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Development of a decision-making framework for collaborative robot (cobot) adoption

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Abstract

Collaborative robots (cobots) are emerging in manufacturing as a response to the current mass customization production paradigm. Before adopting this technology in production processes and benefiting from its advantages, manufacturers need to analyze the investment. Basing such decision solely on financial feasibility is incomplete and other benefits should be included in the adoption decision. Since literature is lacking on a comprehensive decision-making method for cobot adoption, this study aims to address this gap by developing a decision-making framework for cobot adoption, incorporating a comprehensive set of quantitative and qualitative criteria, to be used by decision-makers in manufacturing companies. To achieve that objective, a qualitative study was conducted by collecting data through interviews with key actors in the cobot (or advanced manufacturing technologies) adoption decision process in manufacturing companies. The main findings of this study include, firstly, an extensive list of decision criteria, as well as some indicators to be used by decision-makers, some of which are new to the literature. These criteria were grouped into financial, operational, technological, strategic, human, risk, environmental, and legal categories. Secondly, a decision-making framework for cobot adoption is proposed, as well as a set of guidelines to use it. The framework is based on a weighted scoring method and can be customizable by the manufacturing company depending on its specific context, needs, and resources. In addition to providing a better understanding of the cobot adoption decision process, this study contributes to the literature by enriching and validating the decision criteria to be considered. In practice, it provides a tool to assist decision-makers of manufacturing companies in performing more complete and sustained decision analysis regarding cobots adoption.

Keywords: collaborative robots, advanced manufacturing technology, decision-making, framework, decision criteria, cobot adoption decision

JEL-codes: D70; E22; M19; O14; O22; O33

Resumo

Robôs colaborativos (cobots) têm surgindo na produção industrial como resposta ao atual paradigma de produção de customizada. Antes de adotar esta tecnologia nos processos produtivos e beneficiar das suas vantagens, as empresas industriais devem analisar o investimento. Basear tal decisão apenas na viabilidade financeira é incompleto e outros benefícios devem ser incluídos na decisão de adoção. Como a literatura carece de um método de tomada de decisão abrangente para adoção de cobots, este estudo visa preencher essa lacuna desenvolvendo uma framework de tomada de decisão para adoção de cobots, incorporando um conjunto de critérios quantitativos e qualitativos, a ser usado por tomadores de decisão de empresas industriais. Para atingir este objetivo, foi realizada um estudo qualitativo, sendo os dados recolhidos através de entrevistas com atores-chave no processo de decisão de adoção de cobots (ou tecnologias avançadas de produção) de empresas industriais. As principais conclusões deste estudo incluem, em primeiro lugar, uma extensa lista de critérios de decisão, bem como alguns indicadores a serem utilizados pelos decisores, alguns dos quais são novos para a literatura. Estes critérios foram agrupados em categorias financeiras, operacionais, tecnológicas, estratégicas, humanas, risco, ambientais e legais. Em segundo lugar, é proposta uma *framework* de tomada de decisão para adoção de cobots, bem como um conjunto de orientações para usá-la. A *framework* é baseada no método de pontuação ponderada e é personalizável pela empresa industrial, dependendo do seu contexto, necessidades e recursos. Além de proporcionar uma melhor compreensão do processo de decisão de adoção de cobots, este estudo contribui para a literatura ao enriquecer e validar os critérios de decisão a serem considerados. Na prática, fornece uma ferramenta para auxiliar os tomadores de decisão de empresas industriais a realizar análises de decisão mais completas e sustentadas sobre a adoção de cobots.

Palavras-chave: robôs colaborativos, tecnologias avançadas de produção, tomada de decisão, framework, critérios de decisão, decisão de adoção de cobots

Códigos JEL: D70; E22; M19; O14; O22; O33

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1. Introduction

Current trends in industrial manufacturing include mass customization production (Battaïa et al., 2018) since modern markets demand customized, varied, sophisticated, and high-quality products (Al-Ahmari et al., 2016) in smaller lot sizes (Krüger et al., 2009). The competitive advantages of manufacturers rely on their ability and flexibility to meet such market requirements with shorter lead times and costs (Al-Ahmari et al., 2016), making them increasingly aware of the necessity to invest and adopt advanced manufacturing technologies (AMTs) (Olfati et al., 2020). AMT refers to a family of modern manufacturing technologies (Small & Chen, 1997), whose successful application can provide a company with a number of benefits in terms of competitive advantage, flexibility, quality, productivity, customer satisfaction (Ordoobadi, 2013) profitability, reliability (Olfati et al., 2020), etc. Collaborative robots (cobots) are an example of such advanced technology that can safely work alongside humans (Battaïa et al., 2018). The combination of the "strength and the efficiency of robots with the high degree of dexterity and the cognitive capabilities of humans" provides the much-needed flexibility (Lenz & Knoll, 2014, p. 666).

Cobots have been mainly studied through productivity, quality, safety, ergonomics, and human-robot interaction perspectives (Matheson et al., 2019). Only few researchers have studied the cobot adoption decision - Peron et al. (2020), Fager et al. (2020), Cohen et al. (2021), and Calvo and Gil (2022) have addressed costs and productivity aspects of cobot adoption, but there are other benefits, difficult to measure, that should be included in the adoption decision. Therefore, none of the studies is complete enough to encompass the most relevant criteria for manufacturing companies' managers regarding the decision to adopt cobots.

Since 1984, several evaluation techniques to justify investment in AMT have been presented in literature (Al-Ahmari et al., 2016; Hamzeh & Xu, 2019). Some AMT features can be described using monetary values or other quantitative metrics, while others are intangible or difficult to quantify (Olfati et al., 2020), therefore, decision-making methods have been developed to take into consideration both quantitative and qualitative evaluation criteria. However, decision-makers in companies are not using them in their investment decisions due to their complexity of application (Frank et al., 2013; Small, 2006).

Considering the current manufacturing scenario, the benefits that a cobot can bring to a company, and the lack of a comprehensive decision-making method for cobot adoption, this research aims to develop a decision-making framework for cobot adoption, incorporating a comprehensive set of quantitative and qualitative criteria, to be used by decision-makers in manufacturing companies. Therefore, the following research questions are addressed:

1. Which criteria can be considered in cobots adoption decision?
2. What guidelines should be considered in the development of a decision-making framework for cobot adoption?

The answer to these research questions provides a contribution to the management body of knowledge by enriching and validating the decision criteria to be consider and providing a better understanding of the cobot adoption decision process. In practice, it provides a tool to assist decision-makers of manufacturing companies in performing a more complete and sustained decision regarding cobots adoption.

The remainder of this document is organized as follows. Section 2 reviews the literature on AMT, cobots, important criteria for the decision-making, contributions made to cobot adoption decision, decision-making methods for AMT adoption, and conceptual framework. Section 3 describes the methodology. Section 4 presents the results, describing the decision criteria in detail and presenting the decision-making framework. Section 5 discusses the results and section 6 concludes this study.

2. Literature review

2.1. Advanced Manufacturing Technologies

In general terms, AMTs "can be defined as any type of advanced technology that, when incorporated into a manufacturing operation, has a significant impact on the product, process, and informational aspects of the system" (Ordoobadi & Mulvaney, 2001, p. 159). They comprise a variety of new technologies employed in manufacturing organizations, such as computer-aided design (CAD), flexible manufacturing system (FMS), computer-numerically controlled (CNC) machines, cellular manufacturing system (CMS), computer-integrated manufacturing (CIM) systems, additive manufacturing, automated material handling (AMH) systems and industrial robots (lo Storto, 2018; Small & Chen, 1997).

2.2. Cobots

Collaborative robots, or cobots, are a particular type of advanced manufacturing technologies (Correia Simões et al., 2020) that has been receiving special attention in literature (Lima et al., 2019) due to their growing integration into industry (Marvel & Norcross, 2017).

Colgate et al. (1996, p. 433) first defined a cobot as a "robotic device which manipulates objects in collaboration with a human operator". Meanwhile, there can be different levels of collaboration (Bauer et al., 2016). The cell level is not really a collaboration scenario since the robot is operated in a cage, separately from the human (Bauer et al., 2016). In the coexistence scenario, the robot is cage free; human and robot work alongside each other but do not share the workspace (Bauer et al., 2016). In the synchronized scenario, the human and the robot share the workspace, but only one of them is present in the workspace at a time (Bauer et al., 2016). In the cooperation scenario, humans and robots share the workspace at the same time but they do not work in the same piece simultaneously (Bauer et al., 2016). Finally, in the collaboration mode, besides sharing the workspace, humans and robots work in the same piece at the same time (Bauer et al., 2016). Therefore, what primarily distinguishes cobots from traditional robots is their ability to safely work alongside humans. To ensure a safe and successful operation of collaborative industrial robots, ISO/TS 15066:2016 (*Robots and robotic devices — Collaborative robots*) specifies some safety requirements. Most cobots are already built to comply with these safety requirements (El Zaatari et al., 2019).

This technology can assist humans by taking over monotonous tasks, supporting in high precision or repeatable tasks, or assisting an overloaded worker in fast production processes

(Bauer et al., 2016). In manufacturing industries, cobots are mostly used for material handling (transporting, picking, packing, and palletizing), product testing, welding, and assembly (Sherwani et al., 2020; Villani et al., 2018).

Considering cobot's technical features and possible applications, manufacturing companies might wish to incorporate this technology into their production lines. Nevertheless, that can be a complex decision to make (Cohen et al., 2021). According to Correia Simões et al. (2020) findings, the cobot adoption decision is highly influenced by the economic analysis of the investment. Yet, some benefits are difficult to quantify, hindering the analysis (Correia Simões et al., 2020). Hynek and Janeček (2010) stated that the identification of AMT benefits is a crucial element of the technology adoption. On the ground of these observations, a literature review on the cost and benefits of cobot adoption is provided next.

2.3. Criteria to be considered in cobots adoption analysis

In this section benefits, advantages, and disadvantages of cobot adoption described in the literature are presented, to give some insights into the identification of the most suitable criteria to be considered in the cobot investment decision.

2.3.1. Advantages/Benefits

The main advantage of adopting cobots is the increased **flexibility** that results from the combination of human's intellectual abilities and automated systems efficiency (Djuric et al., 2016). While robots can continuously undertake the activities they were programmed to do with high degrees of precision, speed, and repeatability, humans can provide versatility due to their cognitive skills and ability to quickly adapt to complex environments and unpredictable situations (Krüger et al., 2009; Villani et al., 2018).

Because current markets demand customized products (Battaïa et al., 2018), the increased flexibility from the cobot adoption can lead to higher **competitiveness** (Bi et al., 2021). Bi et al. (2021) further developed the idea that the competitiveness of an enterprise can be measured through its market share, by showing that the market share depends on the varieties and volumes of products made by the enterprise. Another source of competitive advantage is innovation (Simões et al., 2019). Just by adopting cobots, companies can be perceived as innovative among partners and customers (Simões et al., 2019), improving their competitiveness.

Assigning the repetitive or physical loading tasks to the cobot increases the **ergonomics** of the workstation (Vysocky & Novak, 2016). Manufacturing sectors have particularly high absenteeism rates due to Musculoskeletal Disorders (MSD), suffering from the highest economic losses due to it (European Agency for Safety and Health at Work, 2019). MSDs affect the muscles, nerves, blood vessels, ligaments, and tendons, and manufacturing workers are mainly affected by this condition due to the positions, repetitive tasks, and heavy loads manipulated at work (Occupational Safety and Health Administration, n.d.). The experiment conducted by Cherubini et al. (2016) showed that the introduction of a cobot in the assembly process, reduced the operator load by 60% as well as the risk of injuries. Consequently, there was a huge drop in MSDs and the associated costs (Cherubini et al., 2016). Krüger et al. (2009) study also confirmed improvements in ergonomics.

RULA (Rapid Upper Limb Assessment) was mentioned as the best method for ergonomic assessment (Yazdanirad et al., 2018). It was developed to evaluate, without special equipment, the posture, force, and muscle use of individual workers where work-related upper limb disorders are a reality (McAtamney & Nigel Corlett, 1993).

The collaboration between humans and robots can also provide **quality** improvements due to cobot's precision and repeatability along with faster and less demanding quality control processes (Vysocky & Novak, 2016). Salunkhe et al. (2019) employed a cobot in a nut assembly station, a fully manual operation with a quality rate of 70% that reached 99.17% with the integration of the cobot, by finding the proper maximum speed, location, and tools.

If the **safety** standards and procedures regulated by ISO/TS 15066 are followed, the risk of injury is reduced and the worker's safety is improved (Vysocky & Novak, 2016). Realyvásquez-Vargas et al. (2019), registered good achievements in employee safety with the introduction of a cobot in the assembly station. In Cherubini et al. (2016) experience, the collaborative assembly also showed a reduced risk of strain injuries when compared to manual assembly, due to the fact that most of the physical effort is supported by the robot.

Cobots' great **mobility** due to their lightweight (Sherwani et al., 2020) is another benefit as they can be employed in distinct assembly lines or distinct phases within each line (Correia Simões et al., 2020). Gil-Vilda et al. (2017) case study showed that the integration of a cobot into a u-shaped production line did not require additional space when compared to a fully manual situation, due to its collaborative features.

Compared to traditional industrial robots, cobots offer fast set-ups and **ease of**

programming (Matúšová et al., 2019). Any operator with no programming experience can program a cobot (Sherwani et al., 2020) since there are free online essential training and intuitive 3D visualization systems to help them (Universal Robots, n.d.). In some cases, the cobot can even be programmed just by moving the cobot arm (Sherwani et al., 2020).

Payload, maximal reach, number of axes, repeatability, maximal speed, force sensing, and special features comprise cobots' main **technical features** (Cohen et al., 2021). The selection of the cobot model depends on the type of tasks the cobot will perform, which makes technical features an important aspect to consider and to specify before any productivity or economic analysis (Cohen et al., 2021).

Regarding **human-robot collaboration**, on the one hand, the interviewees from Elprama et al. (2017) recognized that cobots can lighten their mental and physical workload. On the other hand, Arai et al. (2010) study showed that operators felt a high-stress level when a robot was moving near them. Since state of the art in human-robot collaboration and human-robot interaction give clear guidelines for better human-robot coexistence (Bejarano et al., 2019), the challenges that might appear during human-robot collaboration (such as stress levels) are expected to be overcome, making this criteria an advantage.

There is no consensus in literature on whether **productivity** is an advantage or a disadvantage. Some authors believe that by working alongside the operator in collaboration, cobots are capable of increasing systems' productivity (Villani et al., 2018). Tsarouchi et al. (2016) reported that the introduction of two cobots in the assembly process allowed a reduction of 78% in the time a human required to perform the task. Gil-Vilda et al. (2017) case study revealed that the integration of a cobot into a u-shaped production line featured a 51% improvement when compared to a fully manual situation. The case study conducted by Antonelli et al. (2016) in a collaborative human-robot cell, showed a total cycle time of 320 seconds in a fully automated scenario, 1100 seconds in a fully manual scenario, and 710 seconds in a collaborative scenario. However, Simões et al. (2019) suggested that in order to assure a safe collaboration between the cobot and the human, the cobot works in low velocities, decreasing productivity. Zanchettin et al. (2019) were also concerned that whenever a cobot is forced to stop, to avoid a collision with a human, its productivity would be severely affected. Bejarano et al. (2019) experiment showed that "The average execution time for a skilled operator alone is 255 secs, in contrast with 358 secs, spent by the cobot collaborating to the same skilled operator, increasing roughly 40% the process time"

(Bejarano et al., 2019, p. 562). In Cherubini et al. (2016) experience, the tasks performed in collaboration with the cobot took four times more than the manual one.

2.3.2. Disadvantages

When deciding whether to invest in a cobot or not, price (or acquisition/purchase cost) and maintenance costs (Cohen et al., 2019) are common aspects of consideration. In some cases, in order to successfully implement cobots in the production or assembly process, new tools, resources, or consultancy services might be crucial (Bauer et al., 2016). Furthermore, with the integration of cobots, human operators will have to perform their tasks differently, raising a need to train operators to safely working alongside a cobot (Enrique et al., 2021). Technicians should be trained on cobot maintenance and operations, or new ones should be hired (Cohen et al., 2019; Enrique et al., 2021). All these aspects represent additional initial costs for cobot adoption.

Notwithstanding the fact that cobots are designed to interact with humans without harming them, a risk assessment must be undertaken (Platbrood & Görnemann, 2018). After understanding the cobot specific safety features, any hazardous situation that might occur should be considered; from the risk analysis results, the company might wish to take additional measures (e.g. safety light curtains or safety laser scanners) (Platbrood & Görnemann, 2018) which encompasses additional costs. Moreover, it could be necessary to train staff to perform such risk assessment and to be knowledgeable in new certified safety systems (El Zaatari et al., 2019).

The table in Appendix A summarizes this section by listing the identified criteria, the reference, and, whenever possible, in which way they were measured or assessed.

2.4. Contributions to cobot adoption decision

This section highlights the literature that has somehow contributed to supporting cobot adoption decisions with financial considerations. A summary of these studies is presented in the following paragraphs. In appendix B, the models' formulations are provided.

Peron et al. (2020) proposed a decision support system based on four variables (throughput, operator and equipment cost, operation time, and type) to suggest when the introduction of assistive technologies becomes profitable. Four different assembly system configurations (manual assembly, manual assembly with the implementation of digital instruction (DIs), manual assembly with the implementation of cobots, and manual assembly with the implementation of both DIs and cobots) were modeled by means of four different cost models and analyzed in-depth with a parametric analysis carried out by varying the variables (Peron et al., 2020). This tool is expected to support practitioners in making decisions related to the assembly system configuration, such as how many workstations and which equipment and technology to install at the system level (Peron et al., 2020).

Fager et al. (2020) developed a cost model to consider the relative cost differences between a manual and cobot-supported process in a picking system concerning three main cost components: cost of operators, equipment, and quality.

Cohen et al. (2021) identified cobots' main capabilities (human support, interaction, intelligence, mobility, actuation, processing and stratus-tracking, safety, and input) and provided a productivity analysis procedure to support cobot acquisition and deployment decisions.

Calvo and Gil (2022) introduced two new parametric models to evaluate the differential cost of assembly (economic dimension) and the differential income from taxes that supports short-term workforce displacement (social dimension) in cobot implementation. The authors provide two equations that allow determining the necessary minimum productivity with respect to implementing cobots in order to obtain positive unitary cost savings, for the economic dimension, and in order to have a positive contribution or compensation (i.e., the support of net replacement income of workforce substitution), for the social dimension.

These models are either focused on costs or productivity, but there are other benefits difficult to measure in monetary terms, such as improved safety, improved ergonomics, improved quality, and improved flexibility that should be included in the adoption decision. Meanwhile, there are no studies focused on the cobot adoption decision phase contrasting all the relevant criteria mentioned in section 2.3., through an investment appraisal perspective.

In order to develop a decision-making framework for cobot adoption, a literature review on existing decision-making methods for AMT adoption will be provided in the next section.

2.5. Decision-making methods for AMT adoption

One of the major challenges in justifying AMT investment is the consideration of all potential benefits (Abdel-Kader et al., 2018). Some benefits can be described using quantitative metrics, while others are intangible or difficult to quantify (Olfati et al., 2020). Consequently, many researchers have criticized the application of traditional investment methods in AMT investments, since they give emphasis to quantitative, financial aspects but ignore the qualitative benefits (Abdel-Kader et al., 2018). Over the past decades, many researchers proposed new decision-making methods to overcome this challenge (Olfati et al., 2020).

The relevant literature on such decision-making methods was analyzed and classified according to Hamzeh and Xu (2019) taxonomy, which consists of the following most common methods for technology selection: Financial analysis, Mathematical programming (MP), Data envelopment analysis (DEA), Fuzzy logic, Analytic Hierarchy Process (AHP), Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), Preference Ranking Organization Method for Enrichment of Evaluations (PROMETHEE), and Hybrid methods. During the article's analysis and systematization, two more methods were added to Hamzeh and Xu (2019) taxonomy: Elimination et Choice Translating Reality (ELECTRE) and Strategic models. The first one because it is another common multi-criteria decision-making (MCDM) method and the second one due to its high adoption and unique approach.

Table 1 provides a brief description of each method. The corresponding strengths and weaknesses are presented in Table 2. Therewithal, a detailed analysis of the selected articles is given in Appendix C. Appendix D organizes the studies per method.

It is important to note that Small (2006) research showed that the recent methods (such as AHP and fuzzy logic) are not being used by decision-makers in their investment decisions due to their complexity of application. This finding was also addressed by Frank et al. (2013). Most decision-makers are more familiar with spreadsheet models (Small, 2006).

Ultimately, some of the most common decision criteria found in literature include costs (e.g. Kahraman et al. (2007)), revenues (e.g. Li (2011)), flexibility (e.g. Al-Ahmari et al. (2016)), quality (e.g. Ordoobadi and Mulvaney (2001)), efficiency (e.g. Li (2011)), space requirements/savings (e.g. Sarkis (1997)), programming flexibility/programmability (e.g. Fu et al. (2019)), technical features such as velocity, capacity, accuracy, reach, repeatability (e.g. Fu et al. (2019)), productivity (e.g. Al-Ahmari et al. (2016)), compatibility (e.g. Randhawa and West (1992)), information (e.g. Wicks and Boucher (1993)), delivery (e.g. Chan et al. (2006)), competitiveness (e.g. Ordoobadi (2013)), public relations (e.g. Chiadamrong and O'Brien (1999)), customer satisfaction (e.g. Ordoobadi (2013)), innovativeness or technology position (e.g. Li (2011)), ergonomics (e.g. Jones et al. (2015)), safety (e.g. Jones et al. (2015)), employee relations (e.g. Ordoobadi (2013)), individual capabilities (e.g. Borges and Tan (2017)), market risk (e.g. Abdel-Kader and Dugdale (2001)), project risk (e.g. Ordoobadi (2008)), eco-friendliness (e.g. Song

Table 1. *Decision-making methods used in AMT selection*

Method	Description
Financial analysis	Financial analysis are investment appraisal techniques usually focused on determining the return of each investment (Hamzeh & Xu, 2019) and includes techniques such as Net Present Value (NPV), Internal Rate of Return (IRR), Return on Investment (ROI) or payback period, and benefit/cost ratio.
Strategic models	Strategic models usually appear in the framework form and include analysis of technical importance, business objectives, competitive advantage, research, and development objectives (Iakymenko et al., 2016).
Mathematical programming (MP)	Mathematical programming is a mathematical model used in decision problems (MirHassani & Hooshmand, 2019). Such models usually require parameters, decision variables, constraints, and objective function, where the objective functions need to be maximized or minimized to meet all constraints (MirHassani & Hooshmand, 2019).
Data envelopment analysis (DEA)	DEA is a non-parametric linear-programming based technique (mathematical programming technique) that focuses on evaluating the relative efficiency of a set of decision-making units (DMU) in the presence of multiple inputs and outputs (lo Storto, 2018). Although DEA is a mathematical programming technique, it is a separate taxonomy on Hamzeh and Xu (2019) work, due to its extensive application.
Fuzzy logic	Fuzzy logic comprises fuzzy models or sets that are a mathematical way to deal with problems that involve a source of vagueness (Karsak, 2002). The concept of a linguistic variable appears as a useful means for providing an approximate characterization of phenomena that are too complex or ill-defined to be described in conventional quantitative terms (Zadeh, 1975). A linguistic variable is a variable whose values are not numbers, but words or sentences. The value of a linguistic variable can be quantified using fuzzy set theory (Karsak, 2002).
Analytic Hierarchy Process (AHP)	AHP is a multi-criteria decision-making method (Wang et al., 2009). The general model decomposes a problem into a hierarchy of inter-related decision elements (Saaty, 2008). The main goal is at the hierarchy top, then are the broad objectives, originating the decision criteria, and at the lower level is usually a set of the alternatives (Saaty, 2008). All the elements of a certain level will go through a pairwise comparison with respect to the related elements in the level just above (Saaty, 2008).
Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS)	TOPSISS is a multi-criteria decision-making method (Wang et al., 2009) based on "the concept that the chosen alternative should have the shortest distance from the positive-ideal solution and the longest distance from the negative-ideal solution" (Kahraman et al., 2007, p. 418). The ideal solution is the one that maximizes the benefit criteria and minimizes the cost criteria (usually, a hypothetical alternative). The negative ideal solution is the one that maximizes the cost criteria and minimizes the benefit criteria (Aliakbari Nouri et al., 2015).
Preference Ranking Organization Method for Enrichment of Evaluations (PROMETHEE)	PROMETHEE is a multi-criteria decision-making method (Wang et al., 2009) whose principle is to rank the alternatives with simplicity and clarity; it is ideal for problems where the alternatives need to be ranked considering several conflicting criteria (Wang et al., 2009).
Elimination et Choice Translating Reality (ELECTRE)	ELECTRE is a multi-criteria decision-making approach that can be applied when a set of alternatives must be ranked according to a set of criteria reflecting the decision maker's preferences (Ateekh-Ur-Rehman et al., 2011). It uses concord, discordance indexes, and threshold values to analyze the outranking relations among the alternatives (Wang et al., 2009).
Hybrid methods	Combination of two or more methods.
Others	Scoring model
	Simulation and Linear additive scoring model
	Internet-based Collaborative Decision Support System (CDSS): knowledge-based systems, simulation (ProModel), and activity-based costing models Digraph and matrix methods
	Intelligent system integrating case-based reasoning (CBR) and the fuzzy ARTMAP (FAM) neural network model Taguchi loss functions SWOT, QFD, NPV, Payback, and MAUT (Multi-Attribute Utility Theory) method Cumulative prospect theory, Neighborhood rough set theory, and Three-parameter interval grey numbers

Source: Author own elaboration

Table 2. *Strengths and weaknesses of the decision-making methods*

Method	Strengths	Weaknesses
Financial analysis	– Easy to use – Precise and accurate when attributes are tangible	– Poor performance under uncertainty – Only takes into account financial and tangible attributes
Strategic models	– Requires less technical data – Directly tied to the goals of the company	– Extremely judgmental – Necessity to use these techniques with economic and analytic ones since they consider only long-term intangible benefits
Mathematical programming (MP)	– Can produce infinite alternatives – Capable of handling large-scale problems	– Lack of capability to weight coefficients – Needs to be used in combination with other methods to weight coefficients – Requires a lot of data – Complex
Data envelopment analysis (DEA)	– Efficiency can be analyzed and quantified – Capable of handling multiple inputs and outputs	– Assumes that all input and output are exactly known – Does not deal with imprecise data – Requires a lot of data – Complex
Fuzzy logic	– Take into account insufficient information – Allows for imprecise input	– Can require numerous simulations before use – Difficult to develop
Analytic Hierarchy Process (AHP)	– Easy to use – Hierarchy structure can easily adjust to fit many sized problems – Take into account a wide range of variables, both qualitative and quantitative	– Time-consuming with large numbers – Does not take into account the uncertainty – Perfect consistency is very difficult – Requires a lot of data
Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS)	– Easy to use and program – The number of steps remains the same regardless of the number of criteria	– Difficult to weigh and keep the consistency of judgment – Its use of Euclidean Distance does not consider the correlation of criteria
Preference Ranking Organization Method for Enrichment of Evaluations (PROMETHEE)	– Easy to use – Needs fewer inputs	– Does not provide a clear method by which to assign weights – The partial ranking is forced into a complete ranking of the alternatives – The generalized criteria need to be defined which may be difficult to achieve by an inexperienced user
Elimination et Choice Translating Reality (ELECTRE)	– Convenient when encountering a few criteria with many alternatives	– Sometimes it is unable to identify the preferred alternative
Hybrid	– Utilizes corresponding strength of each method	– Might be challenging to find the right combination of methods – Requires a lot of data – Usually more complex than other techniques

Sources: Hamzeh and Xu (2019); Iakymenko et al. (2016); Olfati et al. (2020); Wang et al. (2009)

and Wang (2012), and green flexibility (e.g. Bai and Sarkis (2017)). Appendix E provides greater detail on the specific references for each criteria, as well as the several categorizations attributed to it.

2.6. Conceptual Framework

From the findings of the literature review, a conceptual framework (Figure 1) was developed to describe the relevant concepts and to serve as a guide for the subsequent work.

Figure 1. *Conceptual Framework*

Criteria for the evaluation of AMT/cobot adoption decision						
Financial: Costs Revenues	**Operational:** Flexibility Quality Productivity Efficiency Delivery Space/Mobility	**Technological:** Programming Technical features Compatibility Information	**Strategic:** Competitiveness Public relations Customer satisfaction Innovativeness	**Human:** Ergonomics Safety Human-robot relation Individual capabilities	**Risk:** Market risk Project risk	**Environmental:** Eco-friendliness Green flexibility

Methods for the inclusion of the identified criteria in an evaluation process			
Economic: Financial analysis	**Stretegic:** Strategic models	**Analytic:** Programming (MP, DEA) Fuzzy logic MCDM (AHP, TOPSIS, PROMETHEE, ELECTRE)	**Hybrid:** Hybrid methods

Source: Author own elaboration

The criteria for the evaluation of AMT/cobot adoption decision presented in Figure 1 were based on the benefits, advantages, and disadvantages of cobot adoption and the criteria used in the decision-making methods for AMT adoption founded in the literature. In order to classify the decision criteria into the main areas for cobot adoption in a manufacturing companies, seven categories commonly used in the decision-making methods for AMT adoption (e.g., Aliakbari Nouri et al. (2015); Li (2011)) were used: Financial, Operational, Technological, Strategic, Human, Risk, and Environmental.

The methods identified in the literature for the evaluation process are mainly classified into four groups: economic, strategic, analytic, and hybrid (Meredith & Suresh, 1986; Naik & Chakravarty, 1992). Economic approaches include the financial analysis previously described. Strategic approaches are constituted of strategic models. Analytic approaches encompass programming methods (Naik & Chakravarty, 1992) such as MP and DEA; fuzzy logic (Al-Ahmari et al., 2016; Karsak & Tolga, 2001); and MCDM methods (lo Storto, 2018) such as AHP, TOPSIS, PROMETHEE and ELECTRE.

3. Methodology

This research aims to develop a decision-making framework for cobot adoption, incorporating a comprehensive set of quantitative and qualitative criteria, to be used by decision-makers in manufacturing companies. Accordingly, this section outlines the details of the research methodology, from the research design to the data collection method, data analysis, and research quality that led this research.

3.1. Research design

At the core of this research study was a constructivist philosophical perspective that sought to understand the meaning of a phenomenon by examining the perspective of its participants (Creswell & Creswell, 2018). The phenomenon under study was the decision-making process of cobots adoption (or AMT) and the need to gain valuable and detailed insights about it, entailing an exploratory nature to this study, making a qualitative approach suitable.

Knowing that the most recent decision-making methods for AMT adoption are not being used by decision-makers in their investment decisions due to their complexity of application (Small, 2006), it was essential to understand from an empirical perspective how decision-makers are making these decisions. For that reason, the interview research method was used. This was also one of the methods adopted by Borges and Tan (2017) to build a framework for incorporating human factors into the AMT selection decision. The research sample consisted of key actors in the cobot adoption decision process in manufacturing companies, particularly decision-makers who have already adopted cobots but also of key actors in the AMT adoption. Since cobots are still a new technology is the manufacturing context, it was difficult to access manufacturing companies that went through the cobot adoption decision. Consequently, the sample also included decision-makers of AMT adoption, since cobots are an AMT. Participants' availability and willingness to share their experiences was also a crucial aspect, thus, a criterion-based convenience sampling technique (Patton, 2002) was used.

Conducting interviews with professionals that have experienced the decision problem that this study addresses provided useful insights to answer the research questions, since it enriched and validated the decision criteria to be considered and enabled the proposition of a framework adapted to manufacturing companies' context, resources and needs. In fact, getting feedback from experts was suggested by Ordoobadi (2013) as future research.

To assure ethical processes of data collection, an informed consent explaining the research purpose and the procedures to maintain confidentiality was signed by all participants.

3.2. Data collection

For this research purpose, semi-structured interviews with open-ended questions took place, in order to have some guidance on the subjects to address during the interview and to allow the interviewer to clarify certain aspects if needed (Saunders et al., 2016). Therefore, based on the findings of the literature review an interview guide was developed (appendix F). The main topics tackled during the interview included i) identification of the criteria considered in the decision analysis of cobot/AMT adoption; ii) discussion on how to evaluate each criteria; iii) understanding the relative importance of each criteria; iv) learning which decision-making methods were used by managers in the cobot/AMT adoption decision.

The participants involved in this research had different senior job positions, and they were all involved in their companies' decision process of technology adoption. Six (C3, C4, C8, C9, C10, C11) out of the 15 companies had adopted cobots, and one was considering doing so (C1). Several industrial sectors were represented in this research, including automotive, textile, packaging, beverage, food, cosmetics, plastics, electronics, consumer goods, metal, and machinery. Moreover, geographic diversity was also promoted by the contributions from Portuguese, Spanish, Slovenian, and Polish manufacturing companies. Details of the interviewees characterization along with their companies are presented in Table 3 and Table 4. To preserve confidentiality, an ID was assigned to the interviewees, using letter I, and to the companies, using letter C. The number following the I indicates the interviewee number (per company), and the number following the C indicates the company number. Twelve interviews were conducted through video call, on Microsoft Teams, two through phone call, and one in the written form. The data was collected between February and May of 2022 and lasted on average 33 minutes. With the interviewee's consent, the interviews were audio-recorded for data collection accuracy and transcribed into written text. One of the interviewees (I1C6) did not consent to the recording, requiring note-taking.

The sampling process ceased at saturation, i.e. when no new insights or themes emerged from the collected data (Guest et al., 2016). After 15 interviews, the criteria mentioned by the participants were not new or were simple variations of already existing criteria. The same happened with the decision methods described.

3.3. Data analysis

A thematic analysis was conducted using NVivo software. A combination of a deductive and inductive approach was followed, starting with theoretically-derived themes from the

Table 3. *Interview characteristics*

Interviewee	Job title	Interview format	Duration (min)
I1C1	Divisional Industrial Director	Video call	35
I2C1	Project Manager	Video call	
I1C2	CEO	Video call	25
I1C3	Robotics and Automation Technician	Written	-
I1C4	Deputy General Manager / COO	Video call	22
I1C5	Industrialization Engineer	Video call	44
I1C6	Process/Industrialization Engineer	Video call	32
I1C7	Head of IT	Video call	56
I2C7	Head of Operations / Process Engineering	Video call	
I1C8	Industrialization Coordinator	Phone call	28
I1C9	General Manager	Video call	30
I1C10	Factory Process Engineer	Video call	21
I1C11	Coordinator of the industrial automation team	Video call	24
I1C12	Administrative Director	Video call	36
I1C13	Utilities & Energy Project Manager	Video call	40
I1C14	Executive Board Member	Phone call	27
I1C15	Operations Director / Executive Committee Member	Video call	35

Table 4. *Companies' characteristics*

Company	Industrial sector	Plant location	Headquarters	Turnover (2020) [a]	Employees (2020)[a]	Company size	Cobot adoption
C1	Packaging	Portugal	Portugal	27 M€	900	Large	No
C2	Textile	Portugal	Portugal	51 M€	320	Large	No
C3	Cosmetics	Spain	Spain	119 M€	680	Large	Yes
C4	Electronics	Slovenia	Slovenia	2 M€	14	Small	Yes
C5	Automotive	Portugal	Germany	295 M€	1028	Large	No
C6	Consumer goods	Portugal	Canada	50 M€	380	Large	No
C7	Automotive	Portugal	Germany	111 M€	450	Large	No
C8	Automotive	Portugal	France	68 M€	540	Large	Yes
C9	Metals and machinery	Poland	Poland	2 M€	24	Small	Yes
C10	Plastics	Portugal	Portugal	118 M€	1209	Large	Yes
C11	Electronics	Portugal	Germany	1 116 M€	3 631	Large	Yes
C12	Viniculture	Portugal	Portugal	6 M€	40	Small	No
C13	Brewery	Portugal	Portugal	345 M€	830	Large	No
C14	Automotive	Portugal	Portugal	110 M€	622	Large	No
C15	Food	Portugal	Portugal	129 M€	434	Large	No

[a.] Source: SABI Database

conceptual framework (Figure 1) and adding new ones that emerged from the data (Saunders et al. 2016). The first step involved getting familiar with the data, by reading and re-reading the interview transcripts looking for meanings, themes, and patterns (Saunders et al., 2016).

The code scheme was both theory (from the conceptual framework) and data-driven. For the latter, in vivo codes (actual terms used by participants) were used to honor the participant's voice (Saunders et al., 2016). Although most interviews were conducted in Portuguese, the translation into the English language was very careful in order to preserve the terms used by the participants. The codes were organized into themes and sub-themes, i.e., the coded data was grouped into analytic categories, and relationships were identified (Saunders et al., 2016). The main areas of inquiry were coded with structural coding for a general overview (Saldaña, 2016). Next, the decision criteria were organized with subcoding since the general code entries from the literature (e.g.: quality, productivity) required deeper categorizing, and subcategorizing into hierarchies (Saldaña, 2016). To register the participant's ranking of importance assigned to the criteria, the magnitude coding (Saldaña, 2016) was employed. In the final step, themes were refined and the proposed relationships were tested, by seeking alternative explanations that do not confirm the relationship being tested (Saunders et al., 2016). The complete codebook is provided in appendix G.

3.4. Research quality

Lincoln and Guba (1985) proposed credibility, transferability, dependability, and confirmability as the main criteria to evaluate the trustworthiness of constructivist research. For credibility reasons, triangulation via data sources was conducted, by examining the experiences of different informants; the data collection involved only participants willing to collaborate and the opportunity to withdraw from the study or to stop the audio recording at any point was clearly stated, providing a foundation for honest information sharing; frequent debriefing sessions between the researcher and the supervisors were undertaken to get new perspectives and discuss alternative approaches (Shenton, 2004). To enhance transferability, the phenomenon under investigation was clearly described as well as the research context (Shenton, 2004). Likewise, towards dependability optimization, a detailed characterization of the research methodology and procedures for data collection and data analysis was provided (Shenton, 2004). Finally, in order to demonstrate confirmability, quotes of interviewees' ideas were presented along the findings section. The data source triangulation also contributed to confirmability by reducing the investigator bias.

4. Findings

The data obtained from the interviews is presented in this section, with the following structure: 1) decision criteria and their evaluation method; 2) importance of each criteria; 3) relationship between criteria; 4) decision-making methods used by managers in the cobot/AMT adoption decision.

4.1. Decision criteria and their evaluation method

Table 5 presents an extensive list of decision criteria, as well as some indicators to be used by decision makers in cobot/AMT adoption decision. The category column organizes the criteria accordingly to the categories found in literature, except for the legal one which emerged from the data. Each criteria can be divided into sub-criteria (i.e., aspects to be considered in the cobot/AMT investment decision) which can be evaluated in several aways. The fourth column (Indicator/Evaluation method/Elements) provides ways of measuring or evaluating each of the sub-criteria. Whenever the sub-criteria are evaluated by the sum of the elements constituting it, such elements are given. The final column (Source) indicates whether the sub-criteria and corresponding indicator emerged from the literature review or from the interviews.

4.1.1. Financial

In the financial category, three different criteria were addressed by the participants: cost, revenues, profit and traditional investment performance measurements. The **cost** criteria includes the investment cost, maintenance costs (I1C13), operating costs, and equipment depreciation (I1C6 and I1C3). For the <u>investment cost</u>, not only the cobot acquisition price is important but also the integration cost of the technology since all the devices that interact with the equipment must be adapted (I1C8, I1C9, and I1C14). <u>Operating costs</u> include training cost (I1C4), machine utilization cost (I1C6) (such as energy cost (I1C13)), materials cost (I1C13 and I1C15), and labor cost, being the latter the most referred one (8 out of 15 participants). Labor costs were often referred in a cost-saving and not spending perspective. Participants mentioned that the increasing labor costs in the company's country (Portugal and Poland) was a main driver for adopting new technologies. The cobot (or AMT) implementation was actually meant to reduce man labor.

> "*One of the things we measure when we implement robots is the savings that exist at a labor level. It is also one of the reasons why robots are implemented. By implementing this robot, how many people will I save?*" (I1C8)

> "*An assembly line for Portugal usually has more technology than an assembly line in Romania because the minimum wage in Romania is half of the Portuguese. Essentially the purpose of technology is often to replace people at work and the higher the salary, the more this is a solution.*" (I1C5)

Regarding the **revenues** criteria, I1C5, I2C7, and I1C15 referred expected sales volume which is a new criteria compared to literature. According to I2C7:

> "*Investment in technology is always associated with sales volume. […] Producing 1,500,000 pieces per year implies a different technology than if we are thinking of producing 10,000 units a year. […] When the sales volume is not very large, we probably will only have manual stations*".

Lastly, the **profit and traditional investment performance measurements** were also disclosed as a decision criteria. As seen in the literature review, the financial analysis is one of the methods for assisting the technology adoption decision, which includes analysing measurements such as NPV, IRR, ROI, and payback period. Whenever the interviewee does not base his decision only in the financial analysis (or when he uses other decision methods), these measurements are seen as a criteria that competes with other decision criteria (I1C11, and I1C15).

4.1.2. Operational

Similarly to the financial category, all the participants contemplated the operational category. This category embraces flexibility, quality, productivity, efficiency, space/mobility, and ease of operation. The **flexibility** criteria uncovered three types of flexibility: product flexibility, since according to I1C1, implementing a new technology can make the production line more flexible in terms of types of products it can produce just by changing the robot tools; manufacturing flexibility because the changeover systems is faster with an automatic technology, less repetitive and can lighten the difficulties of tuning the equipment (I1C15), and equipment flexibility (I1C9).

The **quality** criteria was mentioned twofold: product quality and process quality, since when deciding to adopt a technology, decision-makers consider the improvements it can bring to the product and/or process quality. To arrange the **product quality** sub-criteria, the quality dimensions of Garvin were used (Garvin, 1984). The conformance dimension of product quality refers to meeting pre-established standards (Garvin, 1984). This form of quality was commonly addressed in the decision criteria for AMT adoption and was also mentioned by I1C4, I1C5, I1C12, and I1C15. Perceived quality was identified from I2C7 statement - "*the customer himself evaluates the quality of the product through its use*". This type of quality can be tracked through the number of customer complaints (I1C13). The performance dimension emerged from the data collected in the interviews. Performance refers to the primary operating characteristics of a product (Garvin, 1984). I1C6 mentioned taking into account the future impact of the technology in the performance of the final product. Because C6 produces safety car seats, performance in this case was the safety of the safety car seats and it had to be assured (I1C6). To evaluate product safety, I1C6 used the Process Failure Mode Effects Analysis (PFMEA) which helps to detect potential failures. **Process quality** sub-criteria were control and reliability. The control aspect was mentioned by I1C4 since with the cobot introduction, they didn't have to double-check anymore. Process reliability was described by I2C7 as the "*degree of process variation", "process accuracy*" and "*robustness*". According to I1C5, the more controlled a company wants the process to be, more technology it will install. A very straightforward way to measure the process reliability is through a capability study which will assess the process capability of delivering the customer specification (I1C5).

On the **productivity** criteria, I1C5 highlighted its importance in the automotive sector, saying that cycle times are very important, and if a technology buys time, it automatically becomes a candidate, unless the acquisition price is very absurd. To estimate such indicator, I1C6 combined three estimates of the cycle time: 1) the supplier's; 2) the company's methods and times team; and 3) his own, based on his professional experience with manufacturing technologies. "*The methods and times teams analyse the time that operators take to do each task and then extrapolate approximately what the machine time will be in the new technology*" (I1C11). Takt time[1], execution time, production rate, and the number of pieces produced per hour per operator were also mentioned by the participants as ways to measure productivity.

Efficiency is a broad term often associated with increased productivity and cost reductions (e.g.: downtime costs, parts replacement costs, etc) (I2C7). Therefore, the productivity criteria or the decrease in operational costs within the costs criteria, were sometimes referred as efficiency. The interviewees using this term, measured efficiency on the productivity perspective as the number of times the lines are stopped due to agglomeration of material or lack of material (I1C1). For the efficiency of raw material consumption in particular, I1C15 used the indicator: finished product divided by the raw material that enters the process.

[1] Takt time refers to the rate at which a company should produce a product to satisfy the total demand. It is calculated by dividing the available production time and the customer demand (I1C8).

The **space and mobility** criteria were addressed by I1C3, I1C8, I1C9, and I1C13. The lack of physical space to implement traditional industrial robots, make it an important criteria for some companies (e.g. C3). Regarding mobility, which refers to the ease of moving the equipment, I1C3 mentioned that although this is not the most important criteria when making the investment decision, it is a great advantage to have.

Three interviewees mentioned the **ease of use** criteria, which is a new criteria and indicates how easy it is to work with the machine (I1C3). For I1C14, if a technology is extremely simple to use, other companies can easily adopt it as well, therefore, some complexity in the technology can be advantageous in a competitive perspective, as long as it is possible to give the necessary training to the teams to know how to work with it.

4.1.3. Technological

The technological category was addressed by 10 out of the 15 participants. It includes programming, technical features, information, and interface language. The ease of **programming** was mentioned as an important criteria by I1C3, I1C4, I1C8, I1C9, and I1C10. The **technical features** were disclosed by six participants (I1C2, I1C3, I1C8, I1C9, I1C11, and I1C13) which referenced payload (kg), axes, repeatability, degrees of freedom, speed, range, impact detection capacity, and gas releases into the atmosphere. These are important aspects to consider towards determining the kind of technology best suited for a given situation (I1C8) and can be found in the technology's data sheet.

For I1C7 and I2C7, the capacity to collect and process **information**/data regarding the product and the process is of paramount importance - "*Information was not part of this major investment and today, in our view, it is essential to create a reliable data collection strategy. The information must be analyzed in real-time to allow us to predict situations in real-time*" (I2C7). I1C15 also mentioned the importance of predicting methods, where information is essential.

The **interface language** was a new and interesting criteria mentioned in this study. For I1C4,

> "*quite big influence on our decision on which producer to choose was first of all the intuitive programming, and the second, but certainly also important, was the interface in our local language. […] In the end, the decision was really for the European producer, because they offered us interface in our native language.*"

4.1.4. Strategic

The strategic category counted with contributions from five participants (I1C1, I1C5, I2C7, I1C10, and I1C10). The identified criteria were already mentioned in literature – innovativeness, competitiveness, company image, and customer satisfaction – but how innovativeness is assessed is new. About **innovativeness**, some participants revealed that they started to investigate cobots as they started to become available in the market (I1C1 and I1C11). According to I1C7,

> *"the main input for us to realize how innovative we are, regards to customer audits and management systems audits. From time to time, the (main) customer audits our company to see if the process we have is good, robust, etc. They may say that another supplier has a better technology for a certain task and this input allows us to position ourselves in relation to the competition."*

Competitiveness was among I1C1 and I1C7 goals, and **company image** was mentioned by I2C7 and I1C5 since adopting a new technology impresses the customers; they like to know that the company is working for the future (I1C5). Lastly, **customer satisfaction** was desired with the possible increase in the product quality (I1C7 and I1C13).

4.1.5 Human

The human category was discussed by almost all participants, 12 out of 15. In the interviewees' opinion, **safety** is one of the most important criteria (e.g. I1C11). To assess safety, I1C11 performs a risk analysis:

> "*In a preliminary phase, we identify the risks that can happen, e.g.: the robot can start screwing with a person's hand under the screwdriver tip; there may be an inadvertent collision of the person with the robot; there may be a pinch for any other reason, not initially foreseen. We then categorize the risks according to their severity (low, negligible, or medium risk) and implement some security measures*".

An indicator pointed out by I1C1 and I1C13 to measure this criteria was the number of accidents. I1C15 used the number of days an employee is in sick leave due to work accidents.

Participants I1C3, I1C4, I1C6, I2C7, I1C8, and I1C15 nominated the **ergonomic** criteria as a key to support humans in complex, repetitive, or heavy tasks and reduce absenteeism (I1C6). I1C6 used the ergonomic guide from Renault to control the ergonomics of a workstation, which specifies the weight to move, the number of repetitions per time, the heights (from the floor to a table and from a table to a shelf), the distances to travel, the necessary forces for handling equipment/assembling components. Both I2C7 and I1C8 performed an ergonomic analysis of the workstation as well. I1C7 added musculoskeletal injuries as an indicator to measure whether people in the workplace have gained any injuries or difficulties due to very repetitive operations, for example. I1C3 provided the frequency index formula used to calculate the frequency of casualties caused by overexertion and repetitive work[2]. Based on the data from the last 2 years, a prediction was made, calculating how much they would be avoided. I1C15 approach was similar to I1C7 and I1C3.

A new criteria that emerged from the data was the **human resources' availability**. Four participants mentioned that the lack of qualified workers or the lack of workers interested in performing the tasks as one of the main reasons for considering technology investment, inevitably influencing the decision making. As I1C1 said:

> "*The issue of human resources has more to do with the quantity and quality of people we have to perform this function and the difficulty is recruiting them. […] There is a strong dependence on people to keep the operation running but it is difficult to find skilled labor.*"

4.1.6. Risk

The risk category includes criteria related to the overall **project** of technology acquisition, from the supplier's service quality to the availability and implementation risk. The <u>supplier's service quality</u> criteria was addressed by I1C3, I1C9, I1C13, and I1C14, where I1C9 explained that the support of the supplier was important since they were not familiar with this technology. To evaluate such criteria, I1C3 mentioned going to fairs, exhibitions, and supplier's facilities to see the technology and evaluate its functionality. I1C13 and I1C14 were concerned with the supplier's experience and trustworthiness, investigating the number of similar projects undertaken and the years of experience of the integration team. <u>Availability</u> is a newly identified criteria by I1C9 as the participant was concerned with how quickly they could get the cobot. A direct way to assess this criteria is through the technology' delivery time (I1C14). Another criteria considered relevant by two interviewees is <u>implementation risk</u>. For I1C8 this is about how easy it is to integrate collaborative robots into production lines and for I1C3 is about the implementation time.

4.1.7. Environmental

Three participants (I1C2, I1C12, and I1C13) mentioned environmental concerns as decision criteria. I1C2 stated that sustainability (in an environmental perspective) is one of the company's pillars, impacting their decisions (I1C2). As a wine producer, C12 lives of natural resources and is strongly affected by climate changes (I1C12). Consequently, for this interviewee, environmental criteria are also very important. Both I1C2 and I1C12 assess this

[2] $\frac{Number\ of\ lost\ time\ injuries\ in\ the\ reporting\ perior \times 1{,}000{,}000}{Total\ hours\ worked\ in\ the\ reporting\ period}$

criteria through the technology's carbon emissions. For I1C13, sustainability is also about being more efficient in energy consumption and producing in renewable ways.

4.1.8. Legal

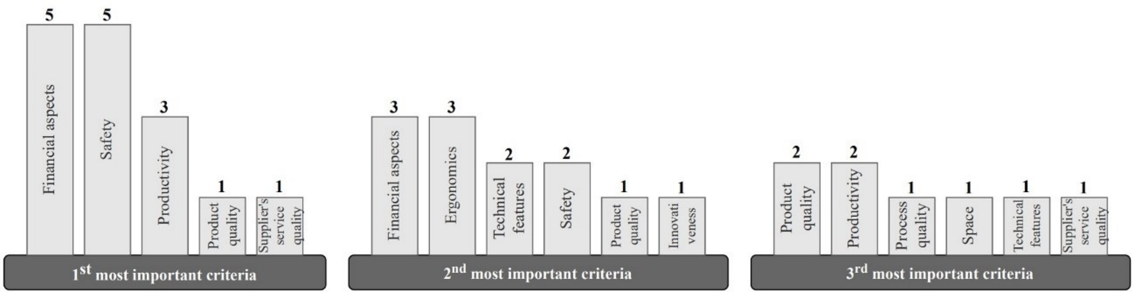
A new criteria identified from the interviews was the commitment to legal requirements, which justified the creation of this category, since it is not suitable in any other category. C12 and C13 produce alcoholic beverages which is a heavily regulated market and sometimes new regulations force changes in the production or packaging system, impacting on the technology to use. An example is the introduction of a new stamp in the bottles (I1C12). Evaluating this criteria means fulfilling or not the legal requirements, it is a 0 or 10 situation (I1C13).

4.2. Importance of each criteria

The importance of each criteria is influenced by the company's values, objectives, as well as specific problems it may be facing. Thereafter, no relationship was identified between the preferences of the interviewees, even for the companies in the same sector.

Participants were asked to rank the criteria they provided by order of importance. Figure 2 illustrates the importance given to the criteria. The first place is shared between financial aspects and safety, with five responses each. Next was productivity with three references. Financial aspects were also ranked second by some participants, tying with ergonomics. Each was mentioned by three different participants. Technical features and safety had two votes for the second place. Lastly, for the third most important criteria product quality and productivity had two votes each.

Figure 2. *Importance of the decision criteria*



Source: Authors own elaboration

Table 5. *Decision criteria for cobot/AMT adoption*

Category	Criteria	Sub-criteria		Indicator/Evaluation method/Elements	Source
Financial	Costs	Purchase cost		Price (Braglia & Petroni, 1999; Cohen et al., 2019; Goh, 1997)	A
		Installation cost		Special tooling costs; safety equipment; hardware development; software development (Bauer et al., 2016; Demmel & Askin, 1996; Kahraman et al., 2007; Platbrood & Görnemann, 2018)	A
		Maintenance cost		System diagnostics; repair and upkeep costs (Cohen et al., 2019; Randhawa & West, 1992)	A
		Operating costs		Labor cost; training cost (with operators and technicians); material cost or efficiency of raw material consumption (finished product / raw material that enters the process) (I1C15); machine utilization cost (e.g.: energy); set up cost (Chan et al., 1999; Cohen et al., 2019; Demmel & Askin, 1996; Enrique et al., 2021; Kahraman et al., 2007; Randhawa & West, 1992)	A
		Opportunity cost		Opportunity cost (Park & Kim, 1995)	LR_AMT
		Depreciation		Depreciation (Kahraman et al., 2000)	IAMT
	Revenues	Expected sales volume		Forecasted sales volume (I1C5; I2C7; I1C15)	I
	Profit and traditional investment performance measurements	Return on sales (Li, 2011)		EBIT/Net sales or Operating profit/Net sales	AMT
		Return on investment (Li, 2011)		(Current Value of Investment−Cost of Investment)/Cost of Investment	IAMT
		NPV		NPV (Frank et al., 2013; I1C1; I1C2)	IAMT
		IRR		IRR (Chan et al., 2006; I1C1)	IAMT
		Payback		Payback period (Frank et al., 2013; I1C1; I1C11; I1C15)	IAMT
Operation al	Flexibility	Product flexibility		Volume of parts, shorter cycle time; decreasing machine setup time (Al-Ahmari et al., 2016; Ordoobadi & Mulvaney, 2001). Range (number) of products that can be manufactured in a given time period (lo Storto, 2018; Sarkis, 1997)	A
		Process flexibility		Decreasing waiting time for parts; decreasing work in process (WIP) (Al-Ahmari et al., 2016; Ordoobadi & Mulvaney, 2001)	BLR
		Demand flexibility		Reduced lead times; reductions in inventory; decreasing time to market (Al-Ahmari et al., 2016; Ordoobadi & Mulvaney, 2001)	BLR
		Equipment flexibility		Increase machine utilization; reduction in idle time and cost (Al-Ahmari et al., 2016; Ordoobadi & Mulvaney, 2001)	A
		Manufacturing flexibility		Reduce material handling time; increase automatic tool change capability; reduce setup time; lower exchangeability and movements; reduce transportation time between workstations (Al-Ahmari et al., 2016)	A
		Volume Flexibility		Average range of production capacity per product type (lo Storto, 2018; Sarkis, 1997)	BLR
		Routing and Scheduling Flexibility (Chan et al., 1999)		Average number of operations per machining center (lo Storto, 2018; Sarkis, 1997)	BLR
		Expansion flexibility (Kreng et al., 2011)			LR_AMT
	Quality	Product quality	Conformance	Defect rate (Ordoobadi, 2013). Rate or qualified products; success rate (Li, 2011; Salunkhe et al., 2019). Rate of waste product; percentage scrap (Li, 2011; Ordoobadi, 2013). Rate of reworking; percentage reworkable (Li, 2011; Ordoobadi, 2013). Conformance to the standards; specifications; reliability (Mohanty & Deshmukh, 1998). Yield: Throughput minus scrap and rework (Sarkis & Talluri, 1999)	A
			Performance	Process Failure Mode Effects Analysis (PFMEA) (I1C6)	I
			Perceived quality	Number of customer complaints (Frank et al., 2013; I1C13)	IAMT
		Process quality	Control	Higher tolerance capability; improved control measures; inspection time/throughput time; rework decreased inspection costs; number of inspections (Jones et al., 2015; Ordoobadi, 2013; Ordoobadi & Mulvaney, 2001)	IAMT
			Reliability	Output/demand; Breakdown time/throughput time (Sawhney, 1991). Capability study (I1C5)	IAMT

Category	Criteria	Sub-criteria	Indicator/Evaluation method/Elements	Source
	Productivity	Productivity in costs	Price of output/labor cost; Price of output/Material cost; Price of output/Capital cost; Price of output/Overhead cost; Price of output/Total cost (Sawhney, 1991). Decreased labor cost; decreased material cost; decreased service cost of using capital (Al-Ahmari et al., 2016; Ordoobadi, 2013); Downtime costs (I2C7)	IAMT
		Productivity in time	Cycle time (Antonelli et al., 2016; Cherubini et al., 2016). Mean flowtime: time required to perform a task (Tsarouchi et al., 2016). Execution time (Bejarano et al., 2019); Takt time (Jones et al., 2015)	IC
		Productivity in units	Work in Process (WIP): Average inventory levels of products in systems (units) (Nagalingam & Lin, 1998; Sarkis, 1997). Inventory level: Average inventory level; Output/Average inventory (Sawhney, 1991)	LR_AMT
		Productivity in units/time	Labor productivity: number of good units divided by man-hour (units/hour/#operators) (Gil-Vilda et al., 2017)	A
		Productivity in time/units	Throughput: hours per unit of production (lo Storto, 2018)	A
		Equipment productivity	Rate of equipment utilization; Rate of machine breakdown (Li, 2011; I1C1)	A
	Delivery	Lead time	Includes: Setup time; Queue time; Move time; Transport time; Process time; Total throughput time (Chan et al., 2006; Sawhney, 1991)	LR_AMT
		Percentage of tardy jobs	Percentage of jobs executed with delay (Mehrabad & Anvari, 2010)	LR_AMT
	Space/Mobility	Floor space requirements	Amount of physical space that is required by the system (square feet) (Gil-Vilda et al., 2017; Sarkis, 1997)	A
		Weight	Cobot weight (Sherwani et al., 2020; Villani et al., 2018)	IC
	Ease of use	Ease of use (I1C3)		I
Technological	Programming	Programmability	Programming time or setup time (Cil, 2004; Sherwani et al., 2020; Villani et al., 2018). Robot's ability to be compatible with different programming codes (Fu et al., 2019)	A
	Technical features	Velocity or Speed	Speed that a manipulator arm can achieve (m/s) (Cohen et al., 2021; Fu et al., 2019)	A
		Load capacity or Payload or Workload	Maximum weight that a robot can lift (kg) (Cohen et al., 2021; Fu et al., 2019; Goh, 1997)	A
		Number of axes	Number of axes (Cohen et al., 2021)	IC
		Memory capacity	Number of points or steps that a robot can store in its memory (Fu et al., 2019)	LR_AMT
		Reach	Maximum distance that can be covered by the robotic manipulator (Cohen et al., 2021; Fu et al., 2019)	A
		Repeatability	Robot's ability to repeatedly return to a fixed position (millimeters) (Cohen et al., 2021; Fu et al., 2019)	A
	Compatibility	Compatibility	Compatibility with existing or new machines, tools, computer control, and communication (Randhawa & West, 1992)	LR_AMT
		Expanded use of technology	Number of other processes/areas in which the technology can be used; Number of other departments/areas that can benefit from the technology (Ordoobadi, 2013)	LR_AMT
	Information	Option for Computer-integrated manufacturing (CIM) (Wicks & Boucher, 1993)		IAMT
		Real-time information (Wicks & Boucher, 1993)		A
	Interface language	Interface language (I1C4)		I
Strategic	Competitiveness	Market Position	Market share (Bi et al., 2021). Competition assessment; market penetration; survivability; vulnerability; demand (Demmel & Askin, 1996)	A
		Growth	Ability to introduce new products; Ability of the system expansion (Nagalingam & Lin, 1998). Increased sales in target market areas (Ordoobadi & Mulvaney, 2001). Capture of new markets with future products: Increased speed for new product introduction (Ordoobadi, 2013)	LR_AMT
	Public Relations	Public Relations	Company image; Company prestige; Service (Demmel & Askin, 1996)	IAMT

Category	Criteria	Sub-criteria	Indicator/Evaluation method/Elements	Source
	Customer satisfaction	Customer satisfaction	Quick response to customer demand: improved delivery reliability, reduced delivery time (Ordoobadi & Mulvaney, 2001). Improved customer image: increased customer satisfaction, decreased complaints (Ordoobadi, 2013)	IAMT
	Innovativeness	Innovativeness / Technology position	New product variation, integration degree of new product development (Li, 2011). Research and development (Chan et al., 1999). Inputs from customer audits and management systems audits (I1C7)	A
Human	Ergonomics	Ergonomics	Operator load (Cherubini et al., 2016). Human physical strain (Krüger et al., 2009). RULA (Rapid Upper Limb Assessment) (McAtamney & Nigel Corlett, 1993). Mental workload (Elprama et al., 2017). Absenteeism rate (I1C6; I1C15). Frequency of casualties caused by overexertion and repetitive work (I1C3). Number of musculoskeletal injuries (I1C7). MSDs associated costs: Absenteeism cost; Medical and insurance-related expenses (European Agency for Safety and Health at Work, 2019)	A
	Safety	Safety	Risk of injuries: Probability of incidence × severity of the injury (Realyvásquez-Vargas et al., 2019). Number of accidents (I1C1; I1C13). Number of days that resulted in employee sick leave due to work accidents (I1C15)	A
	Employee relations	Motivation / Worker morale	Acceptability and enthusiasm for use of the system (Ordoobadi, 2013; Randhawa & West, 1992)	BLR
	Individual capabilities	Individual capabilities	Development of managerial, technical, and basic skills; Labour force empowerment; New skills from training on the new AMT (Borges & Tan, 2017; Randhawa & West, 1992)	LR_AMT
	Human resources availability	Human resources availability (I1C1; I1C5; I1C9; I1C15)		I
Risk	Market risk	Market	Volatility of demand; life of market (Abdel-Kader & Dugdale, 2001)	LR_AMT
	Project risk	Technology	Proven technology; experience in the company; technology novelty risk; obsolescence due to poor timing of adoption; technology reliability (Abdel-Kader & Dugdale, 2001; Ordoobadi & Mulvaney, 2001)	LR_AMT
		Supplier's service quality	Level and variety of services provided by a robot supplier (Fu et al., 2019). Number of similar projects undertaken; years of experience of the integration team (I1C14)	IAMT
		Implementation risk (Jones et al., 2015; Ordoobadi, 2008)	How easy it is to integrate collaborative robots into production lines (I1C8). Implementation time (I1C3)	IAMT
		Substituted risk	Technology substitution cycle (Li, 2011)	LR_AMT
		Resistance to change	Lack of management commitment/leadership; Low employee performance due to resistance to change; Increase in absenteeism due to low employee morale (Ordoobadi, 2013)	LR_AMT
		Availability	Technology's delivery time (I1C9; I1C14)	I
Environmental	Eco-friendliness and green flexibility	Ecological environment	Environmental quality, land usage, green degree (Song & Wang, 2012)	LR_AMT
		Resources consumption	Natural resources consumption, energy consumption (Bai & Sarkis, 2017; Song & Wang, 2012)	IAMT
		Green product flexibility	Volume of green products which are produced during the period (Bai & Sarkis, 2017)	AMT
		Pollution or waste flexibility	Volume of pollutants or wastes which are discharged (Bai & Sarkis, 2017)	AMT
		Recycling flexibility or Biodegradability	Volume of materials in products or wastes which are recycled or can be degraded (Bai & Sarkis, 2017)	AMT
		Environmental management system flexibility	Volume of environmental information which can be identified (Bai & Sarkis, 2017)	AMT
		Carbon emission	Tons of carbon emission (I1C2)	I
Legal	Legal requirements	Legal requirements	Fulfilling or not fulfilling the legal requirements (0 or 10) (I1C13)	I

LR_AMT: Literature review on decision-making methods for AMT adoption LR_C: Literature review on cobot's advantages/benefits and costs
BLR: (Both literature reviews) Literature reviews on decision-making methods for AMT adoption and on cobot's advantages/benefits and costs I: Interviews
IAMT: Interviews and literature review on decision-making methods for AMT adoption IC: Interviews and literature review on cobot's advantages/benefits and costs
A: (All) Interviews, literature reviews on decision-making methods for AMT adoption and on cobot's advantages/benefits and costs

4.3. Relationship between criteria

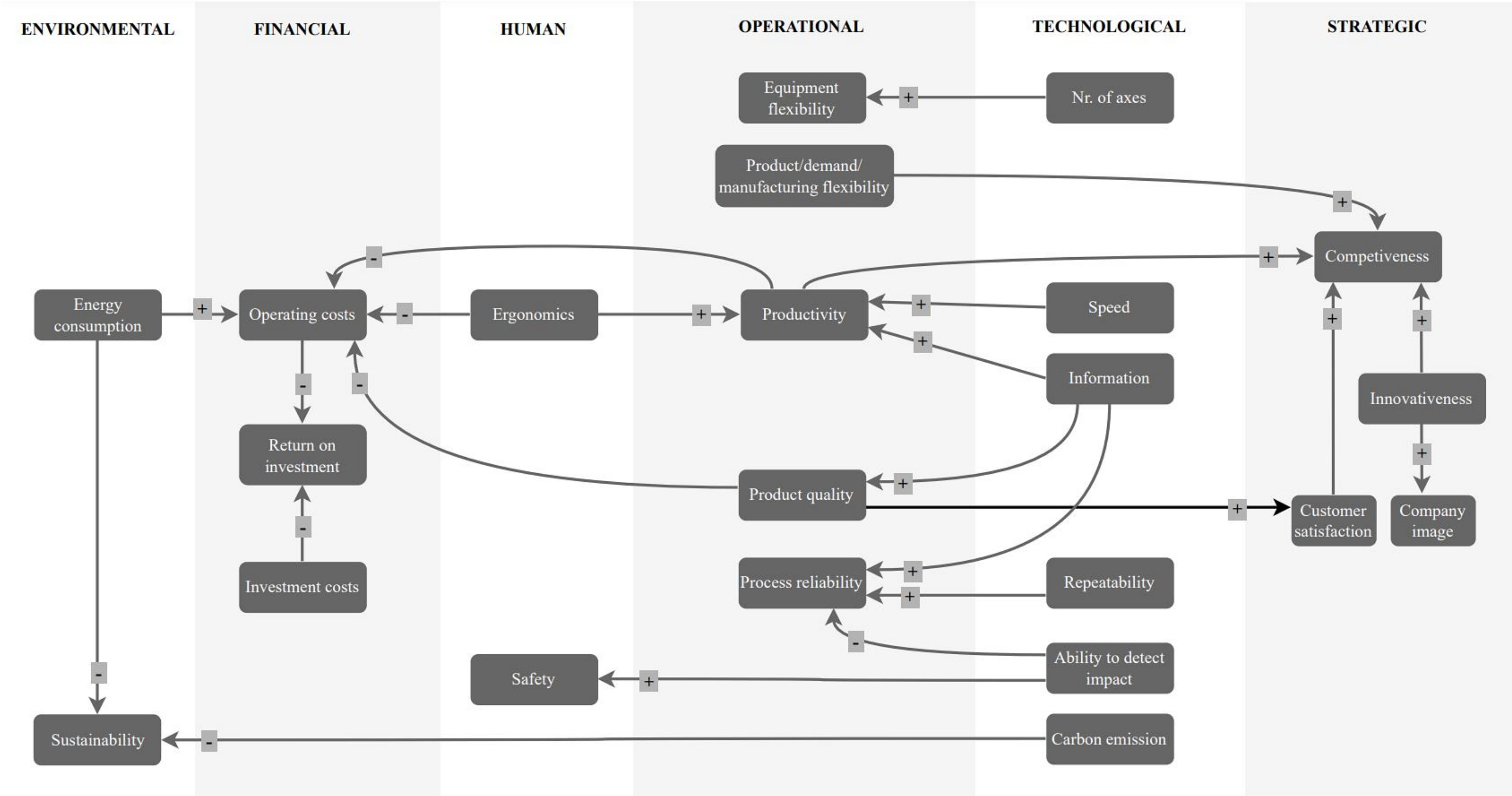
From the interviews it was also possible to identify some relationships between criteria from the same category and between criteria from different categories. A visual representation of the relationships is presented in Figure 3.

The technological category has a tremendous effect on the operational category. More forsooth, the technical features criteria are related to equipment flexibility, productivity, and process quality. According to I1C9, the cobot's six axes give it a lot of flexibility. In line with I1C11, productivity and process quality are a consequence of the cobot's technical features. For example, the speed the cobot can reach determines productivity. The cobot's repeatability positively affects the process reliability within process quality (I1C8). Also, cobots' capacity to detect impacts makes the robot more or less sensitive, where highly sensitive cobots can hinder the process quality (I1C11).

About the information criteria, I1C7 and I2C7 claim that collecting and analyzing the data provides important insights to optimize the production processes (reliability in process quality). With constant collection and processing of information, it is possible to follow everything that is being produced and getting alerts in critical cases that must be corrected. Subsequentially product quality and productivity also improve. Productivity itself is connected to operating costs, either decreasing labor costs or decreasing material costs (I1C7). As I1C10 mentioned, "productivity is already financial return". Similarly, raw material consumption efficiency leverages the return on investment by decreasing material costs (I1C15). Because producing non-conform products results in subproducts or scraps, the efficiency of raw material consumption decreases, increasing the material costs (I1C15). Therefore, product quality also affects operating costs (I1C15). At the same time, efficiency improvements in the productivity perspective enhance the company's competitiveness (I1C1). In this strategic line, innovativeness is associated with improving company image (I1C5) and increasing product quality with increasing customer satisfaction (I1C7). At the environmental level, technical features are linked to sustainability in terms of the gas releases into the atmosphere (I1C1). Furthermore, being efficient in energy consumption is not only good for the environment but can also decrease operational costs (I1C13).

In the human category, ergonomics has an impact on both productivity and operating costs. As already mentioned, non-ergonomic workstations lead to increased absenteeism rates due to MSD, which in turn decreases the productivity of the production line. Besides, whenever

Figure 3. *Relationship between criteria*



Source: Author own elaboration

a worker is absent, the manufacturing company may not only have to pay to the worker on a sick leave but sometimes also needs to hire a new temporary worker to replace the former. Thus, improving ergonomics is not only beneficial for the human but also for the company productivity and cost efficiency, which in turn will lead to other benefits.

4.4. Decision-making methods used by decision-makers in manufacturing companies

After discussing which criteria the participants take into consideration in the decision process, it is essential to understand how they are all related to reach a decision on the adoption.

4.4.1. Financial analysis

The majority of the participants (I1C1, I2C1, I1C2, I1C7, I2C7, I1C8, and I1C10) make use of financial analysis to decide on the adoption of a certain technology even if other elements are taken into consideration. In other words, the project manager responsible for studying the technology acquisition looks at the different criteria he/she finds important, e.g. productivity, safety, or quality, and if the results are suitable, the solution is presented to the board or to the person who makes the final decision. To approve the technology acquisition, the board/shareholders are inevitably interested in the financial return of the investment, focusing their decision on the financial analysis, that is, in the return of investment (ROI) indicator and payback period. But there are some exceptions - according to I1C1 and I1C8, sometimes, the safety criteria overlaps any financial analysis since it is crucial to assure a safe work zone for the employees. Product quality or legal requirements may also be exceptions to this rule (I1C13).

4.4.2. Demonstration of value added

For I1C5, when deciding to adopt a technology, it is key to be able to demonstrate the value added. This method involves identifying clear weaknesses of the current production process and presenting the improvements that the new technology will bring. This can be done through the direct demonstration of the technology and/or the measurement of the obtained results, for example, the reduction of the cycle time.

4.4.3. Weighted scoring method

The decision method described by I1C6 consists of comparing three different business cases: one with a manual station, another with a basic tool, and another with a technology/an automatic machine. For each business case, information about the equipment investment cost, equipment operating costs, and amortization costs are included, besides the product safety, ergonomics, and productivity criteria which are specific for this company. Afterwards, in order to relate all the criteria, the scores of each criteria are added, being that different weights are assigned to each criteria according to their importance. Whenever there is a solution harder to implement, the decision-maker adds to the overall score a risk correction factor. I1C13 used a similar method, but instead of comparing the three aforementioned business cases, he compares different equipment/technology alternatives. The evaluation of each criteria is performed on a scale of 1 to 10 to make the data comparable. At last, the different alternatives are ranked according to their score (sum-product between the criteria evaluation and its weight). I1C14 compared different equipment suppliers but no scale is used, instead, specific indicators for each criteria are registered.

These three participants use the same rationale for decision-making, but they differ in the team's involvement and number of decision-makers. I1C5 prepares all the business cases and fills himself the sheet. The necessary departments are involved in the decision-making as they provide the inputs/information for the decision matrix, but in the end, only I1C5 provides the importance weights and makes the final conclusions and then present to the board. In C13 case, the decision matrix is prepared in group, all the interested parts are involved, so the inputs for the decision matrix are a result of a consensual evaluation. At C14, one person is responsible for doing the procurement, identifying suppliers, and preparing the decision matrix. Afterwards, two different people fill in the matrix and decide on the matter. I1C14 upholds this separation between who is preparing the analysis and who will decide, arguing that if there was a collaborative preparatory work, the decision would be biased by aspects that probably will not be in the matrix.

4.4.4. Reaching a minimum acceptable level

After collecting all the necessary data to evaluate the decision criteria, participants I1C9 and I1C11 seek to reach a minimum acceptable level for each criteria. This process depends on the importance given to each criteria. For example, if the safety criteria is given the highest importance, a technology (investment option) only moves to the next level if it fulfils an acceptable level defined by the decision-maker. Considering that it does, it moves to the second most important criteria, quality, for example. By examining the improvements (or not) the technology can bring to the production process, already tested in a data collection phase, the decision-maker decides if the quality level is acceptable or not. Lastly, if the third most important and last criteria the decision-maker wishes to explore is a financial criteria, payback time, for example, the technology is only acquired if the payback time occurs within the time frame defined by the decision-maker.

4.4.5. General approach

For two of the smaller companies interviewed, the approach is a bit more flexible. I1C4 and I1C12 mentioned to perform the common financial analysis (ROI and payback time) but they recognized that some benefits are difficult to include in such calculations. Thereafter, they discuss the benefits of acquiring such technology with the board and try to understand if the investment is worthy. Most of the time, technology investments are justified as a means for preventing future issues or to improve the company's overall performance and efficiency. Overall, this is a more abstract and general approach that did not include many attempts of quantifying all the criteria (only the financial). Instead, a consensus is reached in a meeting with the interested parties.

4.4.6. Characterization sheet

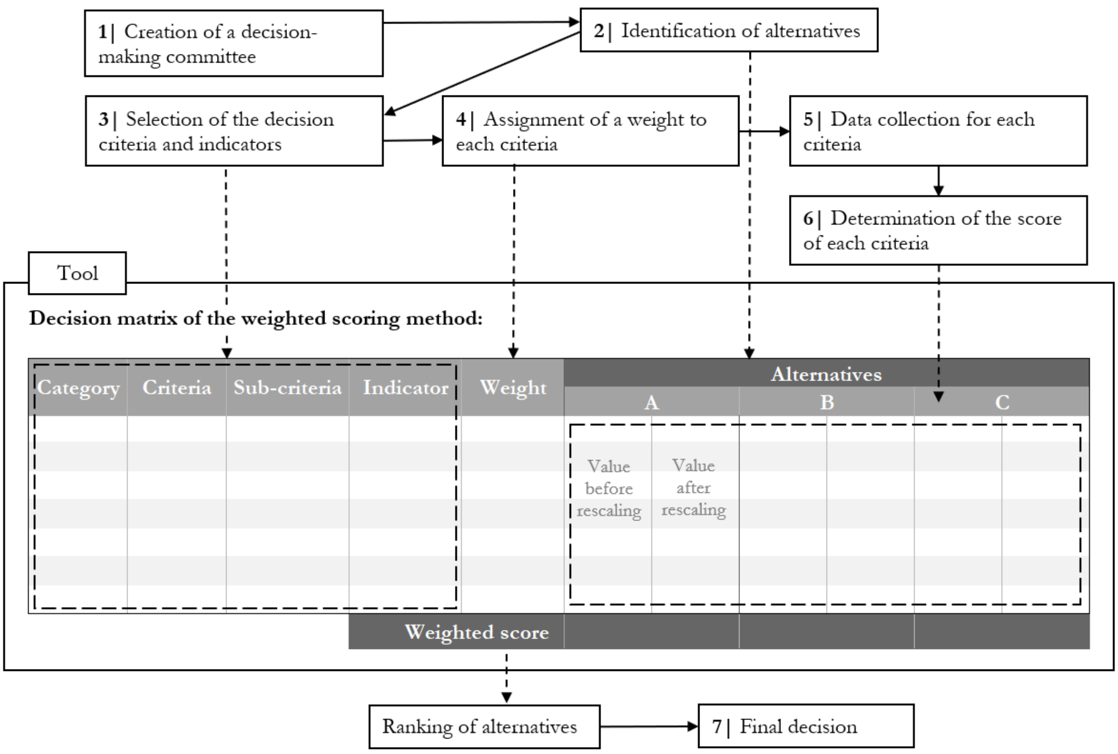
The idea of competing investment projects within the same company was introduced by I1C15. Companies do not have unlimited resources, so not all investment projects can proceed. In C15, each department takes some investment projects for board approval. To make these projects comparable, I1C15's company uses a characterization sheet template for all investments. In this template, teams must present the current situation and the future situation, along with start and end dates, required investment amount, ROI/Payback, tangible benefits, intangible benefits, critical success factors, and comments. Afterwards, there is a comparison/competition of the investment proposals' tangible and intangible benefits and a prioritization is given. Projects given priority one will materialize in the year of analysis, projects given priority two will be studied in the next year, and projects given priority three are discarded.

4.5. Decision-making framework for cobot adoption

In a previous section, literature on decision-making methods for technology adoption was reviewed and the difficulty of applying such methods in real context was stressed by Small (2006) and Frank et al. (2013). Recognising this shortcoming, the framework now proposed considers the interviewees' opinions and requirements.

Three interviewees (I1C6, I1C13, and I1C14) use weighted scoring methods (WSM) for their investment decisions, and another interviewee (I1C1) mentioned that a decision-making method cannot treat all situations equally; it must allow giving greater or lesser preponderance to certain criteria, depending on the problem to be solved. Additionally, some interviewees recognized that different suppliers always need to be compared (I1C3, I1C13, I1C14). Grounded in these findings, a WSM comparing different alternatives seems to suit the decision maker's needs. A key take away is that this method enables accounting for both quantitative and qualitative criteria structurally (Iakymenko et al., 2016). Figure 4 shows the proposed decision-making framework, to which a set of guidelines to use it is provided in the following section. It includes more steps that a general WSM, in order to be more oriented to the cobot adoption decision. Briefly introducing the steps in a general WSM, after identifying the important criteria to the decision, the decision-maker must assign a weight to each criteria, according to their importance. Subsequently, the score of each criteria is determined (i.e., the alternatives are evaluated regarding their performance on each criteria). Combining everything, the weighted score of each alternative is obtained by multiplying the importance weights of each criteria and the evaluation scores of each criteria. Finally, the alternatives are ranked.

Figure 4. *Decision-making framework for cobot adoption*



Source: Author own elaboration

4.6. Guidelines for using the proposed decision-making framework

Based on the literature review and the interviews' results, guidelines to follow when using the proposed decision-making framework are provided, so that manufacturing companies can customize it to their context, needs, and resources. These guidelines regard each step of the decision-making framework, and the tool to use.

4.6.1. Decision-making committee

I1C13 highlighted the importance of making people feel involved in the investment decision (I1C13). The decision-maker should listen to all the stakeholders, not just the finance staff and the technical/engineering personnel but also the operators, who are closer to the factory floor and who will then be working with the technology (I1C13).

The reality is that technology adoption is rarely a single person's decision; it usually involves a committee or a group of experts with different expertise (Fu et al., 2019). Hence, two decision makers might have different opinions on the criteria to consider (I1C14) or the performance of an alternative on qualitative criteria. There are at least two approaches to deal with this struggle: 1) reaching a group consensus through brainstorming or the Delphi method (Cil, 2004); 2) computing the weighted geometric mean (WGM) or the weighted arithmetic mean (WAM) to aggregate all decision-makers answers (Jaganathan et al., 2007).

The latter approach involves having each decision-maker filling the decision matrix and then calculating the geometric or arithmetic mean of the answers. Determining the weights to assign to the decision-makers, which represent each decision-maker's contribution to the final decision, becomes an issue (Kreng et al., 2011). To overcome it, Kreng et al. (2011) proposed a model utilizing the assurance levels of one decision-maker for his/her evaluation as the starting point to determine the weights. The higher a decision maker's confidence, the greater his/her contribution would be to the final decision (Kreng et al., 2011). However, this method requires fuzzy logic, which as seen before, can be overwhelmingly difficult. Besides, WGM or WAM methods do not address the problem of having different opinions on which decision criteria to consider. All in all, it is advisable to reach a consensus through meetings, brainstorming, or the Delphi method.

4.6.2. Identification of alternatives

As already mentioned, some interviewees recognized that different suppliers must be compared. For those situations, the decision-maker(s) should identify the different cobot supplier and/or models to compare. Alternatively, different types of technology can be compares. In this stage, a primary search could occur next to the manufacturing company' usual technology suppliers (I1C11), to understand if they have the required type of technology, and which options. When searching in the market, it is useful to attend innovation fairs, where different manufacturing technologies are presented (I1C3; I1C13).

If the decision-maker(s) does not wish to compare different alternatives, different scenarios can be defined instead. An example are the scenarios used by I1C6: one with a manual workstation, another with a basic tool, and another with a technology/an automatic machine.

4.6.3. Selection of the decision criteria

At this stage of the decision process, the decision-maker(s) should select the decision criteria per category and the corresponding indicator. A list of potential decision criteria is provided in table 5, along with some indicators, from which the decision-maker(s) can select the most suitable ones. Some of these criteria are quantitative, others are qualitative. Decision-maker(s) can also select other decision criteria and other indicators since the decision criteria will differ from one situation to another.

For I1C15, it was important that that concurrent investment projects were comparable. To achieve this level of comparison using the proposed decision-making framework, the decision-maker(s) can establish fixed decision criteria to use for all the investment opportunities.

The relationship between the decision criteria is an important aspect to account for in order to avoid double-counting benefits or costs. Looking at the productivity criteria, because productivity improvements might result in decreased labor and material costs, this criteria can be evaluated by the forecasted decrease in such costs. If a decision-maker(s) chooses simultaneously to include in the decision matrix the costs criteria, and to evaluate productivity by the cost reduction, cost reduction will be counted twice. Another example is the relationship between the cobot's technical features and operational aspects. As previously mentioned, the speed the cobot can reach is an input to determine productivity. Therefore, decision-makers should be aware of these situations and select only one of the criteria. If a company is capable of estimating the operational indicators, the operational criteria can be preferred due to their higher richness and impact on the manufacturing process. Otherwise, the technical features criteria can be used instead.

4.6.4. Weights assignment

The analytic hierarchy process (AHP) technique could be used to determine the relative importance weights (as in Ordoobadi (2013)) but that can be time-consuming and the interviewees did not show any difficulty in empirically assigning weights to the criteria (adding up to 100%), i.e. a simple scoring method, making the latter option preferable for a real context. When more than one sub-criteria is selected, it should also be determined the importance of each sub-criteria to the main criteria. The same happens regarding the importance of each indicator with respect to the criteria or sub-criteria.

4.6.5. Data collection

Any decision matrix needs to be fed with the required data/information in order to give a result. Since the framework is meant to help in decision-making for cobot adoption, the data must concern the future cobot's performance regarding each criteria. One of the ways to collect information about the cobot is by attending fairs to see the technology demonstrations and meet suppliers to learn more about the technology (I1C3). For a more unbiased opinion, visits to competitors' plants or other premises should be arranged to see the cobot in a real industrial setting but also to question the competitors about the technology's performance (I1C13).

Analyzing the cobot's data sheet provided by the supplier will also provide information such as weight, payload, reach, joint ranges, speed, repeatability, footprint, degrees of freedom, programming, power consumption, etc. (I1C3; I1C8) which can sometimes serve as a direct input for the decision matrix, or as bases for projections about other criteria (productivity and process quality, for example).

In order to obtain estimates for the quantitative criteria, companies can also make use of the prototypes made available by the suppliers (I1C6; I1C13; I1C15). Whenever possible, experimenting and testing these prototypes in the company's production lines, will provide real and valuable data for the decision matrix (e.g. product quality, safety). A more flexible way to test the cobot is through virtual simulation. Simulation models recreate the manufacturing process and test the technology under different conditions, without wasting material. They require input data such as machine processing times, capacity, speed (Cil, 2004), product mix, system configuration, etc. (Kakati, 1997), and provide output measures such as throughput time, quality level, system utilization, the effect of break down, level of flexibility, etc. (Kakati, 1997). Literature has used simulation languages like SIMAN, SLAM, SLX, SIMSCRIPT, and simulators like ProModel, WITNESS, ARENA, and TAYLOR (Cil, 2004). Building a simulation model is not a trivial task, it can be costly and time-consuming to develop it and not everyone has the required expertise to do so. In fact, from the 15 interviewees, only one mentioned recurring to simulation projects but with help of a Portuguese Research Centre. Companies facing this difficulty can alternatively rely on the teams' professional experience to estimate and forecast the required data.

4.6.6. Score of each criteria

To quantity qualitative criteria, it is common to use a score in a 0-10 scale (Randhawa & West, 1992). The quantitative criteria are either expressed in monetary values or time units, requiring conversion into the same scale so that quantitative and qualitative criteria are comparable. In traditional WSM, the quantitative criteria are also evaluated on a 0-10 score. As an example, for a cost criteria, 0 represents a very high cost while 10 represents a very low-cost value (Randhawa & West, 1992). However, this would require analyzing every indicator from each quantitative criteria to assign a 0-10 score, which is a highly subjective task and can be a heavy burden for the decision-maker. To overcome this deficiency, the quantitative criteria can be measured through the indicators provided in table 5 (or any other) and normalized to fit the scale of the qualitative criteria score. It should be noted that the models introduced in section 2.4., regarding models developed to quantify some aspects of cobot adoption can and should be used to perform calculations such as operator cost, equipment cost, quality costs, and productivity (throughput). These models are specific to cobots, so they consider the collaborative mode between human and robot.

Recalling I1C5 decision-making method of justifying an investment based on the improvements it can bring compared to the baseline performance, quantitative criteria could be introduced in the decision matrix as the percentage of improvement, whenever suitable. Rescaling these criteria into o 0-10 scale only requires dividing by 10. Some criteria are not feasible of being compared to the baseline performance, such as the investment costs. In such situations, rescaling can be performed as follows: $x' = \frac{(x-min)}{(max-min)} \times 10$. This way, the lack of impartiality pointed out by I1C13 and subjective judgment pointed by I1C14 can be greatly reduced, even though some qualitative criteria still need to be evaluated by the decision-maker assigning a 0-10 score (e.g., ease of use) since no indicator was found. Another way to deal with subjective judgment is by performing sensitivity analyses (Borges

& Tan, 2017), which can be applied either in the weight assignment or in the criteria evaluation.

Two interviewees (I1C9 and I1C11) decide on technology investments based on the fulfilment of a minimum acceptable level for each criteria. Manufacturing companies capable of assigning the target values and specification limits for the acceptable deviation from the target for each criteria can apply the Taguchi loss function, proposed by Ordoobadi (2013) to objectively measure the technologies' performances with respect to the decision criteria. No rescaling is required since all criteria, regardless of the units of measurement, are converted into a common measurement: loss score (Ordoobadi, 2013).

Furthermore, one of the interviewees using WSM disclosed some difficulties in scoring a supplier (on a 0-10 scale) when there is no previous experience with the supplier (I1C13). Literature has suggested fuzzy logic to deal with this type of imprecision and vagueness (Karsak, 2002) however, it is difficult to use this technique (Hamzeh & Xu, 2019), especially for a decision-maker not knowledgeable in mathematical methods. Some other conditions like simplicity would be lost. For this reason, most of the time it is preferable to maintain some imprecision for the sake of the decision-making method simplicity and feasibility.

4.6.7. Final decision

After all the steps of the decision-making framework had been completed, the decision-maker(s) takes the final decision.

For a more visual perception of what a filled decision matrix would look like, an example is provided in figure 5. Based on the decision matrix, the best alternative is the one with the highest score. In this fictional example, the best cobot solution is C.

4.6.8. Tool

One final consideration regards the tool to implement the decision matrix. Ideally, the tool would allow the decision-maker to select the decision criteria per category and the corresponding indicator from a list or a drop-down menu, which can be performed in Microsoft Excel with the data validation feature. There should also be a field to manually insert new decision criteria and new indicators. To avoid the double-counting benefits or costs introduced in 4.6.3, the tool used would automatically eliminate duplicates. However, this can only be assured to the criteria/indicators suggested in the list.

Furthermore, I1C14 mentioned the constant exercise of data standardization and harmonization as a disadvantage of WSM, and an automated Excel sheet can reduce this effort with the rescaling techniques presented in 4.6.6. Overall, Microsoft Excel seems to be a good option since it is widely available and familiar to the decision-makers; all interviewees mentioned using Microsoft Excel in their investment decisions. It is a simple tool to use and can easily be adjusted by the decision-maker(s) with no programming expertise required.

Figure 5. *Example of a filled decision matrix*

Category	Criteria	Sub-criteria	Indicator	Weight	Alternatives						Auxiliary information:
					A		B		C		Baseline performance
Financial	Traditional investment performance measurements			25%							
		Payback	Payback	18%	2	3.33	1.5	0.00	3	10.00	
		NPV	NPV	7%	30 000 €	6.36	23 000 €	0.00	34 000 €	10.00	
Operational	Product quality			10%							
		Conformance	Defect rate	8%	5%	0.50	6%	0.40	3%	0.70	10%
		Perceived quality	Number of customer complaints	2%	20	0	10	5	15	2.5	20
Human	Ergonomics	Ergonomics	Frequency of casualties caused by overexertion and repetitive work	20%	0.2	8.33	0.5	5.83	0.4	6.67	1.2
	Safety	Safety	Number of accidents	30%	10	8	10	8	20	6	50
Risk	Project risk	Supplier's service quality		5%							
			Number of similar projects undertook	3%	3	3.33	2	0	5	10	
			Years of experience of the integration team	2%	2	0	4	10	4	10	
Legal	Legal requirements	Legal requirements		10%	0	0	10	10	10	10	
			Weighted score			5.252121		4.898667		7.239333	

Source: Author own elaboration

To summarize this section, appendix H presents the advantages/disadvantages of the methods used by the interviewees and the requirements/best practices mentioned by them. The last column of the table indicates the proposed measures to tackle the disadvantages and the requirements, or the measures to enjoy the advantages.

6. Discussion

Many of the criteria considered in cobot adoption by the interviewees had already been reported in literature of decision-making methods for AMT adoption. For this reason, only the newly identified and the most important criteria, sub-criteria and indicators will be discussed in this chapter. This study presents 27 general criteria and 73 sub-criteria in which four are new criteria and four are new sub-criteria. The newly mentioned sub-criteria *expected sales volume*, emphasizes the importance given by the interviewees to the financial aspects on investment decisions. Product quality was mentioned in different perspectives, uncovering a new dimension when compared to the decision criteria in literature – performance. Considering the future impact the technology can have in the performance of the final product, the *product performance* sub-criteria emerged with I1C6 contribution. Along with it came the Process Failure Mode Effects Analysis (PFMEA) as an evaluation tool, which can be applied to other types of products besides the one produced on C6 (safety car seats). *Ease of use* and *interface language* show that manufactures are interested in having a technology that they can easily work with; adopting an overly difficult technology to use can difficult the implementation process. A new method to evaluate the innovativeness criteria was brought up by an interviewee, which is through the inputs from customers audits and management systems audits. According to I1C7, these inputs allow the company to position itself in relation to the competition. The *human resources availability* criteria demonstrates that the lack of qualified workers or the lack of workers interested in performing the tasks influences the decision making towards more technology adoption. Still in the human category, the frequency of casualties caused by overexertion and repetitive work (I1C3), and the number of musculoskeletal injuries (I1C7) are some new ways of evaluating ergonomics. *Availability* (of the cobot) highlights the need for a readily available technology. Lastly, *carbon emissions* and *legal requirements* demonstrate that manufacturing companies are also socially responsible.

Cobots are identified as an enabler of industry 5.0 since they place the human welfare at the centre of the production system (Doyle-Kent & Kopacek, 2021). When adopting a cobot, aspects such as ergonomics (mentioned by 6 participants), and safety (mentioned by 8 participants) are taken into consideration, reflecting an increased concerned with the human-worker, and the work environment. It was also shown that improving the ergonomics of the workstation can increase productivity and decrease the costs related to the workers' absence (due to MSD), highlighting the benefits a cobot can bring for the industry, the workers and the society.

Nevertheless, a surprising finding concerns the cobot utilization. What distinguishes cobots from traditional robots is their ability to safely work alongside humans and to be able to assist humans on non-ergonomic tasks due to their collaborative mode (Bauer et al., 2016). Although the data supported the preference of these cobots due to their safety features, it does not fully support the idea that cobots are adopted to assist humans. Considering only the participants who had already adopted cobots, two of them (I1C3, and I1C4) mentioned that one of the prime reasons for the cobots adoption was to free humans from repetitive or heavy tasks, thus the cobot was being used in collaboration with the human. However, the remaining four cobot adopters (I1C8, I1C9, I010, I1C11) were using the cobot in the non-collaboration mode. In these companies, the cobots were not meant to assist people but to replace them.

Moving on to the decision-making methods, literature has proposed a variety of them. From the most traditional financial analysis to strategic models, MP, DEA, fuzzy logic, AHP, TOPSIS, PROMETHEE, ELECTRE, hybrid methods, and others. However, this study results reveal that the interviewed companies are using financial analysis, demonstration of value added, weighted scoring method, reaching a minimum acceptable level, general approach, and a characterization sheet to decide on the technology adoption. These findings corroborate Small (2006) conclusions that the most recent methods (such as AHP and fuzzy logic) are not being implemented by decision-makers in their investment decisions. Small (2006) justifies this event due to the methods' complexity but the present research uncovered two other possible explanations. When questioned about what decision-making methods (models, analyses, or frameworks) they used in their decisions and their opinion regarding the ideal/most suitable decision method, most interviewees did not reveal a clear opinion. They often asked to rephrase the question, suggesting a low knowledge of the decision-making theme. Additionally, many times, the decision-maker responsible for analyzing the technology adoption has other functions, not being able to spend much time performing complex decision analysis neither to become more knowledgeable on decision-making methods.

Overall, the results show that some decision-makers of cobot/AMT adoption are still very tied to the financial aspects of the decision, also because they are not familiar with other methods of decision-making that can include non-financial criteria. Furthermore, some of them did show interest in testing a new decision-making method, especially if it can include qualitative criteria as well.

7. Conclusion

This study aimed to develop a decision-making framework for cobot adoption, incorporating a comprehensive set of quantitative and qualitative criteria, to be used by decision-makers in manufacturing companies.

This study's results are a combination of an exhaustive literature review and the contributions provided by key actors in the cobot/AMT adoption decision process on manufacturing companies. Firstly, it provides an extensive list of criteria that can be considered when deciding on adopting a cobot, as well as some indicators. It counts with 27 general criteria and 73 sub-criteria, from which four criteria and four sub-criteria are new in literature. These criteria were grouped into financial, operational, technological, strategic, human, risk, environmental, and legal categories. The newly mentioned criteria and sub-criteria include *expected sales volume, performance* within product quality*, ease of use, interface language, human resources availability, (cobot) availability* within project risk, *carbon emission* within eco-friendliness, and *legal requirements*.

Interestingly, some of the decision criteria present in literature where not mentioned by the participants. For example, the interviewees addressed three types of flexibility - *Product flexibility, Equipment flexibility, and Manufacturing flexibility* – but literature divides flexibility in many other sub-criteria - *Product flexibility, Process flexibility, Demand flexibility, Equipment flexibility, Manufacturing flexibility, Volume Flexibility, Routing and Scheduling Flexibility, and Expansion flexibility*. Perhaps manufacturing companies are not yet fully aware of the benefits in terms of the flexibility that this technology can bring; or the other types of flexibility do not apply to cobots. Other criteria not addressed by the participants were *delivery, compatibility*, and *market risk*. It could be that in the interviewees' context, these criteria did not have a great influence. In the human category, *employee relations*, and *individual capabilities* were also not stressed by the participants. Possibly because these can be difficult to evaluate.

Furthermore, it was possible to determine that financial aspects, safety, productivity, and ergonomics are among the most important decision criteria for the interviewed companies. The relationships between the criteria were also discussed, disclosing that the technological category has a strong effect on the operational category. The productivity, ergonomics, product quality, and energy consumption efficiency criteria are linked to the financial criteria, since improvements in the former decrease the operating costs, leveraging the return on investment. The competitiveness criteria is positively influenced by the increased flexibility, productivity, product quality, and innovativeness.

Secondly, this study proposes a decision-making framework for cobot adoption, as well as a set of guidelines to use it. This research revealed that decision-makers were not implementing the most recent decision-making methods proposed in literature, not only due to their complexity, and time constraints, but also due to some low knowledge of this thematic. Instead, decision-makers are using financial analysis, demonstration of value added, weighted scoring method, reaching a minimum acceptable level, general approach, and a characterization sheet to decide on the technology adoption. Thereafter, the decision-making framework and the guidelines presented were built upon the empirical perspective of the decision-makers in manufacturing companies and on the literature insights. The outcome was a decision-making framework based on the weighted scoring method, since it enables accounting for both quantitative and qualitative criteria, and assigning greater or lesser weight to each criteria, according to the manufacturing companies' perception of importance. The guidelines include considerations about the decision-making process, namely about decision-makers involvement in the decision process, each step of the weighted scoring method, data collection techniques, and the tool to use.

The diversity of the research sample was critical to enrich the research results. Collecting data from 17 decision makers in senior job positions, in 15 different companies and 11 industrial sectors, and operating in four different countries, provided a comprehensive perspective of the decision process for technology adoption. As such, this research contributes to the literature by enriching and validating the decision criteria to be consider and providing a better understanding of the cobot adoption decision process. From a practical perspective, it guides the decision-maker in acknowledging the full potential of the cobot technology in manufacturing settings. Furthermore, it provides a tool to assist decision-makers of manufacturing companies in performing more complete and sustained decision analyses regarding cobots adoption.

Despite the contributions, this study has some limitations, such as restricted generalization due to its qualitative nature. Nonetheless, this type of research design aims to highlight patterns from real-life situations, providing guidance to other manufacturing firms, and advancing directions for future research. Since cobots are still a new technology in the manufacturing context, it was difficult to access companies and key actors that went through the cobot adoption decision process. To enlarge the sample and to have access to similar experiences, actors in the AMT adoption decision were included as well, since cobots are AMT. In the future, when this technology is more routinized in manufacturing companies, it will be possible to include additional data regarding cobot adoption decision to enlarge the results with new decision criteria or new indicators. In the short-term it is intended to test and validate the proposed framework with manufacturing companies in real context. Another suggestion for future work consists in implementing the framework into Microsoft Excel, a tool with which all decision-makers seem to be familiar with. An automated Excel sheet can make the decision process easier and less time-consuming. Afterwards, the framework could be tested in a real context, through case studies with manufacturing companies. Meanwhile, further research could focus on finding more appropriate ways for handling the relationships between criteria, thus avoiding double-counting on benefits or costs.

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Appendix A. Criteria to be considered in cobots adoption analysis identified from literature

Criteria	Indicator	Assessment/Measurement/Calculation Formula	Reference
Advantages/Benefit			
Flexibility	Ability to adapt	Not specified [a]	Djuric et al. (2016); Krüger et al. (2009); Villani et al. (2018)
Competitiveness	Market share	Market share depends on the varieties and volumes of products made by the enterprise	Bi et al. (2021)
Ergonomics	Operator load	PSA ergonomics scale (from "red" to "medium" level)	Cherubini et al. (2016)
	MSDs associated costs	Absenteeism cost; Medical and insurance-related expenses	Cherubini et al. (2016); European Agency for Safety and Health at Work (2019)
	Human physical strain	Inertia of heavy work pieces	Krüger et al. (2009)
	RULA (Rapid Upper Limb Assessment)	Based on the worker's posture, scores are given for each body part – group A includes the arm and wrist (score A) and group B includes the neck trunk, and legs (score B). Additionally, a muscle use and force score is added to scores A and B: Score A + muscle use and force scores for group A = Score C Score B + muscle use and force scores for group B = Score D Finally, the sum of score C and D generates a single score that represents the level of MSD risk.	McAtamney and Nigel Corlett (1993);
Quality	Success rate	Number of assemblies performed successfully, i.e., with no errors, divided by the number of assemblies performed in total, multiplied by 100	Salunkhe et al. (2019)
Safety	Risk of injuries	Depends on cobot's ability to avoid collision with a human	Cherubini et al. (2016); Vysocky and Novak (2016)
	Risk assessment (of injuries)	Probability of incidence × severity of the injury Possible risks associated with the cobot include: mechanical trapping/machine guards, electricity, pressure/energy release, stored energy, ionizing/non-ionizing radiation, vibration, mechanical load, fire (combustible materials), flammable materials, health risks, abrasions, knock, biological risks	Realyvásquez-Vargas et al. (2019)
Mobility	Mobility	Weight	Sherwani et al. (2020)
	Surface	Total surface occupied by operators, machines, and materials (m^2).	Gil-Vilda et al. (2017)
Programming	Programming time	Time to program the cobot	Matúšová et al. (2019); Sherwani et al. (2020)
Technical features	Payload	Maximum weight the cobot can handle	Cohen et al. (2021)

Criteria	Indicator	Assessment/Measurement/Calculation Formula	Reference
	Number of axes	Number of axes	Cohen et al. (2021)
	Maximal reach	Maximum distance the cobot can reach, measured from the center of the cobot's basis	Cohen et al. (2021)
	Repeatability	Cobot's ability to reach precise locations and orientations (millimeters)	Cohen et al. (2021)
	Maximum speed	The highest speed at which the cobot's end-effector can move	Cohen et al. (2021)
Human-robot collaboration	Mental workload	Not specified [a]	Elprama et al. (2017)
Productivity	Mean flowtime	Time required to perform a task	Tsarouchi et al. (2016)
	Labor Productivity	Number of good units divided by man-hour (units/hour/#operators)	Gil-Vilda et al. (2017)
	Cycle time	$T_{cycle} = \sum_{i=1}^{\#Taks} \left(T_{op}(i) + T_{nva}(i)\right)$ i.e., the cycle time is the sum of each task belonging to the working sequence of two times: the operative time needed to perform the manufacturing process (T_{op}), and the non-value adding time spent for set-up, item loading and unloading, tool maintenance and tool positioning (T_{nva})	Antonelli et al. (2016)
Disadvantages			
Costs	Price	Price (monetary unit)	Cohen et al. (2019)
	Maintenance cost	Maintenance cost (monetary unit)	Cohen et al. (2019)
	Additional initial costs	Cost of new tools, resources, or consultancy services (monetary unit)	Bauer et al. (2016)
		Training costs with operators and technicians (monetary unit)	Cohen et al. (2019); Enrique et al. (2021)
Risk assessment	Costs with additional safety measures	Costs with safety light curtains or safety laser scanners (monetary unit)	Platbrood and Görnemann (2018)
	Costs to train staff	Cost of training staff (monetary unit)	El Zaatari et al. (2019)
Productivity	Execution time	Execution time	Bejarano et al. (2019)
	Cycle time	Cycle time	Cherubini et al. (2016)

Source: Author own elaboration based on the previously mentioned references

[a.] The author(s) do(es) not mention how to measure this criteria.

Appendix B. Models that can contribute to cobot adoption decision

Author (year)	Model	Formula	Notations
Peron et al. (2020)	Cost-per-product model	Final cost per product: $$C^C = n^C \times \frac{(c_{st} + c_{op})}{Q} + n_D^C \times \frac{c_d^C}{Q}$$ Where, Number of stations: $n^C = \frac{t^C \times Q}{3600}$ Time to perform all the operations: $$t^C = t_{S+P}^C + t_{ASS}^C = \alpha \times (1-\beta^C) \times (1-\alpha) \times (1-\gamma^C) \times t$$ Number of stations requiring the presence of the cobot: $n_D^C = \omega \times n^C$	C^C: final cost per product n^C: number of stations c_{st}: cost per hour of the assembly station, including also the services [€/h] c_{op}: cost per hour of the operator [€/h] Q: required throughput [pcs/h] n_D^C: number of stations requiring the presence of the cobot c_d^C: cost per hour of one cobot [€/h] t^C: time to perform all the operations t_{S+P}^C: time spent for searching and picking activities t_{ASS}^C: time spent for assembly activities $\alpha = t_{S+P}^C / t^C$: % of the time spent in searching and picking activities β^C: % of improvement provided on searching and picking activities by the implementation of cobot γ^C: % of improvement provided on assembly activities by the implementation of cobot T: = time spent to complete the operations for the Virtual Average Model, considering both searching and picking and assembly activities [s] ω: % of the assembly station served by the cobot
Fager et al. (2020)	Operator cost	Yearly operator cost: $$C_O^j = t_h \times n_w \times c_o \times n_{op}^j$$ Where, Number of operators required (with a cobot): $n_{op}^{j=2} = \frac{n_d \times n_s}{p^{j=2}}$	C_O^j: yearly operator cost of mode j (1=manual; 2=cobot) t_h: number of working hours per day n_w: number of working days per year c_o: hourly operator cost

Author (year)	Model	Formula	Notations
		Productivity: $p^{j=2} = \frac{t_w \times n_w}{\left[\frac{n'_s}{B \times n_s}\right] \times \left[\frac{t_{set}}{n'_s} + (1-\varphi) \times \left(\frac{L}{v \times n'_s} + q'_s \times t_{pick}\right) + \varphi \times \left(q'_s \times t_{sort}^{j=2}\right)\right]}$	n_{op}^{j}: number of operators required with mode j $p^{j=2}$: productivity with the cobot t_w: no. of seconds in a work day n_w: no. of work days in a year n'_s: no. of order lines on a batch pick list
		Collaboration ratio (how well the collaboration between the operator and cobot works): $\delta = \frac{\frac{L}{v \times n'_s} + q'_s \times t_{pick}}{q'_s \times t_{sort}^{j=2}}$ Collaboration factor: $\varphi = -2.5 \times \delta + 3$	B: batch size n_s: no. of order lines per order t_{set}: time (s) for setup between picking tours φ: collaboration factor L: length (m) of a picking tour v: travelling speed (m/s) q'_s: no. of items per order line on a batch pick list t_{pick}: time (s) for the operator to pick a component $t_{sort}^{j=2}$: time (s) required to sort an item with the cobot δ: collaboration ratio
	Equipment cost	Yearly cost of equipment (with cobot): $C_E^{j=2} = c_e^{j=2} \times n_{op}^{j=2}$	$C_E^{j=2}$: yearly equipment cost in cobot mode $c_e^{j=2}$: yearly cost (€/year) of equipment in cobot mode $n_{op}^{j=2}$: no. of operators required in cobot mode

Author (year)	Model	Formula	Notations
	Quality costs	Quality costs (with cobot): $C_Q^{j=2} = n_d \times n_s \times q_s \times \sum_{k=1}^{5} \left(\rho_\varepsilon^k \times \left(\pi_p^{j=2} \times c_q^{m=1} + \left(1-\pi_p^{j=2}\right) \times \left(\pi_a \times c_q^{m=2} + (1-\pi_a) \times c_q^{m=3}\right)\right)\right)$	$C_Q^{j=2}$: yearly operator cost in cobot mode n_d: no. of orders to complete in a year n_s: no. of order lines per order q_s: no. of items per order line ρ_ε^k: probability of error type k $\pi_p^{j=2}$: probability of correcting an error at the picking area in cobot mode π_a: probability of correcting an error at the internal customer c_q^m: unitary cost (€/error) of correcting an error at picking area (m = 1), at assembly (m = 2), and at end of line inspection (m = 3)
	Yearly total cost	$C_{tot}^j = C_O^j + C_E^j + C_Q^j$	C_{tot}^j: yearly total cost C_O^j: yearly operator cost in mode j C_E^j: yearly equipment cost in mode j C_Q^j: yearly quality cost in mode j
Cohen et al. (2021)	Productivity-based model	Cobot acquisition and deployment are justified as long as the following inequality holds true: $[(cs/(C-cs)) \times THPT] \times 250 \times Life \times Uprofit > Lifecost$ Where, $[(cs/(C-cs)) \times THPT]$ represents the cobot's contribution to the throuput That is, if the overall increased profit due to the cobot is higher than the cobot lifetime costs. Another important inference from this model is the minimal time that a cobot must save to justify its acquisition:	cs: the saved standard time (of the operator) out of C, due to cobot deployment (maybe different than the cobot's moving time) C: takt-time: the standard (nominal) time between each pair of consecutive products leaving an assembly workstation THPT: real throughput of manual workstation without cobot, during one shift, with all detrimental considerations included Life: number of expected cobot deployment years Uprofit: the expected profit due to a produced unit/item Lifecost: lifetime cost of a cobot: purchase, maintenance, and deployment costs throughout the cobot's life (the present value at the acquisition). RHS: right-hand side

Author (year)	Model	Formula	Notations
		$cs > C \times RHS/[1 + RHS]$ Where, $RHS = Lifecost/(THPT \times 250 \times Life \times Uprofit)$	
Calvo and Gil (2022)	Differential Cost Model of Assembly with Collaborative Robots	In order to have a positive contribution or compensation, the necessary minimum productivity is: $\Delta C \geq 0 \implies p_{min} = \frac{C_{CS}}{SQ + C_{MA} + C_{CS}}$	ΔC: unitary differential cost of implementing cobots p_{min}: minimum productivity C_{CS}: cost of cobot system (cost of a set of flexible feeders, grippers and the cobot itself) S: shifts Q: the equivalent cost of equipment to replace one operator on one shift C_{MA}: cost of equipment of manual assembly (the cost of the set of buffer transfer devices and conveyor carrier)
	Modeling Short Term Compensation of Employment Displacement	In order to obtain positive unitary cost savings, the necessary minimum productivity is: $\Delta S = 0 \Longrightarrow p_{min} = \frac{\left(\frac{W}{SQ}\frac{n}{k} + \frac{1}{y_{TX}}\right)\frac{C_{CS}}{W}}{\frac{n}{k}\left(1 + \frac{C_{MA}}{SQ}\right) + \left(\frac{W}{SQ}\frac{n}{k} + \frac{1}{y_{TX}}\right)\frac{C_{CS}}{W} - \frac{WF \cdot n_h}{W \cdot TX \cdot n_c}}$	ΔS: short term compensation of employment displacement p_{min}: minimum productivity W: current annual wages S: shifts Q: the equivalent cost of equipment to replace one operator on one shift n: parts per assembly k: workstations y_{TX}: years of the equipment amortization C_{CS}: cost of cobot system (cost of a set of flexible feeders, grippers and the cobot itself) C_{MA}: cost of equipment of manual assembly (the cost of the set of buffer transfer devices and conveyor carrier) WF: annual subsidy per unemployed displaced headcount or the otherwise called net replacement income

Author (year)	Model	Formula	Notations
			n_h: years during which the extra cost to maintain short-term welfare for displaced workers will be supported due to the increase in productivity with cobots TX: tax rate n_c: years during which there will be an extra return to the society via taxes from the productivity gain with cobots

Source: Author own elaboration

Appendix C. Analysis of decision-making methods for AMT adoption

Author (year)	Method	(Method) Taxonomy	Criteria	Indicators/ Evaluation method/ Elements	Criteria type	How are the criteria being measured/handled?
Soni et al. (1990)	Scoring model	Others	Scheduling Flexibility; Product flexibility; Enhancement of Product Quality; Cost Reduction and Savings; Safety Improvements	-	Quantitative and Qualitative	Decision makers must give ordinal scale weights to rank the importance of strategic or tactical decisions (Very Important = 1.00, Important = 0.75, Necessary = 0.50, Unimportant = 0.25), and ordinal scale weights to measure the performance of each strategic or tactical decisions with respect to each criterion (Superior = 1.00, Good = 0.80, Above Average = 0.60, Average = 0.40, Below Average = 0.20, Poor = 0.00)
Wilkes and Samuels (1991)	A Three Stage Methodology	Financial analysis	Costs and revenues; X-gap	-	Quantitative and Qualitative	Quantitative: NPV Qualitative: management must weigh the intangible elements against the shortfall in present value
Krinsky and Miltenburg (1991)	State-price net present value;	Hybrid methods	Costs and revenues	-	Quantitative	NPV
	Manufacturing strategy map		Cost; Performance; Quality; Delivery time and delivery time reliability; Flexibility; Innovativeness	-	Quantitative and Qualitative	Not specified
Sawhney (1991)	Activity-Based Approach	Financial analysis	Capacity; Operational Productivity; Manufacturing lead time; Inventory; Utilization; Quality; Flexibility; Reliability	Capacity: Theoretical demand; Operational output Operational Productivity: Price of output/labor cost; Price of output/Material cost; Price of output/Capital cost; Price of output/Overhead cost; Price of output/Total cost Manufacturing lead time: Setup time; Queue time; Move time; Transport time; Process time; Total throughput time Inventory level: Average inventory level; Output/Average inventory Resources Utilization: Manpower utilization; Machine utilization Quality: Percentage defectives; Percentage reworkable; Percentage scrap; Rework time/throughput time; Inspection	Quantitative and Qualitative	Manufacturing performance measures are assigned to each criterion, and target levels are assigned for each performance measure. Normalized importance weight is given to each criteria to reflect its importance to the overall strategy. A simulation model provides nonfinancial quantitative performance measures such as lead time, operational output, average inventory level, and equipment utilization. In this analysis, all criteria are presented as percentage achievement of the criteria target level. An overall fulfillment factor is calculated by summing the contributions over each criterion.

Author (year)	Method	(Method) Taxonomy	Criteria	Indicators/ Evaluation method/ Elements	Criteria type	How are the criteria being measured/handled?
				time/throughput time Flexibility: Price of output/Cost of idle equipment; Price of output/Cost of setup; Price of output/Cost of holding inventory; Price of output/Cost of waiting; Price of output/Total cost Reliability: Output/demand; Breakdown time/throughput time		
Kolli and Parsaei (1992)	PROMETHEE II	Preference Ranking Organization Method for Enrichment of Evaluations (PROMETHEE)	Product quality; Manufacturing flexibility; Market response; Costs; Inventory; Lead time	-	Qualitative	Preference functions are assigned to represent the intensity of preference of alternative x over the alternative y (P(x,y)=0 indifference between x and y; P(x,y)~0 weak preference of x over y; P(x,y)~1 strong preference of x over y; P(x,y)=1 strict preference of x over y). Decision-maker provides weights for each criterion, to indicate the level of importance in the decision. Given the preference function for each criterion and weight, a multi-criteria preference index is calculated and ranked.
Lint (1992)	Real options	Financial analysis	Total capital expenditures Non-market related benefits: savings in (in)direct labor costs; savings in space, inventory, and storage Market-related benefits: net cash inflow from extra sales (greater volume and variance flexibility); less scrap, rework; increased product quality	-	Quantitative	Cash flows
Randhawa and West (1992)	Simulation and Linear additive scoring model	Others	Economic (quantifiable): System acquisition and installation costs; Startup costs; Variable production costs; Work-in-process inventory (and shortage) costs; Quality costs; Maintainability costs Operational (quantifiable): Equipment utilization; Throughput rate; Production lead times; Product	Variable production costs: raw material, machine operation, direct and indirect labor, and utility costs Quality costs: inspection, manufacturing accuracy and precision, scrap and rework, and replacement costs Maintainability costs: system diagnostics, repair, and upkeep costs	Quantitative and Qualitative	Quantitative criteria: a simulation module is used to obtain estimates for quantitative criteria. Qualitative criteria: management develops estimates for qualitative attributes. Weights are assigned to each criteria to represent its relative importance using pairwise comparisons. To combine all criteria, the aggregate score for each manufacturing alternative is computed

Author (year)	Method	(Method) Taxonomy	Criteria	Indicators/ Evaluation method/ Elements	Criteria type	How are the criteria being measured/handled?
			accuracy and precision; Shop floor information requirements Space requirements and utilization Qualitative (non-quantifiable): Flexibility; Compatibility; Safety of operations to avoid injuries and accidents; Training availability and quality; Worker morale; Technical and management support	Flexibility: design change accommodation, changes in product mix or market responsiveness, routing and scheduling flexibility, capacity growth Compatibility: with existing or new machines, tools, computer control, and communication Worker morale: or acceptability and enthusiasm for use of the system		consisting of total weighted attribute values for an alternative; sensitivity analyses are performed on criteria weights and criteria values. The alternatives are scored and ranked.
Naik and Chakravarty (1992)	Three hierarchical level framework: strategic, operational, and financial	Hybrid methods	Strategic level: Competitive strategy; Market requirements; System attributes Operational level: System-related technical and performance data; Project cost; Implementation duration; Vendor reputation	Competitive strategy: innovation, customization, product proliferation, price reduction, innovation and product proliferation, innovation and customization, product proliferation and price reduction Market requirements: low price, better product features and design, better product performance and reliability, short delivery time, delivery reliability, wide product line, custom-made products, rapid new product introduction, variable order size System attributes: throughput rate; direct labor; WIP inventory; machine utilization; set-up time; material movement time; tool change time; machining flexibility; routering flexibility; number of product designs; batch size; machining precision; quality inspection; design modification time; storage/retrieval of designs ease; process plan modification; storage/retrieval of material efficiency; information processing and transmission	Quantitative and Qualitative	Strategic level: decision-maker determines the degree of importance of each criterion, using an ordinal scale (very high, high, medium, low, not relevant); the relative suitability of the technology is determined using a scale of 0-10 Operational level: ranked using AHP Financial level: Discounted cash flow techniques.
Datta et al. (1992)	A user-friendly menu-driven software using AHP	Analytic hierarchy process (AHP)	Flexibility; Quality & Reliability; Technical Feasibility; Market position; Technology position; Investment; Throughput; Inventory; Information; Capacity utilization; Employee	-	Quantitative and Qualitative	Relative weights or priorities are given. Pairwise comparisons are performed.

Author (year)	Method	(Method) Taxonomy	Criteria	Indicators/ Evaluation method/ Elements	Criteria type	How are the criteria being measured/handled?
			relations; Human factors (safety and ergonomics)			
Prueitt and Park (1992)	NPV and information quality factor (IQF)	Financial analysis	WIP reduction; Change in Working Capital; Annual Holding Cost Savings; Improved Labor Efficiency; Annual Labor Improvement	-	Quantitative	Cash flows
Wicks and Boucher (1993)	Non-traditional capital investment criteria (NICS)	Hybrid methods	Annual benefit: Labor Material conversion: Lead time Information conversion: Option for CIM; Real time information Strategic activities: Delivery performance; Meeting specifications; Demand response	The present value analysis requires that the following information be supplied for each alternative: investment cost (discounted to the present if being made over a period of time); marginal tax rate; discount rate; time horizon (years of useful life); and the depreciation amount for each year (in dollars).	Quantitative	Pairwise comparisons of evaluation criteria are made to establish the relative importance/relative weights of each criterion, using a 1-9 ratio scale. The implied annual benefit (dollar savings) or cost of criteria and investment alternatives are computed. For the non-monetary criteria, the implied dollar values are calculated based on the ratio of the relative weights of criteria and the dollar value of the annual cost savings criterion. To combine the annual benefits of alternatives with investment costs, time horizon, discount rate, and depreciation amounts and perform a net present value analysis of the investment alternatives is performed.
Park and Kim (1995)	NPV under Activity-based costing (ABC) system	Financial analysis	Revenue; Direct Labor; Direct Material; Activity Costs; Inventory Costs; Unused Activity Cost; Opportunity Costs; Waiting Time Cost; Idle Time Cost	Activity Costs: processing activity cost; tooling activity cost; setup activity cost; purchasing activity cost; material handling activity cost; prevention activity cost; appraisal activity cost; internal failure activity cost; external failure activity cost; computer-software activity cost; inventory handling activity cost, which consists of forklifting activity cost and storage activity cost	Quantitative and Qualitative	All variables are quantified with ABC systems
Chen (1996)	Activity-based costing (ABC)	Financial analysis	Operating expenses: Facility-sustaining activities; Product-sustaining activities; Batch-level activities; Unit-level activities	Facility-sustaining activities: Plant management; Building and grounds; Heating and lighting Product-sustaining activities: Process engineering; Product specifications; Engineering change notice; Product enhancement	Quantitative and Qualitative	Cost drivers (monetary unit)

Author (year)	Method	(Method) Taxonomy	Criteria	Indicators/ Evaluation method/ Elements	Criteria type	How are the criteria being measured/handled?
				Batch-level activities: Set-ups; Material movements; Purchase orders; Inspection Unit-level activities: Direct labor; Materials; Machine costs; Energy		
Demmel and Askin (1996)	Composite programming	Mathematical programming (MP)	Strategic: Internal Relations; Market Position; Mission; Organization; Public Relations; Technology Tactical: Design; Flexibility; Integration; Material; Personnel; Producibility Pecuniary: Operation and Maintenance; Plant and Equipment; Product	Internal Relations: employee morale; employee development; use of skills; quality of work life; compensation; absenteeism Market Position: market share; competition assessment; market penetration; survivability; vulnerability; demand Mission: match to plan; evolution; economic feasibility; focused factory Organization: control; responsiveness; information management Public Relations: company image; company prestige; service Technology: scientific information yield; technological position and availability Design: efficiency; features; lead times; standardization Flexibility: versatility; response to change; batch size; lead-times; throughput Integration: communications; reduced duplication; synergism; data requirements; data usefulness Material: process control; scheduling; part tracking; shop floor control; cost tracking; expediting; handling; planning Personnel: skill requirements; training; safety; direct/indirect; human factors Producibility: consistency; compatibility; feasibility; reliability; capacity; external interface Operation and Maintenance: operating labor; maintenance labor; direct/indirect costs; absenteeism; training; supervision; insurance; overtime; labor turnover; setup; maintenance tools/supplies; production rates; documentation; routings; shop floor control	Quantitative and Qualitative	Pecuniary criteria: traditional discounted cash flow techniques, with the results normalized to a [-1, +1] (worst-best scale) are used. Strategic and tactical criteria: qualitative discounting methods are employed (the decision maker rates the expected performance and assigns weights to each criterion).

Author (year)	Method	(Method) Taxonomy	Criteria	Indicators/ Evaluation method/ Elements	Criteria type	How are the criteria being measured/handled?
				Plant and Equipment: equipment; startup; installation; tooling; spare parts; energy; space; safety equipment; hardware development; software development; depreciation; taxes Product: design changes; inventory; quality; engineering; sales		
	Risk Model	Mathematical programming (MP)	Cash flows, qualitative flows, project length, and interest rates	-	Quantitative	Mean and variance
Stainer et al. (1996)	Four-phase model	Strategic models	Any criteria could have been used	-	Quantitative and Qualitative	Tangible criteria: assessed with economic models. Intangible criteria: assessed with value and portfolio analysis.
Kahraman et al. (1996)	Fuzzy multiobjective linear programming	Fuzzy logic	Productivity; Quality; Flexibility; Reduced lead time	-	Quantitative and Qualitative	Decision makers may assign different weights to the various criteria (and/or constraints). Many of the parametric values of the fuzzy multiobjective LP model developed are readily available or estimated in the accounting department or other departments in a company. The intangible parametric values and resources are difficult to obtain; however, they are not impossible to estimate. For example, the cost of flexibility-related aggregate resources for making a unit or product can be obtained by calculating the unit cost of set-up, waiting, idle, and inventory costs.
Kakati (1997)	NPV with competitive and opportunity gap	Strategic models	Market: Product life cost; Product range; Design change; New product introduction; Delivery; Demand variation; Volume/line; Margin; Quality; Market; Competitor's entry; Changes in market structure; Product differentiation; Stage in life cycle Performance	Performance: i. input data) product mix; machine and total cycle time; system configuration; etc. ii. Output data) throughput time; quality level; system utilization; effect of break down (dependability); level of system flexibility; etc.	Quantitative	Market attributes are analyzed through a strategic opportunity-threat matrix. Performance gap analysis measures the benefits through its contribution to the closing of competitive and opportunity gap. Physical performance analysis is performed to derive output measures like throughput time, quality level, system utilization, effect of break

Author (year)	Method	(Method) Taxonomy	Criteria	Indicators/ Evaluation method/ Elements	Criteria type	How are the criteria being measured/handled?
			Direct and indirect benefits: Speed; Dependability; Quality; Flexibility; Cost			down (dependability), level of system flexibility, etc. using analytical or simulation models. Using the outputs of simulation/analytical model, it is possible to assess the direct benefits from a certain input compared to other proposed or existing setup. Once the firm reaches this stage, the direct benefits can easily be translated into cash inflows and NPV can be calculated.
Sambasivarao and Deshmukh (1997)	Decision support system (DSS): PB; ROI; NPV; IRR; Benefit/Cost analysis; LAM; AHP; TOPSIS; Risk analysis	Hybrid methods	Flexibility; Quality & Reliability; Technical Feasibility; Market position; Technology position; Investment; Throughput; Inventory; Information; Capacity utilization; Employee relations; Human factors (safety and ergonomics)	-	Quantitative and Qualitative	Economic criteria: PB, ROI, NPV, IRR, Benefit/Cost analysis, risk analysis Intangible criteria: LAM (Linear additive model), AHP, TOPSIS
Goh (1997)	AHP	Analytic hierarchy process (AHP)	Performance; Cost; Vendor's Service Quality	Performance: velocity (which is the maximum speed a robot's arm can achieve); load capacity (which is the maximum weight a robot can lift); repeatability (which is a robot's ability to repeatedly return to a fixed position. The mean deviation from that position is a measure of the robot's repeatability) Cost: purchase cost; installation cost; training costs Vendor's service quality: variety of services offered by the vendor	Quantitative and Qualitative	Each decision maker provides numerical values for a pairwise comparison of the decision criteria (scale with values from 1 to 9). Each decision maker provides numerical values for the relative preference of the robots regarding each criteria and sub-criteria (scale with values from 1 to 9). The overall score for each robot is obtained by multiplying the value of each criterion with the criterion's weight and summing these values for all the criteria.
Sarkis (1997)	DEA with cross-efficiency and ranking	Data envelopment analysis (DEA)	Inputs: Total Cost; Time; Labor Requirements; Work in Process; Space RequirementsOutputs: Volume Flexibility; Product-Mix Flexibility; Process/Routing Flexibility	Total Cost: discounted value for operational and investment costsTime: throughput time Labor Requirements: number of employees required to oversee the operations of the FMS Work in Process: average inventory levels of products in systemsSpace Requirements: the amount of physical space that is required by the system Volume Flexibility: range of capacity available on a	Quantitative	Simulation, estimating. forecasting, and other multicriteria scoring and evaluation techniques could be included as methods to value the data and input them into the DEA models.After normalizing the data, efficiency scores are calculated (the weighted sum of the output divided by the weighted sum of the input).

Author (year)	Method	(Method) Taxonomy	Criteria	Indicators/ Evaluation method/ Elements	Criteria type	How are the criteria being measured/handled?
				system to produce products within a given time period Product-Mix Flexibility: range (number) of products that can be manufactured in a given time periodProcess/Routing Flexibility: average number of operations per machining center in an FMS		
Mohanty and Deshmukh (1998)	Nominal Group Technique (NGT) and AHP	Strategic models	Strategic: Finance position; Government advantage; Market position Tactical: Flexibility; Material; Personnel; Design compatibility; Quality Monetary: Cost for organization; Cost for plant/equipment; Product cost	Flexibility: Flexibility of equipment, product, delivery, design, etc. Quality: Indicator of the product quality, conformance to the standards, specifications, etc. and reliability Design: Product features from design to manufacturability point of view Material: Direct and indirect material consumed, their quality and usefulness to the finished product Personnel: Morale, motivation, incentive schemes, shared vision of employees Monetary attributes: Monetary factors include cost for various components such as plant, equipment, product, etc.	Quantitative and Qualitative	Pairwise comparison and prioritized weights for each criteria (scale from 1 to 9). Each alternative is evaluated on each of the attributes by making a similar comparison.
Luong (1998)	AHP and database technology	Analytic hierarchy process (AHP)	Manufacturing lead time; Productivity; Inventory and work in progress; Quality; Flexibility; Integration in the company	-	Quantitative and Qualitative	Through pairwise comparisons, the relative importance of each criteria is determined. After which, the relative weight of each criteria is calculated. After identifying the capabilities of each technology, they can be quantified by converting these capabilities into corresponding weights using the AHP technique. These weights are then stored in a database to be used in the evaluation process. In order to consider the characteristics of a company, the relative weights of the capabilities of technology must be modified according to production type and company function, by

Author (year)	Method	(Method) Taxonomy	Criteria	Indicators/ Evaluation method/ Elements	Criteria type	How are the criteria being measured/handled?
						multiplying the relative weight of each capability by modifying coefficients. The last step is to evaluate the capabilities of each technology with respect to the relative importance of each criteria.
Nagalingam and Lin (1998)	Functional interrelationship matrix (FIRM): AHP; Cost-benefit analysis; Goal programming	Hybrid methods	Direct cost reduction; Indirect cost reduction; Productivity improvements - production related; Productivity improvement - human related; Business strategy	Direct cost reduction: Direct labour (reduction); Material costs (reduction); Material handling costs (reduction); Tooling/fixture costs (reduction); Lead time (reduction) Indirect cost reduction: Maintenance costs (reduction); Prod. plan. and control (reduction); Floor space (reduction); Inspection (reduction) Productivity improvement (production factors): Manufacturing productivity (increase); Machine utilization (improve); Flexibility in batch sizes (improve); Work in progress (reduce); Rework (reduce); Scrap (reduce) Productivity improvement (human related factors): Design flexibility (increase); Production flexibility (increase); Working conditions (improve); Paperwork (reduce) Business strategy: Increase product growth; Increase competitiveness; Ability to introduce new products; Ability of the system expansion	Quantitative	Criteria can be prioritized according to the requirement of the company by the use of AHP, or by a simple scoring method. A performance measure evaluation is provided to select the preferred option. For the option of the AHP module, the performance measure evaluation is performed to compare the decision of either investing in AMTs or maintaining the status quo. For the option of the scoring module, this performance measurement is performed in a single stage. From the weights and ranking supplied in the performance measure evaluation, the suitable sub systems can be selected by calculating the total weight of associated criteria of technology. Functional interrelationship ratio. are calculated to evaluate synergy.
Chan et al. (1999)	Manufacturing strategy map; AHP; State price NPV; Budget/network chart	Hybrid methods	Cost; Performance; Quality; Delivery; Flexibility; Innovativeness	Cost: Product cost; Maintenance cost; High rate of return; Labor cost; Material cost; Performance: Compatibility with existing machine; Work morale; Productivity; Utilization; Machine breakdown; Human integrationQuality: Scraped value; Rework; Conformance; Consistency Delivery: Transportation; Customer services; Time scheduling; Delivery time; Inventory/work in progress; Lead time	Quantitative and Qualitative	Financial data: SP-NPV. Non-financial data: AHP (Pairwise comparison between the criteria; Pairwise comparison of selected technologies regarding the criteria).

Author (year)	Method	(Method) Taxonomy	Criteria	Indicators/ Evaluation method/ Elements	Criteria type	How are the criteria being measured/handled?
				Flexibility: Design change accommodation; Change in product mix; Market responsiveness; Capacity growth; Routing and scheduling flexibility Innovativeness: Research and development; Introduce product variation		
Chiadamrong and O'Brien (1999)	Simulation model; NPV; Sensitivity analysis; Linear additive model or AHP or Fuzzy multiple criteria decision model	Hybrid methods	Quality; Competition; Flexibility; Social Consideration; Process simplicity	Quality: scrap; quality Competition: sales improvement; company image Flexibility: flexibility Social Consideration: job satisfaction; develop supervisor roles Process simplicity: modification; operating simplicity; throughput	Quantitative and Qualitative	Selected performance measurements are collected for further analysis through simulation (SIMAN simulation language). Economic analysis: Results from the simulation models are transformed into monetary units through cost model and a cash flow of every system is built for the purpose of economic analysis under the Net Present Value method (NPV). Analytical analysis: uses sensitivity analysis to simulate each system alternative by determining the variables of interest - benefits, costs, yields, capital, etc. Strategic analysis: three possible approaches, a linear additive model for a simple decision judgment; an analytical hierarchy process for a decision that requires pairwise judgment; and a fuzzy multiple criteria decision model for overcoming the linguistic assessments of strategic issues when the absence of sharply defined criteria is involved. An overall aggregate index is calculated.
Braglia and Petroni (1999)	DEA with restricted weights	Data envelopment analysis (DEA)	Input: Cost Output: Load capacity; Repeatability; Velocity; Handling capacity	Cost: the robot's catalogue price ($) Load capacity: the robot's maximum transportable weight (kg) Repeatability: the measure of the accuracy with which the robot permits the end effector to return to a specific point (mm^{-2}) Maximum velocity: the end effector's maximum attainable speed (m/s) Handling capacity: Diameter (mm), Elevation	Quantitative	Weights and relative efficiency scores are calculated (weighted sum of outputs divided by the weighted sum of inputs).

Author (year)	Method	(Method) Taxonomy	Criteria	Indicators/ Evaluation method/ Elements	Criteria type	How are the criteria being measured/handled?
				(mm), Basic rotation (degrees) (which are work area-related measures of the robot's arm) and Roll (degrees), Pitch (degrees), Yaw (degrees) (that relate to the wrist rotation angles around the three principal aces)		
Sarkis and Talluri (1999)	DEA with ordinal and cardinal measures, in conjunction with new extensions in DEA	Data envelopment analysis (DEA)	Input: Capital and operating costs; Floor space requirements; Vendor reputation Output: Work in process; Percentage of tardy jobs; Yield; Worker approval	Capital and operating costs: \$ Floor space: square feet Yield: throughput minus scrap and rework	Quantitative and Qualitative	Quantitative data: obtained by simulating different manufacturing systems. Ordinal data: measured on an ordinal scale of 1 to 5. Relative efficiency scores for each DMU are calculated, i.e., the sum of weighted quantitative and qualitative criteria.
Talluri et al. (2000)	DEA and Nonparametric statistical procedures	Data envelopment analysis (DEA)	Input: Capital and operating costs; Floor space requirements Output: Qualitative factors; Work in process; Percentage of tardy jobs; Yield	Capital and operating costs: \$ Floor space: square feet Qualitative factors: % Yield: throughput minus scrap and rework	Quantitative	The output measures were obtained by simulating different manufacturing systems. Efficiency scores are calculated. Friedman's test is performed to investigate whether distributions of cross-efficiency scores differ among the systems.
Braglia and Gabbrielli (2000)	Dimensional Analysis (DA) and Revized Weighted Sum Decision Model (RWSDM)	Mathematical programming (MP)	Velocity; Load capacity; Cost; Repeatability; Vendors' service; Programming flexibility	Velocity: m/s Load capacity: kg Cost: \$ Repeatability: mm Vendors' service: experts' judgment Programming flexibility: experts' judgment	Quantitative and Qualitative	Quantitative criteria: data is determined based on the criteria measurement, e.g.: load capacity is measured in kg. Qualitative criteria: mean of the weights assigned to each criteria by the experts (to reflect its relative importance).
Kahraman et al. (2000)	Fuzzy benefit-cost ratio analysis	Fuzzy logic	Revenue; Labour cost; Investment; Depreciation; After-tax cash flow	-	Quantitative	After calculating the present value of benefits (PVB) and the present value of costs (PVC) using triangular fuzzy numbers, the fuzzy benefit-cost ratio is determined.
Talluri and Paul Yoon (2000)	Cone-ratio DEA model	Data envelopmen	Input: Cost Output: Repeatability; Load capacity; Velocity	Cost: \$ Repeatability: mm	Quantitative	Each criteria has a measurement, e.g.: load capacity is measured in kg. The values are then normalized to remove any scale effects. Possible cone scenarios are selected. Different

Author (year)	Method	(Method) Taxonomy	Criteria	Indicators/ Evaluation method/ Elements	Criteria type	How are the criteria being measured/handled?
		t analysis (DEA)		Load capacity: kg Velocity: m/s		orders of preference of criteria represent different cones. Efficiency scores are calculated.
Ordoobadi and Mulvaney (2001)	System-wide benefits value analysis (SWBVA)	Hybrid methods	Increased Flexibility; Increased Quality; Increased Productivity; Expanded Use of Technology; Promotion of Strategic Objectives; Competitive Strengths; Increased Customer Satisfaction; Increased Market Opportunities; Increased Ease of Operation; Improved Employee Relations	Due to the large number of indicators provided by the authors, the reader is advised to consult the source article.	Quantitative and Qualitative	Tangible benefits: NPV, IRR, and Payback (with information provided by the company) Intangible benefit: SWBVA, where each benefit has sub-benefits, and each sub-benefit has benefit indicators. The values for each benefit indicator will be translated into a crisp result for sub-benefit in terms of what percent increase they can expect from the acquisition of the particular AMT being evaluated.
Karsak and Tolga (2001)	Fuzzy multi-criteria decision-making	Fuzzy logic	Initial cost; Operating costs; Maintenance cost; Reduction in floor space; Increase in process flexibility; Increase in volume flexibility; Improvement in product quality	-	Quantitative and Qualitative	Economic criteria: fuzzy discounted cash flow analysis. Strategic criteria: A group of decision-makers assesses the importance weights of the criteria and the suitability of the AMS alternatives under each of these criteria. Fuzzy suitability index values are calculated and ranked.
Abdel-Kader and Dugdale (2001)	A Fuzzy Set Theory (financial analysis and AHP)	Fuzzy logic	Financial: Increased turnover; Net cost savings; Investment; Discount rate; Non-financial: Flexibility; Customer requirements; Lead-time; Quality of output Risk: Market; Technology	Flexibility: variety; volume Customer requirements: new features; responsiveness; delivery Quality: conformance to specifications Market: volatility of demand; life of market Technology: proven technology; reliability of supplier; experience in the company	Quantitative and Qualitative	Financial criteria: fuzzy cash flows. Non-financial criteria: evaluate the fuzzy importance of the non-financial investment criteria and assign ratings to alternative AMT investment projects. Risk: sensitivity analysis to identify the most sensitive variables; The decision-maker is asked to weigh each risk using a fuzzy linguistic scale; The decision maker has to evaluate each alternative AMT project with respect to each risk factor.
Karsak (2002)	Distance-based fuzzy multicriteria decision-making	Fuzzy logic	Capital and operating costs; Required floor space; Work-in-process; Product flexibility; Volume flexibility;	Capital and operating costs: \$ Required floor space: m^2 Work-in-process: units	Quantitative and Qualitative	Quantitative criteria: costs are measured in \$ and required floor space is measured in m^2. Qualitative criteria: linguistic ratings (poor, fair, good, very good) or triangular fuzzy numbers.

Author (year)	Method	(Method) Taxonomy	Criteria	Indicators/ Evaluation method/ Elements	Criteria type	How are the criteria being measured/handled?
	(MCDM): Fuzzy logic and TOPSIS		Expansion flexibility; Lead time reduction; Quality improvements			Aggregate importance weights for the selection criteria is determined; Experts determine the importance weights for each criterion. Proximity of the alternatives to the ideal solution are calculated and ranked.
Talluri (2002)	Single price system model	Mathematical programming (MP)	Purchase cost; Operating cost; Work-in-process units; Percentage tardy; Yield units	Purchase cost: $ Operating cost: $	Quantitative	Each criteria has a measurement, e.g.: purchase costs are measured in $. The alternatives are categorized into dominated and non-dominated systems through an equation; the single price scores are obtained by using an equation (which is the ratio of aggregated benefit to aggregated cost); non-dominated alternatives are ranked.
Karsak and Kuzgunkaya (2002)	Fuzzy multiple objective programming approach: Fuzzy logic and Mathematical Programming	Fuzzy logic	Reduction in labor cost; Reduction in WIP; Reduction in setup cost; Increase in market response; Improvement in quality; Capital and maintenance cost; Floor space used	Reduction in labor cost: % Reduction in WIP: % Reduction in setup cost: % Increase in market response and Improvement in quality: linguistic expressions Capital and maintenance cost: $ Floor space used: square feet	Quantitative and Qualitative	The values are expressed using triangular fuzzy numbers, except for increase in market response and improvement in quality, where linguistic expressions such as weak (W), fair (F), and good (G) are adopted. The importance degrees of the criteria are denoted by linguistic variables such as "low", "moderate" and "high".
Punniyamoorthy and Ragavan (2003)	Strategic decision-making model: Extended Brown–Gibson Model (EBG), AHP and Sensitivity analysis	Strategic models	Objective: Annual cost; Profit; Depreciation Subjective: Flexibility; Learning; Capacity Increment; Exposure to labor unrest	-	Quantitative and Qualitative	Objective criteria: measured in terms of cost and time dimensions. Subjective criteria: AHP (managers evaluate the criteria and sub-criteria and give pairwise comparison values from 1 to 9. Both the subjective and objective criteria are converted into consistent and dimensionless indices to measure the manufacturing system preference measure (MSPM) with a computer program.
Cil (2004)	Internet-based Collaborative Decision Support System	Others	Strategic: High throughput rate; Low direct labour; Low WIP; Variable batch size; Efficient information processing; Low setup time; Flexibility; Efficient	Machine usage cost: hourly cost of using a machine, it includes the initial investment cost of machine and maintenance cost	Quantitative and Qualitative	Strategic level: decision-maker provides the importance ratings between the system capabilities and market requirements and between the system capabilities and manufacturing technology types

Author (year)	Method	(Method) Taxonomy	Criteria	Indicators/ Evaluation method/ Elements	Criteria type	How are the criteria being measured/handled?
	(CDSS): knowledge-based systems, simulation (ProModel), and activity-based costing models		quality control Operational: single capacity location states are an example Economic: Machine usage cost; Overhead cost	Overhead cost: includes set up, load, unload, movement, and inspection cost		using qualitative terms such as high, medium, low, irrelevant. Operational level: A simulation study using ProModel software is employed to study the performance of the alternatives generated by the strategic evaluation. The required configuration data, i.e., the machine processing times, capacity of conveyors, speed of conveyor, etc. are obtained from the database. Economic level: The output of the simulation forms the necessary input for an ABC analysis.
Kim and Kim (2005)	Real options	Financial analysis	Costs and revenues	Monetary value	Quantitative	NPV
Bhattacharya et al. (2005)	Combined AHP/ Quality Function Deployment (QFD) model	Analytic hierarchy process (AHP)	In the case study, the following criteria were adopted: Payload; Accuracy; Life-expectancy; Velocity of robot; Programming flexibility; Total cost	Drive system; Geometrical dexterity; Path measuring system; Robot size; Material of robot; Initial operating cost of robot; Importance weighting of customer requirements	Quantitative and Qualitative	QFD method is applied to identify the technical requirement criteria. AHP is used to measure the priority for each technical requirement and to assess the priorities of each robot alternative for each technical requirement.
Rao (2006)	Digraph and matrix methods	Others	Total costs involved; Work-in-process inventory; Throughput time; Number of employees; Floor space requirement; Volume flexibility; Product-mix flexibility; Routing flexibility	Total cost: millions of dollars) WIP: units Throughput time: hours per unit of production Floor space requirements: thousands of square feet Volume flexibility: average range of production capacity per product type Product-mix flexibility: product types Routing flexibility: average number of operations per machining center	Quantitative and Qualitative	The values for the criteria should preferably be obtained from available or estimated data. The relative importance of criteria is given by the decision maker. With these inputs, a flexible manufacturing system selection index (FMS-SI) is calculated, which is a measure of the degree or extent to which a flexible manufacturing system can be successfully selected for a given industrial application.
Chan et al. (2006)	Fuzzy multi-criteria decision-making: Manufacturing strategy map,	Fuzzy logic	Cost of product; Product performance; Quality; Delivery time and delivery time reliability; Flexibility; Innovativeness	Cost: product cost; maintenance cost; high rate of return; labor cost; material cost Performance: compatibility with existing machine; work morale; productivity; utilization; machine breakdown; human integration Quality: scrapped value; rework; conformance;	Quantitative and Qualitative	Quantitative criteria: evaluated in monetary terms by fuzzy cash flow model. Qualitative criteria: linguistic assessment converted in triangular fuzzy numbers. A group of decision-makers is responsible for assessing the suitability of the alternatives under

Author (year)	Method	(Method) Taxonomy	Criteria	Indicators/ Evaluation method/ Elements	Criteria type	How are the criteria being measured/handled?
	AHP and financial analysis			consistency Delivery: transportation; customer services; time scheduling; delivery time; inventory/work in progress; lead time Flexibility: design change accommodation; change in product mix; market responsiveness; capacity growth; routing and scheduling flexibility Innovativeness: research and development; introduce product variation		each criteria as well as the importance of each criteria using pairwise comparisons. For the latter, the following weighting set are employed: VL = very low, L = low, M = medium, H = high and VH = very high. Fuzzy appropriate indexes are calculated and ranked.
Tan et al. (2006)	Intelligent system integrating case-based reasoning (CBR) and the fuzzy ARTMAP (FAM) neural network model	Others	Cost; Prioritization scores such as technology novelty rating, intellectual property potential, impacts on improving customer services; Risk factors such as resource risk, benefit delivery risk, and technology novelty risk	-	Quantitative	CBR is utilized to support managers in retaining and reusing their previous knowledge on both successfully and unsuccessfully delivered projects to evaluate future projects. FAM is incorporated into the developed system to support incremental learning in a dynamic environment.
Choudhury et al. (2006)	Multi-agent system (MAS) to map the consensus group decision-making (GDM) model	Hybrid methods	Strategic: Financial position; Infrastructural position; Market position; Human resource management Technological: R&D; Manufacturing engineering and planning; Flexibility; Reliability; Maintainability Social: Personnel policies for employees; Working environment; Environmental factors	-	Quantitative and Qualitative	The decision makers present their views on the various criteria and sub-criteria in four different ways. The Consensus Agent transforms the various forms of opinion into Fuzzy Preference Relation using a transformation function. The collective Fuzzy Preference is calculated using OWA operator.
Rezaie and Ostadi (2007)	Integrated dynamic programming model	Mathematical programming (MP)	Total cost	Purchase cost; Salvage value; Production cost (setup costs, processing costs, holding costs)	Quantitative	The objective of the integrated dynamic programming model is to minimize total costs over the planning horizon. A formula has been provided for the cost associated with the manufacturing system in a certain time period.
Jaganathan et al. (2007)	Fuzzy analytic hierarchy process (AHP)	Fuzzy logic	Monetary; Flexibility; Environmental consciousness; Risk; Quality	-	Quantitative and Qualitative	Decision maker performs a reciprocal pairwise comparison to assess the performance of alternatives and the importance of criteria using a

Author (year)	Method	(Method) Taxonomy	Criteria	Indicators/ Evaluation method/ Elements	Criteria type	How are the criteria being measured/handled?
	based group decision support systems					fuzzy scale of his/her choice. Global priorities are given for the alternatives based on the weighted sum method.
Kahraman et al. (2007)	Fuzzy hierarchical TOPSIS	Fuzzy logic	Economical: Investment costs; Operating costs Technical: Repeatability; Speed; Memory capacity; Precision or accuracy; Programmability; Number of axes; Workload	Investment costs: purchase cost; installation cost; special tooling cost Operating costs: maintenance cost; labor cost; training cost	Quantitative and Qualitative	Respondents assign weights of the criteria (sub-criteria) with respect to the goal (criteria), using triangular fuzzy numbers. Fuzzy evaluation scores are calculated for each alternative with respect to each sub-criteria under each main criteria assessed by each respondent (using triangular fuzzy numbers). Distances from the ideal solution are calculated for each alternative.
Karsak (2008)	DEA and triangular fuzzy numbers	Fuzzy logic	Input: Capital and operating cost; Required floor space; Work-in-process Output: Product flexibility; Quality improvement; Lead time reduction	Capital and operating cost: $ Required floor space: m^2 Work-in-process: units Product flexibility and Quality improvement: ordinal scale Lead time reduction: %	Quantitative and Qualitative	"Work-in-process" and "lead time reduction" that cannot be assessed by exact data are represented as triangular fuzzy numbers. "Product flexibility" and "quality improvement" are provided as ordinal data (scale from 1 to 5). Efficiency scores for each FMS alternative are calculated and ranked for an optimistic and a pessimistic scenario.
Ordoobadi (2008)	Fuzzy logic	Fuzzy logic	Organizational costs: Cost of infrastructural requirements; Cost of redefining roles; Implementation risk; Risk of reduction in the knowledge base; Lack of commitment to change; Cost of human resource policy change; Displacement and disruption costs; Organizational restructuring costs; Strain on resources; Staff turnover Human-related costs: Lack of leadership; Lack of management commitment; Cost of employee resistance; Cost of management/staff time; Risk of reduced control; Learning costs; Risk of loss of employment; Fear of unknown and	Drop in future management support; Reduction in versatility of personnel skills; Incompatibility with current operations; Failure due to lack of commitment to change; Low performance; Not completing the implementation; Increase in absenteeism due to low-employee morale; Lower employee performance due to resistance to chance; Project cost overrun; Increase in labor contract costs; Obsolescence due to poor timing of adoption; Increase in learning costs; Reduction in competency	Quantitative and Qualitative	A decision-maker must express his/her perception of the importance of the risk categories in linguistic terms "low," "moderate," "high," or "very high". These linguistic terms will be converted into fuzzy weights with the use of fuzzy membership functions. Decision-maker assesses the performances of each technology with respect to the risks in linguistic terms "excellent," "very good," "good," or "poor". These linguistic terms will be converted into fuzzy performance ratings with the use of fuzzy membership functions. After calculating the aggregate fuzzy score for each technology and converting it into crisp scores, the alternatives are ranked.

Author (year)	Method	(Method) Taxonomy	Criteria	Indicators/ Evaluation method/ Elements	Criteria type	How are the criteria being measured/handled?
			resulting anxiety; Risk of reduced job satisfaction; Motivation redundancy			
Chang and Wang (2009)	Consistent fuzzy preference relations (CFPR)	Fuzzy logic	Not specified	-		A pairwise comparison matrix for the priority weight of attributes is established. The pairwise comparison matrix is normalized, and the attribute weight is aggregated. Pairwise comparison matrix for ratings of alternatives with respect to attributes is established. The prediction weight is determined by multiplying the priority weights of attributes and the evaluation ratings of alternatives.
Wang and Chin (2009)	DEA with double frontiers	Data envelopment analysis (DEA)	The authors do not propose their own criteria, instead, in the numerical examples section, they use the criteria adopted by the example original authors'	-	Quantitative	Efficiencies are measured from an optimistic and a pessimistic point of view, leading to two different rankings for AMTs. To give an overall ranking for the AMTs, an overall performance measure is calculated.
Chuu (2009)	Fuzzy multiple attributes group decision making with multiple fuzzy information	Fuzzy logic	In the case study, the following criteria were adopted: Objective: Required floor space; Capacity; Lead time; Investment cost Subjective: Process flexibility; Product quality; Learning; Exposure to labor unrest	-	Quantitative and Qualitative	Qualitative assessment state: each decision-maker gives an importance grade for each criteria and performance ratings for each alternative with respect to each subjective criteria, in the fuzzy data form. Quantitative evaluation state: quantitative effects of objective criteria are evaluated by experts using approximate numerical values, and then determined by decision-makers. These evaluations are generally assessed in fuzzy data form. Selection state: all the fuzzy data must be converted into a basic linguistic term set. Then an aggregation approach based on MEOWA operators is employed. All the elements of fuzzy suitability vectors are defuzzified and ranked.
Mehrabad and Anvari (2010)	Fuzzy PROMETHEE	Fuzzy logic	Operational: Work-in-process (WIP); Percentage of tardy jobs; Yield (throughput minus scrap and rework)	-	Quantitative and Qualitative	A group of decision makers assesses the importance weights of each criteria and the suitability of each alternative under each criteria.

Author (year)	Method	(Method) Taxonomy	Criteria	Indicators/ Evaluation method/ Elements	Criteria type	How are the criteria being measured/handled?
			Economic: Initial investment; Annual operating cost; Maintenance cost Strategic: Floor space requirements; Increase in process flexibility; Improvement in quality factors; Average percentage of availability and reliability			Operational criteria: simulation models are developed and ran simulation models; the collected data is fuzzified (converted into triangular fuzzy numbers). Economic criteria: fuzzy discounted cash flow analysis is performedStrategic criteria: a suitable value for each alternative relative to each strategic criteria are defined (using fuzzy numbers or linguistic values, here VP = very poor, P = poor, F = fair, G = good, VG) Fuzzy PROMETHEE is used to obtain fuzzy suitability index values of the alternatives and then rank them.
Ateekh-Ur-Rehman et al. (2011)	Elimination et Choice Translating Reality (ELECTRE)	Elimination et Choice Translating Reality (ELECTRE)	In the case study, the following criteria were adopted: Design cost; Manufacturing cost; Machine utilization; Cycle time; Quality; Productivity; Sharing of information; Standardization	-	Qualitative	Decision-makers must select the various criteria and their level of importance on a scale of 1 (not important) to 9 (extremely important). Each decision maker selects advanced manufacturing technologies from the available database. The model computes the weighted measure of each objective criterion and cumulative preference of various AMTs. Then, the model calculates the concordance/preference index.
Li (2011)	Fuzzy theory and Hierarchical analysis	Fuzzy logic	Economic benefits: Cost; Revenue Strategic benefits: Quality; Efficiency; Time; Flexibility; Innovativeness Risk analysis: Applicability risk; Reliability risk; Substituted risk	Cost: material cost, labor cost, manufacturing expense Revenue: return on investment, return on sales Quality: rate of qualified product, rate of waste product, rate of reworking, rate of return product Efficiency: productivity, rate of equipment utilization, rate of machine breakdown, degree of human integration, employee morale Time: product development cycle, delivery time	Quantitative and Qualitative	AHP can be applied to determine the relative importance of each criteria and get its weight, where a 9-point scale is used for the pairwise comparison. The next step is to set up the evaluation rank collection, which is divided into five levels and V = (very high, high, medium, low, very low).

Author (year)	Method	(Method) Taxonomy	Criteria	Indicators/ Evaluation method/ Elements	Criteria type	How are the criteria being measured/handled?
				Flexibility: design change accommodation, change in product mix, market responsiveness, capacity growth, routing, and scheduling flexibility Innovativeness: new product variation, integration degree of new product development Applicability risk: technology standard consistency, manufacturing resources consistency, employee adaptability Reliability risk: technology reliability Substituted risk: technology substitution cycle		
Kreng et al. (2011)	Fuzzy AHP model with group decision	Fuzzy logic	In the case study, the following criteria were adopted: Cost (tangible): Acquisition cost; Maintenance cost; Production cost Flexibility (intangible): Volume; Routing/scheduling; Expansion Quality (intangible): Internal failure cost; External failure cost; Appraisal cost; Prevention cost	-	Quantitative and Qualitative	Decision makers separately perform pairwise comparisons with different assurance levels to determine the importance of the criteria, using triangular fuzzy numbers. The computations are performed with the programs coded in Matlab software.Weighted geometric mean method (WGMM) is used to aggregate all the decision-makers opinions.
Song and Wang (2012)	Fuzzy evaluation	Fuzzy logic	Social benefits: Social environment; Social economic; Ecological environment; Resources inluence Adaptability to society: ability to sustainable development	Social environment: social welfare, social stability Social economic: technology progress, regional economic growth, industry drive Ecological environment: environmental quality, land usage, green degree Resources inluence: natural resources consumption, energy consumption Ability to sustainable development: ability to macro strategy	Quantitative and Qualitative	Decision-maker determines the importance of the criteria in the project's social assessment. To evaluate the value of assessment criteria, a function value between 0-1 is used based on the experts' opinion.
Evans et al. (2012)	Fuzzy decision trees	Fuzzy logic	Technical longevity; Skill level; Process specification; Project cost; Manufacturing objectives; Process/operation cost	-	Quantitative and Qualitative	The weighting represented in the tree reflects the judgment of an expert decision-maker by providing an allowance towards more and less important attributes.

Author (year)	Method	(Method) Taxonomy	Criteria	Indicators/ Evaluation method/ Elements	Criteria type	How are the criteria being measured/handled?
						The requirements of the case are classified. A weighted fuzzy membership value (WMV) is calculated at each criteria within the decision tree to conclude interim fuzzy scores. A final fuzzy score is calculated for each technology. The new case is retained in the new case repository.
Sadeghi et al. (2012)	Fuzzy data and Dual-role factors	Fuzzy logic	Input: Cost Output: Load capacity; Velocity Either input or output: Vendor reputation	-	Quantitative and Qualitative	Qualitative criteria are measured on an ordinal scale that will be converted to fuzzy data using a linguistic scale. Efficiency scores of industrial robots and their inputs/outputs behavior are calculated.
Frank et al. (2013)	SWOT, QFD, NPV, Payback and MAUT (Multi-Attribute Utility Theory) method	Others	In the case study, the following criteria were adopted: Strategic: Production costs; Technical expertise in new product development process; Possible changes in the economy that may reduce investments; Possible new competitors; Difficulties in logistic services in the region; Growing of substitute products; Government incentives; New market trends of customized products; Growing of suppliers of new materials in the region Quality: Lead time; Delay in delivery; Time for assembling in days; Time for assembling in units; Number of customer complaints; Time of employees experience Economic: NPV; Payback	-	Quantitative and Qualitative	Strategic criteria: SWOT; the project team attributes weights to each strength, weakness, opportunity, and threat; interactions within each quadrant are ranked by grades that represent the strategic relevance of each component (e.g.: quadrant 1 denotes to what degree a strength can be implemented in order to take advantage of an opportunity). Quality criteria: QFD; a survey is carried out with customers in order to list the quality items demanded by them; customers will also be asked to determine the rank of those quality items, using a scale from 1 to 10; the level at which a quality characteristic ensures the demanded quality is measured on a scale from 0 to 9; indexes of the quality characteristics are calculated. Economic criteria: NPV and Payback; NPV is expressed in monetary values, which requires conversion into a scale from 0 to 1 (in order to serve as input for MAUT) by applying an s-curve; the Payback is expressed in time, therefore, the same conversion is required. These analyses will serve as inputs for MAUT: the business organization establishes the criteria weights (economic, strategic, quality) according to its priorities; after including the data from the

Author (year)	Method	(Method) Taxonomy	Criteria	Indicators/ Evaluation method/ Elements	Criteria type	How are the criteria being measured/handled?
						other analysis, scores are attributed to the different alternatives.
Tansel İç et al. (2013)	Robot Selection Decision Support System (ROBSEL): Elimination module and which uses Fuzzy AHP module	Fuzzy logic	Production capacity; Flexibility (arm flexibility and reach capacity); Allocated fund	Production capacity: Payload capacity; Repeatability; B-axis motion ranges; T-axis motion ranges Arm flexibility: S-axis motion ranges; L-axis motion ranges Reach capacity: Minimum and maximum vertical reach distances	Quantitative	Once the required values are entered in the elimination module, the feasible set of robots are obtained by the elimination module and provided in the output screen. The feasible set is also simultaneously transferred to the fuzzy AHP module for the ranking process. Fuzzy AHP module requires the decision-maker to fill the pair-wise comparison matrices so that the criteria weights can be determined by the module. Once the pair-wise comparison matrices are filled, the fuzzy AHP module determines the ranking scores of the possible robots.
Ordoobadi (2013)	AHP and Taguchi loss functions	Hybrid methods	Benefits: Increased flexibility; Increased quality; Increased productivity; Expanded use of the technology; Promotion of strategic objectives; Competitive strengths; Increased customer satisfaction; Increased market opportunities; Increased ease of operation; Increased employee relations Risks: Reduction in versatility of personnel skills; Incompatibility with current operations; Low employee performance due to resistance to change; Drop in future management support; Project cost overrun; Increase in absenteeism due to low employee morale; Increase in learning costs; Obsolescence due to poor timing of adoption; Not completing the implementation; Increase in labor contract costs	Increased flexibility: Number of product types, volume of parts, shorter cycle times and setups; Decreased waiting time for parts, decreased work in progress; Reduced lead times, reductions in inventory; Increased machine utilization, reductions in idle cost Increased quality: Lower defect rates, reduced scrap and rework decreased inspection costs; Higher tolerance capability, improved control measures Increased productivity: Decreased labor costs (direct and indirect); Decreased materials costs (direct and indirect); Decreased service costs of using capital; Decreased floor space requirements Expanded use of the technology: Increased number of products, increased product variety; Number of other processes/areas in which the technology can be used; Number of other departments/areas that can benefit from the	Quantitative and Qualitative	AHP methodology is used to determine the relative importance of each criteria (on a scale of 1 to 9). Decision maker is asked to state his/her perception of technologies' performances. To allow rankings of the technology alternatives, the results of the analysis performed so far should be combined and subjective perceptions should be quantified to come up with a single performance score for each technology. Taguchi loss function is considered as a means to accomplish this task. The individual loss scores for each benefit/risk category are calculated. The weighted and composite loss scores are then determined and used for rankings of the technology alternatives.

Author (year)	Method	(Method) Taxonomy	Criteria	Indicators/ Evaluation method/ Elements	Criteria type	How are the criteria being measured/handled?
				technology; Increase in the number of new ventures Promotion of strategic objectives: Increased number of achieved goals; Decreased risk of obsolescence, increased level of progress made on certain goals Competitive strengths: Increased customer satisfaction, increased sales in target market areas; Increase in the percent of the market shareIncreased customer satisfaction: Improved delivery reliability, reduced delivery time, reduced lead timesdecreased customer complaintsIncreased market opportunities: Faster response to changing market demands; Increased speed for new product introductionIncreased ease of operation: Standardization of product designs within families of parts; Shorter cycle times, increased machine utilization and efficiency; Reductions in indirect labor; Availability of real-time informationIncreased employee relations: Increased employee morale/satisfaction, increased labor productivity; Increased learning about advanced technologies, decreased safety hazards		
Aliakbari Nouri et al. (2015)	Fuzzy ANPand Fuzzy TOPSIS	Fuzzy logic	Human: Motivation; Cooperation; Safe; Training Operational: Flexibility; Reliability; Productivity; Quality Financial: Capital; Operating; Maintenance; Implementation	-	Quantitative and Qualitative	Pairwise comparisons are performed considering each criteria relative importance and the importance of each sub-criteria to the main criteria, using a fuzzy linguistic scale. The weights of the criteria are calculated. Alternatives are ranked by applying fuzzy TOPSIS which implies calculating the relative distances between ideal and negative ideal alternatives.
Parameshw aran et al. (2015)	Fuzzy Delphi Method (FDM), Fuzzy	Fuzzy logic	Objective: Equipment cost; Load capacity; Repeatability; Maximum tip speed; Positioning	-	Quantitative and Qualitative	FDM is used to select the list of important objective and subjective criteria based on the decision makers' opinions. Fuzzy AHP method is

Author (year)	Method	(Method) Taxonomy	Criteria	Indicators/ Evaluation method/ Elements	Criteria type	How are the criteria being measured/handled?
	Analytical Hierarchical Process (FAHP), Fuzzy modified TOPSIS or Fuzzy VIKOR and Brown–Gibson model		accuracy; Memory capacity; Manipulator reach; Degree of freedom; Repeatability error; Velocity ratio, Velocity; Vertical reach; Warranty; Delivery time; Ambient temperature Subjective: Man-machine interface; Programming flexibility; Vendor's service contract; Supporting channel partner's performance; Simulation software; Stability; Compliance			then used to find out the weight of each criterion (both objective and subjective). Fuzzy modified TOPSIS or Fuzzy VIKOR method is then used to rank the alternatives based on objective and subjective factors. The rankings obtained are used to calculate the robot selection index based on the Brown–Gibson model.
Jones et al. (2015)	Cost-benefit framework	Financial analysis	Tangible: Time; Cost; Quality Intangible: Health and safety; Flexibility; Managerial/operations; Risk; Strategic objectives	Time: process takt time; process waste; Process person-hours; process up time; process service cycle time; process lifecycle time; process lag time Cost: recurring cost; non-recurring cost Quality: rework in manufacture; process capability; number of inspections Health and safety: process legislation performance; employee relations performance; ergonomics performance Flexibility: process flexibility; product flexibility Managerial/operations: process compatibility with existing operations configuration; technology expansion; installation complexity Risk: development risk; implementation risk Strategic objectives: manufacturing vision; future product vision	Quantitative and Qualitative	Toolsets have been developed to forecast both tangible and intangible criteria in a quantitative manner. Its inputs include functional size drivers, effort drivers, cost drivers, key performance factors (KPF), and weights for each KPF defined by the decision-maker.
Al-Ahmari et al. (2016)	Decision support system (DSS)	Fuzzy logic	Benefits: Increased flexibility (product flexibility; process flexibility; demand flexibility; equipment flexibility; manufacturing flexibility); Increased productivity (single/multiple and or total productivity) Costs (optional): Initial investment; Annual operating; Annual maintenance; Training; Programming; Warranty	Product flexibility: volume of parts; shorter cycle time; decreasing machine setup time Process flexibility: decreasing waiting time for parts; decreasing work in process (WIP) Demand flexibility: reduced lead times; reductions in inventory; decreasing time to market Equipment flexibility: increase machine utilization; reduction in idle time and cost	Quantitative and Qualitative	Benefits: decision maker is asked to determine the relative importance of each benefit criteria and the relative importance of each indicator with respect to the main criteria, using a fuzzy linguistic scale (VI = very important; I = Important; MI = More-or-less important; MU = More-or-less unimportant; U = unimportant). Decision maker rates the alternatives in a pairwise comparison.Costs: IRR and NPV methods.

Author (year)	Method	(Method) Taxonomy	Criteria	Indicators/ Evaluation method/ Elements	Criteria type	How are the criteria being measured/handled?
				Manufacturing flexibility: reduce material handling time; increase automatic tool change capability; reduce setup time; lower exchangeability and movements; reduce transportation time between workstation Single/multiple and or total productivity: decreased labor cost; decreased material cost; decreased service cost of using capital; decreased floor space requirement; decreased production time per unit		
Iakymenko et al. (2016)	Differentiated approach	Hybrid methods	In the case study, the following criteria were adopted: Cost; Quality; Speed; Innovativeness/customization; Sustainability	Throughput rate; Set-up time; Manpower requirement; Level of inventory; Volume flexibility; Mix flexibility; Quality; Floor space requirements; Maintenance ability; Technology supplier support; Work environment safety	Quantitative and Qualitative	Strategic evaluation: weighted scoring models (WSM) or AHP is adopted to assess the importance of each criteria against competing priorities. The absolute and relative importance of the criteria is calculated. Each alternative is assessed against the criteria using the same WSM or AHP method. Financial evaluation: NPV, IRR and Payback analysis. Risk analysis: to be used for the highest ranked technology, adopting techniques such as probability and sensitivity analysis.
Bai and Sarkis (2017)	Cumulative prospect theory, Neighborhood rough set theory and Three-parameter interval grey numbers	Others	Economic/operational flexibility:Machine flexibility; Labor flexibility; Material handling flexibility; Routing flexibility; Operations flexibility; Expansion flexibility; Product flexibility; Modification flexibility Green flexibility:Green product flexibility; Energy flexibility; Environmental Material Flexibility; Pollution flexibility; Waste flexibility; Recycling flexibility; Biodegradability	All the flexibility criteria are measured in terms of volume	Quantitative	To determine the manufacturing state flexibility level for each alternative, decision makers can evaluate the alternatives for each criteria using a linguistic variable (Very Good (VG), Good (G), Medium Good (MG), Medium (M), Medium Poor (MP), Poor (P) and Very Poor (VP)); additionally, the reference points for each flexibility criteria can be determined by the countries' specific environmental regulations, expressed as a linguistic value. After normalizing the information, neighborhood relational matrices for each flexibility criteria are computed using historical information.To determine the weight of each flexibility criteria a normalization equation is

Author (year)	Method	(Method) Taxonomy	Criteria	Indicators/ Evaluation method/ Elements	Criteria type	How are the criteria being measured/handled?
			flexibility; Environmental management system flexibility			used.To determine the flexibility performance, a grey value function is calculated.
Borges and Tan (2017)	Taguchi's Loss Functions	Others	Labor flexibility: Job enlargement; Delegation of tasks; Involvement in decision-making Individual capabilities: Development of managerial, technical and basic skills; Labour force empowerment; New skills from training on the new AMT Employee relations: Better working practices; Job security and welfare; Influence of unions	-	Quantitative and Qualitative	A weighted loss score is calculated for each alternative. The weighted loss score for each of the technologies is composed of the multiplication of the weights and the loss scores calculated for the human criteria, where the weights are based on the ranking of importance set by the decision makers and the loss scores are calculated based on the specification limits set by the decision-makers for the criteria and the perception of the performance of the alternative regarding each criteria (also attributed by the decision-maker).
lo Storto (2018)	Double-DEA framework	Data envelopmen t analysis (DEA)	In the illustrative case, the following criteria were adopted: Input: Total Cost, Work in Progress (WIP), Throughput, Employees, Space RequirementsOutput: Volume flexibility, Production mix flexibility, Routing flexibility	Total Cost: USD millionsWIP: units Throughput: hours/unit Employees: persons Space requirements: thousands of square feet Volume flexibility: average range of production capacity per product type Production mix flexibility: product types Routing flexibility: average number of operations per machining center	Quantitative	The relative efficiency of every technology is calculated by implementing different DEA cross-efficiency models generating the same number of high-order indicators as efficiency vectors. Second, high-order indicators are used as outputs in a SBM-DEA super-efficiency model to obtain a comprehensive DEA-like composite indicator.
Nath and Sarkar (2018)	Fuzzy TOPSIS	Fuzzy logic	In the case study, the following criteria were adopted: Quality; Productivity; Flexibility; Customer Satisfaction; Eco-friendliness	-	Quantitative and Qualitative	Decision makers assign the importance weights of each criteria and the ratings of alternatives with respect to each criterion, using linguistic variables (VL=very low, L=low, M=medium, H=high, VH=very high). After determining the ideal and anti-ideal solution, a closeness coefficient is determined by calculating the distances to both the Fuzzy positive ideal solution (FPIS) and Fuzzy negative ideal solution (FNIS). Then, a Suitability Index (SI) is calculated

Author (year)	Method	(Method) Taxonomy	Criteria	Indicators/ Evaluation method/ Elements	Criteria type	How are the criteria being measured/handled?
						by taking into account the Objective Factor Measurement (OFM) to rank the alternatives.
Fu et al. (2019)	Stochastic multicriteria acceptability analysis for GDM framework (SMAA-2)	Mathematical programming (MP)	In the illustrative examples, the following criteria were adopted: Benefit: Load capacity; Maximum tip speed; Memory capacity; Manipulator reach; Velocity; Vendor service capacity; Programming flexibility Cost: Cost; Repeatability	Velocity: speed that a manipulator arm can achieve Load capacity: maximum weight that a robot can lift Cost: purchase, installation, and training costs Repeatability: robot's ability to repeatedly return to a fixed position Vendor's service quality: level and variety of services provided by a robot supplier Programming flexibility: robot's ability to be compatible with different programming codes Maximum tip speed: speed at which a robot can move in an inertial reference frame. Memory capacity: number of points or steps that a robot can store in its memory Manipulator reach: maximum distance that can be covered by the robotic manipulator	Quantitative and Qualitative	The measurement for each criteria (for each alternative) is obtained based on the elements indicated in a previous column; vendor's service quality and programming flexibility are subjectively determined by experts using a 10-point judgment scale. Objective weight determination methods, namely, Shannon entropy method, CRITIC method, ideal point method, or distance-based method are used to derive the optimal weights associated with each criteria. To achieve a consensus on the results obtained from the experts, SMAA-2 is applied. An open-source software developed is used to determine the rank acceptability indexes and holistic acceptability indexes.
Olfati et al. (2020)	Fuzzy multi-criteria decision making and stochastic programming	Fuzzy logic	Economic: Net present worth (NPW) Strategic: Not specified	Net present worth: Initial cost; Demand; Unit production time; Budget; Unit production costs and selling prices; Inventory level; Shortage level; Production values	Quantitative and Qualitative	Economic criteria: the net present worth (NPW) o each alternative is computed using a linear program with chance constraints. Strategic criteria: the evaluation of each AMT alternative versus the strategic criteria is expressed in a linguistic variable set (VP=very poor, P=poor, F=fair, G=good, VG=very good respectively) by the decision-makers. The decision makers determine the importance of each criterion, using linguistic variables (VL=very low, L=low, M= medium, H=high, and VH=very high). The rank of the alternatives regarding the strategic criteria is based on the calculation of the mean operator. To rank of the alternatives regarding economic criteria, the present worth of each AMT alternative is directly applied. To rank each alternative with

Author (year)	Method	(Method) Taxonomy	Criteria	Indicators/ Evaluation method/ Elements	Criteria type	How are the criteria being measured/handled?
						respect to all the criteria, a weighted mean operator is calculated.
Chu et al. (2020)	DEA common-weight with multiple-input model	Data envelopment analysis (DEA)	In the numerical examples, the following criteria were adopted: Input: Capital and operating cost; Floor space Output: Handling coefficient; Load capacity; Repeatability; Velocity; Qualitative improvement; WIP reduced; Tardiness reduced; Yield increased	Capital and operating cost: \$ Load capacity: piece Repeatability: Velocity: m/s Tardiness reduced: % Yield increased: %	Quantitative	After obtaining the raw data for the criteria (based on the measurements indicated in a previous column), efficiency scores are calculated, and the alternatives are ranked.

Appendix D. Decision-making methods used in AMT selection

Method	Description	Authors/studies
Financial analysis	Financial analysis are investment appraisal techniques usually focused on determining the return of each investment (Hamzeh & Xu, 2019) and includes techniques such as Net Present Value (NPV), Internal Rate of Return (IRR), Return on Investment (ROI), and benefit/cost ratio.	Chen (1996); Jones et al. (2015); Kim and Kim (2005); Krinsky and Miltenburg (1991); Lint (1992); Park and Kim (1995); Prueitt and Park (1992); Sawhney (1991); Wilkes and Samuels (1991)
Strategic models	Strategic models usually appear in the framework form and include analysis of technical importance, business objectives, competitive advantage, research, and development objectives (Iakymenko et al., 2016).	Kakati (1997); Mohanty and Deshmukh (1998); Punniyamoorthy and Ragavan (2003); Stainer et al. (1996)
Mathematical programming (MP)	Mathematical programming is a mathematical model used in decision problems (MirHassani & Hooshmand, 2019). Such models usually require parameters, decision variables, constraints, and objective function, where the objective functions need to be maximized or minimized to meet all constraints (MirHassani & Hooshmand, 2019).	Braglia and Gabbrielli (2000); Demmel and Askin (1996); Fu et al. (2019); Rezaie and Ostadi (2007); Talluri (2002)
Data envelopment analysis (DEA)	DEA is a non-parametric linear-programming based technique (mathematical programming technique) that focuses on evaluating the relative efficiency of a set of decision-making units (DMU) in the presence of multiple inputs and outputs (lo Storto, 2018). Although DEA is a mathematical programming technique, it is a separate taxonomy on Hamzeh and Xu (2019) work, due to its extensive application.	Braglia and Petroni (1999); Chu et al. (2020); lo Storto (2018); Sarkis (1997); Sarkis and Talluri (1999); Talluri and Paul Yoon (2000); Talluri et al. (2000); Wang and Chin (2009)
Fuzzy logic	Fuzzy logic comprises fuzzy models or sets that are a mathematical way to deal with problems that involve a source of vagueness (Karsak, 2002). The concept of a linguistic variable appears as a useful means for providing an approximate characterization of phenomena that are too complex or ill-defined to be described in conventional quantitative terms (Zadeh, 1975). A linguistic variable is a variable whose values are not numbers, but words or sentences. The value of a linguistic variable can be quantified using fuzzy set theory (Karsak, 2002).	[a] Abdel-Kader and Dugdale (2001); Al-Ahmari et al. (2016); Aliakbari Nouri et al. (2015); Chan et al. (2006); Chang and Wang (2009); Chuu (2009); Evans et al. (2012); Jaganathan et al. (2007); Kahraman et al. (2007); Kahraman et al. (2000); Kahraman et al. (1996); Karsak (2002); Karsak (2008); Karsak and Kuzgunkaya (2002); Karsak and Tolga (2001); Kreng et al. (2011); Li (2011); Mehrabad and Anvari (2010); Nath and Sarkar (2018); Olfati et al. (2020); Ordoobadi (2008); Parameshwaran et al. (2015); Sadeghi et al. (2012); Song and Wang (2012); Tansel İç et al. (2013)
Analytic Hierarchy Process (AHP)	AHP is a multi-criteria decision-making method (Wang et al., 2009). The general model decomposes a problem into a hierarchy of inter-related decision elements (Saaty, 2008). The main goal is at the hierarchy top, then are the broad objectives, originating the decision criteria, and at the lower level is usually a set of the alternatives (Saaty, 2008). All the elements of a certain level will go through a pairwise comparison with respect to the related elements in the level just above (Saaty, 2008).	Bhattacharya et al. (2005); Datta et al. (1992); Goh (1997); Luong (1998)

Method	Description	Authors/studies
Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS)	TOPSISS is a multi-criteria decision-making method (Wang et al., 2009) based on "the concept that the chosen alternative should have the shortest distance from the positive-ideal solution and the longest distance from the negative-ideal solution" (Kahraman et al., 2007, p. 418). The ideal solution is the one that maximizes the benefit criteria and minimizes the cost criteria (usually, a hypothetical alternative). The negative ideal solution is the one that maximizes the cost criteria and minimizes the benefit criteria (Aliakbari Nouri et al., 2015).	
Preference Ranking Organization Method for Enrichment of Evaluations (PROMETHEE)	PROMETHEE is a multi-criteria decision-making method (Wang et al., 2009) whose principle is to rank the alternatives with simplicity and clarity; it is ideal for problems where the alternatives need to be ranked considering several conflicting criteria (Wang et al., 2009).	Kolli and Parsaei (1992)
Elimination et Choice Translating Reality (ELECTRE)	ELECTRE is a multi-criteria decision-making approach that can be applied when a set of alternatives must be ranked according to a set of criteria reflecting the decision maker's preferences (Ateekh-Ur-Rehman et al., 2011). It uses concord, discordance indexes, and threshold values to analyze the outranking relations among the alternatives (Wang et al., 2009).	Ateekh-Ur-Rehman et al. (2011)
Hybrid methods	Combination of two or more methods.	(Chan et al., 1999); Chiadamrong and O'Brien (1999); Choudhury et al. (2006); Iakymenko et al. (2016); Nagalingam and Lin (1998); Naik and Chakravarty (1992); Ordoobadi (2013); Ordoobadi and Mulvaney (2001); Sambasivarao and Deshmukh (1997); Wicks and Boucher (1993)
Others	Scoring model	Soni et al. (1990)
	Simulation and Linear additive scoring model	Randhawa and West (1992)
	Internet-based Collaborative Decision Support System (CDSS): knowledge-based systems, simulation (ProModel), and activity-based costing models	Cil (2004)
	Digraph and matrix methods	Rao (2006)
	Intelligent system integrating case-based reasoning (CBR) and the fuzzy ARTMAP (FAM) neural network model	Tan et al. (2006)
	Taguchi loss functions	Borges and Tan (2017)
	SWOT, QFD, NPV, Payback and MAUT (Multi-Attribute Utility Theory) method	Frank et al. (2013)
	Cumulative prospect theory, Neighborhood rough set theory and Three-parameter interval grey numbers	Bai and Sarkis (2017)

[a]. Studies using fuzzy logic also use other decision methods, such as AHP (for example) and although they could be seen as hybrid methods, they were classified as fuzzy logic for better identification of methods using this technique.

Appendix E. Decision criteria identified from literature on decision-making methods for AMT adoption

Criteria	Reference [a]	Category	Reference
Costs	Abdel-Kader and Dugdale (2001); Al-Ahmari et al. (2016); Aliakbari Nouri et al. (2015); Ateekh-Ur-Rehman et al. (2011); Bhattacharya et al. (2005); Braglia and Gabbrielli (2000); Braglia and Petroni (1999); Chan et al. (2006); Chan et al. (1999); Chu et al. (2020); Chuu (2009); Cil (2004); Datta et al. (1992); Demmel and Askin (1996); Frank et al. (2013); Fu et al. (2019); Goh (1997); Iakymenko et al. (2016); Jaganathan et al. (2007); Jones et al. (2015); Kahraman et al. (2007); Kahraman et al. (2000); Kakati (1997); Karsak (2002); Karsak (2008); Karsak and Kuzgunkaya (2002); Karsak and Tolga (2001); Kim and Kim (2005); Kolli and Parsaei (1992); Kreng et al. (2011); Krinsky and Miltenburg (1991); Li (2011); Lint (1992); lo Storto (2018); Mehrabad and Anvari (2010); Mohanty and Deshmukh (1998); Nagalingam and Lin (1998); Parameshwaran et al. (2015); Park and Kim (1995); Punniyamoorthy and Ragavan (2003); Randhawa and West (1992); Rao (2006); Rezaie and Ostadi (2007); Sadeghi et al. (2012); Sambasivarao and Deshmukh (1997); Sarkis (1997); Sarkis and Talluri (1999); Soni et al. (1990); Talluri (2002); Talluri and Paul Yoon (2000); Talluri et al. (2000); Tan et al. (2006); Wilkes and Samuels (1991)	Economic	Cil (2004); Kahraman et al. (2007); Li (2011); Mehrabad and Anvari (2010); Randhawa and West (1992)
		Financial	Abdel-Kader and Dugdale (2001); Aliakbari Nouri et al. (2015)
		Tangible	Jones et al. (2015); Kreng et al. (2011)
		Monetary	Mohanty and Deshmukh (1998)
		Objective	Chuu (2009); Parameshwaran et al. (2015); Punniyamoorthy and Ragavan (2003)
		Pecuniary	Demmel and Askin (1996)
Revenues	Frank et al. (2013); Kahraman et al. (2000); Kim and Kim (2005); Krinsky and Miltenburg (1991); Li (2011); Park and Kim (1995); Wilkes and Samuels (1991)	Economic	(Frank et al., 2013); Li (2011)
Flexibility	Abdel-Kader and Dugdale (2001); Al-Ahmari et al. (2016); Aliakbari Nouri et al. (2015); Bai and Sarkis (2017); Chan et al. (2006); Chan et al. (1999); Chiadamrong and O'Brien (1999); Choudhury et al. (2006); Chuu (2009); Cil (2004); Datta et al. (1992); Demmel and Askin (1996); Jaganathan et al. (2007); Jones et al. (2015); Kahraman et al. (1996); Kakati (1997); Karsak (2002); Karsak (2008); Karsak and Tolga (2001); Kolli and Parsaei (1992); Kreng et al. (2011); Krinsky and Miltenburg (1991); Li (2011); Lint (1992); lo Storto (2018); Luong (1998); Mehrabad and Anvari (2010); Mohanty and Deshmukh (1998); Nagalingam and Lin (1998); Nath and Sarkar (2018); Ordoobadi (2013); Ordoobadi and Mulvaney (2001); Punniyamoorthy and Ragavan (2003); Randhawa and West (1992); Rao (2006); Sambasivarao and Deshmukh (1997); Sarkis (1997); Sawhney (1991); Soni et al. (1990)	Qualitative	Randhawa and West (1992)
		Tactical	Demmel and Askin (1996); Mohanty and Deshmukh (1998)
		Non-financial	Abdel-Kader and Dugdale (2001)
		Subjective	Chuu (2009); Punniyamoorthy and Ragavan (2003)
		Strategic	Cil (2004); Li (2011); Mehrabad and Anvari (2010)
		Technological	Choudhury et al. (2006)
		Operational	Aliakbari Nouri et al. (2015)
		Benefit	Al-Ahmari et al. (2016); Kakati (1997); Li (2011); Ordoobadi (2013)
		Intangible	Jones et al. (2015); Kreng et al. (2011)
Quality	Abdel-Kader and Dugdale (2001); Aliakbari Nouri et al. (2015); Ateekh-Ur-Rehman et al. (2011); Chan et al. (2006); Chan et al. (1999); Chiadamrong and O'Brien (1999); Chu et al. (2020); Chuu (2009); Cil (2004); Datta et al. (1992); Demmel and Askin (1996); Frank et al. (2013); Iakymenko	Tactical	Mohanty and Deshmukh (1998)
		Operational	Aliakbari Nouri et al. (2015); Mehrabad and Anvari (2010)

Criteria	Reference [a]	Category	Reference
	et al. (2016); Jaganathan et al. (2007); Jones et al. (2015); Kahraman et al. (1996); Kakati (1997); Karsak (2002); Karsak (2008); Karsak and Kuzgunkaya (2002); Karsak and Tolga (2001); Kolli and Parsaei (1992); Kreng et al. (2011); Krinsky and Miltenburg (1991); Li (2011); Lint (1992); Luong (1998); Mehrabad and Anvari (2010); Mohanty and Deshmukh (1998); Nagalingam and Lin (1998); Nath and Sarkar (2018); Ordoobadi (2013); Ordoobadi and Mulvaney (2001); Randhawa and West (1992); Sambasivarao and Deshmukh (1997); Sawhney (1991); Soni et al. (1990); Talluri (2002)	Strategic	Cil (2004); Li (2011); Mehrabad and Anvari (2010)
		Tangible	Jones et al. (2015)
		Market	Kakati (1997)
		Non-financial	Abdel-Kader and Dugdale (2001)
		Benefit	Kakati (1997); Li (2011); Ordoobadi (2013)
Space requirements/ savings	Al-Ahmari et al. (2016); Chu et al. (2020); Chuu (2009); Iakymenko et al. (2016); Karsak (2002); Karsak (2008); Karsak and Kuzgunkaya (2002); Karsak and Tolga (2001); Lint (1992); lo Storto (2018); Mehrabad and Anvari (2010); Nagalingam and Lin (1998); Ordoobadi (2013); Randhawa and West (1992); Rao (2006); Sarkis (1997); Sarkis and Talluri (1999); Talluri et al. (2000)	Operational	Randhawa and West (1992)
		Objective	Chuu (2009)
		Strategic	Mehrabad and Anvari (2010)
Programming flexibility/ Programmability	Bhattacharya et al. (2005); Braglia and Gabbrielli (2000); Cil (2004); Fu et al. (2019); Kahraman et al. (2007); Parameshwaran et al. (2015)	Subjective	Parameshwaran et al. (2015)
		Strategic	Cil (2004)
		Benefit	Fu et al. (2019)
		Technical	Kahraman et al. (2007)
Technical features (such as velocity, capacity, accuracy, reach, repeatability)	Bhattacharya et al. (2005); Braglia and Gabbrielli (2000); Braglia and Petroni (1999); Chu et al. (2020); Chuu (2009); Fu et al. (2019); Goh (1997); Iakymenko et al. (2016); Kahraman et al. (2007); Kakati (1997); Parameshwaran et al. (2015); Sadeghi et al. (2012); Sawhney (1991); Talluri and Paul Yoon (2000); Tansel İç et al. (2013)	Objective	Chuu (2009); Parameshwaran et al. (2015)
		Benefit	Fu et al. (2019); Kakati (1997)
		Technical	Kahraman et al. (2007)
Productivity	Al-Ahmari et al. (2016); Aliakbari Nouri et al. (2015); Ateekh-Ur-Rehman et al. (2011); Chan et al. (2006); Chan et al. (1999); Chu et al. (2020); Cil (2004); Datta et al. (1992); Kahraman et al. (1996); Karsak (2002); Karsak (2008); Karsak and Kuzgunkaya (2002); Kolli and Parsaei (1992); Li (2011); Lint (1992); lo Storto (2018); Luong (1998); Mehrabad and Anvari (2010); Nagalingam and Lin (1998); Nath and Sarkar (2018); Ordoobadi (2013); Ordoobadi and Mulvaney (2001); Randhawa and West (1992); Rao (2006); Sambasivarao and Deshmukh (1997); Sarkis and Talluri (1999); Sawhney (1991); Talluri (2002); Talluri et al. (2000)	Operational	Aliakbari Nouri et al. (2015); Mehrabad and Anvari (2010); Randhawa and West (1992)
		Benefit	Al-Ahmari et al. (2016); Li (2011); Ordoobadi (2013)
		Strategic	Cil (2004); Li (2011)
Compatibility	Chan et al. (2006); Chan et al. (1999); Jones et al. (2015); Luong (1998); Ordoobadi (2013); Ordoobadi and Mulvaney (2001); Randhawa and West (1992)	Qualitative	Randhawa and West (1992)
		Managerial/Operations	Jones et al. (2015)
Information	(Ateekh-Ur-Rehman et al., 2011; Cil, 2004; Datta et al., 1992; Sambasivarao & Deshmukh, 1997; Wicks & Boucher, 1993)	-	-
Delivery		Objective	Chuu (2009)

Criteria	Reference [a]	Category	Reference
	Abdel-Kader and Dugdale (2001); Chan et al. (2006); Chan et al. (1999); Chuu (2009); Frank et al. (2013); Kahraman et al. (1996); Kakati (1997); Karsak (2002); Karsak (2008); Kolli and Parsaei (1992); Krinsky and Miltenburg (1991); Luong (1998); Mehrabad and Anvari (2010); Sarkis and Talluri (1999); Sawhney (1991); Talluri (2002); Talluri et al. (2000); Wicks and Boucher (1993)	Strategic	Wicks and Boucher (1993)
		Market	Kakati (1997)
		Non-financial	Abdel-Kader and Dugdale (2001)
		Operational	Mehrabad and Anvari (2010)
Competitiveness	Chiadamrong and O'Brien (1999); Choudhury et al. (2006); Datta et al. (1992); Demmel and Askin (1996); Frank et al. (2013); Kakati (1997); Karsak and Kuzgunkaya (2002); Kolli and Parsaei (1992); Mohanty and Deshmukh (1998); Nagalingam and Lin (1998); Naik and Chakravarty (1992); Ordoobadi (2013); Ordoobadi and Mulvaney (2001); Sambasivarao and Deshmukh (1997)	Strategic	Choudhury et al. (2006); Demmel and Askin (1996); Frank et al. (2013); Mohanty and Deshmukh (1998); Naik and Chakravarty (1992)
		Benefit	Ordoobadi (2013)
Public Relations	Demmel and Askin (1996)	Market	Kakati (1997)
Customer satisfaction	Abdel-Kader and Dugdale (2001); Nath and Sarkar (2018); Ordoobadi (2013); Tan et al. (2006)		
Innovativeness or Technology position	Chan et al. (2006); Chan et al. (1999); Datta et al. (1992); Iakymenko et al. (2016); Jones et al. (2015); Krinsky and Miltenburg (1991); Li (2011); Sambasivarao and Deshmukh (1997); Tan et al. (2006)	Strategic benefit	Demmel and Askin (1996); Li (2011)
		Managerial/Operations	Jones et al. (2015)
Ergonomics	Datta et al. (1992); Jones et al. (2015); Sambasivarao and Deshmukh (1997)	Human factors	Datta et al. (1992); Sambasivarao and Deshmukh (1997)
		Intangible	Jones et al. (2015)
Safety	Aliakbari Nouri et al. (2015); Datta et al. (1992); Demmel and Askin (1996); Iakymenko et al. (2016); Jones et al. (2015); Ordoobadi (2013); Randhawa and West (1992); Sambasivarao and Deshmukh (1997); Soni et al. (1990)	Qualitative	Randhawa and West (1992)
		Personnel	Demmel and Askin (1996)
		Human/human factors	Aliakbari Nouri et al. (2015); Datta et al. (1992); Sambasivarao and Deshmukh (1997)
		Intangible	Jones et al. (2015)
		Benefit	Ordoobadi (2013)
Employee relations	Aliakbari Nouri et al. (2015); Borges and Tan (2017); Chan et al. (2006); Chan et al. (1999); Datta et al. (1992); Demmel and Askin (1996); Mohanty and Deshmukh (1998); Ordoobadi (2008, 2013); Ordoobadi and Mulvaney (2001); Randhawa and West (1992); Sambasivarao and Deshmukh (1997)	Personnel	Mohanty and Deshmukh (1998)
		Human	Aliakbari Nouri et al. (2015)
		Benefit	Ordoobadi (2013)
		Human-related costs	Ordoobadi (2008)
		Intangible	Jones et al. (2015)

Criteria	Reference [a]	Category	Reference
		Qualitative	Randhawa and West (1992)
Individual capabilities (related to training availability)	Aliakbari Nouri et al. (2015); Borges and Tan (2017); Chuu (2009); Ordoobadi (2013); Punniyamoorthy and Ragavan (2003); Randhawa and West (1992)	Qualitative	Randhawa and West (1992)
		Subjective	Chuu (2009); Punniyamoorthy and Ragavan (2003)
		Benefit	Ordoobadi (2013)
		Human	Aliakbari Nouri et al. (2015)
Market risk; Project risk	Abdel-Kader and Dugdale (2001); Braglia and Gabbrielli (2000); Goh (1997); Jones et al. (2015); Li (2011); Naik and Chakravarty (1992); Ordoobadi (2008, 2013); Parameshwaran et al. (2015); Sadeghi et al. (2012); Sarkis and Talluri (1999); Tan et al. (2006)	Risk	Abdel-Kader and Dugdale (2001); Li (2011); Ordoobadi (2013)
		Intangible	Jones et al. (2015)
		Human-related costs	Ordoobadi (2008)
Eco-friendliness	Choudhury et al. (2006); Iakymenko et al. (2016); Jaganathan et al. (2007); Nath and Sarkar (2018); Song and Wang (2012)	Social	Choudhury et al. (2006); Song and Wang (2012)
Green flexibility	Bai and Sarkis (2017)	-	

a. In this column are included references to the authors that have mentioned the exact criteria' word but also authors that have mentioned synonyms or indicators of the respective criteria.

Appendix F. Interview guide

A – Interviewee general information

1. Can you tell me a little about your professional experience?

B - Company general information

2. When did your company adopted collaborative robots? What production technologies exist in your company?
3. Which tasks are performed by those technologies?
4. Is the robot used in collaboration with humans or separate from them?

C – Decision process

5. Please describe how the decision to adopt a cobot was made from motivation/need until technology acquisition.
6. Do you consider the process used in your company to be the most appropriate? If you could, what would you change? Why?

D – Decision criteria

7. Which criteria/factors were considered by your company for the decision to adopt a cobot? Why?

E – Evaluation of each criteria

8. How do you assess/measure each of these criteria?
9. How did you obtain the necessary information?
10. Do you consider the way in which these criteria were evaluated the most correct? What would you change?

F – Importance of each criteria

11. In your opinion, which of these criteria are the most relevant? Why?
12. If you had to make a ranking, how would you do it?

G – Decision-making methods: Methods, models, analyses, or frameworks

13. What method(s)/analysis did you use in this decision?
14. What are the advantages and disadvantages of the method you used?
15. Did the method/decision process incorporated non-economic aspects?

a. If not: Have you felt the need for a method that would allow you to incorporate non-economic aspects? Which aspects?
b. If Yes: What aspects did the method incorporated? How was it used?

16. How did you related all the criteria to reach a final decision?
17. In your opinion, what would be the ideal/most suitable decision-making method?
    a. With inputs from several decision-makers or just one?
    b. A method whose decision is specific to a particular cobot (whether or not to adopt a certain cobot) or a method that compares multiple cobot models/vendors?

H – Tools

18. What tool did you use in your analysis (to implement the method you used)? (excel, software, etc.)

Final question

Would you like to add anything else to the topics covered in this interview?

Appendix G. Codebook

Code	Description	Example	Notes
Decision criteria			
Financial			
Costs	Investment cost (price and implementation cost), maintenance cost, operating cost (labor cost, training, material cost, machine utilization cost, energy, maintenance cost), and depreciation.	We have to see the pros, the cons, the alternatives, the references that exist, the maintenance cost that the machine will have, the operation cost it will have [...] to understand how much we are going to save, because we are going to reduce the number of people, because we are going to save raw materials or because we are going to save energy, for example. (I1C15)	
Revenues	Expected sales volume	Investment in technology is always associated with sales volume. […] Producing 1,500,000 pieces per year implies a different technology than if we are thinking of producing 10,000 units a year. […] When the sales volume is not very large, we probably will only have manual stations. (I2C7)	
Profit and traditional investment performance measurements	NPV, IRR, ROI, and Payback period	I would say that it would be more appropriate to analyse the NPV and the payback, conjointly. (I1C2) Under normal conditions, the payback and the rate of return (IRR) or the NPV are determining elements in the decision-making, they are indicators of the financial analysis. If the financial analysis determines that the project falls within some bounds of what we expect from the technology, we make the decision to acquire it. (I1C1) There is always a metric that I take into account, which is the ROI, the return on investment. That is, to see what is the marginal increase I have, the cost price over the marginal increase, and see how long it take to recover the investment. (I1C12)	
Operational			
Flexibility			
Product flexibility	Range (number) of products that can be manufactured (Sarkis, 1997).	The implementation of the robot made the production line less fixed in the format and type of packaging, being able to be used for various types of packaging by changing the robot tools. (I1C1) Then, an important point in the lines has to do with the different types of part families that go through each piece of equipment, because sometimes it can be complex to do an automation when we have many different parts to pass. (I1C8)	

Code	Description	Example	Notes
Equipment flexibility	Equipment ability to process various operations (Hua & Banerjee, 2001).	In cobots, the way the six axes is implemented gives you a lot of flexibility because the six axes on the wrist of the cobot so you can go somewhere, and then you still have a lot of flexibility. (I1C9)	
Manufacturing flexibility	The ability of the organization to manage production resources and uncertainty to meet various customer requests (Hua & Banerjee, 2001).	The operator is not always able to change the film (for wrapping) easily, so we are also looking for automatic changeover systems to be faster, less repetitive, and to lighten the difficulties of tuning the equipment. (I1C15)	
Quality			
Product quality			
Conformance	Meeting preestablished standards (Garvin, 1984).	The customer specification itself is central. The client gives you a series of criteria that his piece has to fulfill, and you have to be able to prove at an early stage of the project that you are capable of delivering that. (I1C5) If the equipment is not giving an initial response that meets our quality standards, it goes back and forces us to rework. (I1C12)	
Performance	Refers to the primary operating characteristics of a product (Garvin, 1984).	The most important of all would be ensuring the safety of the product. We couldn't take the risk of having a non-okay product coming off the production line. (I1C6)	
Perceived quality	Overall opinion of the customer towards the product (Garvin, 1984).	The customer himself evaluates the quality of the product through its use. (I2C7)	
Process quality			
Control	Refers to controlling measures of the production process.	We always have double-checking, and right now with the cobots, we actually don't need the double-checking anymore, we are 100% sure that the products which are put on the table are really good products. (I1C4)	
Reliability	The process capability of delivering the customer specification (I1C5).	Another issue is reliability, ie, for example, a bolting process. If the process is automated, there is no human factor to put the screws in the wrong way, the screw is either ok or the machine gives an error, someone goes there and fixes it and everything is fine again. If it's a person, the way the person gives it and those little things, very typical of people, end up affecting more. The more controlled you want the process to be, the more technology you will put. (I1C5)	

Code	Description	Example	Notes
		Technologies are always associated with the volume of business and the type of product I want to sell, which can be a more economical product depending on the process I use. If the process is also more robust, that is, if I don't have much variation in the process, the more precise the process, the more quality I have in the product. This is also an ultimate goal; product quality is clearly also essential. (I2C7)	
Productivity	Productivity is a measure of the rate at which goods are produced per unit of input (labor, capital, raw materials, etc).	Cycle times are always an important thing. If a technology buys time, it automatically becomes a candidate, unless the acquisition value is very absurd. (I1C5) We always have to analyze a crucial point. First, it is whether we can meet the expected cycle time on the production line, if we are in accordance with the takt time defined by our customer. The takt time is nothing more than the demand I have for parts about your opening time. That is, if the customer wants to buy 1000 pieces a week, this means that every 50 seconds a piece has to be delivered. (I1C8) But it always has to do with gains... for example on the productivity side, mainly because we started to make the same amount of parts with fewer resources. (I1C15)	If a participant referred an indicator, such as "cycle time", it was also coded as productivity.
Efficiency	The efficiency of a line can be associated with increased productivity and reduced costs (I2C7).	The efficiency of a line can be associated with increased productivity, that is, ensuring that the process is more stable and is always working at its best. And it can also, in some situations, reduce costs: downtime costs, parts replacement costs, etc. (I2C7) If it's going to increase efficiency, then we take the current efficiency and see how many more bottles we're going to produce at the same time and see how much that saves us. (I1C13) The efficiency of raw material consumption is a very simple and very generic indicator, that everyone understands, basically, it is the finished product divided by the raw material that enters the process. (I1C15)	
Space and mobility	Space is the amount of physical space that is required by the system (Gil-Vilda et al., 2017), and mobility refers to the ease of moving the equipment.	The reduced space in our company prevented us from opting for solutions such as those of an industrial robot, they need a fence and a large work area isolated from the operators and a higher economic investment. (I1C3) Easy to move: Similar to the previous case, when buying it it is not the most important thing, but when it comes to working, it is a great advantage that the equipment can be moved with relative ease, in the case of an industrial robotic line this is very complicated or not viable. (I1C3)	

Code	Description	Example	Notes
		If one day I have a problem, I can remove the cobot and put another one there easily. Or I can take that cobot and pull out another line in a different workstation, for example. (I1C8)	
Ease of use	How easy it is to work with the machine (I1C3).	Easy to work with the machine. (I1C3) So how easy it is to operate it. (I1C9) More than simplified technology, it's about the technology being suited to the need to be covered. And being adequate, of course, the more simplified the better. Although that is not that simple, because if the technology is adequate, but it's very simplified, it can probably also have fewer barriers to entry. That is, it may be easier for new competitors to enter this business. And therefore, on the one hand, this complexity q.s. in technology is also advantageous, as long as it is possible to give the necessary training to the teams to know how to work with it. (I1C14)	
Technological			
Ease of programming	Ease of programming to set up the cobot.	Ease of programming: In this case, it is more of a technical evaluation when programming, for a director this point may not apply since he does not have to program it, but when it comes to a technician/operator this point is important. (I1C3) We were kind of looking for as much independence as we can achieve. That meant that most of the programming we will do by ourselves, we will teach ourselves how to use and deal with these robot arms. In the end, quite a big influence on our decision on which producer we choose was the possibility first of all an intuitive programming, and the second, but certainly also important, was the interface in our local language. (I1C4)	
Technical features	Cobot technical characteristics. Payload, maximal reach, number of axes, repeatability, maximal speed, force sensing, and special features comprise cobots' main technical features (Cohen et al., 2021).	Now, I would add the technical capability of the device because with time, with the experience we have now, we see that the robots have different features, they are not the same. Even if they are in the same category. Let's say we use mainly robots with a capacity of ten kilograms. We have two different suppliers on our shop floor, but we see that they are similar, but some small things are different. For example, universal robots, the way the six axes are implemented gives you a lot of flexibility because the six axes on the wrist of the cobot so you can go somewhere, and then you still have a lot of flexibility. The other producers arranged it the other way. For example, universal robot, they have a lift capacity of static ten kilograms, but only in a certain range, not in a complete range of the robot. So these technical factors, the second approach to the subject is becoming more and more	

Code	Description	Example	Notes
		important because we have more knowledge and more experience with how to use these devices. (I1C9)	
		Then there are also the technical characteristics of the equipment, such as speed and repeatability in robot positioning. In this case of collaborative robots, it is also important to detect impacts, how sensitive the robot is. And if these impacts then cause problems in the quality of the process, because sometimes making the robot more sensitive can cause some quality problems. (I1C11)	
Information	How efficient information and statistics regarding the state of production and requirements are processed and supplied to the management (Datta et al., 1992).	Information was not part of this major investment and today, in our view, it is essential to create a reliable data collection strategy. The information must be analyzed in real-time to allow us to predict situations in real-time. (I2C7)	
		We are now very much looking for predictive methods because having an intelligence that can predict through models and through that raw material, what the quality and efficiency of the final product will be, is fundamental. (I1C15)	
Interface language	The language used in the robot interface to interact with its operator/programmer.	In the end, quite a big influence on our decision on which producer to choose, was first of all the intuitive programming, and the second, but certainly also important, was the interface in our local language. […] In the end, the decision was really for the European producer, because they offered us an interface in our native language. (I1C4)	
Strategic			
Competitiveness	Company's ability to compete with other companies.	If we increase our efficiency, we increase our competitiveness. (I1C1)	
		So, then I would say that competitiveness is crucial. (I1C7)	
Company image	Recognition obtained by the manufacturing company for having technologically advanced equipments.	This is a factor that ends up having more weight than it should but, for example, sometimes having more advanced technology impresses customers as well. Customers like that you are working for the future. (...) In other words, having good technologies ends up improving our relationship with customers a lot. (I1C5)	
		Technology is an image too. The customer recognizing that the technology is actually better for the product they are buying is clearly an advantage. Technology brings recognition to the customer; it brings recognition that this technology is the best on the market to manufacture the product they are buying and they probably even consider it to be a very advanced technology for the type of product they are buying. This is also an value added, a	

Code	Description	Example	Notes
		guarantee that the customer is satisfied and surprised with the technology and development of the manufacturing unit it sells. (I2C7)	
Customer satisfaction	Customer satisfaction with the received goods.	If we comply exactly with what the customer expects, the service is considered to be compliant, if not, there is a penalty in terms of the service appreciation and, therefore, this clearly translates into an indicator of satisfaction. (I1C7)	
Innovativeness	Company's policy towards modernization, integration, and innovation (Datta et al., 1992).	I would say that, at the moment, the choice concerns are: price, value/innovation, and quality. […] the main input for us to realize how innovative we are, are customer audits and management systems audits. From time to time, the customer audits our company to see if the process we have is good, robust, etc. They may say that another supplier has a better technology for a certain task and this input allows us to position ourselves in relation to the competition. (I1C7)	
		Pure and simple innovation too. See a new technology, apply it and leverage it for other projects and other areas, so that the industrialization part, even in the budgeting phase of new projects, can already contemplate the use of this technology and the lower use of human resources. (I1C10)	
		The initial motivation, six years ago, was somehow to start integrating a new technology that was appearing on the market, which was collaborative robotics. (I1C11)	
Human			
Ergonomic	Studying people at work to reduce physical/mental stress, injuries resulting from overuse, poor posture, and other musculoskeletal disorders.	The subject of the machine always came from one of two sources, one of which was an ergonomic problem, as we have already said, in which the operation itself was too complex, the weight, the necessary force, etc., or the repetition, we are talking about assembly lines that reached a production rate of more than 200 units per day. Some industries produce more, but the number is still quite significant. (I1C6)	Sometimes the interviewee did not mention the word "ergonomics" exactly, but he/she did express concerns about humans
		I'll give you an example, there's a small spring that we set up. It's so tiny, so tiny, that to be assembled manually would not only need a lot of people, but it would be unthinkable to assemble these springs by hand because this causes a lot of wear and tear to the person. Technology sometimes enters here too. (I2C7)	
		Centennial operations, so to speak, sometimes require repetitive movements and injuries can be associated with these repetitive movements. And so we are also aware of that. That is, if there is an incidence of complaints or injuries that are caused by a repetitive movement,	

Code	Description	Example	Notes
		it also enters the analysis of automating or, eventually, one day, having collaborative robots. (I1C15)	performing repetitive tasks. In these cases, the contribution was also coded as ergonomics.
Safety	Equipment's ability to work close to humans, without injuring them.	Next, it has to do with innovating and using technology that allows us to be more friendly to the environment that surrounds people. And if it was with traditional robotics, we'd have a problem. It would have to be something very closed, while collaborative robotics allows you to do something very open space and allows operators to work on the edge, passing close to the robots. They slow down, speed up, and stop depending on whether or not people are close. (I1C10) But I think in this case of collaborative robots, it was more security issues. That is, the creation of a friendly environment that gives a perception of security to the operators to be able to work and cohabit with the machines. I think that was the main aspect. I think that was a strong point of the decision-making, because if we couldn't have done the same thing with conventional robotics, could we? But we opted for collaborative robotics because we believe that these solutions are usually more user-friendly, more user-friendly for operators, and make the production environment more user-friendly. (I1C11)	
Human resources availability	Shortage of skilled labor (I1C1).	The issue of human resources has more to do with the quantity and quality of people we have to perform this function and the difficulty is recruiting them. […] There is a strong dependence on people to keep the operation running but it is difficult to find skilled labor. (I1C1) The cost and availability of people. Imagine, if I am designing an assembly line with the aim of producing in Portugal and the same assembly line with the aim of producing in Romania or China, for example, you will put more technology on the line for Portugal than on the line for Romania or China, because the availability and cost of having more people in those countries are lower. Essentially, that's the goal, is to try to put more technology to reduce the need for people. (I1C5)	

Code	Description	Example	Notes
		And also the trend that we have less and less employees interested in working three shifts, it's a must-have in our business to have a sufficient, let's say, competitive cost structure. (I1C9)	
Risk			
Project risk			
Supplier's service quality and trustworthiness	Level and variety of services provided by a robot supplier (Fu et al., 2019).	It was a deeply strategic decision. Afterwards, he went to see the two or three suppliers worldwide. Obviously, look at the price, of course, but not only... from the point of view of simplified technology, from the point of view of follow-up, preventive and corrective maintenance that these suppliers provide or not. Also from the point of view of training and manuals, for example, that they are committed to giving our teams so that they know how to work with the machine and also the financial solidity of these suppliers. If we had two suppliers, there is one that is cheaper, provides more training, provides more support, etc. but it is in a very critical financial situation... the choice is probably on the other supplier because these machines are machines that will last for many years. (I1C14) Examples of criteria: previous experience of the supplier or service provider, previous experience in similar projects or implementations, the experience of the team, etc. (I1C14) Also one of the criteria for me was the support and the approach of the distributor. It was important because it was a new field. But I overestimated the know-how of this distributor. (I1C9)	
Implementation risk	Risk of not completing the implementation (Ordoobadi, 2008).	Implementation time: the time is relatively short, in a couple of months you can have the palletizing system working. (I1C3) Our first approach started with collaborative robots because collaborative robots are easy to integrate into production lines. (I1C8)	
Availability	How quickly can we get the technology (I1C9).	The other thing was the availability: how quickly can we get it. (I1C9) Examples of quantitative criteria: price, payment terms, delivery times. (I1C14)	
Environmental			
Sustainability	Responsible production lines to preserve the environment. Avoiding carbon emission,	Sustainability is one of the company's pillars and as such ends up impacting our decisions. The company, for example, has also invested in photovoltaic panels recently; is replacing all	

Code	Description	Example	Notes
	being more efficient in energy consumption, and producing in renewable ways.	fleet with electric vehicles instead of being a combustion vehicles or explosion engines. So it was also one of the determining factors. (I1C2) We count the tons of carbon released into the atmosphere. (I1C2) There are also more and more issues linked to environmental aspects. We are linked to viticulture, therefore, environmental issues are also starting to weigh more and more in our assessment. (I1C12) Sustainability implies being more efficient in energy consumption and producing in renewable ways. (I1C13)	
Legal			
Legal requirements	Fulfilling new regulations that force changes in the production or packaging system.	I realize that due to a legal requirement, I'm going to have to put another seal on the bottle or something else. I assume that if it is something that has continuity and materiality, it will immediately influence the acquisition of the equipment. Therefore, in this case, the criterion may be to respond to a legal requirement that will take place from a certain moment onwards. (I1C12) And then there's always another before that are legal obligations: which is, if we have to comply with something legal, we have to comply with the law. (I1C13) If it's a matter of legislation, either I comply with the law or I don't. Therefore, there is no turning back, either it goes forward or we are committing an illegality. It's a matter of 0 or 10. (I1C13)	
		Importance of each criteria	
1st			
Financial	Participants who rated financial aspects (ROI, payback, costs, etc.) as the most important criteria.	Innovation is important, but no one will innovate if they don't have a return. So here, the most important factor is always the same, the financial return on investment. (I1C10) The first will have to be the financial one because if there is no positive NPV or a relatively short payback... especially with the instability that we are experiencing in prices, it is even difficult to make long-term forecasts. By making long-term forecasts, we run a much greater risk of not getting our economic part right. So this part of having a short-term return also helps us to know how the investment risk is minimized. (I1C2)	

Code	Description	Example	Notes
Safety	Participants who rated safety as the most important criteria.	Safety is always a key factor in our company. I would say security first, then financial, and then technical features. (I1C11) In my opinion, one of the most important factors is safety and space. (I1C3)	
Productivity	Participants who rated productivity as the most important criteria.	The first is always productivity. Productivity is already financial return, so to speak. (I1C10) But for sure, the time-consuming was the first one on the list. (I1C4)	
Product quality	Participants who rated product quality as the most important criteria.	The most important of all would be safety, ensuring the safety of the product. If the machine theme came up through Process Failure Mode Effects Analysis, we usually already knew we were going to acquire a machine. Because we are talking about a product safety issue, we are talking about homologated products, products tested in crash tests, etc., a very complex and costly product legalization process and we could not take the risk of having a product that was not ok getting out of the production line. So, there the safety was a total roadblock. Until that problem was solved, the rest was optional. (I1C6)	
Legal requirements	Participants who rated legal requirements as the most important criteria.	In this order, eventually: legal obligations - that is, if we have to fulfill something legal; we have to comply with the law. Then, worker safety, product quality, and economic savings. (I1C13)	
2nd			
Financial	Participants who rated financial aspects (ROI, payback, costs, etc.) as the second most important criteria.	Safety is always a key factor in our company. I would say security first, then financial, and then technical features. (I1C11) I would say the way we have discussed it. So it's safety feature first, then the price, then let's say the service from the supplier, from the seller side. (I1C9)	
Ergonomics	Participants who rated ergonomics as the second most important criteria.	But for sure, the time-consuming was the first one on the list. And then of course, if you can make your work job easier, this is always a bonus because all the workers appreciate that. (I1C4) Next, I would say ergonomics because we could accept a slight drop in productivity, compensate with a second line, or make an assembly line in T or Y, something, or even a pre-assembly to overcome that, but we couldn't jeopardize the ergonomics part because we already had very high absenteeism. And then also the human factor because we want people to enjoy working here. Therefore, ergonomics I would say came second. (I1C6)	

Code	Description	Example	Notes
Safety	Participants who rated safety as the second most important criteria.	In this order, eventually: legal obligations - that is, if we have to fulfill something legal; we have to comply with the law. Then, worker safety, product quality, and economic savings. (I1C13)	
Technical features	Participants who rated technical features as the second most important criteria.	I would say first the financial part and then the technical features that are also linked to the environmental part in terms of the release of gases into the atmosphere, even ash or things like that. (I1C2)	
Product quality	Participants who rated product quality as the second most important criteria.	Second, is the importance of the automated process. That is, let's say that, for example, you want to assemble something and you have ten people to assemble it and it will be a 100% manual process. And you have a scale that already pays you to buy a machine that replaces something, the first machine you are going to buy is the one that replaces the most important process for the final quality of the product. (I1C5)	
Innovativeness	Participants who rated innovativeness as the second most important criteria.	I would say that, at the moment, the choice concerns are: price, value/innovation, and quality, in this order. (I1C7)	
3rd			
Product quality	Participants who rated product quality as the third most important criteria.	In this order, eventually: legal obligations - that is, if we have to fulfill something legal; we have to comply with the law. Then, worker safety, product quality and economic savings. (I1C13) I would say that, at the moment, the choice concerns are: price, value/innovation, and quality, in this order. (I1C7)	
Productivity	Participants who rated productivity as the third most important criteria.	Therefore, ergonomics I would say came second, after safety and ends up ahead of productivity. (I1C6)	
Technical features	Participants who rated technical features as the third most important criteria.	Safety is always a key factor in our company. I would say security first, then financial, and then technical features. (I1C11)	
Supplier's service quality	Participants who rated supplier's service as the third most important criteria.	I would say the way we have discussed it. So it's safety feature first, then the price, then let's say the service from the supplier, from the seller side. (I1C9)	
Efficiency	Participants who rated efficiency as the third most important criteria.	After that (payback) there is the issue of security and then efficiency. (I1C1)	
Process quality	Participants who rated process quality as the third most important criteria.	For me it's cycle time first, repeatability second, and reliability third. (I1C8)	Reliability is a sub-criteria of

Code	Description	Example	Notes
			process quality.
Space	Participants who rated safety as the third most important criteria.	I would rank the following way: work safety, protect the employee, space. (I1C3)	
		Data collection	
Benchmarking	Visiting competitors' plants or other references to learn more about the technology.	When the investment is high, what we do is benchmark - we ask to go see the technology at work. Sometimes it's difficult, we have to go a little further, because they are companies that compete with us so we have to travel more. (I1C15)	
		Ask other factories that were already working with collaborative robotics systems, this is very useful. Getting in touch with the right person, either at a fair or through LinkedIn, can make your job much easier. (I1C3)	
		See the competition, talk to the competition... when I say competition I mean references, it doesn't have to be competition. It can be any company that has the same operating principle. (I1C13)	
Data sheet	Using the technology's data sheet provided by the supplier to learn about the technical features.	The other aspect was the technical characteristics. It also underwent an initial analysis of what appears on the data sheets of the machines, and we later proved, with some work in production, that there was no issue. (I1C11)	
		There are data sheets for each of the robots and it is possible to know, for example, what is the level of rotation, how many degrees it can get, what is its range, what is its speed, and so on. (I1C8)	
		Technical manuals and manufacturers' data sheets, which contain, for example: weight, payload, reach, joint ranges, speed, repeatability, footprint, degrees of freedom, control box size, I/O ports, I/O power supply, communication, programming, noise, IP classification, power consumption, collaboration operation, materials, temperature, power supply, and cabling. (I1C3)	
Fairs	Attending fairs to see the technology demonstrations and to meet distributors.	For example, the equipment can be seen in other competitors of ours, there is often this ease of understanding what are the advantages that this equipment brings. Or at equipment fairs where we are always talking in general about significant values. Therefore, it is necessary to have the closest possible perception in the fund of the result of that investment in qualitative terms. (I1C12)	

Code	Description	Example	Notes
		Request quotes from distributors, attend fairs to see and meet distributors. (I1C3)	
Prototype	Requesting prototypes to the suppliers to test the technology.	We asked the suppliers if it is possible to go and see some equipment installed, even if it is in competition. Sometimes they have prototypes, that is, they send us small pieces of equipment to the factory for us to test, or we send samples there. (I1C13) We have a very good relationship with suppliers, in the sense that whenever someone develops something we always raise our hand to be the first to participate in the project and test it. We always try to get free prototypes and help with development. (I1C15)	
Simulation	Replicating in a digital model a production system's needs, where there are already circuit optimization tools, machines, speeds, everything is associated. (I1C1)	In another application that we are working with AGV systems, which are not robots but have the same type of system, here we are already working with an external company. In this case with a Portuguese Research Centre that is doing the project and simulations to see how the behavior in the areas is. And here we already have a component of some collaboration because there are routes, he has to understand people, stop and interact with people, and therefore this is the area in which we are currently working and which here is taking a long time. (I1C1) The simulators, for example in the case of AGVs, depict/map the activities and tasks that are performed and then place machines with their own cycles of supply, maintenance, all these things and simulate the frequencies of inbounds and outbounds on the lines and go there and do all these circuits. So, basically, it's replicating what the needs are, in a digital model where there are already circuit optimization tools, machines, speeds, all of this is associated. (I1C1)	
Proof of concept and Pilot projects	Proof of concept (POC) is evidence obtained from a pilot project, which is executed to demonstrate the technology acquisition feasibility.	But we have a robotics partner and we've used their collaborative robots, and we're doing proofs-of-concept with other robot brands. (I1C10) In terms of methodology or decision process on the issue of technologies, one of the processes we use is to carry out pilot projects with universities, incorporating projects in which students commit to making and testing a certain technology, and applying a certain process in practice. (I1C7) Pilot projects are often attempts to understand how technologies can be used to improve the activity. (I1C7)	

Code	Description	Example	Notes
Methods, Models, Analyses, or Frameworks			
Financial analysis	Financial analysis are investment appraisal techniques usually focused on determining the return of each investment (Hamzeh & Xu, 2019) and includes techniques such as Net Present Value (NPV), Internal Rate of Return (IRR), Return on Investment (ROI), or payback time, and benefit/cost ratio.	We have a financial analysis model built by our company, which analyses all projects. Let's say it's a template where a series of data is introduced in specific places and then some indicators come out, a sensitivity analysis. There's something out there that says whether it's well done or poorly done. (I1C1) Under normal conditions the payback and the rate of return (IRR) or NPV are determining elements in the decision-making of the financial analysis, they are indicators of the financial analysis. (I1C1) We take into account some of these requirements when we prepare the terms of reference, in an initial concession phase. But truly, what it says starts, doesn't start is the financial return. (I1C8) We try to have an average payback period of two years on our investments. In other words, we analyze, imagine, you have a production line in which you have two machines that make a deformation in a tube and you know that to have these two machines working in a year, just in paid direct labor, imagine 45,000 €. You know that the cost of implementing the integration because it is not just the robot that has a cost... when we want to make an automatic process, all the devices around the equipment have to be adapted and a new design and conception is carried out new to allow integration with the robot. It's not just the cost of purchasing the robot, it's the entire cost of peripheral devices. Imagine, we know that it will cost us €90,000, ok, it's worth the investment to pay it off in two years. It's the average, which we want for the investments, it's a payment for two years. (I1C8)	
Demonstrate value added	Identifying clear weaknesses of the previous production process and presenting the improvements that the new technology will bring compared to the previous process (I1C5).	In the decision-making process to decide whether or not to go for a technology, there is a lot of experience, that is, a company does things in a certain way and I have a technology that ends up doing the same thing; I present the technology and if I can show the improvements over the previous process if I can look at the previous process and identify clear weaknesses and then say "do you see these weaknesses? I have this technology now and that's over". You won, you won right away. The most important factor is to be able to demonstrate the value added of the technology. This can be through the direct demonstration of the technology or in the measurement of the obtained result and reduction, for example, of the time. Cycle times are always an important thing. If a	

Code	Description	Example	Notes
		technology buys time, it automatically becomes a candidate, unless the acquisition value is very absurd. Times in the automotive industry are often a very important driver. (I1C5)	
Weighted scoring method	Tool used to generate a score that helps compare alternatives, by selecting the decision criteria and weighting them by importance.	For example, when deciding on OutSystems technology or any other technology for this type of satellite applications, we use a kind of comparative maps to understand what the different alternatives are and what are the different implications of advantages and disadvantages, risks, opportunities that may bring, of flexibility that they may have greater or lesser. […] A set of qualitative criteria and relevance weights are defined for these qualitative criteria. […] weighting is to say that we have three qualitative indicators that together are worth 25% of the supplier's assessment and in these 25% distributed by the three indicators, one is worth ten, the other is worth 8%, the other is worth 7%. (I1C14)	
		When it was an ergonomics situation, in the first instance, we had to make a business case for each of the alternatives. I compare the manual scenario, compare the scenario of having a more basic tool, sometimes a tool even produced by us in CNC, or having a machine with various degrees of automatism, complexity, and comparing the various business cases. For each of the scenarios we have to have the investment of the machine, the costs of operating the machine, the OPEX of the machine over the amortization time of the machine, we are talking about 3 years in most cases and seeing the productivity of the machine: the negative gain or positive productivity gain generated by the machine and then just compare. […] a scorecard was created that summed the scores for each criterion, with a weighting that assigned different weights. (I1C6)	
Reaching a minimum acceptable level	Seeking to reach a minimum acceptable level for each criteria.	I would say that a final decision is to have a win win win. Or we are reaching the minimum levels of each aspect. That is, the first aspect has to be safe, if there is any security risk, regardless of payback or even performance, if it is not safe, it does not advance. From that point on, ok, it's safe, there are no risks for operators, let's go to the part, perhaps, of the performance or the quality that this performance will give rise to in production as well. In other words, this is the performance, the quality that we have already verified in the prototype is also good, it is within the acceptable range - it is acceptable, let's go to the next level. The next level I would say is to reach a payback in the order of 10 to 18 months of work. Let's say it like this. That is, if we make the investment and if this investment has a payback of the solution, a year, a year and a half, at most two years, it will be interesting for the solution to move forward. (I1C11)	

Code	Description	Example	Notes
		Basically, we wanted to make sure that for each of these criteria, the solution we chose is at least a minimum acceptable level, you know. So, if we look at the financial side: ok, this makes sense, the calculation is positive. Whether we take this robot or that robot, it's okay. For safety: it has to be a minimum level. So, we have reduced the number of options to these options which were positive in all of these criteria. And then it showed up that at that point it was Universal Robots. (I1C9)	
General approach	Discussing the benefits of acquiring such technology with the board and trying to understand if the investment is worthy (I1C12).	This analysis is carried out in the areas in which this equipment touches, because it may not touch any environmental issue, for example, but in the areas in which it touches on those that we have mentioned, and as I told you, an analysis is also made of the profitability that this investment will provide us. […] There are circumstances where we are unable to determine a materially ROI, a supported ROI. Now, intrinsically we have to think that those benefits that we are going to have are worthy of the investment in question, as is logical. […] When we went ahead with an investment in creating Power BI panels, there was also no list here in terms of resources... Basically, I'm improving the information that flows and it will improve the company's performance and efficiency. But this is an abstract and general question. I can't quantify that. (I1C12)	
Characterization sheet	Using a characterization sheet template to present all the investment projects to the board in a comparable way.	I can then share the template that we filled out. It's relatively open, but it has scope for tangible benefits to intangibles, and obviously, when we're trying to get a project approved, it has to be as clear and as obvious as possible. In other words, we must be convinced of it and the arguments must be sustained. And when there is an impact on people's health, when there is an impact on the level of absenteeism, when there is an impact on efficiencies, it is written there. (I1C15) At the moment it works like this: there is a clash of ideas between the tangible and intangible benefits, there is a prioritization because we are from several directions and there are obviously no resources for everyone to invest in the dimension that they often propose to do, and then a priority comes out and we move on to execution. (I1C15)	

Appendix H. Advantages/disadvantages and requirements/best practices mentioned by the interviewees

Model	Advantages	Disadvantages	Proposed measures to tackle this aspect
Financial analysis	- Simple (I1C8); - Straightforward (I1C15)	- The financial analysis may determine that it is not profitable to acquire a certain technology due to its high acquisition price. However, other companies in the same market segment adopting other decision methods may acquire technology, making our company less competitive or lagging behind in innovation (I1C8); - Sometimes it is difficult to determine the ROI (I1C12); - Incomplete (I1C14)	The WSM allows considering several criteria, such as strategic and financial, making it a more complete method.
Demonstrate added value	- Straightforward, easy to explain, and easily accepted (I1C5)	- Limited to suppliers who can demonstrate the technology, potentially missing out on other opportunities (I1C5); - Ignores many aspects (I1C5)	- With the proposed framework, demonstration of the technology is optional. - Besides, WSM allows considering several criteria.
Weighted scoring method	- Simple (I1C6); - Easy way to justify a decision (I1C13); - Comprehensive since it includes more than financial criteria (I1C13); - Transparency (I1C13);	- Susceptible to lack of impartiality (I1C13);	- Whenever possible, use indicators to evaluate the decision criteria, and then rescale into a 0-10 scale.
		- Difficulty in rating a supplier (on a scale of 0 to 10) when there is no previous experience with the supplier (I1C13);	- Fuzzy logic helps to deal with this type of imprecision and vagueness (Karsak, 2002), but it was not recommended since it is difficult to use this technique (Hamzeh & Xu, 2019).
		- Constant exercise of data standardization and harmonization to make it comparable (I1C14);	- Automated Excel sheet can reduce this effort.
		- Two decision-makers might have different perceptions of the criteria to consider (I1C14);	- Group decision-making: meetings, brainstorming or Delphi method.
		- Subjective judgment (I1C14)	- Whenever possible, use indicators to evaluate the decision criteria, and then rescale into a 0-10 scale; Perform sensitivity analysis.
Reach minimum acceptable level	-	-	- WSM with the Taguchi loss function to evaluate the criteria (as in Ordoobadi (2013)).
General approach	- Fast (I1C12)	- Sometimes less thoughtful initiatives can be taken (I1C12)	- The WSM allows considering several criteria, in a structured manner, therefore, all initiatives can be well thought.
Characterization sheet	- Simple (I1C15) - Makes different projects comparable (I1C15)	-	- WSM can also make concurrent investment projects comparable if it is equally adopted for all investments decisions (using the same criteria).

Requirements/Best practices	Proposed measures to tackle this aspect
- Easily parameterized (I1C1); Needs to be simple (I1C9);	- WSM is easy to apply.
- Not very time consuming (I1C6);	- WSM in an automated excel sheet.
- Financial aspect must always be included (I1C1; I1C3);	- WSM allows considering several criteria, including the financial one.
- All stakeholders must be involved in the decision (I1C1; I1C3; I1C6; I1C13);	- Group decision-making: brainstorming, Delphi method, WGM or WAM. The first two are the recommended methods considering the interviewed company's needs.
- It cannot be a single model that treats all situations equally. It must allow giving greater or lesser preponderance to certain criteria, depending on the problem to be solved (I1C1);	- WSM allows assigning weights to each criteria, according to their importance.
- Different suppliers always need to be compared (I1C3; I1C13; I1C14);	- WSM comparing different alternatives.