An AHP and Fuzzy AHP Multifactor Decision Making Approach for Technology and Supplier Selection in the High-Functionality Textile Industry

Adrian Coronado Mondragon, Ernesto Mastrocinque, Jung-Fa Tsai and Paul Hogg

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An AHP and fuzzy AHP multi-factor decision-making approach for technology and supplier selection in the high-functionality textile industry

Adrian E. Coronado Mondragon*
School of Management, Royal Holloway University of London
Egham, Surrey, UK
adrian.coronado@rhul.ac.uk

Ernesto Mastrocinque
Faculty of Engineering, Environment and Computing, Coventry University
Coventry, UK
ac3445@coventry.ac.uk

Jung-Fa Tsai
Department of Business Management, National Taipei University of Technology
Taipei, Taiwan, ROC
jftsai@ntut.edu.tw

Paul J. Hogg
Royal Holloway University of London
Egham, Surrey, UK
paul.hogg@rhul.ac.uk

*Corresponding author

Abstract

Using the lamination process in the high-functionality textile industry this paper investigates the development of an approach for technology and supplier selection based on twelve factors affecting manufacturing technology selection with respect to the supply chain. In many manufacturing industries, technology selection still represents a challenging and not fully understood area especially when it comes to choosing between competing technologies with similar levels of performance. The methodology employed identified two competing lamination technologies with high levels of development and mechanization: full lamination/solvent type and dot lamination/solvent free. This was followed by the identification of multiple factors affecting manufacturing technology selection with respect to the supply chain, the use of Analytical Hierarchy Process (AHP) techniques and a case study involving site visits and interviews with senior management of a company operating in the high-functionality textiles industry. The analysis of empirical data gathered from the case study revealed how supply chain-related factors are more important than those directly related to the technical merit of the technology such as low cost manufacturing or automation. The proposed approach has the potential to be transferable to other industries using lamination processes and/or advanced fiber and fabric technology.

Index Terms— technology selection; supplier selection; AHP techniques; supply chain; high-functionality textile industry

1. Introduction

Organizations are aware that the selection of manufacturing technology has major implications on business performance and the entire supply chain. In a context characterized by the introduction of new paradigms like Industry 4.0 comprising new technologies in manufacturing, still companies need to be able to respond to uncertainty because of highly volatile demand [1] and the resulting consequences this may have in the business and management of supply chains. The consolidation of paradigms like Industry 4.0 which represents the current trend of automation technologies in the manufacturing industry [3] still requires making sound decisions involving technology selection as this will determine seamless integration of manufacturing supply chains.

The academic literature provides examples involving the selection and deployment of certain types of technologies and evaluation techniques such as RFID in retail operations using real options analysis [4], the utilization of pre-treatment technologies in co-combustion plants using mixed integer linear programming [5], the control of inventory problems associated to the technological advances of transistor-liquid crystal technology using fuzzy multiple objective programming [6] and the use of analytical hierarchy process (AHP) [7] combined with strategic model for the selection of manufacturing technologies to promote manufacturing and supply chain collaboration and coordination [2,8].

The use of AHP and in particular fuzzy AHP has captured the attention of a significant number of researchers. AHP has been employed to aid in multi-criterion decision-making problems, particularly when qualitative criteria are involved [79]. However AHP is unable to process ambiguous variables, hence some scholars have made use of fuzzy logic in order to deal with uncertain information [79]. The literature provides cases about the use of fuzzy AHP and decision making. For example, Chan et al. [79] used fuzzy AHP and life cycle assessment to develop an approach to assess the overall environmental performance of a product design throughout its entire life cycle. Their intention was to assist product designers and engineers identify and differentiate designs that are more environmentally conscious. Van de Kaa et al. [80] developed a multi-attribute approach based on fuzzy AHP to compute weights and determine the outcome of technology standards battles. In technology standards battles researchers have been interested in assessing which technology is in the best position to win the battle. Furthermore, using pairwise comparison, Wang et al. [81] developed a criteria system and then applied fuzzy AHP to evaluate R&D projects in China; their proposed system had the potential to be extended to other fields that include investment selection in venture capital and corporate capital budgeting.

Decision making involving technology selection can be affected by several factors, however supply chain and supplier-related factors have become prominent in manufacturing organizations. Jain et al. [9] indicated supplier selection is a multifaceted problem relating qualitative and quantitative multi-criteria and according to them, supplier selection is one of the key activities of purchase management in supply chain. Supplier selection is regarded by many as the most important activity of a manufacturer to curb costs [10]. Saen [11] pointed out that in the supplier selection process, suppliers are screened and selected as part of the company's supply chain. The researcher used the work by [12, 13] to summarize that manufacturers follow two strategies for supplier selection. The first strategy, single sourcing, involves selecting the best single supplier that meets all demands. The second one, multiple sourcing, is about selecting an appropriate combination of suppliers based on achieving maximum efficiency or profit. The available literature on supplier selection is extensive and is a topic well researched. On the other hand, the study of the interface between supplier and technology selection has been hardly covered in the literature.

Manufacturing processes do get affected by the outcome of technology and supplier decisions. One particular manufacturing process facing important decision making involving technology and supplier selection is lamination. The lamination process consists of manufacturing a material by stacking/superimposing multiple layers resulting in superior properties in terms of stiffness, strength, insulation and stability among others. The assembly of laminated materials makes use of adhesives, heat, welding and pressure. Industries that use lamination in their manufacturing processes include high-functionality textiles, cladding, glass-reinforced plastic and composite materials/carbon fiber among others. Lamination in textiles is an area with many potential end-use applications and possible markets for all types of textile fabrics [65]. Lamination is an important process in high-functionality textiles, an industry that has experienced significant growth in recent years. High-functionality textiles represent one of the most dynamic sectors of the international textile and clothing industry [14]. In 2019 high-functionality textiles used in sports/outdoor applications had a revenue of US $84 billion [87].

This work makes a contribution to the growing body of the literature focusing on decision making involving technology selection by presenting a comprehensive, wide-ranging approach that includes a number of factors closely associated to the supply chain and supplier selection in a manufacturing environment. Lamination in high-functionality textiles was the manufacturing process chosen for this research. As previously mentioned lamination is a key manufacturing process present in some high-tech industries. Recent frameworks about the use of fuzzy AHP and technology selection did not consider factors involving supplier capabilities and the supply chain. For example, the authors in [79] used an electronic product to illustrate their framework, however the criteria compiled left out factors involving supplier capabilities and supply chain with only packaging and transportation considered. In the analysis of technology standards battles involving wireless technologies, the criteria presented in [80] also did not contemplate supplier-related capabilities and supply chain factors.

The aim of this work is to contribute to improve the understanding of technology decision making in a manufacturing environment by considering supplier selection and supply chain-related factors. For that purpose the objective of this study is to develop an approach for manufacturing technology and supplier selection that includes the identification of multiple factors affecting manufacturing technology selection with respect to the supply chain and the use of the principles of Analytical Hierarchy Process (AHP) and fuzzy AHP techniques. Focusing on a particular manufacturing process – lamination, the lamination process, this research investigates the particularities of manufacturing technology and supplier selection associated to two competing lamination technologies: full lamination/solvent type and dot lamination/solvent free using an industry case in the high-functionality textiles industry.

2. Literature review

This section provides a review of the literature available on supplier and technology selection and the identification of related factors. The review includes a discussion on AHP techniques (including AHP and fuzzy AHP) and the description of the lamination manufacturing process. In this research two competing textile lamination technologies are presented as the manufacturing technologies evaluated by the managers of a company operating in the high-functionality textiles industry.

2.1 Review of the literature on supplier and technology selection

The literature on supplier and technology selection is an area still drawing interest from researchers. The review presented by He and Zhang [17] identified that supplier selection can be achieved by two steps comprising an evaluation index system and developing an applicable model. Their work came across 18 pre-selected indicators grouped in terms of product level, qualification, cooperation ability and environmental competitiveness. Some of the pre-selected indicators identified included product qualification rate, quick ratio, equipment, order completion rate, among others. Interestingly, the authors pointed out that there is still not a unified standard for establishment of index system for supplier selection.

The review provided by Wetzstein et al. [18] indicated the importance of supplier selection as one of the most significant processes in the purchasing and supply management function. The authors indicated that previous research in the areas has especially focused on selection criteria or on various mathematical optimisation approaches that trade off multiple criteria analytically to select the optimal supplier(s). Nonetheless, research on supplier selection still relies on the use of analytical techniques, namely AHP and fuzzy AHP, in order to assist business organizations in decisions pertaining their supply chains. AHP still continues to be employed in methodologies for supplier selection. For example, using a set of 63 tier-one suppliers in the Korean automobile industry, Park and Lee [19] introduced a hybrid approach for supplier evaluation, selection, and improvement where AHP is used to rate external function importance. Also in the automotive industry Jain et al. [9] presented an integrated fuzzy multi-criteria decision-making approach comprising AHP and one Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) applied to the selection of a headlamp supplier.

Yang et al. [20] developed an integrated process that allows manufacturing systems to create a performance measurement model. Performance criteria from the literature and an expert questionnaire were utilized prior to building the performance measurement model. Analytical hierarchy process (AHP) and the analytical network process (ANP) were employed to determine the weight of each criterion when generating the performance model for manufacturing systems. Paramasivam et al. [21] used three multi-attributes decision-making methods, namely matrix approach, analytical hierarchical process (AHP), and analytical network process (ANP). These methods provided selection indices for different alternatives considered. To test their solution the authors considered the selection of a milling machine with the problem solved using a diaphragm and matrix approach, AHP and ANP methods.

The substitution of process of technologies can be assisted by decision-making approaches. For example, Achillas et al. [22] provided a decision-making methodological framework for selecting additive manufacturing techniques that may substitute traditional manufacturing technologies using a criteria comprising cost, lead time, quality, together with existing production strategies that involve conventional production methods. In a scenario involving manufacturing technology implementation, Evans et al. [23] presented a decision support system that uses factual information of historical decisions to calculate confidence factors for the successful adoption of potential technologies for a given set of requirements. The technique used by the authors was based on a fuzzy-decision-tree algorithm. Also decision-making and technology selection in supply chain management have received significant attention in recent years. For example, decision-support tools that can assist organizations in the design and configuration of their supply chain are particularly important in many industries experiencing high levels of growth and uncertainty. It has long been acknowledged that change and uncertainty in business environments are primary causes of great loss in manufacturing industries [24, 25].

Inter-organizational or extended enterprise concepts have completely eluded the manufacturing technology researchers [8]. Suppliers/supply chain issues are strictly related to the manufacturing technology selection process since different manufacturing technologies might require different raw materials from different suppliers or might affect the configuration of the supply chain. Technology selection problems cannot ignore the relationships between suppliers and the supply chain behind a particular manufacturing process. To address this issue, Farooq and O'Brien [2] developed a framework that considered supply chain issues within the manufacturing technology selection process.

The technology selection process needs to consider the availability of suppliers to provide a particular type of technology with the specified materials/parts at the required rates. Overall, suppliers and supply chain issues need to be taken into account as criteria for the selection of the right manufacturing technology. However, it depends on the particular company, sector and processes to prioritise the several criteria involved in the decision-making process of technology selection. For this purpose, AHP represents a valuable tool allowing decision makers to rate and rank the factors affecting technology selection.

2.2 AHP-based decision-making approaches in the supply chain context

The operation of the supply chain can achieve multiple benefits as a result of sound technology selection decisions. According to Rosenzweig et al. [26] technologies and strategies affecting manufacturing operations result in better competitiveness and improvement programmes. Technology selection plays a fundamental role in the configuration of the supply chain, as opportunities and threats are normally associated with a technology alternative in the supply chain context [8]. Joshi et al. [27] stated that technology represents a key variable for identifying competitive policies, production strategy, innovations, creativity and commercialization activities among others. The rating of technology-related factors can be considered of high priority as new technologies and new technological developments have the potential to affect the supply chain performance.

Technology selection can be seen as a task that can have multiple ramifications and it can be assessed in different ways. The work by Farooq and O'Brien [2] indicated that technology is commonly assessed in terms of financial benefits, nonetheless, these models have been subjected to criticism by many. The same authors highlighted that technology selection models should address shortcomings that include aspects such as: a) the technology selection processes fail to incorporate risk calculations in strategic technology selection; b) the threats associated with a technology alternative have not been considered in the technology selection process and therefore neglecting their importance in technology evaluation; and c) lack of support for the inclusion of inter-organizational factors in the technology selection decision making environment.

In the academic literature there are some examples that have identified factors and attributes for the purpose of selecting manufacturing technologies and supply chain partners. Farooq and O'Brien [28] proposed a framework that combines supply chain and manufacturing together. Among the elements included in the framework are the evaluation of the current supply chain, identification of critical supply chain factors, planning range, identification of manufacturing technologies, detailed assessment of identified technologies and risk assessment of technology alternatives. In their work on supplier selection Wu and Barnes [29] developed a three-stage model for partner selection criteria formulation based on the identification of 116 generic supplier evaluation attributes applicable to any industry. The authors created a general hierarchy criteria comprising eight major groups including one for production and logistics and another one for technology and knowledge.

One important aspect of this research is to keep a concise and inclusive list of factors. The identification of factors on supplier and technology selection in manufacturing supply chains can become a complex task, hence the factors listed and validated in the works by [29, 30, 2] and [31] and other references were used in identification process used in this study. The twelve factors identified include: 'technology used by our suppliers' [32]; 'technology used by our customers' [32]; 'automation' [33]; 'rapid manufacturing/prototyping' [34]; 'capacity sizing and high volumes manufacturing' [35]; 'reduce supply chain cycle time' [36]; 'low cost manufacturing' [29]; 'return on investment' [37]; 'supply chain performance' [38]; 'on-time deliveries/service level to customer' [39, 40]; 'hire/train staff with new skills' [41] and 'reduce environmental impact' [42]. The scope of the twelve factors identified cover managerial and financial aspects but also operational aspects at the supply chain level. Moreover, these twelve factors have been tested in a survey comprising technology selection in the UK composite materials supply chain [31]. The composite materials industry relies on the extensive use of high-tech fibres as it is the case of high performance textiles industry. A summary of the twelve factors selected can be found in table 1.

	Factor	**Reference**
C1	Technology used by our suppliers	[32]
C2	Technology used by our customers	[32]
C3	Automation	[33]
C4	Rapid manufacturing/prototyping	[34]
C5	Capacity sizing and high volumes manufacturing	[35]
C6	Reduce supply chain cycle time	[36]
C7	Low cost manufacturing	[29]
C8	Return on investment	[37]
C9	Supply chain performance	[38]
C10	On-time deliveries/service level to customer	[39, 40]
C11	Hire/train staff with new skills	[41]
C12	Reduce environmental impact	[42]

Table 1. Selected factors for technology selection

The review of articles on supplier selection show a significant presence of the use of AHP. The process of technology selection can be assisted by the use of well-known decision-making support techniques such as AHP, a theory of measurement for dealing with quantifiable and intangible criteria that has been applied to numerous areas. AHP is a problem-solving framework and a systematic procedure for representing the elements of any problem [43]. Viera et al. [44] developed a framework for designing logistic operations based on AHP methods and then applied to a sports fashion retailer for decision making process. Gürcan et al. [45] proposed a model based on AHP for third party logistic provider selection. Breaz at al. [46] proposed a method based on AHP for selecting the industrial robot for milling applications. Sustainability represents another topic of interest in the supply chain context. Luthra et al. [47], proposed a framework for sustainable supplier selection using AHP, based on 22 sustainable supplier selection criteria identified from literature and experts' opinion. The framework was then applied on a real-world case in the automotive industry in India. Karaman and Akman [48] applied AHP and fuzzy linguistic variables in the Turkish airline industry to assess Corporate Social Responsibility (CSR) programs. Regarding supply chain performance and risk, AHP has been applied by Dong and Cooper [49] to develop a supply chain risk assessment framework and Katiyar et al. [50] proposed an integrated model combining the partial least squares and analytic hierarchy process to compute the supply chain performance index. Both supplier and technology selection continue to be relevant topics of research in the literature using tools such as AHP. However, opportunities exist to investigate them in one single approach comprising technology and supplier selection at the same time this work agrees with He and Zhang [17] assertion that there is still not a unified standard for establishment of index system for supplier selection and also for technology selection.

Ordoobadi [51, 52] used fuzzy logic and AHP to rank advanced manufacturing technology for supplier selection in a supply chain context. In his work Palma-Mendoza [53] investigated supply-chain re-design by using the popular Supply Chain Operations Reference (SCOR) model to identify relevant processes and SCOR model performance attributes and metrics. This enabled the author to create an evaluation criteria to conduct an AHP analysis for target process selection. Based on the results obtained AHP can aid in deciding which supply chain processes are better candidates to re-design in light of predefined criteria. The author tested the proposed model using an application in the Airline Maintenance, Repair and Operations (MRO) supply chain to enable the selection of a target for re-design and the identification of relevant supply chain processes.

AHP has the merit to be a simple and powerful tool for multi-criteria decision-making, however, in the view of Kwong and Bai [54] the crisp scale used in the judgment process might not be sufficient to take into account the uncertainty associated with the human judgment. Vagueness characterize the linguistic assessment of human feelings and judgements, hence it is not reasonable to represent it in terms of precise numbers. Alternatively, it feels more confident to give interval judgements than fixed value judgements. Conventional AHP is based on the pairwise comparison using a crisp nine-point scale replicating human preferences. Fuzzy AHP has been used to rate the importance of lean supply chain management practices for the healthcare sector [55].

In a recent work by Awasthi et al. [56], fuzzy AHP has been used for supplier selection in the context of sustainable global supply chain. Dožić et al. [57] used fuzzy AHP to select aircraft types meeting market conditions and airline's requirements. In a study conducted by Thengane et al. [58] a cost-benefit analysis is performed to compare eight different hydrogen production technologies using AHP and fuzzy AHP techniques.

In the textiles industry it is possible to find cases of the use of AHP for the purpose of selection of manufacturing flexibility options and supplier selection in sustainable supply chains. For example, Mishra et al. [59] applied integrated AHP and TOPSIS to develop an approach to determine the most important type of manufacturing flexibility in a fashion apparel firm. The authors defined manufacturing flexibility in terms of volume flexibility, new product flexibility, product-mix flexibility and delivery flexibility. Amindoust and Saghafinia [60] presented a framework for textile suppliers' sustainability evaluation criteria. In their work the researchers applied fuzzy set theory to cope with the subjectivity of the opinions of decision makers. The researchers used a real-life supplier selection problem for the textile industry to show the feasibility of the proposed model.

Based on the list of twelve factors produced in table 1 and the use of AHP techniques for technology selection, Fig. 1 depicts the first stage of the approach considered for the selection of a specific manufacturing technology. The first stage based on AHP consists of filling the pairwise comparison matrix for the twelve factors identified in order to express the relative importance of one criterion over another with the goal of selecting a manufacturing technology. Once the criteria have been ranked, the twelve pairwise comparison matrices are filled in order to express the importance of each manufacturing technology alternative over another with respect to each criteria. The priority weights of each manufacturing technology can be calculated by weights per technology multiplied by weights of the corresponding criterion. The highest score of the manufacturing technology gives the idea about the best option to select for a specific manufacturing process.

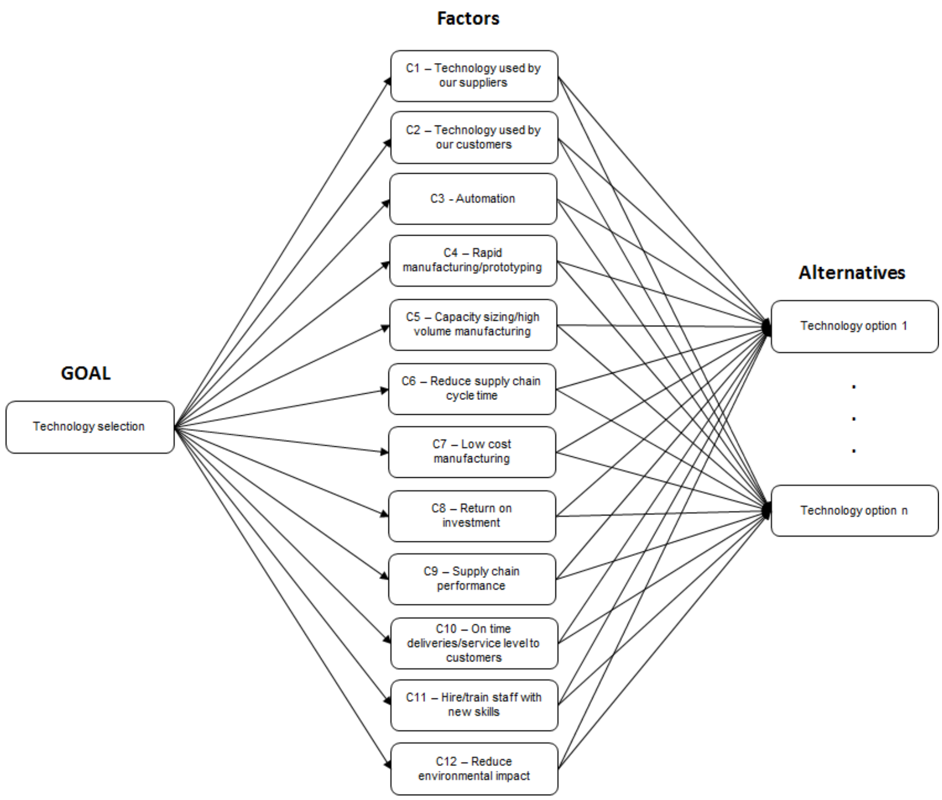

Fig. 1. Twelve factors for selection criteria of different technology options

Additionally, this research work has considered the use of fuzzy AHP to further reveal the particularities of the interface of manufacturing technology and supplier selection. Fuzzy set theory has demonstrated advantages when it comes with dealing with vague, imprecise and uncertain contexts and to some extent it resembles human reasoning in its utilization of approximate information and uncertainty to make decisions. While conventional AHP is based on the pairwise comparison using a crisp nine-point scale replicating human preferences, fuzzy AHP makes use of an intervals scale [54] in order to take into account the uncertainty due to the human judgment. For this purpose, fuzzy set theory has been integrated to address uncertainty in AHP decision-making process [61, 62]. Priority weights for each criterion can be calculated from the comparison matrix according to the procedure described in [62]. In the context of supply chain management, fuzzy AHP has been widely used to solve problems such as supplier selection and supply chain design/planning [34, 63, 64].

In fuzzy AHP each point of the Saaty's scale has been substituted by a numerical interval characterized by a membership function, which assigns to each object a grade of membership ranging between 0 and 1 [61]. Furthermore, the most simple and commonly used membership function is represented by a triangular shape as depicted in Fig. 2. Here the fuzzy number is a triplet of values such as (a1, a2, a3) which represent the smallest possible value, the most promising value and the largest value. The linguistic scale, its corresponding crisp values (1 to 9) for AHP and fuzzy triangular scale are indicated in table 2.

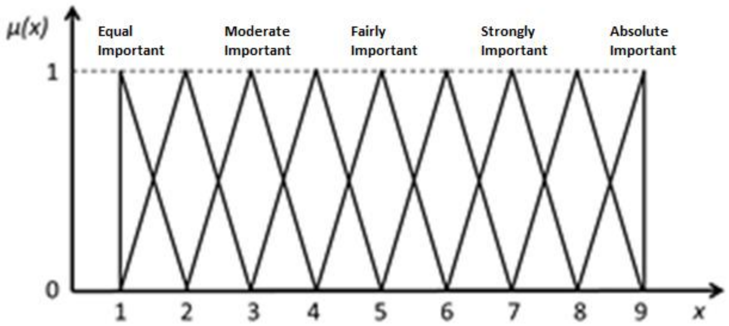

Fig. 2. Triangular membership functions for Saaty's nine point scale

Linguistic judgement scale	**Crisp scale**	**Reciprocal crisp scale**	**Fuzzy triangular scale (a_1,a_2,a_3)**	**Reciprocal fuzzy triangular scale (1/a_3,1/a_2,1/a_1)**
Just equal	1	1	(1,1,1)	(1,1,1)
Equal important	1	1	(1,1,2)	(1/2,1,1)
Equal-moderate important	2	½	(1,2,3)	(1/3,1/2,1)
Moderate important	3	1/3	(2,3,4)	(1/4,1/3,1/2)
Moderate-fairly important	4	1/4	(3,4,5)	(1/5,1/4,1/3)
Fairly important	5	1/5	(4,5,6)	(1/6,1/5,1/4)
Fairly-strongly important	6	1/6	(5,6,7)	(1/7,1/6,1/5)
Strongly important	7	1/7	(6,7,8)	(1/8,1/7,1/6)
Strongly-absolute important	8	1/8	(7,8,9)	(1/9,1/8,1/7)
Absolute important	9	1/9	(8,9,9)	(1/9,1/9,1/8)

Table 2. Judgement scale for AHP and Fuzzy numbers

The rationale for choosing triangular membership functions is that fuzzy AHP methodology is based on the use of triangular membership functions rather than other shapes. Therefore, the use of triangular membership functions is not the authors' choice, but it is dictated by how fuzzy AHP was conceived. This is extensively confirmed by the literature reviewed in this manuscript, where fuzzy AHP methodology was always applied using triangular membership functions.

2.3 Choosing a technology for lamination process in high-functionality textiles

We believe there is a compelling case to investigate technology and supplier selection in a manufacturing environment based on the challenges, growth opportunities and economic impact that certain sectors are experiencing. Production of-high functionality textiles is highly technical and requires a high-degree of expertise and know-how. High-functionality textiles undergo specialized surface treatments for applications including heat and fire protection; protective clothing; medical textiles; wound care textiles; geotextiles; fiber-reinforced composites for sustainable energy applications, fibers and textiles for civil engineering applications, leisure and sport [14]. The Textile Center of Excellence [15] mentioned that laminated fabrics are widely employed in high performance apparel where fabrics are required to be waterproof yet breathable, a laminate membrane laminates (e.g. Gore Tex® micro-porous membranes) often consist of a non-textile membrane sandwiched between two textiles. More recently, functional textiles (e.g. advanced fiber and fabric technology) have been included in the Committee on Foreign Investment in the United States (CFIUS) list – as the U.S. Congress enacts the Foreign Investment Risk Review Modernization Act (FIRRMA) to identify and to control the export, re-export, and transfer of 'emerging and foundational technologies' that are essential to national security [16].

This research focuses exclusively on high-functionality textiles as there are two main lamination technologies commonly used in their production: solvent type lamination (full lamination) and solvent free lamination (dot lamination). Singha [66] explained that solvent-based adhesives can be used to laminate micro-porous membranes to textile fabrics to provide a barrier against liquids. According to the author solvent-based polyurethane that cures in the presence of moisture is sprayed on the fabric and the membrane is nipped against the adhesive surface, then the two are held together while cross-linking takes place to form the necessary bonding. On solvent-free lamination (dot lamination), Singha [66] explained that adhesive lamination can be used to laminate two fabrics by applying an aqueous-based pressure-sensitive adhesive by knife-over-roller spreading. The author stated that the pressure-sensitive adhesive can be spread on a release paper and then transfer coated to the textile material, which can then be combined with a second fabric by bringing these into contact under heat and pressure to remove the water. Examples of the adhesives used include natural and synthetic rubber, styrene-butadiene resins (SBRs), polyvinyl alcohol and acrylic polymers. Fig. 3 depicts the two lamination processes investigated, the main materials used in the process, the criteria of factors associated with manufacturing technology selection evaluated using AHP techniques and the output of the process which goes to meet various customer requirements. Fig. 3 shows the lamination process is preceded by dyeing and followed by sewing and joining.

In recent years it has become evident technologies based upon aqueous coating systems, foam coating, hot melt or even warm melt systems are becoming more important than the older solvent coating processes on the grounds of lower environmental pollution [65]. The review of the literature discussed in this and previous sections motivated the formulation of the research questions for this work:

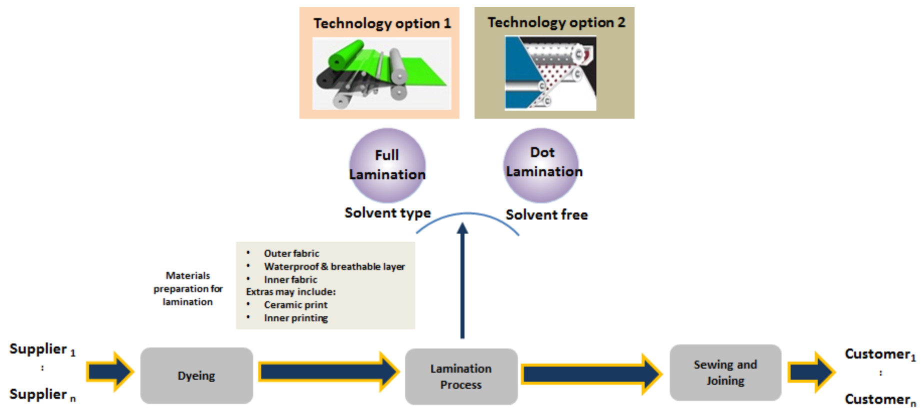

Fig. 3. Full lamination/solvent type and dot lamination/solvent free processes investigated

- What are the factors to take into account for manufacturing technology selection considering the supply chain and applicable to lamination processes validated in high-functionality textiles?

- How to design a multi-factor decision-making approach for manufacturing technology and supplier selection using AHP and fuzzy AHP techniques applicable to lamination processes validated in high-functionality textiles?

In order to answer the research questions, we propose a specialized approach based on the elements previously discussed in the literature. This approach is depicted in Fig. 4 where suppliers/supply chain factors are taken into account as factors affecting technology selection. Here we consider the different supplier options after the AHP techniques and interviews have been performed. As part of the AHP/fuzzy AHP procedure, after the pairwise comparison of factors and technology options with respect to each factor, a consistency ratio CR needs to be computed for each matrix, as described in more details later in section 4. If CR for each matrix is lower or equal to 0.10, then rankings for factors and alternative options can be computed, otherwise the inconsistencies in the judgment need to be fixed using an algorithm (in this paper we used the algorithm proposed by Xu and Wei [67]). After this, if CR is still greater than 0.10, the expert/decision maker will have to repeat the judgement stage until the consistency criterion is satisfied for all matrices. After the selection of the technology using AHP/fuzzy AHP, the decision maker(s), which can be company manager(s), should look at the suppliers available to meet that particular technology. If it happens the supplier options are not satisfactory, the decision maker should go for the second rated technology option and then look at the suppliers available.

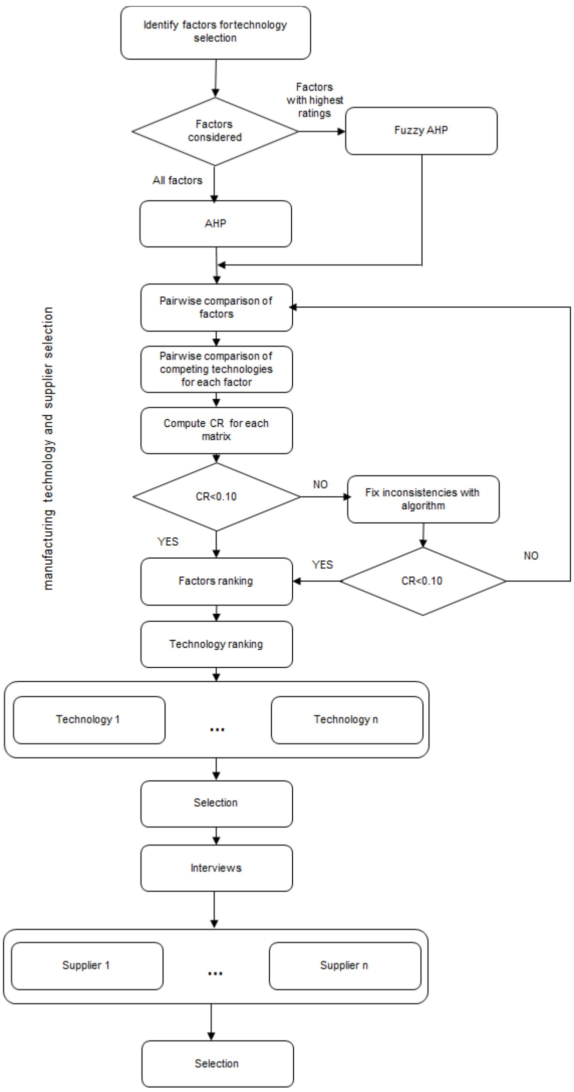

Fig. 4. Proposed approach for decision-making involving manufacturing technology and supplier selection

The following section shows the methodology employed based on the proposed approach to test twelve factors with respect to the supply chain using AHP techniques applicable to lamination processes and validated in high-functionality textiles. This is followed by interviews with senior managers to confirm the findings of the AHP analysis and select a supplier that matches the characteristics of the lamination technology selected. Two competing lamination technologies are used in this research.

3. Methodology and validation considerations for the study

A recent literature review on quantitative models for supply chain performance evaluation conducted by Lima-Junior and Carpinetti [68], revealed that the most used techniques are AHP and DEA, while fuzzy logic is the most common approach used to deal with uncertainty and vagueness. Although these models have been applied to real cases, most of them do not include a validation procedure. Furthermore, Kubler et al. [69] conducted a survey on AHP and fuzzy AHP techniques finding that fuzzy AHP is mostly used in Manufacturing, Industry and Government sectors, and Asia represents the main geographical area of application. Therefore, the above-mentioned techniques represent the most suitable methods to achieve the objectives of our research. Moreover, the majority of the articles reviewed in sections 2.1 and 2.2 make use of case studies to apply the proposed decision-making frameworks and our research is not an exception.

Although the nature of the work undertaken can be closely associated to applied research, the case study methodology is suitable given the type of questions being investigated. The use of case study is a methodology which has been thoroughly explained by Yin [70]. Buganza et al. [71] highlighted that the case study methodology approach permits a holistic and contextualized analysis. This methodology is appropriate for the initial phases of the exploratory nature of research work like the analysis of factors related to the technology selection of two competing technologies in the high–functionality textiles industry. Quantitative methods such as surveys do not provide the depth for investigating the phenomenon closely and identify the mechanisms by which the variables interrelate [70]. Barrat et al. [72] defined the qualitative case study as an empirical research that primarily uses contextually rich data from bounded real-world settings to investigate a focused phenomenon.

This research involving a case study in the high-functionality textile sector follows the guidelines proposed by Seaman [73], where visits to the participating sites were planned to obtain first-hand information from tours of specific facilities and services, interviews with individuals or groups, or observations of specific activities at the sites. Following Seaman's [73] guidelines, visits were used to obtain reports, brochures, and examples of products or services made available at the sites, also enabling the opportunity to obtain first-hand information about users or activities in the particular setting investigated. Another benefit of adopting Seaman's guidelines is the ability to evolve the data collection strategies on site, depending on the topics the evaluator determines are important to probe for obtaining additional information. As recommended by Dubé and Paré [74] in this work two research questions were formulated to provide the direction of enquiry and enable the connection between the research and its practical and theoretical contributions. Case studies can follow a deductive approach, a positivist case study deals with deductive theory testing, addressing, reliability and increasing degrees of freedom. Apart from following Seaman's guidelines on site visits, the use of interviews with senior management relates to the purpose of validation and reliability of this study, as it can be used to confirm the rates given to the selection factors and the results from the use of AHP and fuzzy AHP techniques. Creswell [75] commented that using a single research method to conduct research may cause bias whilst Gill and Johnson [76] mentioned that the combination of research methods provide opportunities for methodological triangulation.

3.1 Characteristics of participating company

The company that participated in the case study is a leader in the high-functionality textiles sector. Its high-functionality textiles covers applications such as winter sport jackets, rainwear, casual wear, golf wear, hunting wear and luxury casual wear. The company has been in business for about 15 years, with an annual turnover of over $25 million USD and with about 20% of the company expenditure going to research and development. The study covered a period of 12 months ending in the summer of 2015. During the development of the study several interviews took place involving the company director, sales assistant, staff for sales and marketing and people with knowledge of manufacturing operations. The interviewees have an accumulated expertise in high-functionality textiles of many decades. From a technical aspect this company can be considered at the very top in the industry. Table 3 summarizes details about the participating company. Table 4 shows details about the people that participated in the study including manager role and the reasons for selection.

Characteristics	Total number
Finished products/Stock keeping units (SKUs)	1000+
Suppliers	15
Manufacturing plants (outsourced)	5
Warehouses	3
Distribution centres	2
Customers	50

Table 3. Details of participating company

Manager role	Reasons for selection
Company director	Company founder and with experience of various decades in the high-functionality textiles sector
Sales assistant	Understanding of market demand and knowledge of all the lines of products offered to customers worldwide
Manufacturing-lamination, sales and marketing	Expertise on the two lamination technologies evaluated in this study: full lamination/solvent type and dot lamination/solvent free
Manufacturing-dying	Expertise on the dying process used for the type of textiles evaluated in the study

Table 4. Characteristics of the managers that participated in the study

Sites visited during the development of this work included dyeing and lamination facilities and some sewing and joining operations. In recent years the company has experienced substantial growth in different markets around the world. Hence the importance to have access to the technology and the suppliers required to meet the needs of customers. The company does not fully own production facilities (in some cases partially owns them) as all operations have been outsourced to contractors which are located no more than 80 km away from the company's offices. Lamination for this company is an important process that involves selection between two competing technologies. Demand experienced in the past couple of years shows a considerable increase in dot lamination/solvent free products, particularly in Europe where there is a more pervasive culture of sustainability. Lamination processes in high-functionality textiles are well defined and have high levels of automation.

The gathering of data for this research comprises the factors identified in [2] where their technology selection framework integrates elements of manufacturing within a supply chain. During the development of this research managers were asked to rate the factors in selecting manufacturing technology with respect to their supply chain. The answers provided were analyzed with AHP and fuzzy AHP techniques and then confirmed and analyzed in depth with senior management using interviews.

4. Analysis of results from AHP, fuzzy AHP and interviews with managers.

The answers the company gave to each of the factors evaluated are expressed in the comparison matrix shown in table 5 using the linguistic judgement scale presented previously in table 2.

Criteria	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	AHP weights	Fuzzy AHP weights
C1	1	5	1	1/5	1/5	1/5	1/3	1/3	1/5	1/7	1/3	1/3	0.0248	0
C2	1/5	1	7	1/5	1/5	1/5	1/3	1/5	1/7	1/7	1/5	1/5	0.0202	0
C3	1	1/7	1	1/5	1/3	1/5	1/3	1/5	1/7	1/9	1/5	1/5	0.0143	0
C4	5	5	5	1	1	1	5	1/3	1/5	1/7	1/3	1/3	0.0552	0
C5	5	5	3	1	1	1/3	1/3	1/5	1/7	1/7	1/3	1/5	0.0367	0
C6	5	5	5	1	3	1	5	1/3	1/5	1/7	1	1/3	0.0648	0
C7	3	3	3	1/5	3	1/5	1	1/3	1/7	1/7	1/5	1/5	0.0335	0

C8	3	5	5	3	5	3	3	1	1/5	1/5	3	3	0.1139	0.1054
C9	5	7	7	5	7	5	7	5	1	1	5	3	0.2232	0.3699
C10	7	7	9	7	7	7	7	5	1	1	1	5	0.2298	0.4247
C11	3	5	5	3	3	1	5	1/3	1/5	1	1	3	0.0983	0.0558
C12	3	5	5	3	5	3	5	1/3	1/3	1/5	1/3	1	0.0854	0.0442

Table 5. Company answers to criteria pairwise comparison matrix and resulting weights using AHP and fuzzy AHP

The consistency analysis for the judgement matrices for factors related to the selection of manufacturing technology was confirmed with Saaty's consistency ratio CR=CI/RI=(((λ_max-n))/(n-1))/RI (CI consistency index, λ_max largest eigenvalue of the matrix, n size of the matrix and RI random consistency index equal to 1.48 for a 12x12 matrix, see [77], which states that for a value equal or smaller to 10% then the inconsistency is acceptable. Although CR for the criteria comparison matrix showed a value around 15%, using the algorithm for fixing the inconsistencies proposed by [67], it was proven to reach a value of 0.097 without changing significantly the priorities (with values of sigma=0.3652<1 and delta=1.7924<2 (see [67, 78]). For this reason, the authors have preferred to leave the company's ratings unchanged.

The main difference between the AHP and fuzzy AHP is that the latter gives a weight different from zero only for five factors, which are the factors with the highest weights obtained by the AHP. Those factors are: On-time deliveries/service level to customer, Supply chain performance, Return on investment, Hire/train staff with new skills and Reduce environmental impact. As a matter of fact, using the AHP, the remaining factors received weights which are much lower than the other five factors. Therefore, the fuzzy AHP approach considers those factors as irrelevant.

Based on the proposed approach, the analysis of AHP and fuzzy AHP was followed by detailed interviews with the director of the company and his sales assistant who explained and validated the reason for the above ratings. The answers given reflect the highly competitive nature of high-functionality textiles. The managers expressed that many of the factors assessed are closely related to each other. For example, On-time deliveries/service level to customer represents the most important factor in the relationship with customers as materials have to be delivered just before the start of the peak season. This factor inherently affects the performance of the supply chain (rated second place), from dyeing, to lamination, to the delivery of the fabric that will be cut and sawn to make the clothes for winter sports. Return on investment came third in this exercise as the managers agreed that the company invests in state-of-the-art machinery to produce fabrics of better quality. Investment takes place in production facilities where the company has a particular interest. Hiring and training staff came at number four as the interviewed managers see it as part of the type of investment required to run the business.

Reduce environmental impact came fifth, and this rating relates to the higher score obtained by dot lamination/solvent free technology. For example, the managers explained that customers are becoming more environmentally conscious, particularly in Europe. Sixth was rapid manufacturing and prototyping. This obeys to the fact that giving customers prototypes on time is key for getting bulk orders. Prototypes size may be from 10-15 yards with bulk orders of 200 yards and more.

Reduce supply chain cycle times as the average lead times for processing customer orders is two weeks. If a specific design is in stock it may be possible to fulfil a customer order in two days but that seldom happens. This company does not manufacture to stock. Capacity sizing is also important as big orders from customers may take a vast allocation of production time available. A major sports manufacturer may place orders of about 20 – 30 million yards. High end functional fabrics used in winter sports might be in the order of 3 million yards representing 65% of the company’s revenue.

Regarding Low cost manufacturing, the managers explained that the company has to have competitive costs, if price is too high there will be no orders. When it comes to Technology used by our customers and Technology used by our suppliers, the interviews with the managers confirmed that both factors are closely related to each other as customers are always interested in the lamination technology that will be used to manufacture the fabric they need.

On Automation and Rapid manufacturing/prototyping it can be said that factors directly related to the technical merit of the technology such as low cost manufacturing or automation, are not seen as a priority to the company as these have already been achieved. The company is now targeting the improvement of supply chain-related aspects such as supply chain performance and service level, although priorities still comprise economic and environmental issues.

Table 6 shows the ratings given by the company to the two competing lamination technologies with respect to each factor. The overall weights for the two technologies are shown in Fig. 5.

C1	Full	Dot	AHP weight	Fuzzy AHP weight
Full	1	1/3	0.25	0
Dot	3	1	0.75	1
C2	Full	Dot	AHP weight	Fuzzy AHP weight
Full	1	1/3	0.25	0
Dot	3	1	0.75	1
C3	Full	Dot	AHP weight	Fuzzy AHP weight
Full	1	1/5	0.1667	0
Dot	5	1	0.8333	1
C4	Full	Dot	AHP weight	Fuzzy AHP weight
Full	1	1/3	0.25	0
Dot	3	1	0.75	1
C5	Full	Dot	AHP weight	Fuzzy AHP weight
Full	1	1/3	0.25	0
Dot	3	1	0.75	1
C6	Full	Dot	AHP weight	Fuzzy AHP weight
Full	1	1/3	0.25	0
Dot	3	1	0.75	1
C7	Full	Dot	AHP weight	Fuzzy AHP weight
Full	1	1/3	0.25	0
Dot	3	1	0.75	1
C8	Full	Dot	AHP weight	Fuzzy AHP weight
Full	1	5	0.8333	1
Dot	1/5	1	0.1667	0
C9	Full	Dot	AHP weight	Fuzzy AHP weight
Full	1	3	0.75	1
Dot	1/3	1	0.25	0
C10	Full	Dot	AHP weight	Fuzzy AHP weight
Full	1	1	0.5	0.5
Dot	1	1	0.5	0.5
C11	Full	Dot	AHP weight	Fuzzy AHP weight
Full	1	1	0.5	0.5
Dot	1	1	0.5	0.5
C12	Full	Dot	AHP weight	Fuzzy AHP weight

Full	1	1/9	0.1000	0
Dot	9	1	0.9000	1

Table 6. Company answers to the pairwise comparison matrices for lamination technologies options with respect to the criteria used

The use of two different AHP methodologies gives completely different results when it comes to rate the lamination technologies. As a matter of fact, AHP gives almost the same weight around 0.50 to both technologies, while the fuzzy AHP rewards the full lamination/solvent-based technology with a far higher weight of 0.72 compared to the 0.28 obtained by the dot lamination/solvent free. The different results are due to the fact that the fuzzy AHP rates the less important factors with 0 and therefore takes into account only the top rated ones when it comes to the final calculation.

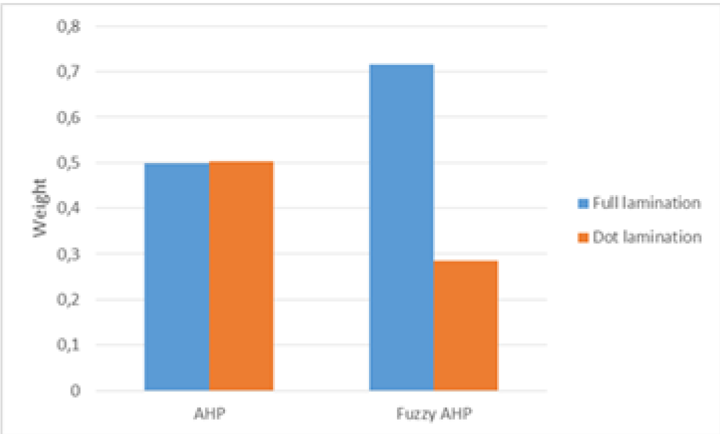

Fig. 5. Overall ratings associated to full lamination and dot lamination technologies

When it comes to supplier selection, both full lamination and dot lamination in high-functionality textiles are highly technical operations. Furthermore there are even fewer suppliers who can provide both technologies under the same roof. Opting for a single supplier capable of offering full lamination and dot lamination technologies represents an attractive proposition. In this case single sourcing involves selecting the best supplier that meets the demands on quality, lead times, costs and customer service. A multiple sourcing solution favouring maximum efficiency or profit may not be in the interest of a customer. In fact, the use of more than one supplier may result in an increase in the variability of the processes and rising quality issues. Another aspect we found affecting supplier selection has to do with a company buying a stake in a supplier which will guarantee slots in future production schedules. This scenario actually took place with the company participating in the study which bought a stake in the preferred supplier capable of providing both full lamination and dot lamination solutions.

Manufacturing technology and supplier selection can be notably influenced by the conditions of the supplier providing a certain type of technology to the customer. Nonetheless the proposed approach has significant managerial implications as it can assist companies to identify elements characterising the manufacturing technology and supplier decision-making processes.

A sensitivity analysis was conducted to demonstrate the robustness of both AHP and fuzzy AHP models. The aim of this analysis is to understand how changes in the weights of the factors affect the priorities of the alternatives. Regarding the AHP model, twelve scenarios were investigated. In each scenario one factor weight at the time was increased by 25% while the others reduced accordingly (sum constant and equal to 1) and the corresponding changes in the priorities of the alternatives were calculated. In Fig. 6 bars represents the weights of the factors for each scenario, while lines are the values of the priority weights for the alternatives. Results show that the changes in the factors weights do not have a major impact on the priorities of the alternative except for scenarios 8 and 9 (full lamination priority weight is approximately 0.51 and dot lamination priority weight is approximately 0.49), where the full lamination become the preferred option compared to dot lamination. However, this is an acceptable result given that the final weights of the alternatives were originally almost the same and the final ranking remains stable for ten scenarios out of twelve.

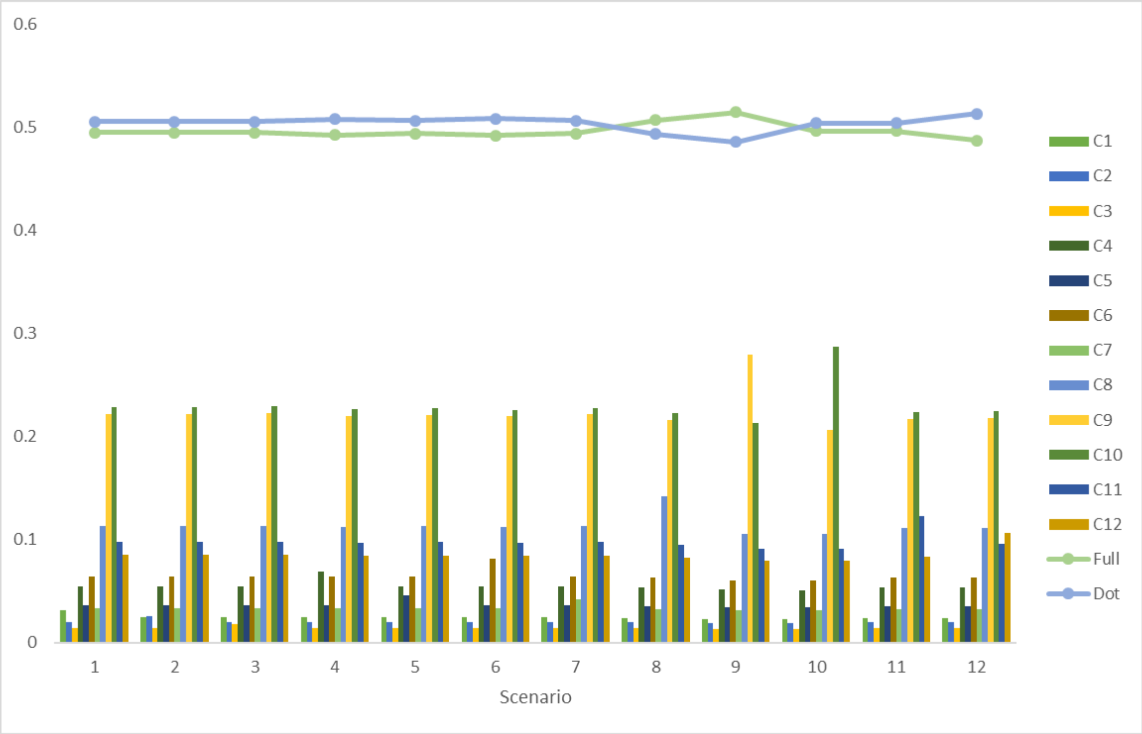

Fig. 6. Sensitivity analysis chart for AHP model

Finally, the robustness of the model is confirmed by the sensitivity analysis conducted on the fuzzy AHP model (see Fig. 7).

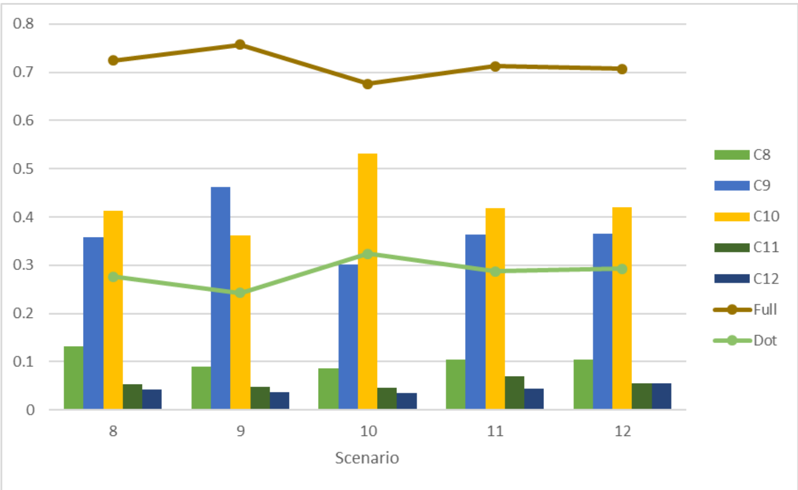

Fig. 7. Sensitivity analysis chart for fuzzy AHP model

Analogously to previous analysis, each factor weight was increased by 25%. However, in this case there are only five useful scenarios given that the weights of the first seven criteria were originally equal to zero. Results show no significant change in the weights of the alternatives, and the final ranking remain the same for all the scenarios confirming the robustness of the proposed approach.

The research undertaken in this work possesses intrinsic characteristics that make it susceptible for reproducibility and transferability in other sectors. One of them is the composite materials sector which supports the development of innovative manufactured products in several industries including automotive, construction, aerospace, marine, renewable energy, medical equipment, railway, sports, etc. The France-based JEC Group has reported the composite materials sector will experience a demand of 12 million tons with a value of US $103 billion by the year 2021 [82]. Fiber reinforced polymers (FRPs) or polymer matrix composites (PMCs), comprise a matrix material (a polymer based resin) that surrounds and supports a reinforcement which can be fibers, particles or flakes). The resultant PMC has properties that are advantageous compared to those of either the matrix or the reinforcement when used on their own [83]. In composite materials lamination can be found during layup processes where flat sheets of composite materials are manipulated into shape [84]. In the aerospace sector laminated composites are used to replace metallic materials in primary structures with the objective of reducing aircraft weight and maintenance requirements [85]. The same methodology employed to assess lamination in high-functionality textiles using competing technologies can be replicated to assess competing technologies/methods for lamination of composites materials. Managers working in the composites sector can be asked to rate the same factors presented in this work. Therefore, it would be interesting to see the rates given to factors like low cost manufacturing and automation. Competing technologies that can be considered for lamination in composite materials include tow placement vs. hand layup. Additionally, the composite materials sector can benefit from the expertise accrued in the high-functionality textiles sector as this has developed higher levels of automation compared to composite materials. Composite materials are included in the CFIUS list (e.g. advanced fiber).

Another sector where the methodology proposed for the evaluation of lamination technologies can be transferred is cladding manufacturing. The construction sector makes extensive use of cladding which is used for the purpose of improving the aesthetics of buildings as well as providing thermal insulation and weather resistance. The global cladding market size was estimated at US $70.59 billion in 2016 [86]. Competing technologies that can be assessed include high pressure lamination and roll bonding among others.

5. Conclusions

This work investigated the importance of factors affecting the selection of a manufacturing technology in the context of a technically advanced industry. A case study about a high functionality textile company was conducted to select a lamination technology among two competing options. The proposed approach comprising AHP and fuzzy AHP techniques plus the use of interviews with senior management shows its viability as an analysis tool because of its strength in capturing the vagueness characterizing human judgment and its simplicity and ability to solve multi-criteria decision making problems.

The results obtained have shown that service level and supply chain performance are the most important factors for the company when it comes to consider the selection of a manufacturing technology. Additionally return on investment, hire/train people with new skills and environmental impact emerged to be important factors for this case in the high-functionality textile sector. Also full lamination/solvent type appeared to be the suggested technology option for high-functionality textile manufacturing according to the fuzzy AHP approach, while both technologies seem to have the same importance if AHP is used.

The study demonstrated that the identification of factors affecting technology selection with respect to their supply chains is important to high-tech industries like high-functionality textiles facing challenges in terms of standardization of processes and materials. These might have implications in the configuration of robust, resilient and fast supply chains that can mitigate the effects of uncertainty attributed to technology selection.

In industries actively seeking to adopt the use of new materials as well as new manufacturing technologies to produce innovative products, a key aspect to consider is represented by the challenges related to the selection of manufacturing technology with respect to the supply chain. This is highly relevant in an industry like high-functionality textiles where the use of advanced fiber and fabric technology has been recognized by the US Foreign Investment Risk Review Modernization Act (FIRRMA) as an emerging and foundational technology essential to national security. Hence, there is potential the rating of factors affecting technology selection may benefit the entire high-functionality textile industry. However, the limitation of this work is that the results are based on one single case study and a limited number of factors. Nonetheless, in the future it may be possible to refine the model and extend the scope of the study to include more companies in the high-functionality textile industry which face the challenge of choosing between two competing technologies. Regarding policy implications, this work may contribute to the creation of industry-specific unified standards that may facilitate supplier and technology selection. Finally, the strategic importance and the economic growth experienced by industries relying on advanced fiber and fabric technology and lamination processes (e.g. high-functionality textiles, composite materials/carbon fiber and cladding) justify the need of a selection approach that considers the interface between manufacturing technology and supplier.

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