates the impact on the development of skills and knowledge within the workforce, encompassing the availability and effectiveness of training programs that enhance employees' capabilities and career advancement opportunities. Employer attractiveness measures a company's ability to attract highly qualified employees by assessing factors such as benefits, work culture, and career development opportunities. Innovation capability is assessed through the following criteria: Synergistic integration capability, manufacturing capabilities, design capabilities, speed/flexibility, and differentiation/customer value add. The synergistic integration capability is concerned with the seamless communication and coordination required for product and assembly innovations. It assesses the company's ability to integrate different components and understand customer needs in order to enhance the overall customer experience. The manufacturing capabilities refer to the range of activities, technologies, and resources that a company possesses to produce goods or components. They emphasize process innovations, including expertise in process engineering, quality control, supply chain management, equipment utilization, and production scalability. Design capabilities are of paramount importance for the generation of innovative products. These capabilities integrate expertise, activities, and resources to create products that are aligned with the needs of the customer. This integration is achieved through market research, ideation, prototyping, and industrial design. Speed and flexibility are critical aspects of innovation. Speed is defined as the time to market of an innovation, while flexibility addresses the ability to adapt quickly to changing market demands and upcoming technologies. It is of the utmost importance to differentiate and add value to the customer in order to deliver unique benefits to them. This ensures that the customer receives distinctiveness, value, and competitive advantage, which in turn leads to increased customer satisfaction. The costs criterion includes capital expenditures, unit costs, cash flow impact, risk of supply outage, and transaction costs. Capital expenditures (CapEx) refer to the funds invested by a company in long-term assets or infrastructure, such as equipment, machinery, buildings, or technology. These investments are made with the intention of improving or expanding the company's operations and capabilities. Unit costs are the expenses incurred for producing each unit of a manufactured good, assembly, or component. They are used to evaluate the efficiency and cost-effectiveness of the production process. The cash flow impact refers to the influence or effect of specific events, decisions, or factors on the amount and timing of cash inflows and outflows within a business. It assesses how these impacts affect overall financial liquidity and stability. The risk of supply outage measures the likelihood of disruptions or interruptions in the availability of essential resources, materials, or components required for a company's operations. It evaluates the potential adverse effects on the company's ability to meet customer demands and fulfill orders. Transaction costs encompass the expenses associated with the transaction itself, such as the definition of requirements, search costs, and the risk of opportunism. They assess the efficiency and economic implications of conducting business transactions.

By understanding these criteria and their sub-criteria, companies can better assess their production segment allocation, make informed decisions, and implement strategies that enhance their overall impact and competitiveness.

3.4. AHP computational foundation

The Analytical Hierarchy Process (AHP) is based on the work of Saaty [25] and differs from other multi-attribute decision-making methods such as utility analysis by adding multiple levels of hierarchy and a method of pairwise comparison as shown in Fig. 4. Overall, AHP can be divided into three steps. First, the weighting of the criteria and sub-criteria is determined, then the scores of the alternatives are determined, and from these the weighted scores of the alternatives are formed.

The weighting of the criteria and sub-criteria or the scores of the alternatives are determined by comparing the respective elements in pairs. For example, if there are three criteria, each criterion is compared with the other two, and the importance relative to the others is determined using the fundamental scale of 1–9 or the reciprocal values. This results in a comparison matrix that is normalized using the 'Eigen Vector Method' [25] so that the sum of the criteria weights is 1.

In the first step, the criteria are first ranked in order of importance to determine the weights of the criteria. Then, the weights of the sub-criteria are determined by multiplying the subordinate weight of the sub-criteria (i.e., their importance for the superordinate criterion) by the weight of the associated criterion. The sum of all resulting sub-criteria weights for all criteria is also 1.

In the second step, all alternatives are compared with respect to the fulfillment of each sub-criterion and scores are obtained after normalization. The sum of the scores of all alternatives for each sub-criterion is again 1.

In the final step, the weighted scores can be determined by multiplying the weights per sub-criterion by the scores of the alternatives for that sub-criterion. The alternative with the highest sum of all weighted scores is then preferred, and the weighted scores reflect how well an alternative performs based on the areas considered important.

3.5. Case study selection and sampling

To ensure a high degree of congruence with the research objective, as well as to ascertain the viability of the study, a set of criteria were meticulously employed in the selection of case studies. These criteria encompassed the following:

- **Affiliation with an established automotive manufacturer or battery supplier:** All participants are employed by a reputable automotive manufacturer that possesses a portfolio encompassing electric vehicles, or by a Tier 1 battery supplier. To obtain the most current insights, participants were selected who were in an active role in their company during the period of the interview.
- **Exposure to make-or-buy decisions in battery technology:** All participants are involved in decision-making processes for EV batteries or important strategic assemblies or components and have insights into key strategic motives for action. This includes roles in management, purchasing, production management, and production-related development.

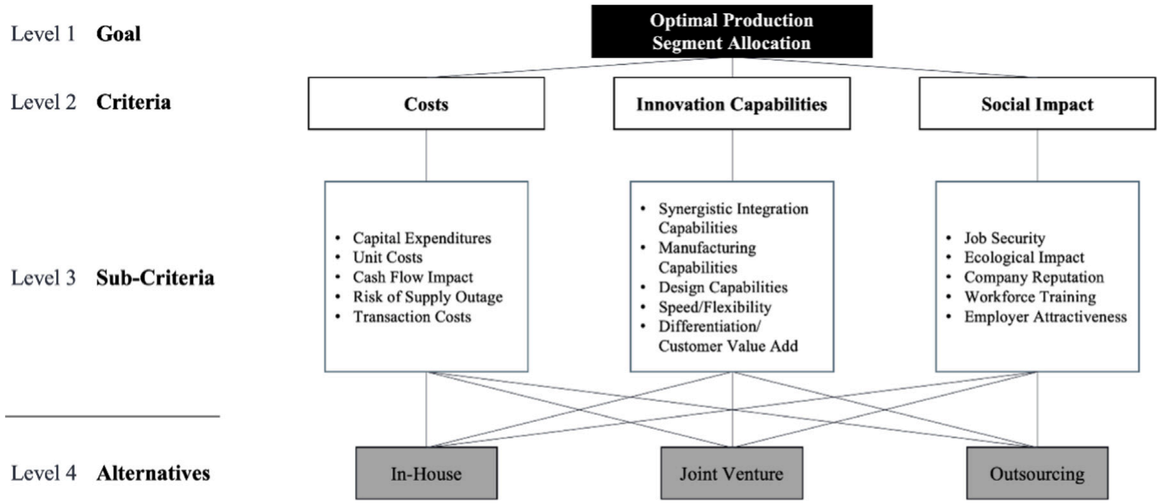

Fig. 3. Hierarchy structure of the previously developed AHP model.

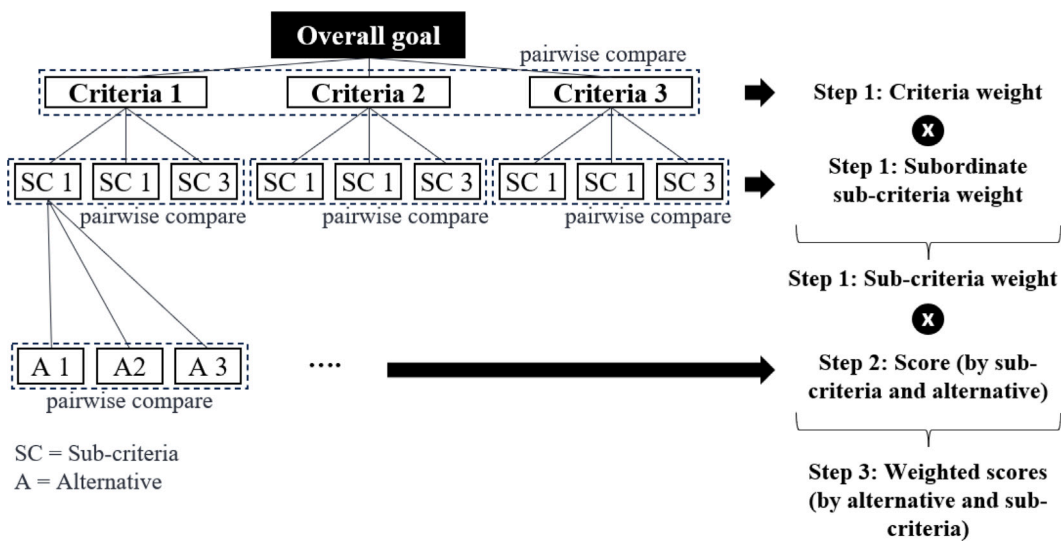

Fig. 4. Structure of AHP inputs and outputs.

- **Geographical diversity:** Care was taken to find participants for the case studies from as many different regions as possible so that ultimately, participants from Europe, North America, and Asia were included in the study.
- **Market diversity:** The selected case studies should be diverse in terms of their market positioning. This should primarily be reflected in the fact that OEMs from different price segments should be included.
- **Accessibility of participants:** Some of the participants in the case studies were found and contacted via the researchers' existing extended network. However, the number of researchers and the breadth of the network meant that the quality of the participant selection could be kept high.

3.6. Data collection

The data was collected through the implementation of case study-based semi-structured interviews. Each interview was conducted with one participant on a specific case study via video conference and lasted for two hours. The following procedure was used:

1. **Introduction:** An introduction was made to the participants and the general model for decision-making, as well as the process of the AHP.
2. **General company information:** General data on the company and the nature of the production system were requested.
3. **Product/assembly-specific questions:** The product or assembly to be evaluated was explained, classified strategically, and relevant overarching decision motives were explained.
4. **AHP weights and scores:** The weights of criteria and sub-criteria, as well as the alternative scores, were determined using the three-way comparison with the fundamental scale from 1 to 9 and its reciprocals. Based on the resulting weighted scores, the interviewees were able to continuously adapt their scores to reflect realistic and sensible decision-making.
5. **Model evaluation:** In accordance with the preceding process and the model outcomes, the interviewee was asked to evaluate the selection of criteria and sub-criteria, the overall model approach, and the congruence of results with actual decision-making results using a Likert scale ranging from 1 (very low) to 7 (very high). They were also requested to provide a rationale for their evaluation.

3.7. Data analysis and AHP execution

The analysis and AHP was based on a multi-step process and was partially conducted during the interviews as well as afterwards:

1. **Normalization and Consistency:** Pairwise comparisons were normalized during the interviews using the eigenvalue method. The eigenvalue method was normalized during the interviews and it was checked that all comparisons were made consistently according to the consistency ratio.
2. **Weighted scores and aggregation:** Based on all pairwise comparisons, the weighted scores of all alternatives and the total scores were calculated so that it is clear which alternatives are to be preferred and what strengths and weaknesses each alternative has and how much weight they carry.
3. **Sensitivity analysis:** Particularly sensitive comparisons were presented again to respondents to ensure that these comparisons were made carefully and in line with the company's strategic decision line.
4. **Verification of results:** During the interviews, all intermediate and final results were reviewed with the respondents for possible input errors and representativeness.
5. **Cross-case study evaluation:** The different overall decisions, weightings, and evaluations of alternatives were compared across all case studies. This was done by grouping by decision and averaging the weighted scores within groups and across groups. In addition, qualitative information about the company, the product/assembly, and the strategy was included for interpretation.

4. Application to industrial case studies

Six automotive original equipment manufacturers (OEMs) and one battery cell manufacturer were selected as subjects for a case study. In order to gain a comprehensive understanding of the subject matter, a conscious effort was made to include interviews with representatives from a diverse range of OEMs, including those originating from the United States, Europe, and Asia. The overall insights of the case studies are presented first, followed by individual case studies in individual sections and in Table 1.

4.1. Overview of components

In the conducted case studies, the battery components of battery electric vehicles (BEVs) were analyzed to understand their influence on production segment allocation decisions in the automotive industry. The components studied included battery cells, battery management systems, battery current collectors, and battery packs. The selection of case studies was based on the guideline of integrating several components of strategic importance and the availability of interviewees. Battery cells were the focus of four case studies (Case Studies 2, 4, 5, and 7), emphasizing their crucial role in determining vehicle performance, range, and lifespan. The battery management system was examined in one case study (Case Study 1), highlighting its importance in monitoring and controlling the battery pack's performance. Battery current collectors were analyzed in one case study (Case Study 3), as they are essential for conducting electrical current between the battery packs and the vehicle's power systems. Lastly, battery packs were the subject of one case study (Case Study 6), focusing on their impact on vehicle performance and cost structure.

4.2. Overall insights

The main insights can be gained by analyzing the overall results of the seven case studies. The analysis considers both the averages across all case studies and the differences between companies that ultimately chose either the "In-House" or "Outsourcing" alternatives. To better understand decision-making patterns, the first four case studies, where companies decided on in-house production, were compared with the remaining three, where companies opted for outsourcing.

Overall, the priorities of the alternatives were as follows: 0.408 for "In-House", 0.278 for "Joint Venture", and 0.314 for "Outsourcing." These values reflect how all companies, regardless of their final choice, evaluated the three alternatives. Among companies that chose the "In-House" option, they assigned it a higher priority of 0.527 when evaluating the alternatives, whereas those that opted for outsourcing rated the "Outsourcing" option lower, at 0.459. The "Joint Venture" option was the least favored overall, but its relative importance remained between "In-House" and "Outsourcing" when analyzed in both separate groups, though it was consistently close to the least preferred alternative.

The criteria used for decision-making were weighted as follows: "Social Impact" received a weight of 0.092, "Innovation Capabilities" 0.415, and "Costs" 0.495. These weightings were largely consistent across both groups, with minor differences of less than 2 percentage points between companies that opted for "In-House" production and those that chose "Outsourcing". This consistency suggests that both groups applied similar criteria in evaluating their alternatives. When considering sub-criteria, the most heavily weighted factor overall was "Unit Costs", with an average weight of 0.193. This was followed by "Design Capabilities" at 0.116, with other sub-criteria showing more variation in their importance. However, once looking at the companies' final decisions, the sub-criteria begin to diverge. For those companies that selected the "In-House" alternative, "Design Capabilities" had a weight of 0.146, followed by "Cash Flow Impact" at 0.112. On the other hand, companies that chose "Outsourcing" placed more importance on "Capital Expenditure" at 0.123 and "Manufacturing Capabilities" at 0.117. This divergence suggests that while companies across the board considered similar sub-criteria, they valued these factors differently based on their chosen strategy.

In terms of priorities for the "In-House" alternative, both "Costs" and "Innovation Capabilities" were major drivers, with "Unit Costs" having a priority of 0.063, followed by "Differentiation/Customer Value Add" and "Design Capabilities", both at 0.051. Although all companies assessed these priorities, there were notable differences between those that ultimately chose "In-House" production and those that opted for "Outsourcing". For the evaluation of the "Outsourcing" alternative, costs were significantly more important than innovation capabilities, with "Unit Costs" having a priority of 0.088, followed by "Capital Expenditure" at 0.056, and "Manufacturing Capabilities" at 0.035. The priority gap between "Unit Costs" for "In-House" production at 0.042 and "Outsourcing" at 0.149 was particularly large, reflecting the different perspectives of companies leaning towards these respective alternatives.

The analysis also revisits the "Technology Multiplier" intended to capture the added value of producing in-house. The sub-criteria of "Innovation Capabilities" that drove companies to choose in-house provide preliminary insights into potential key drivers within the EV-battery industry. Looking at the overall priorities across all case studies, the most important sub-criteria were "Differentiation/Customer Value Add" (0.051), "Design Capabilities" (0.051), and "Speed/Flexibility" (0.034). However, in cases where companies specifically chose "In-House" production, the priorities shifted, with "Design Capabilities" at 0.071, "Differentiation/Customer Value Add" at 0.063, and "Speed/Flexibility" at 0.040. This indicates that companies opting for in-house production emphasized design and differentiation more than the general sample.

Table 1
Consolidated results: Case studies 1 to 7.

	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7
(1) Criteria Weights [in %]							
Social Impact	6.72	20.00	5.88	5.56	10.00	5.88	9.09
Innovation Capabilities	48.87	20.00	52.94	50.00	50.00	41.18	27.27
Costs	44.40	60.00	41.18	44.44	40.00	52.94	63.64
(2) Weighted Scores by Alternative and Sub-Criteria [in %]							
In-House	36.27	52.53	48.81	73.25	27.34	29.46	17.75
Job security	2.59	3.63	0.38	0.18	0.78	0.51	0.54
Ecological impact	0.59	0.41	0.70	0.00	1.44	0.21	0.69
Company reputation	0.65	2.16	2.14	1.47	1.20	2.43	0.45
Workforce training	0.25	3.30	0.06	0.26	0.51	0.05	0.19
Employer attractiveness	0.39	3.55	0.11	0.20	0.24	0.06	1.06
Synergistic integration capability	3.90	3.55	4.68	1.29	1.42	2.12	2.99
Manufacturing capabilities	1.50	0.79	0.77	10.32	1.38	0.55	1.15
Design capabilities	1.60	0.95	15.69	10.32	6.52	0.24	0.18
Speed/Flexibility	0.73	0.57	4.68	10.18	4.74	2.47	0.50
Differentiation/Customer value add	13.16	3.55	0.77	7.63	1.45	8.72	0.36
CapEx spent	1.14	0.63	1.24	0.17	0.34	1.76	1.28
Unit costs	2.19	3.16	13.35	15.84	1.78	1.99	6.07
Cash flow impact	1.71	18.54	0.17	0.24	0.74	0.99	0.62
Risk of supply outage	2.07	5.68	2.42	14.85	1.78	3.71	1.11
Transaction costs	3.81	2.06	1.66	0.30	3.01	3.67	0.55
Joint Venture	33.19	27.82	31.94	14.44	27.34	34.46	25.82
Job security	0.78	0.73	0.08	0.03	0.26	0.07	0.18
Ecological impact	0.32	0.41	0.70	0.01	1.44	0.21	1.38
Company reputation	0.25	2.16	0.71	0.18	1.20	1.21	0.23
Workforce training	0.08	1.10	0.02	1.55	0.51	0.02	0.57
Employer attractiveness	0.17	0.71	0.04	1.21	0.12	0.02	1.06
Synergistic integration capability	3.90	0.71	1.56	0.16	0.47	2.12	2.99
Manufacturing capabilities	3.01	3.17	0.77	1.29	4.15	1.65	5.76
Design capabilities	3.20	2.86	15.69	1.29	6.52	0.71	0.18
Speed/Flexibility	0.73	0.19	1.56	1.45	2.37	4.94	0.50
Differentiation/Customer value add	6.58	0.71	0.77	1.09	1.45	4.36	0.36
CapEx spent	1.99	3.16	3.71	1.04	1.03	5.29	6.42
Unit costs	6.58	3.16	4.45	2.26	3.56	5.96	3.04
Cash flow impact	3.42	6.18	0.84	1.18	1.48	2.98	1.86
Risk of supply outage	0.90	1.89	0.81	1.65	1.78	3.71	1.11
Transaction costs	1.27	0.69	0.24	0.04	1.00	1.22	0.18
Outsourcing	30.53	19.65	19.25	12.31	45.32	36.08	56.43
Job security	0.24	0.40	0.05	0.02	0.16	0.06	0.11
Ecological impact	0.18	0.14	0.14	0.02	0.72	0.21	2.07
Company reputation	0.14	0.43	0.71	0.18	1.20	0.81	0.15
Workforce training	0.04	0.37	0.02	0.03	0.17	0.01	0.06
Employer attractiveness	0.07	0.51	0.02	0.20	0.05	0.01	0.35
Synergistic integration capability	1.95	0.51	0.67	0.16	0.28	0.71	1.50
Manufacturing capabilities	1.50	0.79	0.77	1.29	9.68	2.75	8.06
Design capabilities	1.60	0.95	3.14	1.29	6.52	0.71	0.89
Speed/Flexibility	2.19	0.19	0.67	1.27	1.58	7.41	1.50
Differentiation/Customer value add	3.29	0.51	0.77	0.95	1.45	1.74	0.36
CapEx spent	5.21	5.68	6.18	1.38	3.08	8.82	8.99
Unit costs	6.58	3.16	4.45	2.64	12.44	7.94	24.30
Cash flow impact	6.84	3.71	0.84	1.18	2.22	3.97	3.09
Risk of supply outage	0.26	1.89	0.48	1.65	5.33	0.53	3.34
Transaction costs	0.42	0.41	0.33	0.03	0.43	0.41	1.65
(3) Number of Sensitive Comparisons							
Number of sensitive inputs	13	2	3	0	2	20	1

The overall results across the case studies, excluding Case Study 2, indicate generally positive feedback with ratings mostly between "rather good" and "very good." This positive reception supports the relevance of the factors considered in defining the "Technology Multiplier". The suitability of pre-selected criteria, which are integral to defining the "Technology Multiplier", was commonly rated as "good," though some participants suggested potential extensions, such as the inclusion of quality-related and logistical aspects to enhance the comprehensiveness. The overall model approach was also rated as "good" to "very good," reflecting a strong appreciation for its structure and utility in capturing the long-term strategic value associated with in-house production, which aligns with the core idea of the "Technology Multiplier". Some comparisons, however, were noted to be not entirely applicable in all scenarios.

In evaluating whether the model results reflected good decision-making relevant, feedback ranged from "good" to "very good". Most respondents found the model generally accurate in capturing factors contributing to the multiplier effect, although some noted the complexity of interactions within the model, which might make it difficult to capture all relevant factors influencing the "Technology Multiplier". The model's potential value for strategic make-or-buy decisions was mostly rated as "rather good" to "good." While respondents found it useful as a starting point for quantifying long-term value beyond immediate cost considerations, one participant pointed out that it assumes very controlled environments and would require further analysis and refinement for broader, practical application of the "Technology Multiplier" in diverse contexts.

Overall, the model received favorable feedback, with smaller suggestions for refinement and possible extensions that could enhance its

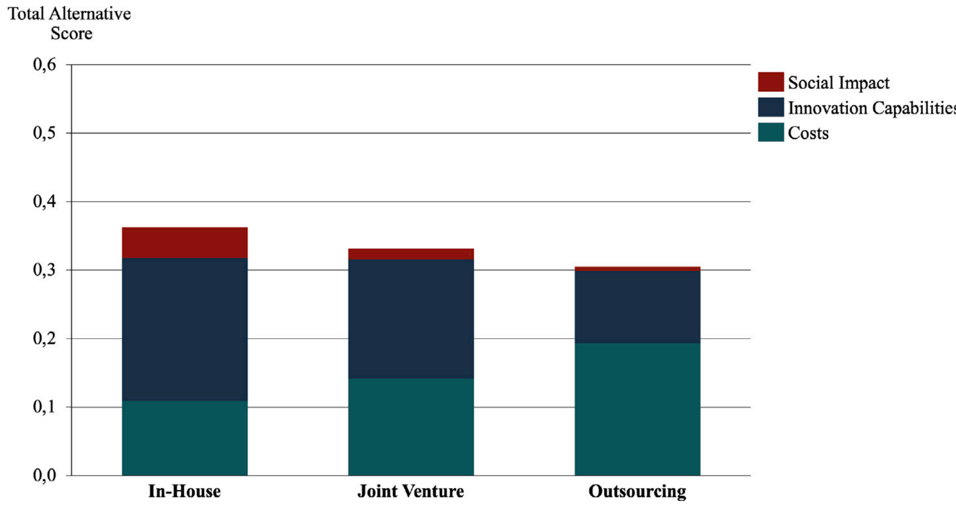

Fig. 5. Priorities by alternative case study 1.

effectiveness in defining and applying the "Technology Multiplier". Participants recognized its potential in aiding strategic decisions by capturing the long-term benefits of in-house production, which aligns with the core idea of the "Technology Multiplier". However, Case Study 2 performed slightly worse than the others, receiving more "rather good" ratings and more critical feedback across the evaluated aspects. This suggests that additional factors may need to be considered within the "Technology Multiplier" framework to accommodate different contexts and improve its robustness.

4.3. Case study 1

A production planner from a car manufacturer specializing in sports cars participated in this study, with the battery management system of a battery electric vehicle (BEV) as the subject of analysis. Both engineering and manufacturing are involved in make-or-buy decisions, often guided by management. The initial assessment is semi-structured, followed by detailed cost and feasibility studies. Joint ventures are frequently considered, offering increased involvement and control at reduced costs. Key decision factors include competency development, cost, feasibility, and employment.

The results suggest to produce in-house, mainly because of the sub-criteria "Innovation Capabilities", especially because of "Differentiation/Customer Value Added", as shown in 5. Comparing the results with the other case studies, it is clear that the alternatives were closer to each other, while the innovation aspects were prioritized even more strongly than others. This could be due to the market position in the premium segment, which often requires in-house technological expertise, while at the same time outsourcing non-core activities due to smaller scale.

The sensitivity analysis results in 13 sensitive comparisons. The comparisons between the "In-House" and "Joint Venture" alternatives for the sub-criterion "Differentiation/Customer value add" have shown particular sensitivity. Considering the scores for the "Innovation Capability" sub-criteria of the "In-House" alternative, the results suggest that the sub-criterion "Differentiation/Customer value add" with a score of 0.132, as well as the sub-criterion "Synergistic integration capability" with a score of 0.039, have the greatest impact on a "Technology Multiplier".

4.4. Case study 2

An innovation manager from a leading automotive manufacturer producing combustion engine vehicles, hybrid vehicles, and BEVs participated in this study. The focus was on the battery cell of a fully electric vehicle. EV battery cell manufacturing is complex, encompassing material sourcing, production, assembly, inspection, and intricate systems like cooling, firmware, energy, and load management. The decision-making process is typically led by the vehicle's lead engineer and supply chain management, with return on investment analysis and consideration of core competencies. The approach varies depending on the component, and there is no standardized procedure. The cell's significance for vehicle performance, cost, and market differentiation is a dominant decision factor.

The results suggest in-house production, mainly due to the "cost" sub-criteria with the highest score for "Cash Flow Impact" as shown in 6. The comparison with other case studies shows a strong preference for in-house production. Interestingly, this is not driven by innovation as in other cases, and social impact aspects are considered the strongest in all cases. A possible explanation for the deviation from the other cases is a more innovation-driven strategic focus of the company, while at the same time a stronger focus on social aspects.

The sensitivity analysis results in 2 sensitive comparisons. The comparisons between the "In-House" and "Joint Venture" alternatives for the sub-criterion "Cash flow impact" has shown particular sensitivity. Considering the scores for the "Innovation Capability" sub-criteria of the "In-House" alternative, the results suggest that the sub-criterion "Synergistic integration capability" with a score of 0.035, as well as the sub-criterion "Differentiation/Customer value add" with a score of 0.035, have the greatest impact on a "Technology Multiplier".

4.5. Case study 3

A manufacturing engineer from an electric car manufacturer participated in this case study, focusing on battery current collectors. These components are crucial for conducting current from the engine or charging station to individual battery packs. The decision-making process typically involves product development, manufacturing engineering, purchasing, and finance, with return on investment analysis playing a significant role. However, "gut feeling" decisions are not uncommon. Given the functional criticality of battery current collectors and the need for end-to-end quality control, in-house production is often favored.

The evaluation resulted in a recommendation to produce in-house, driven by innovation aspects, with a focus on the sub-criteria "Design Capabilities" as shown in 6. The results show a slightly stronger-than-average preference for in-house production, while joint venture is seen as a stronger alternative than outsourcing. With the special case of battery current collectors, our interviewee pointed out the very poor

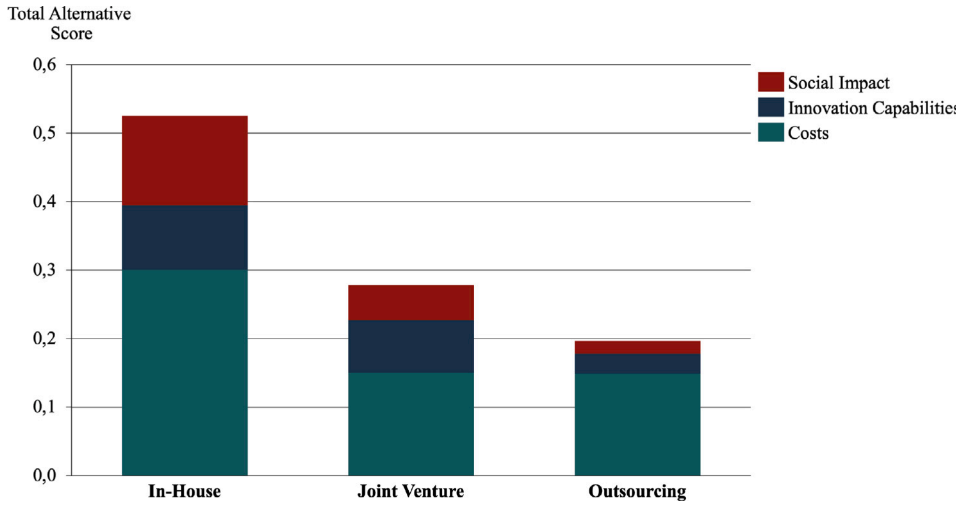

Fig. 6. Priorities by alternative case study 2.

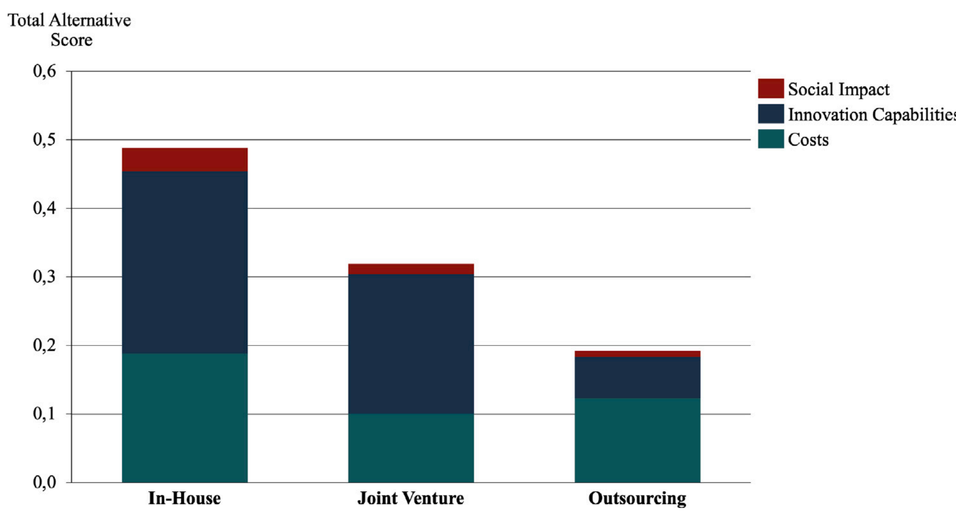

Fig. 7. Priorities by alternative case study 3.

performance of suppliers in this field, justifying the resulting scores (see Fig. 7).

The sensitivity analysis results in 3 sensitive comparisons. The comparisons between the "In-House" and "Joint Venture" alternatives for the sub-criterion "Design capabilities" has shown particular sensitivity. Considering the scores for the "Innovation Capability" sub-criteria of the "In-House" alternative, the results suggest that the sub-criterion "Design capabilities" with a score of 0.157, as well as the sub-criterion "Synergistic integration capability" with a score of 0.047, have the greatest impact on a "Technology Multiplier".

4.6. Case study 4

A cell manufacturing engineer from an electric car manufacturer participated in this study, focusing on battery cells. The battery cells were described as complex and challenging to produce, resulting in high scrap rates and difficulties in achieving high-quality standards. They are critical for BEV production competitiveness and customer value, determining the car's range. A variety of functions, including engineering, product development, purchasing, finance, and leadership, are involved in the make-or-buy decision. A typical rule for in-house production is a positive return on investment after a specific time or if production relates to a special critical competence.

The comparisons resulted in a very clear recommendation to produce in-house, driven by innovation aspects, with "Unit Costs" still being the most important sub-criterion as shown in 8. This case shows the clearest preference for in-house production among all cases, while following a comparable distribution of criteria scores within each alternative. A possible explanation for the deviation from other cases is the high confidence of this OEM to produce low-cost batteries on a large scale, based on a very long presence in the EV industry.

There are no sensitive comparisons. Considering the scores for the "Innovation Capability" sub-criteria of the "In-House" alternative, the results suggest that the sub-criterion "Manufacturing capabilities" with a score of 0.103, as well as the sub-criterion "Design capabilities" with a score of 0.103, have the greatest impact on a "Technology Multiplier".

4.7. Case study 5

A cell test engineer from a premium car manufacturer participated in this study, which focused on battery cells. Battery cells are a critical strategic component as they determine many critical aspects of the car, such as performance, range and product life, while being highly complex to design and manufacture. In addition to purchasing, quality management, engineering and product development have a strong influence on the make-or-buy decision due to the technical challenges

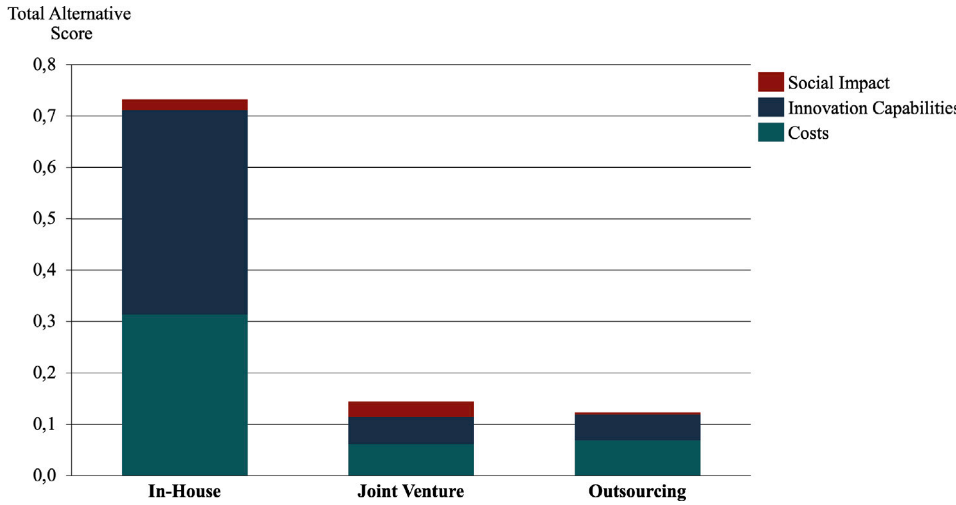

Fig. 8. Priorities by alternative case study 4.

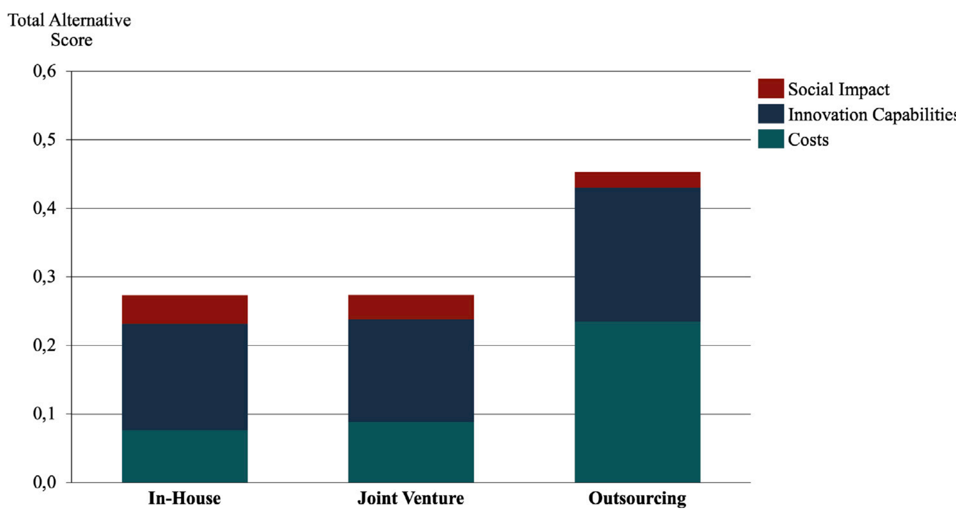

Fig. 9. Priorities by alternative case study 5.

of battery cells. For most of the battery components, the company tries to limit its processes to the assembly process.

This case provides an interesting perspective, preferring to outsource for cost and innovation reasons, with a high score in the "Unit Costs" sub-criterion, as shown in 9. While the weighted aspects of the decision are quite similar in the comparisons, the OEM prefers to outsource. The deviation from other cases is mainly due to the technological capabilities and market focus of this company. As a premium manufacturer, it is more difficult to achieve critical levels of production to enable large-scale battery cell production and to amortize upfront R&D investments.

The sensitivity analysis results in 2 sensitive comparisons. The comparison between the "Capital Expenditures" and "Transaction costs" sub-criteria has shown particular sensitivity. Considering the scores for the "Innovation Capability" sub-criteria of the "In-House" alternative, the results suggest that the sub-criterion "Design capabilities" with a score of 0.065, as well as the sub-criterion "Speed/Flexibility" with a score of 0.047, have the greatest impact on a "Technology Multiplier".

4.8. Case study 6

A M&A manager from a premium car manufacturer participated in this study, which focused on battery packs. Battery packs are described as very important to the car in terms of safety performance and cost. The processes associated with battery packs are less complex than the actual battery cells but still have a high impact on cost competitiveness. A wide range of functions are involved in the make or buy process. A particular limiting factor in the selection of potential alternatives is the different voltage architectures of the overall batteries. Especially when evaluating potential acquisitions of suppliers, technical and financial fit are the most important aspects.

This case shows a preference for outsourcing driven primarily by cost, which is reflected in a lower "Capital Expenditures" as shown in 10. In comparison, this case is special because of its preference for outsourcing, while at the same time the joint venture scores very high. Although the dominance of the decision to outsource is less strong, the results can be explained by the premium market positioning, comparable to case 5. However, the interviewee seems to value strategic partnerships in joint ventures.

The sensitivity analysis results in 20 sensitive comparisons. The comparisons between the "In-House" and "Joint Venture" alternatives for the sub-criterion " Unit Costs" has shown particular sensitivity. Considering the scores for the "Innovation Capability" sub-criteria of the "In-House" alternative, the results suggest that the sub-criterion "Differentiation/Customer value add" with a score of 0.087, as well as the sub-criterion "Speed/Flexibility" with a score of 0.025, have the greatest impact on a "Technology Multiplier".

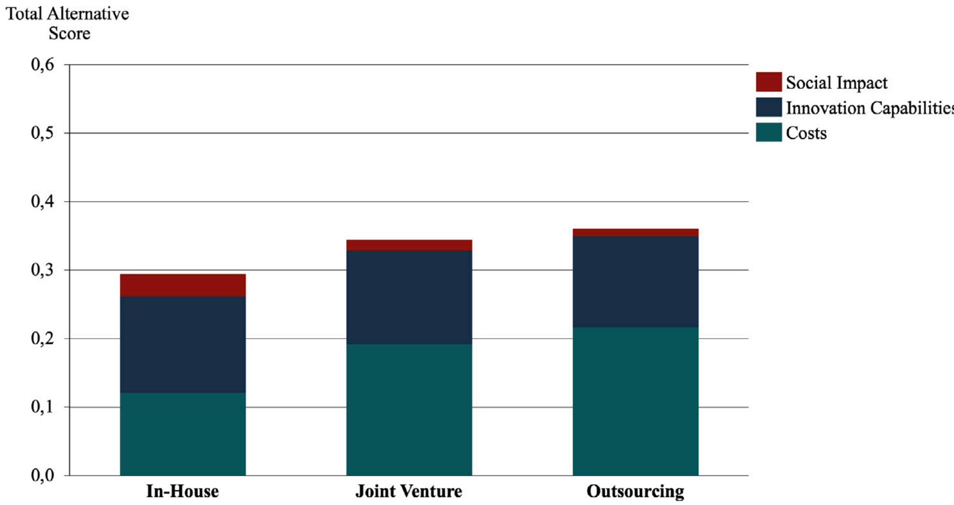

Fig. 10. Priorities by alternative case study 6.

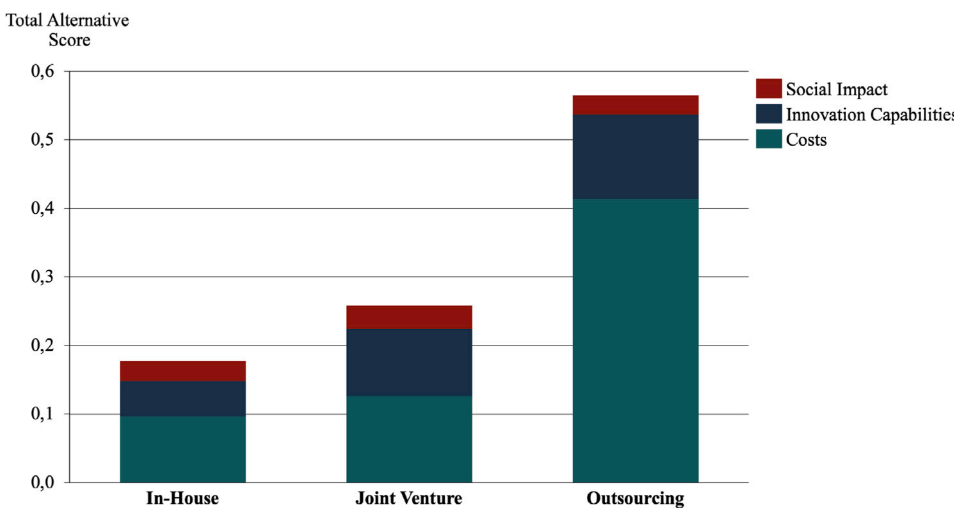

Fig. 11. Priorities by alternative case study 7.

4.9. Case study 7

A cost engineer from a battery cell manufacturer participated in this study, which focused on battery cells. This study was included to reflect the decision-making process of automotive OEMs from a supplier's perspective and potentially provide additional insights to the other case studies conducted with OEMs. Battery cells are a critical strategic component for automotive OEMs. As a supplier, the company is the object of a make-or-buy decision rather than the decision-maker. The manufacturing processes are generally straightforward at a high level but require extreme precision at an atomic level. Numerous hidden factors such as temperature and storage processes can affect the result, creating a "black box" effect with delays between cause and effect of several days. The process requires a highly controlled environment to ensure accuracy. As a result, few OEMs have mastered the large-scale industrialization of battery cell manufacturing and there is a high demand for externally sourced battery cells.

The results show a very high score for outsourcing production, mainly driven by the cost aspect, especially the sub-criteria of "Unit Costs", as shown in 11. The result is very different from any other case because of the high preference for outsourcing due to cost reasons. As a cost engineer from a specialized battery cell manufacturing company, the interviewee was much more skeptical about the long-term competitiveness of in-house OEM production.

There is only 1 sensitive comparison. The comparisons between the "In-House" and "Joint Venture" alternatives for the sub-criterion "Unit Costs" has shown particular sensitivity. Considering the scores for the "Innovation Capability" sub-criteria of the "In-House" alternative, the results suggest that the sub-criterion "Synergistic integration capability" with a score of 0.030, as well as the sub-criterion "Manufacturing capabilities" with a score of 0.012, have the greatest impact on a "Technology Multiplier".

5. Discussion

The results from the seven case studies offer insights into the decision-making processes of automotive manufacturers and their approaches to production segment allocation, particularly concerning battery components in BEVs. The application of the AHP provided a structured framework to assess the relative importance of various criteria and sub-criteria influencing make-or-buy decisions. This discussion interprets these findings, highlighting patterns, divergences, and implications for the development of a "Technology Multiplier" framework.

5.1. Dominance of cost and innovation capabilities

Across all case studies, "Cost" and "Innovation Capabilities" emerged as the most significant criteria, with average weights of 0.495

and 0.415, respectively. This underscores the dual focus of automotive manufacturers on achieving cost efficiency while fostering innovation to maintain competitive advantage. The high weighting of “Unit Costs” (average weight of 0.193) reflects the industry’s sensitivity to production expenses, especially given the substantial investment required for battery technology development and manufacturing systems.

Companies that opted for in-house production placed more emphasis on “Innovation Capabilities”, particularly “Design Capabilities” (weight of 0.146) and “Differentiation/Customer Value Add” (weight of 0.113). This indicates a strategic inclination towards leveraging in-house expertise to create unique value propositions and maintain control over critical technological aspects. In contrast, companies favoring outsourcing attributed higher importance to “Capital Expenditure” (weight of 0.123) and “Manufacturing Capabilities” (weight of 0.117), suggesting a preference for minimizing upfront investments and relying on external partners for manufacturing expertise.

5.2. Preference patterns in production alternatives

The evaluation of production alternatives revealed a general preference for “In-House” production (average score of 0.408), followed by “Outsourcing” (0.314) and “Joint Venture” (0.278). However, this preference varied depending on the company’s strategic orientation, production volumes, and market positioning.

Our case studies suggest a nuanced relationship between vertical integration and price segment. High-volume manufacturers appear to favor in-house production to achieve cost advantages through economies of scale. For instance, in Case Study 2 and Case Study 4, companies operating in high-volume market segments opted for in-house production, leveraging their scale to reduce unit costs and enhance cost efficiencies. Premium manufacturers, while valuing technological aspects and product differentiation, often face challenges in ramping up production due to lower volumes and higher capital requirements. In Case Study 5 and Case Study 6, both premium manufacturers, the companies opted for outsourcing, placing higher importance on “Unit Costs” and “Capital Expenditure.” This suggests a strategy to minimize upfront investments and manage costs effectively, given the difficulty in achieving economies of scale with lower production volumes. An exception is observed in Case Study 1, where a sports car manufacturer decided to pursue in-house production. In this case, the need for differentiation and control over product quality outweighed the challenges associated with lower production volumes. The emphasis on “Design Capabilities” and “Differentiation/Customer Value Add” indicates that, for specialized or niche products, in-house production is strategically important despite potential cost disadvantages.

These observations suggest that the necessity for in-house production may be influenced by production volumes and the strategic importance of differentiation. High-volume manufacturers may choose in-house production to exploit economies of scale. Mid-volume premium manufacturers or those facing significant capital constraints may lean towards outsourcing to manage costs effectively. However, given the limited number of case studies and data points, these patterns should be interpreted with caution. The decisions are influenced by a complex interplay of strategic priorities, market positioning, production volumes, and technological considerations. Further research with a larger sample size would be necessary to validate these trends and better understand the factors influencing make-or-buy decisions in the automotive industry.

5.3. Role of “Technology Multiplier” factors

The concept of a “Technology Multiplier” aims to quantify the long-term value added by in-house production capabilities. The case studies provided preliminary insights into the potential key drivers of this multiplier within the EV-battery industry. Sub-criteria under “Innovation Capabilities” such as “Design Capabilities”, “Differentiation/Customer Value Add” and “Speed/Flexibility” were identified as having significant impact, especially among companies that chose in-house production.

For example, companies in Case Studies 1 and 4 demonstrated that strong in-house “Design Capabilities” and the ability to offer differentiated products contributed to their competitive advantage and justified the higher investment in in-house production. These factors align with the notion of a “Technology Multiplier”, where the long-term benefits of innovation and product differentiation outweigh immediate cost considerations.

5.4. Feedback on the AHP model and framework applicability

Participants generally provided positive feedback on the AHP model and its applicability to strategic make-or-buy decisions. The suitability of the pre-selected criteria was rated as “good”, with a few participants suggesting the inclusion of additional aspects such as quality-related factors, logistical considerations, and political or environmental dimensions. The overall model approach was also well-received, with ratings between “good” and “very good”, indicating that the methodology was sound and useful for structuring complex decision-making processes.

Some participants noted limitations, mentioning that capturing all interactions between factors can be challenging and that the model may require controlled variables to be fully applicable. A few participants raised concerns about the applicability of certain criteria, like “Transaction Costs”, which may not be significant in all scenarios. These insights suggest that while the AHP model provides a valuable starting point, it may require customization and extension to fully accommodate the specific contexts and complexities of different companies.

5.5. Implications for the “technology multiplier” framework development

The findings from the case studies support the iterative development of the “Technology Multiplier” framework. The emphasis on “Innovation Capabilities” among companies favoring in-house production provides backing for including sub-criteria like “Design Capabilities” and “Differentiation/Customer Value Add” as key components of the multiplier. These factors contribute to long-term competitive advantages that are not immediately quantifiable through cost considerations alone.

Moreover, the variation in criteria weighting between companies suggests that the “Technology Multiplier” should be adaptable to different strategic orientations and market positions. A one-size-fits-all approach may not be sufficient, and the framework should allow for customization based on the specific priorities and contexts of individual companies.

5.6. Limitations and areas for further research

While the case studies offer valuable insights, they also highlight limitations that should be addressed in future research. The sample size is relatively small and focused on the automotive industry, specifically BEV battery production. Expanding the research to include a broader range of industries and products could enhance the generalizability of the findings.

Additionally, the qualitative nature of some factors and the potential for interdependencies between criteria pose challenges for the AHP model. Incorporating methods to account for these complexities, such as integrating fuzzy logic or conducting more extensive sensitivity analyses, could improve the robustness of the framework.

Finally, some selected feedback from a few participants suggests a need to consider external factors like political, environmental, and logistical aspects that can influence make-or-buy decisions. Future iterations of the “Technology Multiplier” framework should explore ways to integrate these dimensions to provide a more comprehensive tool for strategic decision-making.

6. Conclusion

The application of the AHP in seven case studies provided a structured and insightful approach to understanding the factors influencing make-or-buy decisions in BEV battery production. The findings emphasize the importance of balancing cost considerations with innovation capabilities and highlight the potential of the "Technology Multiplier" framework to quantify long-term value creation.

By identifying key drivers like "Design Capabilities" and "Differentiation/Customer Value Add," this research provides a basis for a quantifiable model to guide production segment allocation decisions. Addressing current limitations and adding more factors will improve its broad applicability. The next step involves defining the "Technology Multiplier," converting case study insights into a measurable framework. The model will then undergo data validation to ensure robustness across different manufacturing contexts, followed by industry partner refinement for practical use. The goal is a comprehensive, iterative framework that supports strategic make-or-buy decisions by quantifying long-term value.

In conclusion, this research supports the development of a quantifiable model to assist manufacturers in making informed production decisions. By refining and validating the "Technology Multiplier" through ongoing research, the objective is to provide a valuable tool that captures the balance between cost efficiency and innovation capabilities, ultimately contributing to more strategic and value-driven decision-making in the manufacturing industry.

CRediT authorship contribution statement

Roman Girke: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Louis Schäfer:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Tanja Maier:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **Florian Stamer:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Shun Yang:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization. **Jung-Hoon Chun:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization. **Gisela Lanza:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The stay abroad as a visiting researcher at Massachusetts Institute of Technology (MIT) in Boston, MA was funded by the Karlsruhe House of Young Scientists (KHYS).

Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.jmsy.2025.06.008.

References

[1] Friedli T, Mundt A, Thomas S. Strategic Management of Global Manufacturing Networks. Berlin, Heidelberg: Springer Berlin Heidelberg; 2014.
[2] Reich RB. Technology trends and their application in US industry. Econ Dev Rev 1986;4:6–8.
[3] Hayes RH, Pisano GP. Beyond world-class: the new manufacturing strategy. Harv Bus Rev 1994;72:77–86.
[4] Shih W. Why high-tech commoditization is accelerating . MIT Sloan Manag Rev 2018;59(4):53–8.
[5] Naor M, Coman A, Wiznizer A. Vertically integrated supply chain of batteries, electric vehicles, and charging infrastructure: A review of three milestone projects from theory of constraints perspective. Sustainability 2021;13(7):3632.
[6] Hofmann E. Linking corporate strategy and supply chain management. Int J Phys Distrib Logist Manage 2010;40(4):256–76.
[7] Casson M. The theory of vertical integration: A survey and synthesis. J Econ Stud 1984;11(2):3–43.
[8] Armour HO, Teece DJ. Vertical integration and technological innovation. Rev Econ Stat 1980;62(3):470.
[9] Huth C. Strategische Planung der Fertigungstiefe bei Unsicherheit und Dynamik: Ein simulationsbasierter Ansatz am Beispiel der Fertigung von Traktionsbatterien. Springer-Verlag; 2014.
[10] Teece DJ. Tesla and the reshaping of the auto industry. Manag Organ Rev 2018;14(3):501–12.
[11] Stamer F, Girke R, Yang S, Chun J-H, Lanza G. Effect of technology multiplier: A framework for analysis of innovation perspectives on production segment allocation. CIRP J Manuf Sci Technol 2024;55:272–91.
[12] Dou Z, Wu B, Sun Y, Wang T. The competitiveness of manufacturing and its driving factors: A case study of G20 participating countries. Sustainability 2021;13(3):1143.
[13] Jauch LR, Wilson HK. A strategic perspective for make or buy decisions. Long Range Plan 1979;12(6):56–61.
[14] Peters S, Chun J-H, Lanza G. Digitalization of automotive industry – scenarios for future manufacturing. Manuf Rev 2016;3:1.
[15] McIvor R. A practical framework for understanding the outsourcing process. Supply Chain Manag: Int J 2000;5(1):22–36.
[16] Steven AB, Dong Y, Corsi T. Global sourcing and quality recalls: An empirical study of outsourcing-supplier concentration-product recalls linkages. J Oper Manage 2014;32(5):241–53.
[17] Gunasekaran A, Irani Z, Choy K-L, Filippi L, Papadopoulos T. Performance measures and metrics in outsourcing decisions: A review for research and applications. Int J Prod Econ 2015;161:153–66.
[18] Kusiak A. Smart manufacturing. Int J Prod Res 2018;56(1–2):508–17.
[19] Poazi FDW, Tamunosiki-Amadi JO, Fems M. The resource-base view of organization and innovation: Recognition of significant relationship in an organization. World Acad Sci Eng Technol Int J Soc Behav Educ Econ Bus Ind Eng 2017;11:697–704.
[20] Lawson B, Samson D. Developing innovation capability in organisations: A dynamic capabilities approach. Int J Innov Manag 2001;05(03):377–400.
[21] Smith M, Busi M, Ball P, Van Der Meer R. Factors influencing an organisation's ability to manage innovation: A structured literature review and conceptual model. Int J Innov Manag 2008;12(04):655–76.
[22] Teece DJ. Business models, business strategy and innovation. Long Range Plan 2010;43(2–3):172–94.
[23] Morgan J. Electric vehicles: the future we made and the problem of unmaking it. Camb J Econ 2020;44(4):953–77.
[24] Bozorg-Haddad O, Zolghadr-Asli B, Loáiciga HA. A Handbook on Multi-Attribute Decision-Making Methods. Wiley; 2021.
[25] Saaty TL. A scaling method for priorities in hierarchical structures. J Math Psych 1977;15(3):234–81.
[26] Emrouznejad A, Marra M. The state of the art development of AHP (1979–2017): a literature review with a social network analysis. Int J Prod Res 2017;55(22):6653–75.
[27] Cabigiosu A. Open and collaborative innovation in the automotive industry. In: The green transition of the automotive industry. Cham: Springer International Publishing; 2023, p. 131–59.