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Effect of technology multiplier: A framework for analysis of innovation perspectives on production segment allocation

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ABSTRACT

In the realm of production systems, determining the optimal segment allocation remains a central concern. While several existing models address this issue, a significant gap remains as many overlook the critical role of innovation and lack a holistic perspective. This paper presents a model that emphasizes innovation capabilities and introduces the concept of a "Technology Multiplier" underscoring the compounding influence of technology and innovation on production segment allocation decisions. Within this work, we focus on preliminary studies to establish the "Technology Multiplier" concept employing an Analytical Hierarchy Process (AHP) with sensitivity analysis. The validity of our approach is demonstrated through four case studies from three industries, illustrating the relevance of our elaborated metrics for the concept of "Technology Multipliers". In particular, a leading automotive company uses our findings to reach a more appropriate strategic decision aligned with innovation and production growth, compared to its previous decisions. These results not only demonstrate a robust fit with our proposed metrics but also indicate that our framework lays the foundation for further research on the "Technology Multiplier", enriching the decision-making process for production segment allocation.

1. Introduction

The issue of the production segment allocation of internal and external processes in the context of production system design has remained a central concern for researchers and practitioners over time [1–3]. The notion of production segment allocation within a firm encompasses the extent to which the necessary processing steps for the final product are carried out in its own production system. In determining production segment allocation, firms need to strategically position themselves within the value chain [4] and define the set-up of their production system [5,6]. Segment allocation in production planning plays a critical role in production management as it has a significant impact on the configuration of the production system, such as manufactured products, process technologies used, labor, machine capacity, and logistics [2]. Moreover, decisions regarding production segment allocation influence the degree to which organizations engage in optimizing manufacturing processes, strategically deploying production equipment and automation, and meticulously designing their manufacturing systems. By determining how to allocate production segments, companies effectively determine their level of involvement in the critical tasks that define their technological competitiveness in the industry [2,7]. These include integrating the latest technological advances, adapting to economic changes, and managing production networks. Such decisions are fundamental not only to aligning with technological and economic drivers but also to improving the overall agility and resilience of manufacturing operations [8], making the study of production segment allocation an important aspect of the field of manufacturing science and technology.

The planning of segment allocation in production has become increasingly important in the context of globalization, which offers expanded opportunities for outsourcing. The phenomenon of globalization has a significant impact on production systems, fostering economic integration and thereby increasing efficiency, cost-effectiveness, and facilitating the incorporation of innovative technologies such as automation, virtual reality, and flexible manufacturing systems [9]. Globalization has enabled the flow of people, goods, and information across borders, creating global supply chains for components, assemblies, and products with standardized processes. As a result, firms can source their needs from a worldwide network of suppliers, many of which have specialized, achieved high quality, and benefited from

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economies of scale. In the 1990s and 2000s, outsourcing became a management trend triggered by Japanese firms to achieve operational efficiency. In their quest for short-term financial gain, many firms have turned to offshoring or outsourcing their production to regions that offer immediate cost advantages [10]. Recent developments, such as the phenomenon of reshoring, where previously outsourced manufacturing activities are reintegrated internally, suggests strategic misalignments in many of these cases, and emphasize the need to reassess some of these past outsourcing decisions [11]. Today, the configuration of production systems and their supply networks have a significant impact on the competitiveness of firms [12]. 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 [13]. Moreover, with the increased complexity resulting from globalization, traditional metrics, especially those driven by short-term cost considerations, often fail to adequately address the broader implications for the competitiveness of production systems. It is becoming increasingly clear that a holistic perspective is needed, one that considers not only direct financial factors, but also the long-term strategic implications of decisions related to production segment allocation and the configuration of production systems.

The concept of a “Technology Multiplier”, similar to the concept of an economic multiplier, could highlight the extent to which investments in internal production systems could provide benefits beyond mere short-term financial gains. It could provide an understanding of the real long-term value that in-house production could bring in terms of technological innovation and adaptation. The “Technology Multiplier” hypothesis proposes quantifying these benefits associated with domestic manufacturing that go beyond the primary production of goods. It indicates that engaging in-house manufacturing allows firms to gain not only tangible products but also a significant wealth of knowledge, expertise, and capabilities. This intellectual capital 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. However, finding meaningful measures of the "Technology Multiplier" effect for a production segment allocation decision remains a challenge.

One aspect that can be better addressed by the more comprehensive perspective of a “Technology Multiplier” is a firm’s innovation capability, which, according to Porter, is the basis for a firm’s ability to differentiate itself and ensure its long-term competitiveness [4]. Beyond shaping the structure of supply chains and manufacturing processes, segment allocation subtly influences a firm’s ability to innovate. Therefore, to remain competitive in the long run, companies should consider the implications of determining the segment allocation of manufacturing for their innovation capabilities in their decision-making processes. The determination of production segment allocation can also have far-reaching implications for an organization’s set-up of its production system [14]. 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 [15].

1.1. Underlying theories

From a theoretical perspective, the question of production segment allocation in the context of the theory of the firm provides explanatory approaches as to how companies design their production system in the context of the whole value chain. In the literature, transaction cost economics (TCE) and the resource-based view (RBV) are among the most common theoretical approaches.

The TCE approach, articulated by Williamson [16], emphasizes the fact that the utilization of markets always incurs costs and is subject to certain inefficiencies, thus generating transaction costs. This paradigm suggests that firms choose the governance structure for their production system and network that minimizes their transaction costs. The approach delineates governance structures into buy, make, and hybrid forms. The theory tends to favor a solution within the production system of the firm (make solution), especially when transaction costs in a market setting are high.

While the TCE approach focuses on minimizing transaction costs through appropriate governance structures, the RBV complements this by emphasizing the role of the firm’s unique production system and how leveraging it can create a competitive advantage. The RBV originated from Barney [17] and considers firms as bundles of resources that form the basis for creating a competitive advantage. The resources of a firm are categorized into physical capital resources, human capital resources, and organizational capital resources. According to Barney, the extent to which a resource contributes to the creation of a competitive advantage depends on whether it is valuable, rare, inimitable, and non-substitutable. In the context of production systems, the RBV underscores the role of proprietary processes, equipment, and learning capabilities, to achieve competitive manufacturing performance [18]. A “Technology Multiplier” could be a key metric that measures the incremental value derived from improved resources, covered in the RBV theory, relative to the inherent costs of acquisition, implementation, and operations, thereby helping firms to discern the true efficiency of their strategic investments in the production system.

A crucial aspect in the literature regarding the enhancement of competitiveness is innovation [19]. An organization’s existing resources not only shape its innovation capabilities but these capabilities themselves can also be considered a valuable, unique, and inimitable resource [20]. According to the OECD [21], innovation can be categorized into product innovations, process innovations, marketing innovations, and organizational innovations. In the context of this study, product and process innovations are particularly relevant. Product innovations pertain to improved characteristics of a good or service, while process innovations focus on enhancing production or logistics. The ability to achieve such improvements is defined by Lawson and Samson [22] as innovation capabilities, which refers to “the ability to continuously transform knowledge and ideas into new products, processes, and systems for the benefit of the firm and its stakeholders”. In certain cases, the ownership of R&D and production facilities can enhance technological innovation [14]. The concept of a "Technology Multiplier" could support to better understand this phenomenon.

1.2. Related work

First, a comprehensive literature search is conducted to identify existing approaches to determine optimal segment allocation and could contribute to the conceptualization of a "Technology Multiplier". After a thorough search, the existing models are supplemented by models referenced in the context of broader meta-studies. The models tend to focus on different perspectives and mostly refer to the make-or-buy decision or outsourcing. In the following, we present an overview of previous work, which identifies gaps in existing models and derives approaches for the development of our framework. The existing models are also evaluated based on a set of selected criteria relevant to our approach, ensuring their relevance and applicability to the current study as well as the research gap (cf. Table 1). Each criterion is introduced with a number, e.g. (1), in the subsequent sections.

As the question of optimal segment allocation is a recurring issue in production, there are already numerous approaches in the literature to provide decision support [23]. A comprehensive comparison of 133 existing approaches can be found in the work of Huth [15]. The main approaches include theory-based approaches such as TCE or the RBV, as well as strategic and multi-criteria approaches.

Theory-based descriptive approaches rely heavily on existing theories and generally focus on a limited number of valuation dimensions for decision-making. Models based on the TCE approach often emphasize the asset specificity of a transaction [24,25]. Decision-making can

Table 1
Make-or-buy model comparison.

	Venkatesan 1992	Probert 1996	Canez et al. 2000	Udo 2000	Yang and Huang 2000	Baines et al. 2005	McIvor 2009	Benama et al. 2014	Medina-Serrano et al. 2020
Method									
Matrix							x		
Decision tree	x						x		
Phase model		x	x			x			
Multi-criteria decision-making method				x	x			x	x
Requirement									
(1) Operationalizability of the approach	◑	●	◕	◕	◑	●	◑	◑	●
(2) Qualitative and quantitative goals	◕	◕	◕	●	●	●	◔	◕	●
(3) Adaptability of factors	○	◔	◕	◕	◕	◕	○	○	◕
(4) Diverse motivations	◕	◔	◕	◕	◕	◕	◑	◑	●
(5) Use at the assembly-level	●	◑	●	○	○	○	◕	○	◕
(6) Applicability from a production perspective	◕	◑	◑	○	○	◑	◑	●	◕
(7) Consideration of innovation capability	◑	◔	◔	○	◑	◔	◑	◔	◑

● high degree of fulfillment ○ low degree of fulfillment

also be represented by a decision matrix [26]. TCE has a strongly market-oriented perspective and rarely evaluates the actual object of the transaction. This gap is filled by resource-based approaches, which focus on determining the best sourcing decision based on available resources and capabilities [1]. Central to this is the concept of core competencies, which assumes that companies should engage in activities that are aligned with their core competencies or build core competencies in that area [27]. In Venkatesan's approach [28], components are classified using a decision tree. First, subsystems are classified based on the performance of in-house production versus outsourcing. For strategically relevant subsystems, decisions are then made for component families as to whether they are strategically relevant components or commodities. A final decision is made based on the available resources for strategic parts and the competitive production of commodities. While the approach provides a general decision structure there is only limited guidance for operationalization provided (1). McIvor's model [29] combines the decision dimensions of TCE and RBV in a decision tree created based on case studies. Different recommendations are made for scenarios such as in-house production and various contract models based on contributions to competitiveness, relative capability, and the risk of opportunistic behavior. A notable limitation of McIvor's model is its focus on qualitative data, which precludes the integration of qualitative and quantitative goals (2). A general limitation of theory-based models, including McIvor's, is their low adaptability in terms of variable adaptability (3), as such models are confined within the parameters of specialized theories.

There are also strategic approaches that focus even more on the positioning and long-term goals of the firm. Probert [30] developed a ten-step model that includes initial categorization, internal and external analysis, evaluation of strategic alternatives, and selection of a strategy. Probert's approach is very cost-focused and, like the theory-based models discussed earlier, includes only a limited range of motives to justify a make-or-buy decision outcome (4). The model of Baines et al. [31] is also intended to support decision-making from a strategic perspective and shows a more comprehensive approach to operationalize this in a workshop-based format. It includes a customized definition of key criteria but takes an activity-oriented perspective rather than an assembly level perspective (5).

Many of the models only allow binary decisions for selected factors, and decisions regarding the determination of segment allocation can consist of multiple, sometimes contradictory objectives. In contrast, Canez et al. [23] consider a diverse set of factors in the areas of technology and manufacturing processes, costs, supply chain management, and support systems, and provide a simple phase model for evaluation. There are also several approaches using techniques of multi-criteria decision-making. Udo [32] provides a methodologically specific approach, evaluating the areas of strategic importance, stakeholders' interests, vendor issues, cost operations, and industry environment using an Analytical Hierarchy Process (AHP), although in the context of IT outsourcing. Yang and Huang [33], also in the context of IT outsourcing, formulated a model that evaluates factors in the areas of quality and technology within an AHP framework. Consequently, neither the approach proposed by Udo [32] nor that by Yang and Huang [33] enables evaluation at the sub-assembly level (5) in production (6). Benama et al. [6] developed a model that focuses on reconfigurable manufacturing systems and uses simplified weighting and evaluation methods. Various factors from the areas of cost, technical capability, social-economic objective, and risk are considered. A method related to the AHP, from multicriteria decision-making, TOPSIS, is used in the work of Medina-Serrano et al. [1]. The model provides decision support for make-or-buy questions in production based on various factors in the areas of strategy, resources, performance, and the risk of opportunistic behavior. Overall, none of the previously mentioned models place a strong emphasis on the innovation capabilities (7) needed to foster long-term competitive advantage in the production system. While related work offers different perspectives, the concept of a quantified "Technology Multiplier" remains an underexplored area. Its importance lies in its potential to capture not only the immediate benefits of in-house production, but also the longer-term quantitative value added associated with innovation. By considering this multiplier, decision makers are better equipped to weigh the broader implications of production segment allocation, especially in an era where rapid technological advances are essential to maintaining a competitive edge.

The primary goal of this research is to establish a first basis for the development of a "Technology Multiplier". A major challenge is to find relevant metrics that make such an effect quantitatively measurable. In addition to identifying the initial driving metrics, our objective is to establish a preliminary framework for subsequent development. Based on the existing literature, relevant factors are identified which, in the sense of the "Technology Multiplier", can add value to innovation capability in a production segment allocation decision. However, since these factors may be case-specific or of a more qualitative nature, we propose a holistic framework consisting of a factor pre-selection, an analytical hierarchy process and a sensitivity analysis. In particular, the use of this framework allows an indicative quantification of the pre-selected factors in real industry examples by means of weights and scores. Beyond the background of the "Technology Multiplier", this study represents an application of the AHP to the production segment allocation. We expand the traditional AHP by including a sensitivity analysis to consider uncertainties. As the preceding analysis of related work has shown, our proposed holistic framework could extend the existing landscape of make-or-buy models for the first time by a framework with a strong focus on the innovation capabilities of manufacturing firms production systems. This could mean that the framework could be useful beyond the sense of a preliminary study of the "Technology Multiplier" in a complementary way as a general indicative combined analysis for the application of a "Technology Multiplier" or even as a general decision support framework for make-or-buy decisions.

2. Methodology

The methodology of this study is part of the overarching objective of exploring the concept of a "Technology Multiplier". While only the first stage of the preliminary research approach outlined here is covered in this study, we aim to underscore the contribution of the methodology and findings of this specific study to the broader context of our research. The ongoing findings are intended to refine the conceptualization of a "Technology Multiplier." In the course of this refinement, it is possible that the research approach will also have to be adapted, which is why we refer to it here as preliminary.

2.1. Preliminary overall research approach to establish a technology multiplier

The preliminary research approach shown 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 divided into two main phases: Initial Pre-Studies and Technology Multiplier Definition, each of which consists of several distinct stages.

The Initial Pre-Studies phase begins with General Initialization, where the goal is to conduct initial research to identify driving metrics and test them with manufacturing firms from various industries. This stage uses literature reviews and case studies to collect both qualitative and semi-quantitative data, focusing on a broad but limited set of initial metrics with a small sample size. The next stage, Product Specific Initialization, applies these initial metrics to specific products within the same industry to refine their applicability, again using case studies to gather targeted insights. This phase continues to focus on qualitative and semi-quantitative data with a small sample size.

The second phase, Technology Multiplier Definition, begins with model development. The goal here is to transform the refined metrics into a quantifiable model suitable for calculating the “Technology Multiplier” and could use multivariate regression techniques to develop the model. This stage emphasizes quantitative data to ensure robustness, with a focus on model formulation rather than sample size. The next stage, Quantification with Data Training, aims to quantify the model metrics using large-scale industry data to validate and adjust the model, could continue the use of multivariate regression techniques with a large sample size and predominantly quantitative data. The final stage, Validation and Refinement, is designed to validate the “Technology Multiplier” model with industry partners and refine the metrics and weights as necessary. This stage could utilize both multivariate regression and case studies for final adjustments, focusing on quantitative data for precise validation with a small sample size, ensuring detailed validation with key industry partners.

This research approach ensures a detailed and iterative development process from initial metric identification to final model validation. It integrates both qualitative and quantitative approaches, progressively refining the metrics and model through real-world application and industry collaboration. The goal of this structured approach is to create a robust and applicable “Technology Multiplier” that improves manufacturing segment allocation decisions by quantitatively measuring long term value.

2.2. Methodology for general initialization

In the development of our framework for the General Initialization phase, a qualitative research approach is used. The research

	Focus of this study	The subsequent stages, building on the first study, 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.

methodology is based on a combination of the already presented literature review, a framework development, and a validating case study approach. The literature review within the previous section was conducted to understand the existing theories and findings related to production segment allocation, providing a solid foundation for the study. The AHP model is used due to its effectiveness in dealing with complex decision-making problems, allowing us to systematically evaluate and prioritize the factors affecting production segment allocation similar to a reverse engineering. Lastly, a validating case study approach is used in real-world scenarios by applying it and reflecting the results with the status quo decisions of the companies. The nature and results of the application of the framework in the case studies provide insights into what factors might be relevant for the development of a "Technology Multiplier" by analyzing the scores within the AHP. The scores allow a first semi-quantification of the importance of different metrics.

Decisions about production segment allocation can be highly complex and require careful consideration of various qualitative and quantitative aspects [5]. 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 AHP, which is based on pairwise comparisons of criteria and alternatives [34]. By using the AHP and later applying it in case studies, we can gain valuable insights into which factors are highly relevant for the development of a "Technology Multiplier". The AHP was first introduced by Saaty [35] and further developed in his subsequent work [36,37]. Since the introduction of the AHP, it has been considered an established method in the field of MADM [38], which is also reflected in the overall increasing number of publications over the last two decades [39].

At the beginning, the hierarchy of the decision problem is formulated. The AHP consists of an overall objective or question to be answered. Based on the objective, different criteria are derived, which are further divided into sub-criteria. For the decision problem, different alternatives are determined, which represent the last hierarchy level. The objects of a hierarchy level are then compared regarding their priority for the respective higher hierarchy level. The criteria are compared in terms of their priority for the higher-level objective, and the sub-criteria are compared in terms of their priority for the criteria. The alternatives are then compared across all sub-criteria and finally, all weights are combined into an overall score of the alternatives for meeting the overall objective. The high weight of a sub-criterion implies an initial relevance of the sub-criterion for the concept of a "Technology Multiplier". If there is a strong preference for the "In-House" alternative, in relation to a strongly weighted sub-criterion of "Innovation Capability", the resulting overall score indicates an influence on the "Technology Multiplier". The AHP can therefore help narrow down the range of key metrics. All comparisons are made using an integer score from 1 to 9 and its reciprocals, which can also be translated into a linguistic metric, in a reciprocal matrix for each comparison on all levels. The eigenvalue method is used to convert the matrices into a weighting. The largest eigenvalue of the matrix can be used to check whether the Consistency Ratio (CR) is below 0.1. If the CR is 10 % or less, as specified by Saaty, the matrix is acceptably consistent. Otherwise, the matrix evaluation should be revised. The criteria are derived from the existing literature. An in-depth analysis is carried out for the sub-criteria of innovation. The research for sub-criteria is structured as follows: collection of relevant aspects in literature, clustering of aspects, filtering for aspects suitable to our defined requirements, and final selection of sub-criteria that best represent their overall criteria. Since the use of the AHP requires linear independence of the criteria and sub-criteria [40], care was taken to ensure that they were formulated as independent and non-overlapping as possible. However, due to case-specific differences and the qualitative nature of some factors, it is not always possible to exclude interdependencies in realistic scenarios [41].

In addition to consistency and independence, another important aspect to consider is uncertainty in decision-making. Several methods can be used to mitigate potential uncertainties in decision-making processes, including fuzzy logic approaches, integration with the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), or conducting sensitivity analyses [38]. Recognizing the inherent uncertainty of input information in decision scenarios, and with the goal of maintaining broad accessibility to individuals in the case studies who may not be well versed in nuanced aspects such as fuzzy logic, we chose to implement a sensitivity analysis. This approach allows for the examination of how variations in input parameters affect the decision outcome, thereby providing insight into the robustness of the conclusions drawn from the analysis. This strategy ensures a balance between the rigor of dealing with uncertainty and the pragmatic need for the methodology to be accessible to practitioners.

We validate our theory-based framework within four different case studies, following a deductive approach as described by Johannson [42]. The aim of these case studies is to verify whether the framework adds value in determining optimal production segment allocation and to test the suitability of the defined criteria and sub-criteria for decision-making and potential inclusion in a "Technology Multiplier". We also use these case studies to identify areas for improvement. We select the case studies from manufacturing companies frequently confronted with determining optimal production segment allocation and with which our research team has a good relationship, ensuring transparent insight into the decision-making process. The case studies' implementation consists of a general classification, the implementation of the framework, and an evaluation of the framework results. We use the general classification to understand the previous decision process and the context of the decision. In the implementation of the framework, we apply it and prioritize the criteria, sub-criteria, and alternatives in a pairwise comparison. Next to that, we perform the sensitivity analysis. In the evaluation of the results, we consider the framework's suitability for decision-making and whether the framework's recommendations align with the actual or planned business decisions.

3. Proposed framework

The framework shown in Fig. 2 consists of three phases, namely the selection of the objects of analysis, the execution of the AHP and the evaluation of the results, which will be presented in detail in the

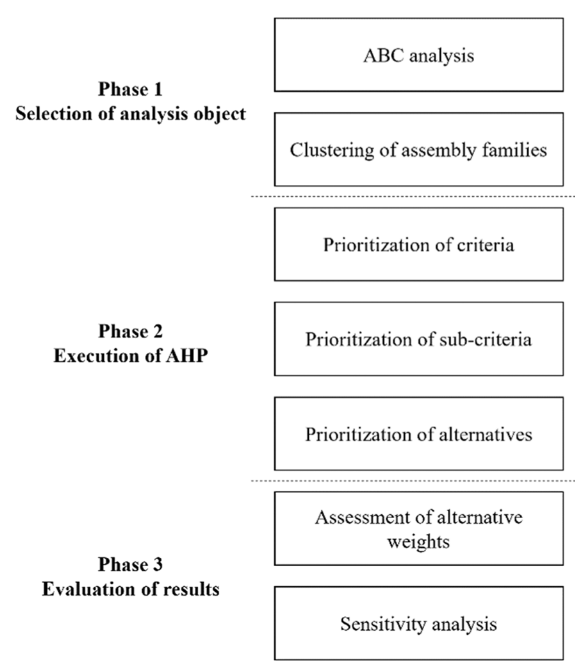

Fig. 2. Proposed framework.

following sections. In general, our proposed model is designed for use in discrete manufacturing. However, the ability to consider the assembly or component level allows for flexible application along the manufacturing value chain from component suppliers to original equipment manufacturers. The quality of the model results depends heavily on the quality of the inputs. For this reason, it is recommended that all steps of the framework are performed with an interdisciplinary team of experts from distinct functions and that decisions are continuously reviewed.

First, it is necessary to handle the complexity of the product architecture. Therefore, once an initial product or set of products for analysis is selected in advance, a modified ABC analysis is used to efficiently select key assemblies or components of a specific product and group them into families for synergy considerations. This is followed by the execution of the Analytical Hierarchy Process (AHP), which serves as the core to determine the optimal production segment allocation of manufacturing, considering criteria of “Cost”, “Innovation Capabilities”, and “Social Impact”. The final stage is the evaluation of the results, where the results of the AHP are carefully analyzed, with sensitivity analysis ensuring the robustness and reliability of the results, culminating in a comprehensive and informed decision-making process.

3.1. Identification of relevant criteria and alternatives

Among the three criteria examined in this paper, the primary focus is on the “Innovation Capabilities” criterion, reflecting the importance of innovation capabilities for manufacturing companies. An in-depth analysis of this criterion is undertaken as shown in Fig. 4 because, as our previous evaluation has shown, existing models often provide only indirect or insufficient insights into innovation-related sub-criteria. The first step involves the collection of 100 capabilities and enablers relevant to innovation, derived from an extensive review of 90 references. These collected insights are then organized, leading to the formation of 25 aspects in 5 groups through a process of clustering as presented in Table 2. This is followed by a filtering process to identify those aspects that are particularly suitable for evaluation at the component level. Many of the collected factors are not suitable for our approach as they refer to aspects, which can be only evaluated on a firm level such as the aspects of “Innovation Culture” or “Organizational Structure”. In addition, these aspects undergo a filtering process that focuses on their overall suitability within the defined criteria for our framework. The final stage involves the careful formulation of the five most important factors and subsequent formulation of the sub-criteria. These factors are selected based on their ability to best represent their respective overall clusters.

Based on the extensive list of factors from innovation capabilities literature shown in Table 2, we propose to include the following five sub-criteria for the “Innovation Capabilities” criterion: The first is “Synergistic Integration Capabilities” and covers the previously identified aspects of “Synergies” [49], “Communication/Coordination” [43–55] and selected dimensions of “Knowledge” [46,56–61]. This sub-criterion emphasizes the importance of seamless architecture, communication, and coordination, especially for innovations that involve highly codependent components or require a holistic architectural understanding. These capabilities are key to creating a superior customer experience. The second is “Manufacturing Capabilities”, which refers to the breadth of activities, technologies, and resources a firm can leverage to produce goods or components [49,77]. This sub-criterion includes expertise in process engineering, quality control, supply chain management, equipment utilization, and production scalability, with a particular focus on process innovation. The third is “Design Capabilities”, which encourages innovation by integrating expertise, activities and resources to create customer-centric products [49,77]. This includes market research, ideation, prototyping, and industrial design, and leverages emerging technologies for improved functionality and aesthetics, with a particular focus on product innovation. The sub-criteria of “Manufacturing Capabilities” and “Design Capabilities” are also often referred to by overarching aspects such as “Core Competence/Familiarity” [10,50,51], “Engineer/Workforce Skills” [19,22,72–75,78–82], “Resources” [19,50,73,75,82–87] or “Technological Capabilities” [19,48–50,55,76,88,89]. The fourth sub-criterion, “Speed and Flexibility”, represents a critical aspect of innovation and is frequently covered in existing literature [46,48,50,84,86,111,121]. It emphasizes the ability to respond quickly to changing market demands and to take advantage of emerging technologies. Here, the speed aspect focuses on the time to market of an innovation, while the flexibility aspect focuses on the adaptability to product or process changes. Finally, the fifth sub-criterion is “Differentiation/Customer Value Add”, covering the aspects of “Differentiation” [1,50] and is also related to the “Industry Life Cycle” [87,113,114] and the “Market Innovation Impact” [49,76]. This sub-criterion is highly market-centered and focuses on providing unique benefits to customers, thereby differentiating offerings from competitors. It underpins distinctiveness and value, which secures competitive advantage, and ultimately leads to increased customer satisfaction.

For the overarching “Cost” criterion, we propose the integration of five distinct sub-criteria. First, the “Unit Costs” sub-criterion emphasizes the central role of evaluating the unit cost of production or acquisition. Harrigan [89] states that a primary objective in make-or-buy decisions is to optimize unit costs, an aspect confirmed by Kloock and Schiller [129], who emphasize its importance as a metric for evaluating product performance. Second, the “Transaction Costs” sub-criterion addresses the multiple costs associated with procuring a product or service from an external entity. Following Williamson’s framework [16], these costs range from the intricacies of defining requirements to the complexities of finding suppliers and transferring knowledge. This perspective is consistent with the models proposed by Vining et al. and Fill et al. [24,25], which emphasize the centrality of transaction costs in strategic decision-making. The third sub-criterion, “Risk of Supply Outage”, provides a nuanced understanding of potential supply chain disruptions. Nooraie and Parast [130] highlight the vulnerabilities inherent in supply chains, particularly in the context of outsourcing. The consequences of such disruptions are manifold, ranging from production stops to reputational damage, especially during periods of increased demand [6131]. The “Capital Expenditures” sub-criterion, our fourth consideration, mainly relates to the capital expenditures inherent in in-house production. Moser et al. [132] describe the dual nature of these expenditures, encompassing both the initial establishment and the subsequent maintenance of the production system. Conversely, the act of outsourcing, while avoiding capital expenditure, incurs ongoing costs and represents a potential risk mitigation strategy as postulated by Teece [87]. To

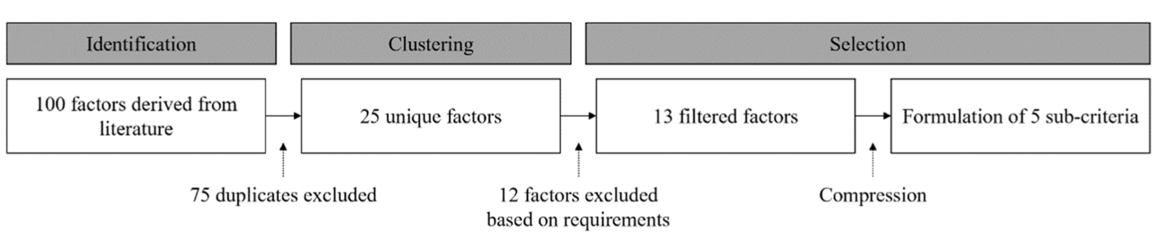

Fig. 3. Structure of innovation capabilities review.

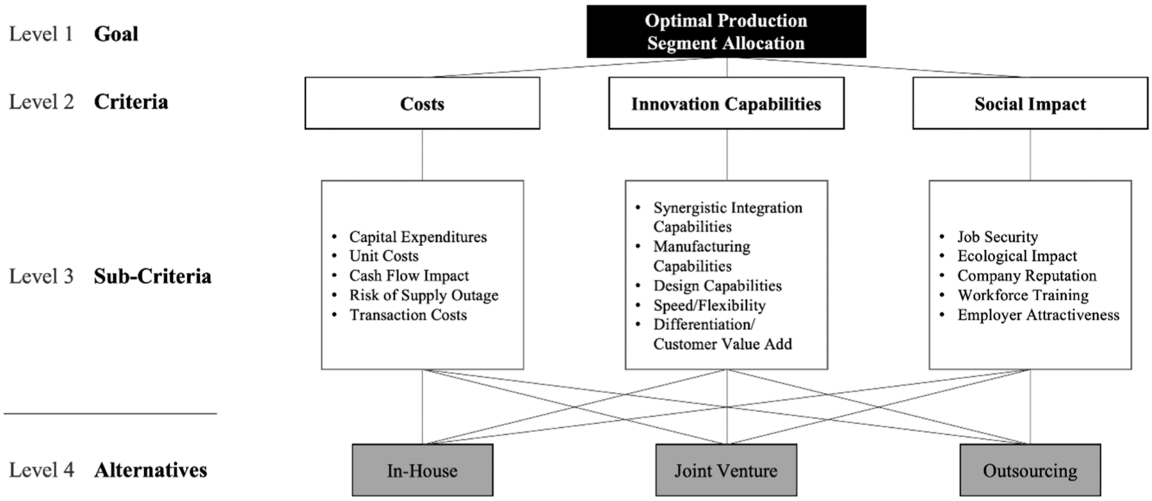

Fig. 4. Hierarchy structure of the proposed model.

Table 2
Cluster and aspects of innovation capabilities review (aspects in brackets were not included in the later formulation of sub-criteria).

Knowledge	Manufacturing and Design	Organization	Market	Other
Communication /Coordination [43–55] Knowledge[46,56–61] (Learning Ability)[19,22,46,51,54,60,62–75] (Patents/Know-How Protection)[76] (R&D Intensity)[76] (Science relations)[76]	Core Competence /Familiarity[10,50,51] Design Capabilities[49,77] Engineer/Workforce Skills[19,22,72–75,78–82] Manufacturing Capabilities[49,77] Resources[19,50,73,75,82–87] Technological Capabilities[19,48–50,55,76,88,89]	(Innovation Culture)[22,46,54,90–96] (Innovation Process)[19,22,69,72–75,81,82,85,97–101] (Strategy)[22,46,48,51,62,64,73,74,84,94,102,103] (Team and Leadership)[43,46,50,64,84,104–108] (Organizational Structure)[19,22,48,50,54,69,73–75,81,82,85,109–112]	Differentiation[1,50] Industry Life Cycle[87,113,114] Market Innovation Impact[49,76]	(Creativity)[46,54,115–120] Speed/Flexibility[46,48,50,84,86,111,121] Synergies[49] (Feasibility)[49] (Finance)[46,61,70,96,112,117,122–128]

conclude our proposed sub-criteria, the “Cash Flow Impact” sub-criterion emphasizes the importance of cash flow as an evaluative measure at the firm level. Probert [133] underscores its importance, and Moser et al. [132] elaborate on the profound influence of factors such as capital expenditures and product price volatility on cash flow dynamics. This perspective is supported by Jauch and Wilson [134], who argue that firms with robust cash positions are inherently better equipped to invest in in-house solutions.

For the “Social Impact” criterion, we recommend considering five different sub-criteria. The “Job Security” sub-criterion addresses the implications of decisions related to in-house versus outsourced manufacturing activities on the continuous job security for employees. As Brem and Elsner [5] elucidate, opting for external activities can lead to layoffs, subsequently impacting the morale of the entire workforce. The “Workforce Training” sub-criterion underscores the influence of these decisions on employee training and skill development. On-the-job training remains a pivotal method in manufacturing [135] and especially junior employees often receive training while executing their primary tasks [136]. Consequently, an individual’s skill set becomes intrinsically linked to the activities a firm chooses to undertake or outsource. The “Employer Attractiveness” sub-criterion has gained prominence, especially amidst the ongoing challenges of talent acquisition and retention. As Alnıaç ıka et al. [137] posit, qualified employees are instrumental in adding value to their organizations, enhancing overall performance. Variations in production segment allocation can influence a firm’s attractiveness to potential employees, thereby affecting its competitive positioning in the talent market. The “Company Reputation” sub-criterion examines the broader implications of a firm’s operational boundaries on its public image. Activities such as offshoring, especially when outsourcing activities integral to a brand’s identity, can influence corporate reputation. Smith et al. [138] emphasize that a solid corporate reputation can bolster a manufacturing firm’s societal standing and its relationships within the business community. Given its potential as a competitive advantage, corporate reputation becomes a pivotal factor in decision-making [139]. To conclude our proposed sub-criteria, the “Ecological Impact” sub-criterion accentuates the environmental repercussions of outsourcing. In the age of globalization, extended supply chains can obscure environmental externalities, underscoring the need to assess the sustainability implications of such decisions, as highlighted by MoosaviRad et al. [140]. Moreover, the ecological consequences vary based on the production’s geographical location, given the diversity in regulatory requirements across countries, as noted by Medeiros et al. [70].

We considered three primary alternatives: in-house manufacturing, outsourcing, and the establishment of a joint venture. Each of these alternatives presents its own set of benefits, risks, and complexities, which are systematically analyzed and compared using the framework to determine the optimal approach. We included the joint venture alternative because joint ventures can offer a good combination of the benefits of full integration and external solutions [89,133,141].

3.2. Phase 1: selection of analysis object

The first phase of the framework involves the selection of objects for analysis. The goal of this phase is to determine which assemblies or components of a manufacturing company’s product will be the subject of analysis and how subordinate assemblies across the selected products will be consolidated into units of analysis. The choice of the overarching product must be made in advance and often requires aspects such as market research and forecasting that go beyond the manufacturing technology aspects covered in this work. A modified form of ABC analysis is used to select the most significant assemblies or components of a product in a time and cost-efficient manner. To account for potential synergies and economies of scale, and to avoid unnecessary multiple evaluations of similar assemblies or components, they are grouped into families when multiple products are the subject of the study.

ABC analysis is an inventory management technique rooted in the Pareto principle, suggesting that a small percentage of products often represent the majority of costs or efforts [142]. While other boundaries are possible [143], items are classified by costs using the boundaries suggested by Swamidass for the manufacturing context [144]: "A" items represent 20 % of total items but account for 80 % of costs. "B" items represent 30 % of total items and 15 % of costs. Meanwhile, "C" items make up the remaining 50 % of total items but contribute only 5 % of costs. The primary analytical focus is on "A" items, with subsequent attention given to "B" and "C" items based on available resources and their importance to the overall decision problem. For an assembly level analysis, the ABC analysis is performed on the assemblies of a previously defined product, and for a component level analysis, the ABC analysis is performed on the components of an assembly. Costs are considered here because the value of assemblies of components often reflects their technological complexity and therefore their importance to the value creation of manufacturing companies and their innovation potential. Depending on the product and the manufacturing strategy, other methods may also be suitable.

Analogous to the models of Venkatesan [28] and Probert [133], which form component families at the component level for evaluation, the decision to determine the production segment allocation on the assembly level should be summarized for similar assemblies, if possible. This can lead to a holistic, consistent decision and reduce the analysis effort. The specific reasons for clustering assemblies or components may vary from case to case but should be based largely on characteristics in the production system, such as the similarity of materials, required production equipment, and manufacturing processes to be performed.

The assembly or component preselection and the optional formation of families are the basis for the following steps. The subsequent phase involving the application of the AHP, and evaluation should be performed separately for each assembly or component family formed. We recommend performing the outlined procedure on an assembly level first. However, it is conceivable that the initial question concerns a manufacturing firm that operates as a supplier and whose products cannot be further broken down into assemblies, or that the analysis must be performed at a higher level of detail for other reasons. In such a case, the pre-selection can be done using the modified ABC analysis and the clustering can also be done at the sub-assembly and component level.

3.3. Phase 2: execution of analytical hierarchy process

The core of the framework is the Analytic Hierarchy Process (AHP), which is repeated for each previously formed assembly or component family. In the following the hierarchy with its associated criteria, sub-criteria, and alternatives shown in Fig. 4 is presented. Furthermore, the steps of the AHP are described, which include the prioritization of the criteria and sub-criteria, the fulfillment of the alternatives for the sub-criteria, the consistency check, and the formation of overall scores for the solution alternatives.

The top level of the AHP is the overall objective, which is to determine the optimal production segment allocation. “Cost”, “Innovation Capabilities”, and “Social Impact” are proposed as criteria for determining the optimal production segment allocation. A crucial part of the framework is to consider the impact of production segment allocation on the innovation capability. As discussed earlier, this aspect can be central to competitiveness, but is only marginally considered in existing models. In addition, the costs of each alternative are compared. Since outsourcing decisions, in particular, can have a strong impact on the social environment, e.g., on the workforce in the case of job cuts, the social impact of an alternative is also considered. Each criterion consists of five different sub-criteria described in the following paragraphs. The number of five sub-criteria was chosen to ensure a sufficient level of detail in the evaluation criteria and to keep the implementation effort at a moderate level. Regarding the implementation effort, it should be noted that in pairwise comparisons, each additional comparison factor must be compared with all existing comparison factors, which is why the additional effort for each additional comparison factor increases exponentially.

The first step of the actual AHP is to prioritize the three criteria of “Cost”, “Innovation Capabilities”, and “Social Impact” in a pairwise comparison based on their importance to the overall objective of determining the optimal production segment allocation. All steps of the AHP are specific to an assembly or component family, and it is important that the evaluations are carried out specifically for that family and not just at a higher corporate level. Accordingly, criteria and sub-criteria such as “Unit Cost” or “Design Capabilities” may have different priorities for different assemblies. The pairwise comparison is made using the comparison table by Saaty as shown in Table 3 [37]. All criteria are compared one after the other and the intensity of the importance is plotted in a collected matrix. This matrix is reciprocal so that the number of direct comparisons can be reduced. Thus, three individual comparisons are made for the criteria level. The criteria are then weighted using the eigenvalue method, see Saaty [35]. Next, a total of three runs of pairwise comparisons, one per criterion, are made for the criteria and their sub-criteria. Here, the priority of the five sub-criteria associated with the parent criterion is performed. For example, the sub-criteria of “Design Capabilities” and “Manufacturing Capabilities” are compared with respect to their priority for the criterion of “Innovation Capabilities”. The evaluations are also documented in a reciprocal matrix to subsequently determine the weighting of the sub-criteria within the criterion. At the sub-criterion level, 30 individual comparisons are made, 10 for each of the three criteria. Then, all three alternatives are compared with each other in terms of their fulfillment of the sub-criteria. While the scale allows for a consistent representation of the factors, in practice, it may be necessary to perform additional supporting analysis to better evaluate the criteria and sub-criteria. In our later application, we were able to refer back to past production segment allocation decisions so that participants had a good understanding of the estimation process and could easily apply the scale.

In principle, the pairwise comparisons are carried out as before and a weighting result is obtained, which corresponds more to a concrete evaluation. Based on three alternatives, which are compared three times in pairs for each of the 15 sub-criteria, 45 individual comparisons are made for the alternative level. For each alternative, the multiplication of the weight of the associated criterion, the weight of the sub-criterion, and the weight of the alternative for the sub-criterion is added across all sub-criteria, resulting in an overall score for each alternative. The

Table 3
The fundamental scale by Saaty [37].

Intensity on Scale	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Moderate importance	Experience and judgment favor one activity over another
5	Strong importance	Experience and judgment favor one activity over another
7	Very strong importance	Activity is favored and its dominance demonstrated in practice
9	Extreme importance	Evidence favoring one activity over another is of the highest order
2,4,6,8	Intermediate values	Compromise is needed between two adjacent judgments
Reciprocals	If activity i is compared to j, then j has the reciprocal with i	

resulting overall scores help us understand which sub-criteria have high relevance for a "Technology Multiplier". However, before calculating the total score for each alternative, it is useful to perform a consistency check using the consistency ratio. A consistency ratio of 0 indicates perfect consistency, while higher values indicate greater inconsistency. According to Saaty [37], a consistency ratio of 0.1 or less is considered acceptable. If the ratio exceeds this threshold, it is imperative to reevaluate the judgments. The calculation of the consistency ratio involves several steps. First, the priority vector is obtained from the pairwise comparison matrix. Next, the principal eigenvalue is derived from this vector, which leads to the calculation of the consistency index. Finally, the consistency ratio is obtained by dividing the consistency index by the random index, which is a predetermined value corresponding to the size of the matrix and can be found in Saaty [36]. By comparing the consistency index to that of a random matrix, it is possible to assess the degree of consistency in the decision process. The calculated consistency index helps to identify potential inconsistencies in their judgments and prompts necessary revisions to increase the reliability of the decision-making process. The entire process can be implemented using specialized AHP software.

3.4. Phase 3: evaluation of results

After conducting pairwise comparisons and calculating the overall results, we carefully analyze the priority weights obtained to determine the relative importance of the criteria and alternatives. These weights serve as a quantitative representation of the decision maker's preferences and are instrumental in determining the most favorable option among the alternatives. Compared to ad-hoc decision-making, AHP enhances the understanding of sub-criteria across different alternatives with quantified weighted scores for each sub-criterion and alternative.

To ensure the robustness and reliability of our findings, we also perform a sensitivity analysis on the AHP results. The sensitivity analysis involves varying the input data, such as the pairwise comparison matrices, within certain ranges to observe the effect on the final result. By performing this analysis, we can assess the stability of our conclusions and identify any potential inconsistencies or uncertainties in the decision process. Sensitivity analysis provides valuable insights into the robustness of the selected alternative and helps us understand the range of variations in criteria weights that could potentially change the final decision [145]. We then discuss and interpret the results of the sensitivity analysis, providing a comprehensive evaluation of the AHP results and strengthening the credibility of our conclusions. We recommend focusing the sensitivity analysis on the weighted scores of the sub-criteria for each alternative that have the most significant impact on the overall score of each alternative. Systematic pairwise comparisons can then be varied at all levels.

4. Case study results

In this section, we present the results of our comprehensive case studies, derived from a series of four interviews with different companies that frequently face make-or-buy decisions. For feasibility reasons, we have shortened the first framework phase of selecting the analysis object and focus on performing the AHP, sensitivity analysis and evaluation of results for only one assembly or component for each case. Case Study 1 examines the decision-making process of an automotive OEM regarding the production of batteries for battery electric vehicles, analyzed from the perspective of a production planner. Meanwhile, Case Study 2 examines another automotive OEM's decision related to seat production, based on an interview with a supply manager. Case Study 3 is conducted at the component level and was carried out with a manager in the application engineering department of an automotive supplier, focusing on the production of a subframe bearing. Case Study 4 was conducted with production managers of a household appliance manufacturer about the decision to produce baskets for dishwashers. The detailed results on sub-criteria level are included in Appendix 1–4.

4.1. Case study 1

For Case Study 1, an interview was conducted with a production planner from an automotive OEM company. The subject of analysis during the framework implementation was the battery of a battery electric vehicle (BEV). Within the company, both engineering and manufacturing are typically involved in make-or-buy decisions and are often directed by management. There is no standardized procedure for the initial evaluation in the decision-making process yet, but rather a semi-structured assessment of selected factors that is later supplemented by more detailed cost and feasibility studies. In addition to the typical alternatives of in-house or make-or-buy production, joint ventures are often discussed. These often offer the advantage of increased involvement and control at significantly reduced costs. Key decision factors usually include the development or retention of strategically important competencies, cost considerations, overall feasibility, and employee commitment.

Pairwise comparisons yielded criteria priorities of 0.444 for "Cost", 0.489 for "Innovation Capabilities", and 0.067 for "Social Impact". Among the most important sub-criteria, given their respective higher level criterion weightings, were "Differentiation/Customer Value Add" at 0.231, "Unit Cost" at 0.155, "Cash Flow Impact" at 0.121, and "Synergistic Integration Capabilities" at 0.097. These priorities were assigned due to the high strategic importance of the battery, especially for future market differentiation. At the same time, it is one of the most expensive components in a vehicle, making unit costs also relevant. The impact on cash flow is also a priority, as battery production is associated with high investments. The battery is considered the technological core of electric vehicles, with profound implications for the overall design and production of the vehicle, making a comprehensive understanding of its integration into the overall vehicle paramount. The evaluation of the alternatives favored the "In-House" solution with a priority of 0.363, while the "Joint Venture" option received 0.332 and the "Outsourcing" alternative 0.305 as shown in Fig. 5. The most important sub-criterion for an "In-House" decision is "Differentiation/Customer Value Add", as it is assumed that this approach can offer a technologically superior product that is different from other vehicles. Less important concerns are that the "In-House" solution has the highest "Transaction Costs" and provides greater "Job Security". In contrast, the "Joint Venture" and "Outsourcing" alternatives better performed for "Unit Costs". In particular, "Outsourcing" promises a better "Cash Flow Impact" and a better "Capital Expenditures". All matrices of pairwise comparisons have a consistency ratio below 0.1, indicating a sufficient consistency. However, when performing the sensitivity analysis, it becomes clear that certain variables of these comparisons are more sensitive than others. Specifically, there are 13 sensitive variables. The comparisons between the "In-House" and "Joint Venture" alternatives, as well as between the "Outsourcing" and "Joint Venture" alternatives, both under the "Differentiation/Customer Value Add" sub-criterion, have shown particular sensitivity. Another sensitive comparison is between the "Innovation Capabilities" and "Cost" criteria. For instance, as soon as the "Joint Venture" alternative is rated as equivalent to or better than the "In-House" alternative under the sub-criterion "Differentiation/Customer Value Add", the "Joint Venture" alternative emerges as the overall best-evaluated option. The sensitivity analysis in Fig. 6 shows the changes of the overall alternative scores when the comparative rating just between these two alternatives for this specific sub-criterion is varied. The sensitivity range of 1/9 to 9 is based on the fundamental scale in Table 3 and reflects the strongest preferences for one alternative over the other. A ranking from 1/9 to 1/2 represents a preferred compared ranking of the "Joint Venture" alternative, while 2 to 9 represents a preference of the "In-House" alternative and 1 represents an equal rating. The analysis indicates that "In-House" is no longer the overall preferred alternative

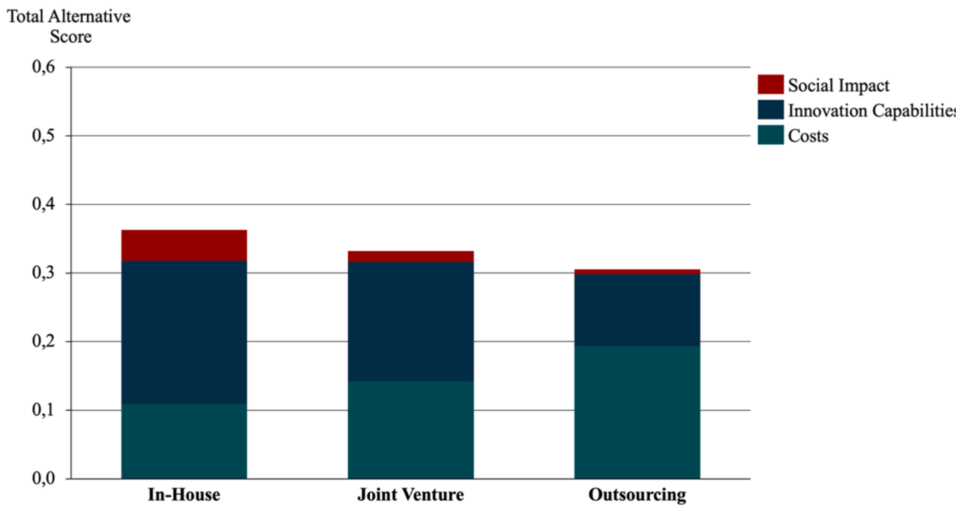

Fig. 5. Final weights Case Study 1.

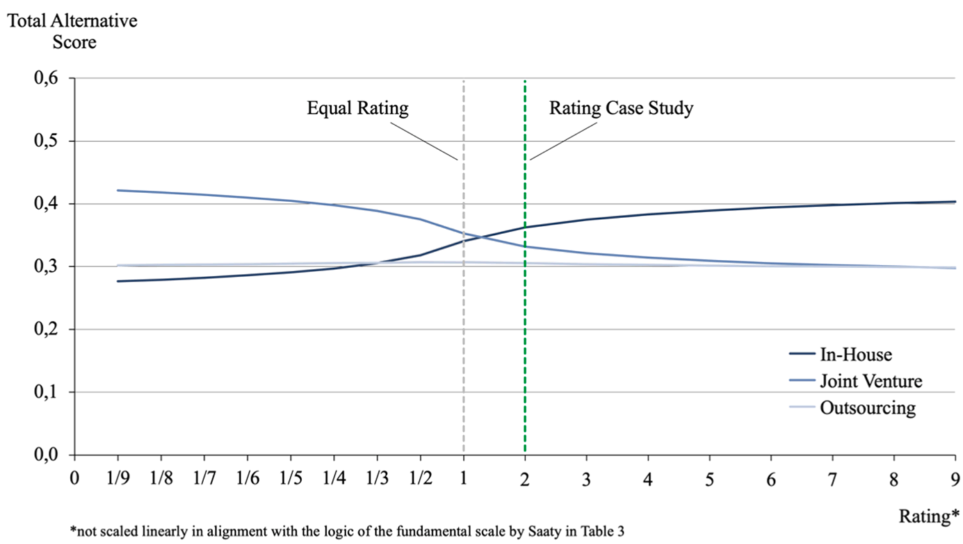

Fig. 6. One-way sensitivity analysis of the comparison between the "In-House" and "Joint Venture" alternatives for the sub-criterion "Differentiation/Customer Value Add".

when changing the ranking from a slight preference of 2 to an equal importance of 1 compared with the "Joint Venture" alternative for the "Differentiation/Customer Value Add" sub-criterion.

The results of the framework accurately reflect the actual past decision to manufacture the battery in-house. The calculated weighted scores, which form the overall evaluation of the alternatives, also validate the overall decision. Although the overall scores of the alternatives are relatively close to each other, this accurately reflects that the decision-making process in this case is not trivial. For previous products, an outsourcing strategy was used, while for the latest generation of products, the decision was made to choose an in-house solution for the first time due to strategic reasons. The most weighted sub-criteria actually played a crucial role in the real decision. The sensitivity analysis emphasizes caution given the large number of sensitive variables identified. It is advisable to create different scenarios to account for these sensitivities. In addition, efforts should be made to increase both the predictability and reliability of the pairwise comparisons, ultimately leading to more informed decisions. Overall, the pre-defined criteria and sub-criteria were found to be reasonable and largely comprehensive beyond this particular example. It was noted that the framework can be useful in practice, providing an initial solution that can be supplemented with more in-depth analysis. Especially in rapidly evolving markets, it's important to conduct ongoing assessments, as both supplier capabilities and internal factors can change. In addition, the interviewee stated, that in the automotive industry in particular, the transition to e-mobility and various crises have increased the importance of such issues. Considering the scores for the "Innovation Capability" sub-criteria of the "In-House" alternative, the results suggest that the sub-criteria "Differentiation/ Customer Value Add" with a score of 0.131 has the greatest impact on a "Technology Multiplier".

4.2. Case study 2

For Case Study 2, an interview was conducted with a supply manager of an automotive OEM company. The subject of analysis for the framework implementation was the assembly of vehicle front seats and rear seats. Typically, the company's direct purchasing, finance, production, engineering, and plant management departments are involved in make-or-buy decisions. Standardized procedures, such as performing return-on-investment calculations, are used to make decisions, although these tend to be cost-driven. Other factors, such as security of supply, are also considered, but in a less formal way. Typically, alternative actions are limited to full in-house production or full outsourcing. The decisions are predominantly cost-driven, with capital expenditure playing a significant role. Dependence on suppliers is also a key strategic factor.

Pairwise comparisons yielded a priority of 0.467 for “Cost” and “Innovation Capabilities” and 0.067 for “Social Impact”. Among the most important sub-criteria, when weighted by the overarching criteria, were “Speed/Flexibility” at 0.228, “Risk of Supply Outage” at 0.200, “Unit Cost” at 0.196, and “Manufacturing Capabilities” at 0.143. This score reflects the company’s overall goal of achieving flexible, high-quality production at efficient costs with a high degree of protection against supply disruptions. The evaluation of the alternative actions led to a preference for the “In-House” solution with a priority of 0.583. In contrast, the “Joint Venture” alternative received a score of 0.285 and the “Outsourcing” alternative only 0.131 as shown in Fig. 7. The dominance of the “In-House” alternative can be attributed to its highest scores in all of the high-priority sub-criteria mentioned above. This was based on the rationale that reducing the complexity of the supply chain would lead to fewer expected supply disruptions and increased flexibility. Economies of scale and the elimination of many production and logistics processes are expected to result in better unit costs. The increased incentive to continuously improve quality and costs implies the expectation of building better manufacturing capabilities. Although “Outsourcing” would have less impact on capital expenditures and cash flow, these factors were not highly valued in this case. The “Joint Venture” alternative ranks between the other two solutions on most sub-criteria. All matrices of pairwise comparisons have a consistency ratio below 0.1, indicating sufficient consistency. The sensitivity analysis has shown that there is no single sensitive variable within the pairwise comparisons that would change the result, given that the scores of the different alternatives diverge significantly.

The results of the framework are consistent with the company’s previous decision to produce seats and rear benches in-house. The calculated weighted scores, which form the overall assessment of the alternatives, provide a good rationale for this overall decision. In fact, the most important sub-criteria in the decision to manufacture the seats and rear benches in-house were covered by the framework. Beyond this case study, the interviewee expressed that the provided sub-criteria and criteria covered all relevant aspects to make a structured, informed make-or-buy decision in a reasonable time. It was noted that the scores of other alternatives lagged very significantly behind the in-house decision. This discrepancy is probably due to Saaty’s rating scale, as a rating of “slightly more important” in a pairwise comparison, for example, already leads to a weighting of approximately three times. Considering the scores for the "Innovation Capability" sub-criteria of the "In-House" alternative, the results suggest that the sub-criteria "Speed/Flexibility" with a score of 0.104 as well as the sub-criteria "Manufacturing Capabilities" with a score of 0.095 have the greatest impact on a "Technology Multiplier".

4.3. *Case study 3*

Case Study 3 was conducted with an application engineering manager at an automotive supplier. The subject of the analysis was a plastic component of a car subframe bearing. In contrast to the other case studies, which focused on the assembly level, this case study focuses on the component level. For this study, the decision was made at the component level rather than the assembly level. Typically, a make-or-buy decision involves various functions such as application engineering, development, production, controlling, and even the board of directors. There is no standardized process for such decisions. However, the stakeholders involved in the decision-making process are relatively experienced as such issues arise frequently. It was emphasized that there are indeed differences between new products and existing products with established production processes. Cost considerations are often the most important factor in decision-making.

Pairwise comparisons revealed criterion priorities of 0.529 for “Cost”, 0.412 for “Innovation Capabilities” and 0.059 for “Social Impact”. Among the most important sub-criteria, given their respective higher level criterion weightings, were “Unit Cost” at 0.232, “Synergistic Integration Capabilities” at 0.168, and “Cash Flow Impact” at 0.155. The financial aspects are particularly important in this example because the plastic components are relatively simple, so a favorable cost structure is key. In addition, when considering the remaining components of the product and mastering the plastic manufacturing processes, synergistic effects are evident. The evaluation of the alternatives favored the “In-House” solution with a priority of 0.516, while the “Joint Venture” option received 0.266 and the “Outsourcing” alternative 0.218 as shown in Fig. 8. The “In-House” solution is preferred because “Unit Cost” and “Synergistic Integration Capabilities” were rated highest for this solution. In addition, the evaluation of “Design Capabilities” also favors this alternative. On the other hand, the “Outsourcing” option offers a better “Cash Flow Impact” and more favorable “Capital Expenditures”. The “Joint Venture” alternative essentially falls between the ratings of the other two alternatives. All matrices of pairwise comparisons have a consistency ratio below 0.1, indicating adequate consistency. The sensitivity analysis of the evaluations shows that there are two sensitive variables. The comparison between “In-House” and “Joint Venture” under the sub-criterion “Unit Costs” has the highest sensitivity as shown

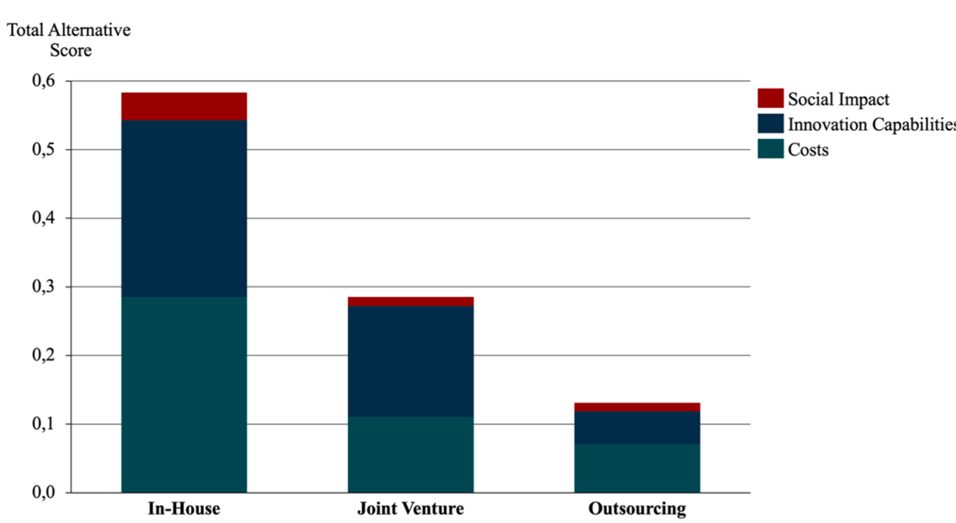

Fig. 7. Final weights Case Study 2.

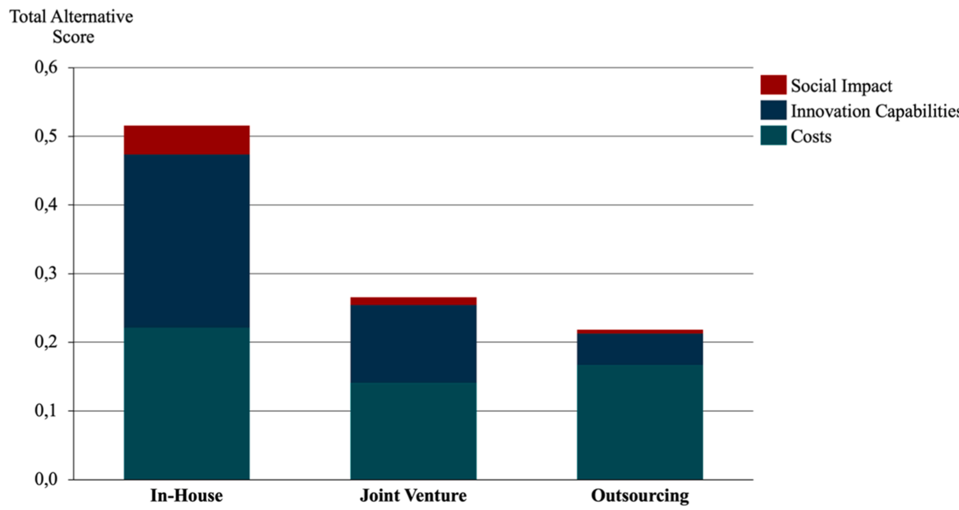

Fig. 8. Final weights Case Study 3.

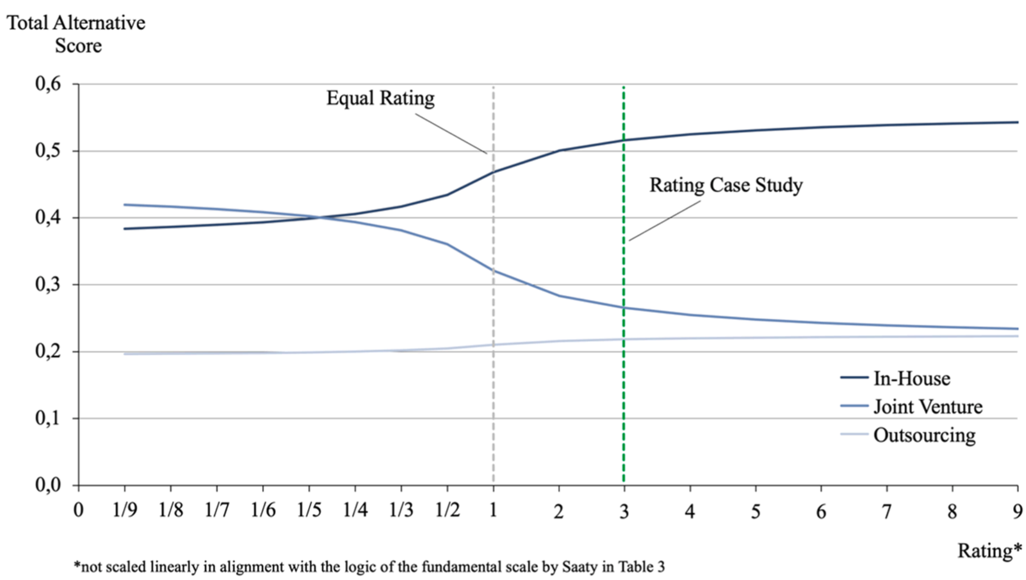

Fig. 9. One-way sensitivity analysis of the comparison between the “In-House” and “Joint Venture” alternatives for the sub-criterion “Unit Costs”.

in Fig. 9. The other comparison between “In-House” and “Outsourcing” under the “Unit Costs” sub-criterion has a lower sensitivity since the gap of the overall score to the “In-House” alternative is even higher.

The framework results accurately reflect the actual decision made for this case study. In particular, the chosen weightings and predefined factors allowed the cost motives to be well represented. It was also possible to consider that, in response to the increasing market demand for lightweight solutions, synergies for plastics production could be exploited. It was also mentioned that the implementation was understandable and that a practical application was conceivable. It was also noted that for such a framework, it is essential that the decision has a long-term strategic orientation. To achieve this, it was suggested to run the evaluation in several iterations for different time horizons. Considering the scores for the "Innovation Capability" sub-criteria of the "In-House" alternative, the results suggest that the sub-criteria "Synergistic Integration Capabilities" with a score of 0.128 has the greatest impact on a "Technology Multiplier".

4.4. Case study 4

For Case Study 4, we interviewed three production managers from an appliance manufacturer. The focus of this analysis was the dishwasher, specifically its basket on a component level. Within the company, the decision-making process typically involves the Production Management, R&D, Purchasing, Factory Manufacturing Engineering, Controlling, and the Executive Board. The primary drivers of the decision are usually the alignment with the technology roadmap, cost implications, quality standards, and service responsiveness, particularly in terms of time to market. While the company’s standard approach to make-or-buy decisions often leans toward basic cost calculations, no standardized holistic process for decision making exists.

Pairwise comparisons for the overarching criteria revealed a priority of 0.081 for “Social Impact”, 0.342 for “Innovation Capabilities”, and 0.577 for “Costs”. Going deeper into the sub-criteria, the most relevant ones, when contextualized by their overarching criteria, were “Manufacturing Capabilities” with 0.160, “Unit Costs” with 0.186, and “Cash Flow Impact” with 0.186. The assessment shows that cost considerations are clearly paramount. The evaluation of the alternatives revealed a nuanced picture. The “In-House” solution scored a priority of 0.250, with particular strengths in “Job Security” and “Design Capabilities”. The “Joint Venture” alternative scored 0.345, with its best performance in “Differentiation/Customer Value Add”. Meanwhile, the “Outsourcing” alternative scored the best priority of 0.405, excelling especially in terms of “Cash Flow Impact” and “Unit Costs”. All comparison matrices show sufficient consistency with a consistency ratio below 0.1. The sensitivity analysis of the evaluations indicates that there are eight sensitive variables. The most significant among them is the comparison between “Joint Venture” and “Outsourcing” under the sub-criterion “Cash Flow Impact” as shown in Fig. 11. Another crucial comparison is the weighting of the criteria “Innovation Capabilities” versus “Costs”. Additionally, the weighting of the criteria “Social Impact” in relation to “Costs” also exhibits notable sensitivity.

Reflecting on the results, the findings were realistic and aligned with the company’s past decisions. The usefulness of the framework was evident, and the pre-defined factors were confirmed as relevant to the decision-making process. It was expressed, that after using the first indicative results of the framework it is highly important to further quantify potential benefits of each alternative. However, a challenge that emerged was the forecasting aspect, which requires much information. The interviewees also highlighted that the involvement of experts from various functions is essential for a holistic and well-founded assessment. Considering the scores for the "Innovation Capability" sub-criteria of the "In-House" alternative, the results suggest that the sub-criteria "Manufacturing Capabilities" with a score of 0.052, as well as the sub-criteria " Design Capabilities" with a score of 0.045, have the greatest impact on a "Technology Multiplier".

5. Discussion

Our proposed framework was designed based on requirements derived from shortcomings of existing models in the literature. The flexibility inherent in the AHP framework promotes the framework’s “Adaptability of Factors” (3) and provides room for future refinement. The structure of the AHP allows the framework to address “Diverse Motivations” (4), providing users with the ability to evaluate the prioritization of criteria and sub-criteria on a case-by-case basis. The case studies have shown that there are different perceptions of the importance of individual criteria and sub-criteria among different firms. This phenomenon can often be explained by the fundamentally different value proposition that these firms have within their respective industry. For example, Case Study 1 involved a premium car manufacturer, and it highlighted the critical importance of differentiation, particularly in the high-performance metrics related to powertrain and battery in the luxury segment. Their strategic priorities aligned with a focus on enhancing the product’s ability to differentiate itself. By contrast, Case Study 2 pertained to a car manufacturer that aimed to reach a broader market. Their focus was on optimizing production processes for efficiency and cost reduction, making their technology accessible to a wider range of customers. Case Study 3 dealt with an automotive supplier producing plastic components for its end product that were essential to the functionality but may not have been directly linked to the perceived quality by the end consumer. As a result, the company’s focus was on cost-effectiveness. Similarly, Case Study 4, which focused on a home appliance manufacturer, revealed that although the product was essential, it was relatively straightforward. The basket was expected to meet basic criteria and be priced affordably, as it did not have a significant impact on the perceived quality of the overall product. In Case Study 1, there was a strong emphasis on innovation, with decisions being driven by a strong focus on developing new capabilities, particularly in-house. In contrast, Case Studies 2 and 3 balanced their approach between cost and innovation, also favoring in-house production. On the other hand, Case Study 4 prioritized cost over innovation, leading to a preference for outsourcing. The different emphasis on innovation may be explained by the technological intensity of the products in each case. For example, the high-tech nature of the products in Case Study 1 may require a greater focus on innovation, while the lower-tech products in other cases, such as Case Study 4, allow for a more cost-oriented strategy. We effectively addressed the “Qualitative and Quantitative Goals” (2), balancing elements such as innovation capabilities with tangible metrics like costs. The inclusion of the “Innovation Capabilities” criteria with its specific sub-criteria ensures comprehensive “Consideration of Innovation Capabilities” (7). The “Operationalizability of the Approach” (1) was notably demonstrated in our case studies, as all interviewees indicated its suitability for real-life make-or-buy decisions with reasonable effort. The framework’s ability to address requirements for the “Use at the Sub-Assembly Level” (5) is evident as we incorporated this in the definition of the sub-criteria and validated its application in Case Studies 1 and 2. Finally, through the conducted case studies, the framework’s “Applicability from a Production Perspective” (6) was substantiated, as corroborated by feedback from interviewees in the production domain. The general robustness of our proposed framework is underscored by the feedback from our case study participants. Not only did they acknowledge that the framework facilitates well-reasoned decisions for the case-specific examples, but they also confirmed that the criteria and sub-criteria we selected encompassed the key metrics essential to a make-or-buy decision. In order to include aspects of a production segment

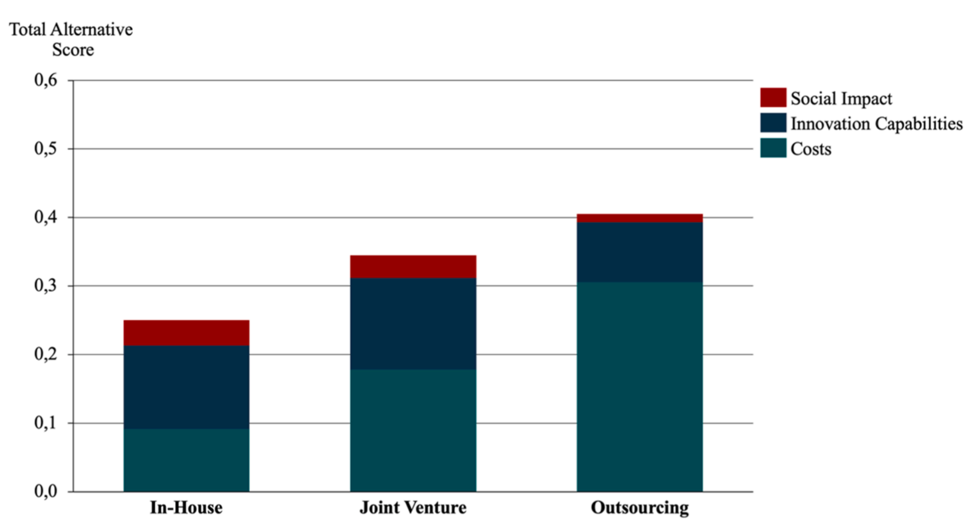

Fig. 10. Final weights Case Study 4.

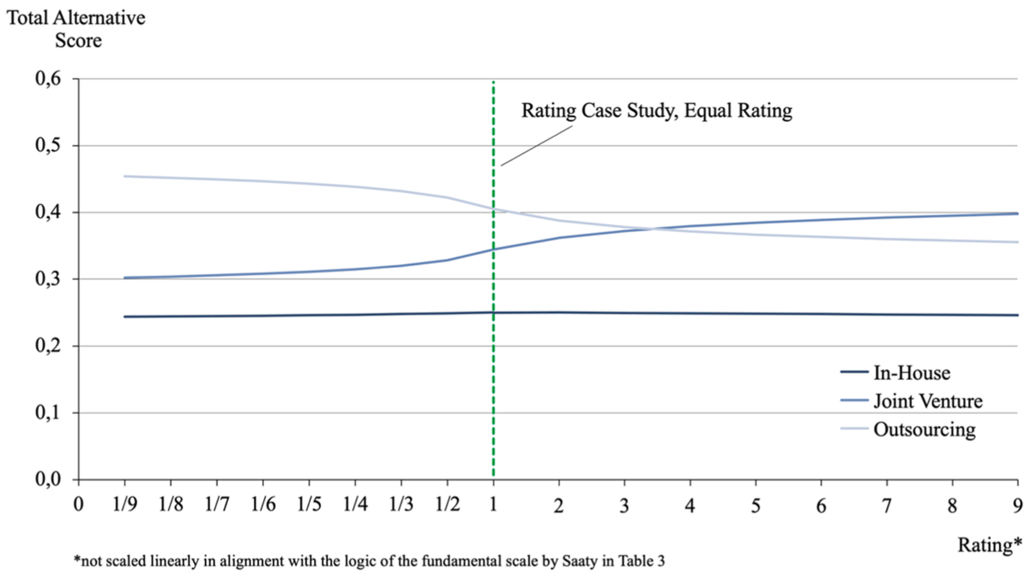

Fig. 11. One-way sensitivity analysis of the comparison between the “Joint Venture” and “Outsourcing” alternatives for the sub-criterion “Cash Flow Impact”.

allocation decision that go beyond a short-term cost-driven consideration in the sense of a "Technology Multiplier", the consideration of the sub-criteria could provide initial information. In particular, the sub-criteria of the "Innovation Capabilities" criterion for the "In-House" alternative are highly relevant here, as they cover aspects that are value-creating for manufacturing companies when integrating a production segment into their own production system. In all case studies, the set of sub-criteria derived from the literature was generally rated by the case study participants as complete and largely free of overlaps for the decision. Each of the sub-criteria of the "Innovation Capabilities" criterion was a driving factor for considering integration into the company’s own production system in at least one case study. The case studies are therefore an initial indication that the selected sub-criteria can significantly justify why the integration of a production segment into one’s own production system can be value-creating. Therefore, the concepts of the sub-criteria of "innovation capability" proposed in this paper should be considered in the further development of a "Technology Multiplier" concept. In order to facilitate the conversion of observed preferences into driving metrics for a "Technology Multiplier," it will be necessary to further refine them in accordance with the preliminary framework shown in Fig. 1.

While our framework provides advanced solutions for make-or-buy decisions, it has limitations. First and foremost is the challenge of subjectivity. Because it is based on human judgment, there is a potential for bias or differing interpretations. In particular, the AHP introduces issues of scale, as evaluators may weigh criteria differently, potentially yielding different results even with identical data. This variability can limit the reliability of the framework across users. As comprehensive as our framework is, it does not account for unpredictable variables, such as sudden market shifts or supply chain disruptions. The structure of AHP allows for a summation of the evaluation of individual factors. From an architectural perspective, not including “KO” criteria could overlook important non-negotiables for certain scenarios. In applying the AHP, it is essential to maintain linear independence among the selected criteria and sub-criteria. Efforts have been made to make these elements as distinct and non-redundant as possible. However, the inherent complexity of specific cases and the qualitative attributes of certain sub-criteria mean that the complete elimination of interdependencies may not always be achievable in real-world settings [41]. Finally, our conclusions are also based on the results of specific case studies. While these provide valuable feedback, they may not encompass all possible scenarios and industries, potentially affecting the generalizability of our findings. In order to account for the effects of subjectivity and the differences between different industries, it would be advisable to consider this in follow-up studies. According to the preliminary framework that has been proposed in Fig. 1, it would be highly beneficial for future studies to be conducted with a higher number of case studies in specific industries on a specific product.

Overall, based on the continuous alignment with the defined requirements in the framework design and the insightful feedback from our case studies, the framework appears to adeptly address the defined criteria. However, while it presents itself as a promising tool in the make-or-buy decision landscape, the acknowledged limitations underscore areas for potential refinement and emphasize the importance of contextual application.

6. Conclusion

The make-or-buy decision has long been a pivotal point for manufacturing firms to decide whether to produce components in-house or to purchase them from external suppliers. In response to the limitations observed in traditional decision frameworks, our research aimed to establish a more comprehensive and adaptable framework based on the AHP with a strong focus on innovation capabilities to ensure the long-term competitiveness of production systems. We deepen the understanding of the "Technology Multiplier" by applying the AHP specifically to segment allocation within the manufacturing sector. Our methodology goes beyond the conventional use of AHP by incorporating a sensitivity analysis component that allows for the consideration of potential uncertainties and by using the AHP as a proxy for relevant innovation metrics. Rather than simply identifying a superior option, our use of AHP has facilitated the discovery of key metrics associated with the "Technology Multiplier".

We conducted several case studies within manufacturing industries. These industries are undergoing significant changes and developments. The subjects ranged from battery production, seat production, and subframe bearing production to the production of baskets for dishwashers, each offering unique insights and specific concerns to the decision process. Our framework was not only able to reflect the real decisions made by the companies in our studies, but also provided valuable insights into the underlying criteria driving those decisions. In addition, the feedback from respondents was largely positive, underscoring the framework’s real-world applicability and effectiveness. By systematically evaluating both qualitative and quantitative objectives, our framework promises a holistic assessment of various make-or-buy scenarios. However, like all frameworks, it has its limitations. The inherent subjectivity of AHP provides flexibility but also introduces variability. Our study identified potential biases, scaling challenges, and unexpected market variables as major concerns.

In conclusion, our proposed framework represents a leap forward in refining the make-or-buy decision process, particularly in industries where innovation considerations are paramount. While it lays the groundwork for a more nuanced, adaptable, and comprehensive decision framework, it also paves the way for further research to refine its methodology and expand its applicability. Future efforts in this area must seek to address the limitations of the framework and ensure that manufacturing firms can rely on it as a valuable tool for navigating the complexities of segment allocation when designing their production systems. From the results of our study, we have identified factors that are likely to be of significant importance in relation to the "Technology Multiplier" concept. Integrating our decision framework as an indication, combined with the "Technology Multiplier" concept for a more robust quantification, seems to be a promising approach for future research. In line with our preliminary framework, future research should focus specifically on understanding the various metrics by different industry and product in order to then quantify the "Technology Multiplier" in more detail.

CRediT authorship contribution statement

Florian Stamer: Writing – review & editing, Writing – original draft, Project administration, Methodology, Conceptualization. **Roman Girke:** Writing – review & editing, Writing – original draft, Methodology. **Gisela Lanza:** Supervision, Conceptualization. **Shun Yang:** Supervision, Methodology, Conceptualization. **Jung-Hoon Chun:** Supervision, 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.

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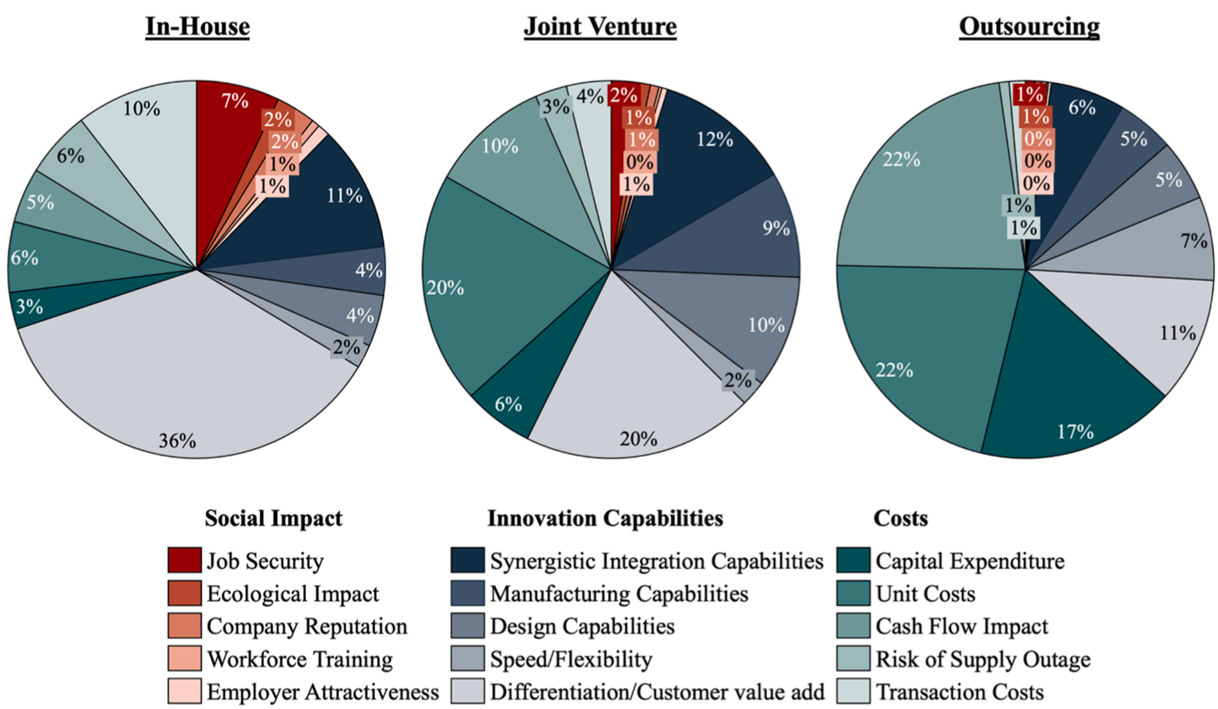
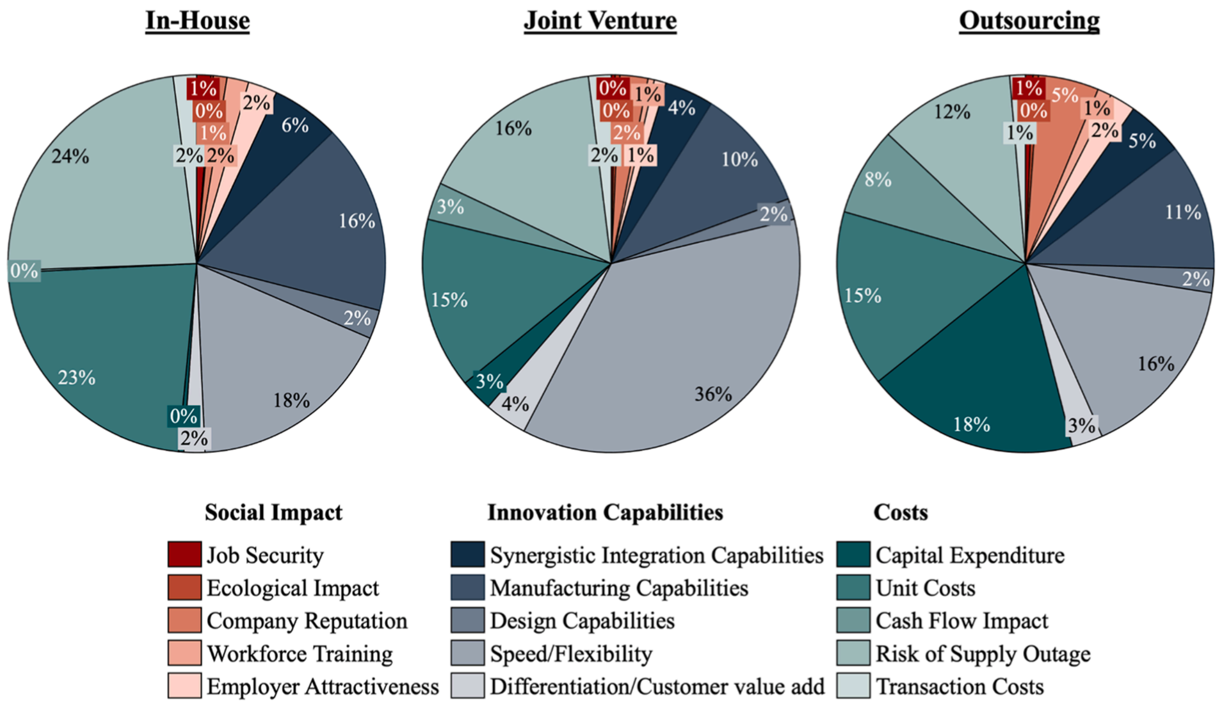
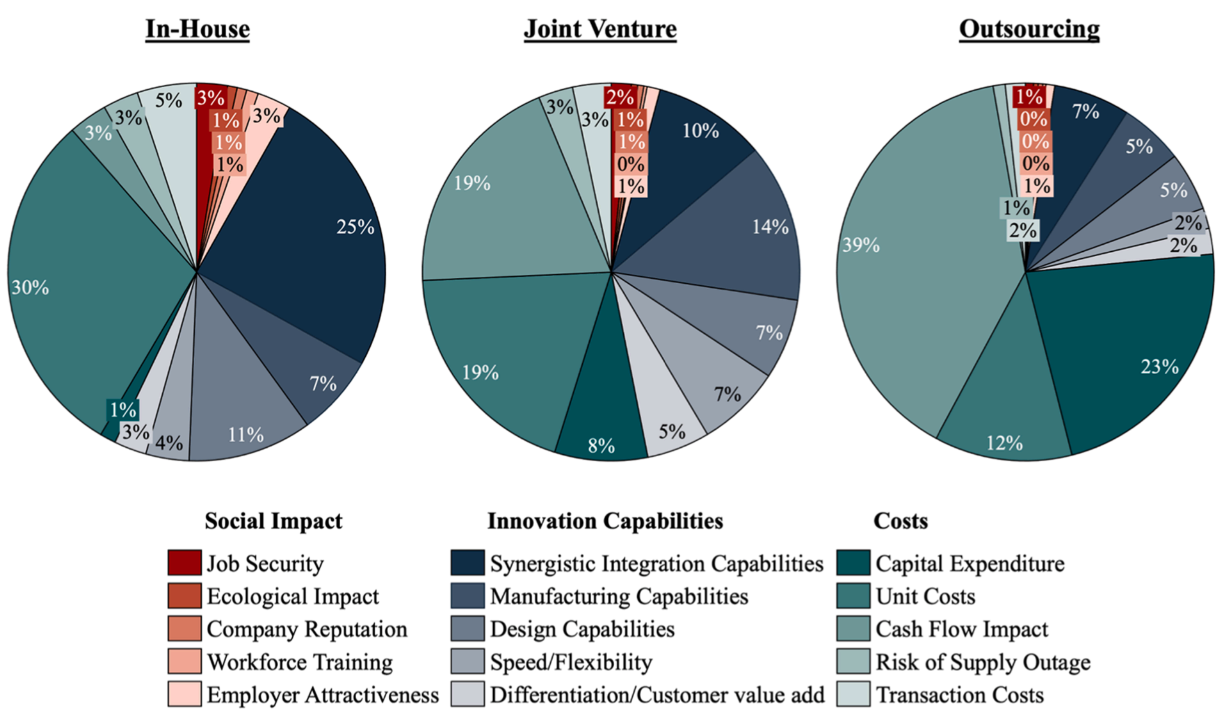
Appendix A. Final weights Case Study 1 by sub-criteria



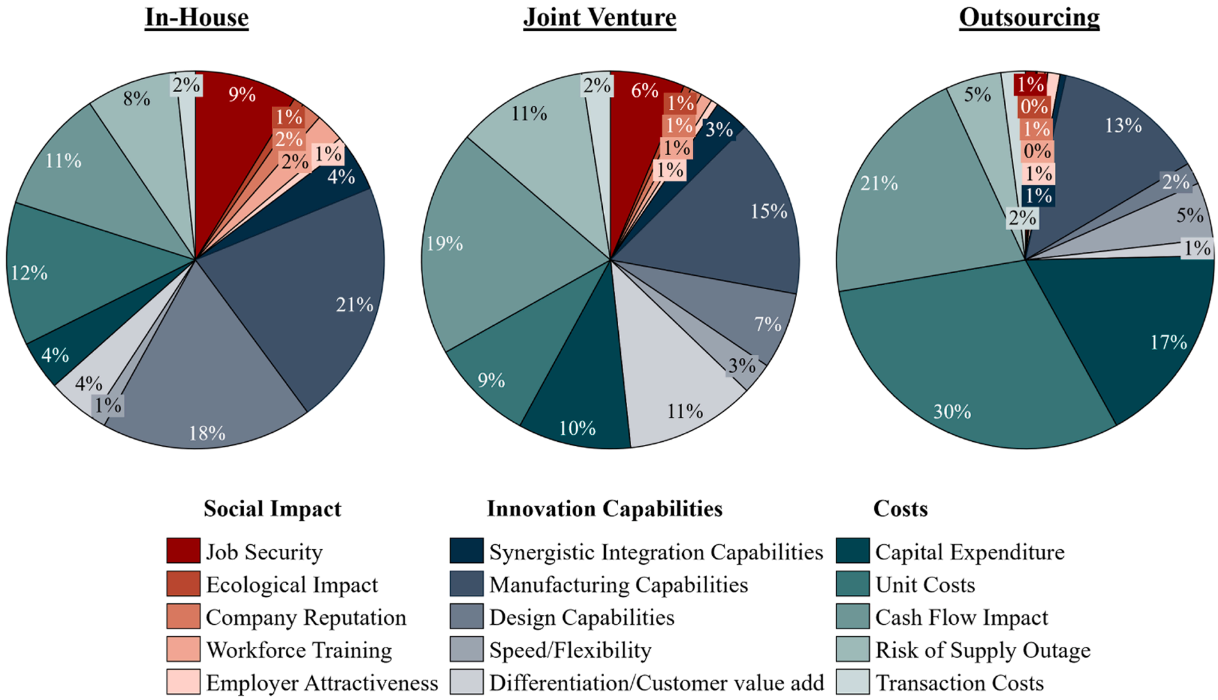
Appendix B. Final weights Case Study 2 by sub-criteria



Appendix C. Final weights Case Study 3 by sub-criteria



Appendix D. Final weights Case Study 4 by sub-criteria



References

[1] Medina-Serrano R, González-Ramírez R, Gasco-Gasco J, Llopis-Taverner J. Strategic sourcing: developing a progressive framework for make-or-buy decisions. J Ind Eng Manag 2020;vol. 13(1):133. https://doi.org/10.3926/jiem.2858.

[2] Probert DR, Jones SW, Gregory MJ. The make or buy decision in the context of manufacturing strategy development. Proc Inst Mech Eng, Part B: J Eng Manuf 1993;vol. 207(4):241–50. https://doi.org/10.1243/PIME_PROC_1993_207_086_02.

[3] Grossman GM, Helpman E. Integration versus outsourcing in industry equilibrium. Q J Econ 2002;vol. 117(1):85–120. https://doi.org/10.1162/003355302753399454.

[4] Porter ME. How competitive forces shape strategy. In: Asch D, Bowman C, editors. Readings in Strategic Management. London: Macmillan Education UK; 1989. p. 133–43.

[5] Brem A, Elsner R. Make-or-buy decisions on technology-intensive products: insights from the consumer goods industry. Int J Innov Manag 2018;vol. 22(06):1850046. https://doi.org/10.1142/S1363919618500469.

[6] Benama Y, Alix T, Perry N. Supporting Make or Buy Decision for Reconfigurable Manufacturing System, in Multi-site Context (Berlin Heidelberg). In: Grabot B, Vallespir B, Gomes S, Bouras A, Kiritsis D, editors. Advances in Production Management Systems. Innovative and Knowledge-Based Production Management in a Global-Local World, vol. 438. Berlin, Heidelberg: Springer; 2014. p. 150–8 (Berlin Heidelberg).

[7] 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; vol. 13(3):1143. https://doi.org/10.3390/su13031143.

[8] S. Kinkel, B. Rieder, D. Horvat, and A. Jäger, The effects of in-house manufacturing and outsourcing on companies' profits and productivity, *23rd International Annual EurOMA Conference*, 2016.

[9] Ikumapayi OM, Oyinbo ST, Akinlabi ET, Madushele N. Overview of recent advancement in globalization and outsourcing initiatives in manufacturing systems. Mater Today: Proc 2020;vol. 26:1532–9. https://doi.org/10.1016/j.matpr.2020.02.315.

[10] McIvor R. A practical framework for understanding the outsourcing process. Supply Chain Manag: Int J 2000;vol. 5(1):22–36. https://doi.org/10.1108/13598540010312945.

[11] McIvor R, Bals L. A multi-theory framework for understanding the reshoring decision. Int Bus Rev 2021;vol. 30(6):101827. https://doi.org/10.1016/j.ibusrev.2021.101827.

[12] Hofmann E. Linking corporate strategy and supply chain management. Int J Phys Distrib Logist Manag 2010;vol. 40(4):256–76. https://doi.org/10.1108/09600031011045299.

[13] Casson M. The theory of vertical integration: a survey and synthesis. J Econ Stud 1984;vol. 11(2):3–43. https://doi.org/10.1108/eb002575.

[14] Armour HO, Teece DJ. Vertical integration and technological innovation. Rev Econ Stat 1980;vol. 62(3):470. https://doi.org/10.2307/1927118.

[15] Huth C. Strategische Planung der Fertigungstiefe bei Unsicherheit und Dynamik. Wiesbaden: Springer Fachmedien Wiesbaden,; 2014.

[16] Williamson OE. The economics of organization: the transaction cost approach. Am J Sociol 1981;vol. 87(3):548–77. https://doi.org/10.1086/227496.

[17] Barney J. Firm resources and sustained competitive advantage. J Manag 1991; vol. 17(1):99–120. https://doi.org/10.1177/014920639101700108.

[18] Schroeder RG, Bates KA, Junttila MA. A resource-based view of manufacturing strategy and the relationship to manufacturing performance. Strateg Manag J 2002;vol. 23(2):105–17. https://doi.org/10.1002/smj.213.

[19] 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;vol. 12(04):655–76. https://doi.org/10.1142/S1363919608002138.

[20] Francis Deinmodei W. Poazi, Jasmine O. Tamunosiki-Amadi, and Maurice Fems, The Resource-Base View Of Organization And Innovation: Recognition Of Significant Relationship In An Organization, 2017, doi: 10.5281/zenodo.1129862.

[21] OECD. Statistical Office of the European Communities. Oslo Manual. OECD,; 2005.

[22] Lawson B, Samson D. Developing innovation capability in organisations: a dynamic capabilities approach. Int J Innov Manag 2001;vol. 05(03):377–400. https://doi.org/10.1142/S1363919601000427.

[23] Cánez LE, Platts KW, Probert DR. Developing a framework for make-or-buy decisions. Int J Oper Prod Manag 2000;vol. 20(11):1313–30. https://doi.org/10.1108/01443570010348271.

[24] Vining A, Globerman S. A conceptual framework for understanding the outsourcing decision. Eur Manag J 1999;vol. 17(6):645–54. https://doi.org/10.1016/S0263-2373(99)00055-9.

[25] Fill C, Visser E. The outsourcing dilemma: a composite approach to the make or buy decision. Manag Decis 2000;vol. 38(1):43–50. https://doi.org/10.1108/EUM0000000005315.

[26] Walker G. Strategic sourcing, vertical integration, and transaction costs. Interfaces 1988;vol. 18(3):62–73. https://doi.org/10.1287/inte.18.3.62.

[27] Prahalad CK, Hamel G. The Core Competence of the Corporation (Berlin Heidelberg). In: Hahn D, Taylor B, editors. Strategische Unternehmungsplanung — Strategische Unternehmungsführung: Stand und Entwicklungstendenzen. Berlin, Heidelberg: Springer; 2006. p. 275–92 (Berlin Heidelberg).

[28] Venkatesan R. Strategic sourcing: to make or not to make. Harv Bus Rev 1992;vol. 70(6).
[29] McIvor R. How the transaction cost and resource-based theories of the firm inform outsourcing evaluation. J Oper Manag 2009;vol. 27(1):45–63. https://doi.org/10.1016/j.jom.2008.03.004.
[30] Probert DR. The practical development of a make or buy strategy: the issue of process positioning. Integr Manuf Syst 1996;vol. 7(2):44–51. https://doi.org/10.1108/09576069610111891.
[31] Baines T, Kay G, Adesola S, Higson M. Strategic positioning: an integrated decision process for manufacturers. Int J Oper Prod Manag 2005;vol. 25(2):180–201. https://doi.org/10.1108/01443570510577029.
[32] Udo GG. Using analytic hierarchy process to analyze the information technology outsourcing decision. Ind Manag Data Syst 2000;vol. 100(9):421–9. https://doi.org/10.1108/02635570010358348.
[33] Yang C, Huang J-B. A decision model for is outsourcing. Int J Inf Manag 2000;vol. 20(3):225–39. https://doi.org/10.1016/S0268-4012(00)00007-4.
[34] Bozorg-Haddad O, Loáiciga H, Zolghadr-Asli B. A handbook on multi-attribute decision-making methods. Wiley,; 2021.
[35] Saaty TL. A scaling method for priorities in hierarchical structures., J Math Psychol 1977;vol. 15(3):234–81. https://doi.org/10.1016/0022-2496(77)90033-5.
[36] Saaty RW. The analytic hierarchy process—what it is and how it is used. Math Model 1987;vol. 9(3-5):161–76. https://doi.org/10.1016/0270-0255(87)90473-8.
[37] Saaty TL. How to make a decision: the analytic hierarchy process. Eur J Oper Res 1990;vol. 48(1):9–26. https://doi.org/10.1016/0377-2217(90)90057-I.
[38] 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;vol. 55 (22):6653–75. https://doi.org/10.1080/00207543.2017.1334976.
[39] Khan AU, Ali Y. Analytical Hierarchy Process (AHP) and analytic network process methods and their applications: a twenty-year review from 2000-2019. IJAHP 2020;vol. 12(3). https://doi.org/10.13033/ijahp.v12i3.822.
[40] Ishizaka A, Labib A. Analytic hierarchy process and expert choice: benefits and limitations. OR Insight 2009;vol. 22(4):201–20. https://doi.org/10.1057/ori.2009.10.
[41] Huang J-J, Chen C-Y. Using markov random field and analytic hierarchy process to account for interdependent criteria. Algorithms 2023;vol. 17(1):1. https://doi.org/10.3390/a17010001.
[42] Johansson R. On case study methodology. Open House Int 2007;vol. 32(3):48–54. https://doi.org/10.1108/OHI-03-2007-B0006.
[43] Nahm AY, Vonderembse MA, Koufteros XA. The impact of organizational structure on time-based manufacturing and plant performance. J Oper Manag 2003;vol. 21(3):281–306. https://doi.org/10.1016/S0272-6963(02)00107-9.
[44] Suwannaporn P, Speece MW. Assessing new product development success factors in the Thai food industry. Br Food J 2010;vol. 112(4):364–86. https://doi.org/10.1108/00070701011034394.
[45] van der Panne G, van Beers C, Kleinknecht A. Success and failure of innovation: a literature review. Int J Innov Manag 2003;vol. 07(03):309–38. https://doi.org/10.1142/S1363919603000830.
[46] Dziallas M, Blind K. Innovation indicators throughout the innovation process: an extensive literature analysis. Technovation 2019;80-81:3–29. https://doi.org/10.1016/j.technovation.2018.05.005.
[47] Roebuck C. Constructive feedback: key to higher performance and commitment. Long Range Plan 1996;vol. 29(3):328–36. https://doi.org/10.1016/0024-6301(96)00028-3.
[48] Abrunhosa A, Moura E Sá P. Are TQM principles supporting innovation in the Portuguese footwear industry? Technovation 2008;vol. 28(4):208–21. https://doi.org/10.1016/j.technovation.2007.08.001.
[49] Friedli T. Technologiemanagement. Berlin/Heidelberg: Springer-Verlag,; 2006.
[50] Damanpour F. Organizational Innovation: a meta-analysis of effects of determinants and moderators. Acad Manag J 1991;vol. 34(3):555–90. https://doi.org/10.2307/256406.
[51] Crossan MM, Apaydin M. A multi-dimensional framework of organizational innovation: a systematic review of the literature. J Manag Stud 2010;vol. 47(6):1154–91. https://doi.org/10.1111/j.1467-6486.2009.00880.x.
[52] Vega-Jurado J, Gutierrez-Gracia A, Fernandez-de-Lucio I. Does external knowledge sourcing matter for innovation? Evidence from the Spanish manufacturing industry. Ind Corp Change 2009;vol. 18(4):637–70. https://doi.org/10.1093/icc/dtp023.
[53] Soosay CA, Hyland PW, Ferrer M. Supply chain collaboration: capabilities for continuous innovation. Supply Chain Manag: Int J 2008;vol. 13(2):160–9. https://doi.org/10.1108/13598540810860994.
[54] Iddris F. Innovation capability: a systematic review and research agenda. Interdiscip J Inf, Knowl, Manag 2016;vol. 11:235–60. https://doi.org/10.28945/3571.
[55] Buzzell Robert D. Is vertical integration profitable? Harv Bus Rev 1983 ([Online]. Available:), ⟨https://hbr.org/1983/01/is-vertical-integration-profitable⟩.
[56] Gold AH, Malhotra A, Segars AH. Knowledge management: an organizational capabilities perspective. J Manag Inf Syst 2001;vol. 18(1):185–214. https://doi.org/10.1080/07421222.2001.11045669.
[57] Salavou H, Baltas G, Lioukas S. Organisational innovation in SMEs. Eur J Mark 2004;vol. 38(9/10):1091–112. https://doi.org/10.1108/03090560410548889.
[58] Kato M, Okamuro H, Honjo Y. Does Founders' Human Capital Matter for Innovation? Evidence from Japanese Start-ups. J Small Bus Manag 2015;vol. 53 (1):114–28. https://doi.org/10.1111/jsbm.12094.
[59] Kamasak R. Creation of firm performance through resource orchestration: the case of ÜLKER. Compét Rev 2015;vol. 25(2):179–204. https://doi.org/10.1108/CR-02-2014-0005.
[60] Caloghirou Y, Kastelli I, Tsakanikas A. Internal capabilities and external knowledge sources: complements or substitutes for innovative performance? Technovation 2004;vol. 24(1):29–39. https://doi.org/10.1016/S0166-4972(02)00051-2.
[61] Sawang S, Unsworth K. A model of organizational innovation implementation effectiveness in small to medium firms. SSRN Electron J 2011. https://doi.org/10.2139/ssrn.2168595.
[62] Martensen A, Dahlgaard JJ, Mi Park-Dahlgaard S, Grønholdt L. Measuring and diagnosing innovation excellence – simple contra advanced approaches: a Danish study. Meas Bus Excell 2007;vol. 11(4):51–65. https://doi.org/10.1108/13683040710837928.
[63] Romijn H, Albaladejo M. Determinants of innovation capability in small electronics and software firms in southeast England. Res Policy 2002;vol. 31(7):1053–67. https://doi.org/10.1016/S0048-7333(01)00176-7.
[64] Hittmar S, Varmus M, Lendel V. Proposal of evaluation system for successful application of innovation strategy through a set of indicators. Procedia Econ Financ 2015;vol. 26:17–22. https://doi.org/10.1016/S2212-5671(15)00796-0.
[65] Kerssens-van Drongelen IC, Cooke A. Design principles for the development of measurement systems for research and development processes. RD Manag 1997; vol. 27(4):345–57. https://doi.org/10.1111/1467-9310.00070.
[66] March JG. Exploration and exploitation in organizational learning. Organ Sci 1991;vol. 2(1):71–87. https://doi.org/10.1287/orsc.2.1.71.
[67] Aggeri F, Elmquist M, Pohl H. Managing learning in the automotive industry – the innovation race for electric vehicles. Int J Automot Technol Manag 2009;vol. 9 (2):123. https://doi.org/10.1504/IJATM.2009.026394.
[68] Haghseta F, Choucri N. Organizational Innovation (Netherlands). In: Kauffman JM, et al., editors. Mapping Sustainability, vol. 11. Dordrecht: Springer; 2007. p. 85–99 (Netherlands).
[69] Neely A, Filippini R, Forza C, Vinelli A, Hii J. A framework for analysing business performance, firm innovation and related contextual factors: perceptions of managers and policy makers in two European regions. Integr Manuf Syst 2001; vol. 12(2):114–24. https://doi.org/10.1108/09576060110384307.
[70] de Medeiros JF, Ribeiro JLD, Cortimiglia MN. Success factors for environmentally sustainable product innovation: a systematic literature review. J Clean Prod 2014;vol. 65:76–86. https://doi.org/10.1016/j.jclepro.2013.08.035.
[71] Astebro T, Michela JL. Predictors of the Survival of Innovations*. J Prod Innov Manag 2005;vol. 22(4):322–35. https://doi.org/10.1111/j.0737-6782.2005.00129.x.
[72] Kallio A, Kujansivu P, Parjanen S. Locating the weak points of innovation capability before launching a development project. Interdiscip J Inf, Knowl, Manag 2012;vol. 7:21–38. https://doi.org/10.28945/1563.
[73] Tang HK. An integrative model of innovation in organizations. Technovation 1998;vol. 18(5):297–309. https://doi.org/10.1016/S0166-4972(98)00009-1.
[74] Tang H. An inventory of organizational innovativeness. Technovation 1998;vol. 19(1):41–51. https://doi.org/10.1016/S0166-4972(98)00077-7.
[75] Saunila M. Performance measurement approach for innovation capability in SMEs. Int J Product Perform Manag 2016;vol. 65(2):162–76. https://doi.org/10.1108/IJPPM-08-2014-0123.
[76] Coombs JE, Bierly PE. Measuring technological capability and performance. RD Manag 2006;vol. 36(4):421–38. https://doi.org/10.1111/j.1467-9310.2006.00444.x.
[77] Perunović Z, Mefford R, Christoffersen M, McIvor R, Falls D. An analysis of vendor innovation capability in the contract electronics manufacturing industry. Prod Plan Control 2016;vol. 27(10):797–809. https://doi.org/10.1080/09537287.2016.1139210.
[78] Mostafa M. Factors affecting organisational creativity and innovativeness in Egyptian business organisations: an empirical investigation. J Manag Dev 2005; vol. 24(1):7–33. https://doi.org/10.1108/02621710510572326.
[79] Bharadwaj S. Making innovation happen in organizations: individual creativity mechanisms, organizational creativity mechanisms or both? J Prod Innov Manag 2000;vol. 17(6):424–34. https://doi.org/10.1016/S0737-6782(00)00057-6.
[80] Ahmed PK. Culture and climate for innovation. Eur J Innov Manag 1998;vol. 1(1):30–43. https://doi.org/10.1108/14601069810199131.
[81] Martínez-Román JA, Gamero J, Tamayo JA. Analysis of innovation in SMEs using an innovative capability-based non-linear model: a study in the province of Seville (Spain). Technovation 2011;vol. 31(9):459–75. https://doi.org/10.1016/j.technovation.2011.05.005.
[82] Wan D, Ong CH, Lee F. Determinants of firm innovation in Singapore. Technovation 2005;vol. 25(3):261–8. https://doi.org/10.1016/S0166-4972(03)00096-8.
[83] Nohria N, Gulati R. Is slack good or bad for innovation? Acad Manag J 1996;vol. 39(5):1245–64. https://doi.org/10.2307/256998.
[84] Subramanian A, Nilakanta S. Organizational innovativeness: exploring the relationship between organizational determinants of innovation, types of innovations, and measures of organizational performance. Omega 1996;vol. 24 (6):631–47. https://doi.org/10.1016/S0305-0483(96)00031-X.
[85] Laforet S. A framework of organisational innovation and outcomes in SMEs. Int J Entrep Behav Res 2011;vol. 17(4):380–408. https://doi.org/10.1108/13552551111139638.
[86] A. Panagopoulos, Closed Vs Open Innovation, in pp. 1–4.
[87] Teece DJ. Profiting from technological innovation: Implications for integration, collaboration, licensing and public policy. Res Policy 1986;vol. 15(6):285–305. https://doi.org/10.1016/0048-7333(86)90027-2.

[88] Madsen SR, Miller D, John CR. Readiness for organizational change: do organizational commitment and social relationships in the workplace make a difference? Hum Resour Dev Q 2005;vol. 16(2):213–34. https://doi.org/10.1002/hrdq.1134.
[89] Rudie Harrigan K. A framework for looking at vertical integration. J Bus Strategy 1983;vol. 3(3):30–7. https://doi.org/10.1108/eb038975.
[90] Cassiman B, Veugelers R. In search of complementarity in innovation strategy: internal R&D and external knowledge acquisition. Manag Sci 2006;vol. 52(1): 68–82. https://doi.org/10.1287/mnsc.1050.0470.
[91] Lenfle S. Exploration and project management. Int J Proj Manag 2008;vol. 26(5): 469–78. https://doi.org/10.1016/j.ijproman.2008.05.017.
[92] Naranjo-Valencia JC, Jiménez-Jiménez D, Sanz-Valle R. Studying the links between organizational culture, innovation, and performance in Spanish companies. Rev Latinoam De Psicol 2016;vol. 48(1):30–41. https://doi.org/10.1016/j.rlp.2015.09.009.
[93] Slater SF, Mohr JJ, Sengupta S. Radical product innovation capability: literature review, synthesis, and illustrative research propositions. J Prod Innov Manag 2014;vol. 31(3):552–66. https://doi.org/10.1111/jpim.12113.
[94] Martins EC, Terblanche F. Building organisational culture that stimulates creativity and innovation. Eur J Innov Manag 2003;vol. 6(1):64–74. https://doi.org/10.1108/14601060310456337.
[95] González-Benito Ó, Muñoz-Gallego PA, García-Zamora E. Entrepreneurship and market orientation as determinants of innovation: the role of business size. Int J Innov Manag 2015;vol. 19(04):1550035. https://doi.org/10.1142/S1363919615500358.
[96] Dewangan V, Godse M. Towards a holistic enterprise innovation performance measurement system. Technovation 2014;vol. 34(9):536–45. https://doi.org/10.1016/j.technovation.2014.04.002.
[97] Boeddrich H-J. Ideas in the workplace: a new approach towards organizing the fuzzy front end of the innovation process. Creat Innov Manag 2004;vol. 13(4): 274–85. https://doi.org/10.1111/j.0963-1690.2004.00316.x.
[98] Brem A, Voigt KI. Innovation management in emerging technology ventures – the concept of an integrated idea management. Int J Technol, Policy Manag 2007;vol. 7(3):304. https://doi.org/10.1504/IJTPM.2007.015113.
[99] Merx-Chermin M, Nijhof WJ. Factors influencing knowledge creation and innovation in an organisation. J Eur Ind Train 2005;vol. 29(2):135–47. https://doi.org/10.1108/03090590510585091.
[100] Bessant J, Lamming R, Noke H, Phillips W. Managing innovation beyond the steady state. Technovation 2005;vol. 25(12):1366–76. https://doi.org/10.1016/j.technovation.2005.04.007.
[101] Knight RM. Corporate innovation and entrepreneurship: a canadian study. J Prod Innov Manag 1987;vol. 4(4):284–97. https://doi.org/10.1111/1540-5885.440284.
[102] Damanpour F, Evan WM. Organizational innovation and performance: the problem of "organizational lag". Adm Sci Q 1984;vol. 29(3):392. https://doi.org/10.2307/2393031.
[103] Huang X, Soutar GN, Brown A. Measuring new product success: an empirical investigation of Australian SMEs. Ind Mark Manag 2004;vol. 33(2):117–23. https://doi.org/10.1016/S0019-8501(03)00034-8.
[104] Griffin A. An interim report on measuring product development success and failure. J Prod Innov Manag 1993;vol. 10(4):291–308. https://doi.org/10.1016/0737-6782(93)90072-X.
[105] Cooper RG, Kleinschmidt EJ. Major new products: what distinguishes the winners in the chemical industry? J Prod Innov Manag 1993;vol. 10(2):90–111. https://doi.org/10.1111/1540-5885.1020090.
[106] Graner M, Mißler-Behr M. Key determinants of the successful adoption of new product development methods. Eur J Innov Manag 2013;vol. 16(3):301–16. https://doi.org/10.1108/EJIM-08-2012-0084.
[107] March-Chordà I, Gunasekaran A, Lloria-Aramburo B. Product development process in Spanish SMEs: an empirical research. Technovation 2002;vol. 22(5): 301–12. https://doi.org/10.1016/S0166-4972(01)00021-9.
[108] Daft RL. A dual-core model of organizational innovation. Acad Manag J 1978;vol. 21(2):193–210. https://doi.org/10.2307/255754.
[109] Aragón-Correa JA, García-Morales VJ, Cordón-Pozo E. Leadership and organizational learning's role on innovation and performance: lessons from Spain. Ind Mark Manag 2007;vol. 36(3):349–59. https://doi.org/10.1016/j.indmarman.2005.09.006.
[110] Flynn BB, Schroeder RG, Sakakibara S. A framework for quality management research and an associated measurement instrument. J Oper Manag 1994;vol. 11 (4):339–66. https://doi.org/10.1016/S0272-6963(97)90004-8.
[111] Saleh SD, Wang CK. The management of innovation: strategy, structure, and organizational climate. IEEE Trans Eng Manag 1993;vol. 40(1):14–21. https://doi.org/10.1109/17.206645.
[112] Idris A, Seng Tey L. Exploring the motives and determinants of innovation performance of Malaysian offshore international joint ventures. Manag Decis 2011;vol. 49(10):1623–41. https://doi.org/10.1108/00251741111183799.
[113] Stigler GJ. The division of labor is limited by the extent of the market. J Political Econ 1951;vol. 59(3):185–93. https://doi.org/10.1086/257075.
[114] Bode C, Bogaschewsky R, Eßig M, Lasch R, Stölzle W. Supply management research. Wiesbaden: Springer Fachmedien Wiesbaden,; 2022.
[115] Yang C, Zhang Q, Ding S. An evaluation method for innovation capability based on uncertain linguistic variables. Appl Math Comput 2015;vol. 256:160–74. https://doi.org/10.1016/j.amc.2014.12.154.
[116] Ayob A, Hussain A, Mustaffa MM, Majid RA. Assessment of creativity in electrical engineering. Procedia - Soc Behav Sci 2012;vol. 60:463–7. https://doi.org/10.1016/j.sbspro.2012.09.407.
[117] Edison H, bin Ali N, Torkar R. Towards innovation measurement in the software industry. J Syst Softw 2013;vol. 86(5):1390–407. https://doi.org/10.1016/j.jss.2013.01.013.
[118] Chiesa V, Coughlan P, Voss CA. Development of a technical innovation audit. J Prod Innov Manag 1996;vol. 13(2):105–36. https://doi.org/10.1111/1540-5885.1320105.
[119] Amabile TM. Motivating creativity in organizations: on doing what you love and loving what you do. Calif Manag Rev 1997;vol. 40(1):39–58. https://doi.org/10.2307/41165921.
[120] Amabile TM, Conti R, Coon H, Lazenby J, Herron M. Assessing the work environment for creativity. Acad Manag J 1996;vol. 39(5):1154–84. https://doi.org/10.2307/256995.
[121] Krasniqi BA, Pula JS, Kutllovci E. The determinants of entrepreneurship and small business growth in Kosova: evidence from new and established firms. Int J Entrep Innov Manag 2008;vol. 8(3):320. https://doi.org/10.1504/IJEIM.2008.019533.
[122] Makkonen T, van der Have RP. Benchmarking regional innovative performance: composite measures and direct innovation counts. Scientometrics 2013;vol. 94 (1):247–62. https://doi.org/10.1007/s11192-012-0753-2.
[123] Chiesa V, Frattini F, Lamberti L, Noci G. Exploring management control in radical innovation projects. Eur J Innov Manag 2009;vol. 12(4):416–43. https://doi.org/10.1108/14601060910996909.
[124] Avermaete T, Viaene J, Morgan EJ, Pitts E, Crawford N, Mahon D. Determinants of product and process innovation in small food manufacturing firms. Trends Food Sci Technol 2004;vol. 15(10):474–83. https://doi.org/10.1016/j.tifs.2004.04.005.
[125] de Felice F, Petrillo A. Key success factors for organizational innovation in the fashion industry. Int J Eng Bus Manag 2013;vol. 5:27. https://doi.org/10.5772/56882.
[126] Palmberg C. The sources and success of innovations —Determinants of commercialisation and break-even times. Technovation 2006;vol. 26(11): 1253–67. https://doi.org/10.1016/j.technovation.2005.09.019.
[127] Flor M, Oltra M. Identification of innovating firms through technological innovation indicators: an application to the Spanish ceramic tile industry. Res Policy 2004;vol. 33(2):323–36. https://doi.org/10.1016/j.respol.2003.09.009.
[128] Tsai W. Knowledge transfer in intraorganizational networks: effects of network position and absorptive capacity on business unit innovation and performance. Acad Manag J 2001;vol. 44(5):996–1004. https://doi.org/10.5465/3069443.
[129] Kloock J, Schiller U. Marginal costing: cost budgeting and cost variance analysis. Manag Account Res 1997;vol. 8(3):299–323. https://doi.org/10.1006/mare.1996.0048.
[130] Vahid Nooraie S, Parast MM. Mitigating supply chain disruptions through the assessment of trade-offs among risks, costs and investments in capabilities. Int J Prod Econ 2016;vol. 171:8–21. https://doi.org/10.1016/j.ijpe.2015.10.018.
[131] Aldrighetti R, Battini D, Ivanov D, Zennaro I. Costs of resilience and disruptions in supply chain network design models: a review and future research directions. Int J Prod Econ 2021;vol. 235:108103. https://doi.org/10.1016/j.ijpe.2021.108103.
[132] Moser P, Isaksson O, Okwir S, Seifert RW. Manufacturing management in process industries: the impact of market conditions and capital expenditure on firm performance. IEEE Trans Eng Manag 2021;vol. 68(3):810–22. https://doi.org/10.1109/TEM.2019.2914995.
[133] Probert DR. Developing a make or buy strategy for manufacturing business. Institution of Engineering and Technology,; 1997.
[134] Jauch LR, Wilson HK. A strategic perspective for make or buy decisions. Long Range Plan 1979;vol. 12(6):56–61. https://doi.org/10.1016/0024-6301(79)90056-6.
[135] Riding R, Mortimer J. A study of the on-the-job training of production line operatives in manufacturing companies. Int J Train Dev 2000;vol. 4(2):111–23. https://doi.org/10.1111/1468-2419.00100.
[136] Swamidass P. New directions for on-the-job training in manufacturing. Dev Learn Organ: Int J 2003;vol. 17(1):10–2. https://doi.org/10.1108/13697230310458503.
[137] Alnıaçık E, Alnıaçık Ü, Erat S, Akçin K. Attracting talented employees to the company: do we need different employer branding strategies in different cultures? Procedia - Soc Behav Sci 2014;vol. 150:336–44. https://doi.org/10.1016/j.sbspro.2014.09.074.
[138] Smith AD, Rupp WT, Motley D. Corporate reputation as strategic competitive advantage of manufacturing and service-based firms: multi-industry case study. Int J Serv Oper Manag 2013;vol. 14(2):131. https://doi.org/10.1504/IJSOM.2013.051826.
[139] Veh A, Göbel M, Vogel R. Corporate reputation in management research: a review of the literature and assessment of the concept. Bus Res 2019;vol. 12(2):315–53. https://doi.org/10.1007/s40685-018-0080-4.
[140] S.H. MoosaviRad, S. Kara, and S. Ibbotson, Outsourcing decisions and environmental sustainability, in pp. 1494–1499.
[141] Bresnahan TF, Salop SC. Quantifying the competitive effects of production joint ventures. Int J Ind Organ 1986;vol. 4(2):155–75. https://doi.org/10.1016/0167-7187(86)90028-7.
[142] Swamidass PM. Encyclopedia of production and manufacturing management (US). Boston, MA: Springer,; 2000.

[143] Kheybari S, Naji SA, Rezaie FM, Salehpour R. ABC classification according to Pareto's principle: a hybrid methodology. OPSEARCH 2019;vol. 56(2):539–62. https://doi.org/10.1007/s12597-019-00365-4.

[144] Multiple Criteria ABC Analysis (US). In: Swamidass PM, editor. Encyclopedia of Production and Manufacturing Management. Boston, MA: Springer; 2000. p. 476 (US).

[145] Erkut E, Tarimcilar M. On sensitivity analysis in the analytic hierarchy process. IMA J Manag Math 1991;vol. 3(1):61–83. https://doi.org/10.1093/imaman/3.1.61.