Criteria to consider in a decision model for collaborative robot (cobot) adoption: A literature review

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***Abstract*—Collaborative robots are being increasingly used by manufacturing companies due to their potential to help companies cope with market volatility. Before introducing this technology, companies face the decision phase where they determine the investment feasibility. Decision models for cobot adoption can assist decision-makers in this task, but they require previous identification of decision criteria. Since existing literature overlooked this issue, this study aims to provide a list of decision criteria that can be considered in the cobot adoption decision process. These criteria were identified by a literature review of the benefits, advantages, and disadvantages of cobot adoption. Results show that flexibility, competitiveness, ergonomics, quality, safety, space, mobility, ease of programming, technical features, human-robot collaboration, and productivity are important aspects to consider when deciding whether to invest in cobots. The findings of this study provide a better understanding of the decision process for cobot adoption by listing decision criteria along with some indicators, which is an important input for the design of a decision-making process.**

Keywords*—advanced manufacturing technology, collaborative robots, decision-making, decision criteria

I. Introduction

Changes in customer requirements, demanding greater product variety at competitive costs with a short time to market, created the mass customization production paradigm [1]. Collaborative robots (also known as cobots) emerged as a technology to help companies cope with this increasing market volatility [1] since the safe collaboration between the human and the robot allows the combination of the 'strength and the efficiency of robots with the high degree of dexterity and the cognitive capabilities of humans' [2, p. 666].

In order to introduce this technology into production processes, manufacturing companies usually undertake the decision, implementation, and operation phases [3]. Correia Simões, et al. [4] findings suggest that the cobot adoption decision is highly influenced by the economic analysis of the investment, specifically through a cost-benefit analysis. At the same time, participants in their study referred that some benefits are difficult to quantify, hindering the analysis. Grounded in [4], Cohen, et al. [5] identified the need for a detailed model for cobot justification, which first requires settling decision criteria [6]. According to [6], the first step in developing a decision model for technology evaluation is identifying the relevant criteria, i.e. the identification of risks and benefits of adopting a new technology.

Literature in decision models for cobot adoption is scant, and the definition of decision criteria is an even more overlooked issue. Therefore, this study aims to provide a list of decision criteria that can be considered in cobot adoption analysis. For this purpose, a literature review on the benefits, advantages, and disadvantages of cobot adoption was conducted.

The main contribution of this study lies in providing a better understanding of the decision process for cobot adoption by listing decision criteria along with some indicators, which is an important input for the design of a decision-making process.

The remainder of this paper is organized as follows. Section II introduces the basic concepts. Section III describes the literature review method. Section IV presents the results, briefly describing each criteria and putting forth how they can be evaluated. Lastly, section V concludes this paper.

II. Basic concepts

A. Collaborative robots

Collaborative robots, or cobots, are one of the enabling technologies of industry 4.0 [7] and a particular type of advanced manufacturing technologies (AMT) [4] that has been receiving special attention in literature [8] due to its growing integration in industry [9].

Colgate, et al. [10, 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 [11, 12]. The most basic level – cell – is not really a collaboration scenario since the robot is operated in a cage, and the human does not enter the robot's workspace [11]. In the coexistence scenario, the robot is cage free; human and robot work alongside each other but do not share the workspace [12]. In the synchronized scenario, the human and the robot share the workspace, but they perform tasks interchangeably; only one of them is present in the workspace at a time [11]. In the cooperation scenario, humans and robots share the workspace at the same time but they do not work in the same piece simultaneously [12]. Finally, in the collaboration mode, besides sharing the workspace, humans and robots work in the same piece at the same time [12]. Therefore, 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 [13].

This technology can assist humans by taking over monotonous tasks, providing support in high precision or repeatable tasks, or assisting an overloaded worker in fast production processes [11]. In manufacturing industries, cobots are mostly used for material handling (transporting, picking, packing, and palletizing), product testing, welding, and assembly [14, 15].

B. Adoption decision

Considering cobot's technical features and possible applications, manufacturing companies might wish to adopt this technology into their production processes. Nevertheless, that can entail a complex decision process [5].

According to [3], the process of introducing a cobot can be divided into three phases: i) the decision phase, in which a company assesses whether it is useful and feasible to introduce a cobot solution; ii) the implementation phase, in which the cobot's specifications have to be clarified and settled; and iii) the operation phase, in which the cobot is run, monitored, and evaluated within the production environment.

This study focuses on the decision phase, where is important to study the relative advantage of collaborative robots in comparison to traditional robots, or even staying in the same situation [4]. Decision models for technology adoption can assist decision-makers in this task [6]. Developing such a decision model first requires the specification of decision criteria by identifying the risks and benefits of adopting a particular technology [6]. Thus, a literature review on the benefits, advantages, and disadvantages of cobot adoption is essential.

III. Method

The literature review method was adopted to identify criteria to be considered in the investment decision for cobot adoption. Literature review as a methodology effectively identifies and synthesizes prior studies of a subject in order to provide new knowledge [16], making this approach suitable.

To gather the relevant literature the Web of Science and Scopus databases were utilized. In the first stage, an overall search for the benefits, advantages, and disadvantages of cobot adoption by manufacturing companies was performed. The search was conducted based on the title, abstract, and keywords, combining critical keywords, and the respective synonyms provided in Table I. The results were filtered to include only articles, proceedings/conference papers, and, papers written in English, from which 10 articles were selected for further analysis. In a second stage, the references of the articles yielded by the first search expression were consulted, i.e., the snowballing technique was employed. From this stage, ten other papers and two grey literature elements were analyzed. The third stage involved learning more about some criteria, when necessary, using the search expression provided in Table I. This search was also conducted based on the title, abstract, and keywords, and filtered to include only articles, proceedings/conference papers, and written in English papers. At this stage, nine papers were considered relevant to the subject.

TABLE I. SEARCH EXPRESSION FOR COBOT ADOPTION CRITERIA

1st stage: *overall search for the benefits, advantages, and disadvantages*	
Keywords	***Synonyms***
Cobot	cobot; collaborative robot; human-robot collabor*
Benefits, advantages, and disadvantages	benefit*; advantage*; cost*; disadvantage*
Manufacturing	manufacturing; industry
Search expression	(cobot OR collaborative robot OR human-robot collabor*) AND (benefit* OR advantage* OR cost* OR disadvantage*) AND (manufacturing OR industry)
2nd stage: *consulting the references on the articles yielded by the 1st search expression*	
3rd stage: *deepen the knowledge of some of the benefits, advantages, and disadvantages found*	
Keywords	***Synonyms***
Cobot	cobot; collaborative robot; human-robot collabor*
Criteria	quality; productivity; flexibility; safety; ergonomic*; human-robot collab*; program*
Search expression	(cobot OR collaborative robot OR human-robot collabor*) AND (quality; productivity; flexibility; safety; ergonomic*; human-robot collab*; program*)

Source: Authors elaboration

IV. Findings

Some of the benefits, advantages, and disadvantages herein presented are not exclusive to cobot adoption, they can apply to other robots. Nevertheless, they are still worthy of consideration in cobot adoption by manufacturing companies since they can influence the adoption decision.

A. Advantages/Benefits

1) Flexibility

The main advantage of adopting cobots is the increased flexibility that results from the combination of humans' intellectual abilities and automated systems efficiency [15, 17, 18]. While traditional 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 [15, 18].

2) Competitiveness

Current markets demand customized products [1], creating the need for flexible machines that can be easily adapted to changing production conditions [19]. Cobots con comply with such requirements since a single cobot can perform distinct tasks [14]. Hence, the increased flexibility from the cobot adoption can lead to higher competitiveness [20]. Bi, et al. [20] 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 [21]. Just by adopting cobots, companies can be perceived as innovative among partners and customers [21], improving their competitiveness.

3) Ergonomics

Assigning the repetitive or physical loading tasks to the cobot increases the ergonomics of the workstation [22]. Manufacturing sectors have particularly high absenteeism rates due to Musculoskeletal Disorders (MSD), suffering from the highest economic losses due to it [23]. 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 [24]. The experiment conducted by [25] 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 [23]. The studies of Akella, et al. [26] and Krüger, et al. [18] also confirmed improvements in ergonomics.

RULA (Rapid Upper Limb Assessment) was mentioned as the best method for ergonomic assessment [27]. 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 [28].

4) Quality

The collaboration between humans and robots can also provide quality improvements in the production process due to cobot's precision and repeatability [18, 22] along with faster and less demanding quality control processes [22]. Salunkhe, et al. [29] 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.

5) Safety

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 [22]. In fact, ISO TS 15066 provides guidelines to evaluate the severity of the risk and the possibility of avoidance [15]. Realyvásquez-Vargas, et al. [30] registered good achievements in employee safety with the introduction of a cobot in the assembly station. In [25] 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. Bloss [31] and Sherwani, et al. [14] also mentioned safety as a benefit of collaborative robots.

6) Space and mobility

Cobots' great mobility due to their lightweight is another benefit when compared to traditional robots [14, 15] as they can be employed in distinct assembly lines or distinct phases within each line [4, 31]. Additionally, the required floor space for cobot installation is lower [13], in terms of total surface occupied by operators, machines and materials (m^2) [32]. Gil-Vilda, et al. [32] case study showed that the integration of a cobot into a u-shaped production line did not required additional space when compared to a fully manual situation, due to its collaborative features.

7) Ease of programming

Compared to traditional industrial robots, cobots offer fast set-ups and ease of programming [33]. Any operator with no programming experience can program a cobot [14] since there are free online essential training and intuitive 3D visualization systems to help them [34]. In some cases, the cobot can even be programmed just by moving the cobot arm [14].

8) Technical features

Payload, maximal reach, number of axes, repeatability, maximal speed, force sensing, and special features comprise cobots' main technical features [5]. 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 [5].

9) Human-robot collaboration

Regarding human-robot relations, when implementing automation systems, humans are usually worried about being replaced, and although that was the case with regular robots, it is not with cobots [35]. Cobots and humans are expected to work as a team [35], combining each other's strengths as mentioned earlier. On the one hand, the interviewees from [36] recognized that cobots can lighten their mental and physical workload. On the other hand, [37] 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 gives clear guidelines for better human-robot coexistence [38], the challenges that might appear during human-robot collaboration (such as stress levels) are expected to be overcome, making this criteria an advantage.

10) Productivity

There is no consensus in literature on the impact of cobot adoption on productivity. Some studies indicate that productivity increased with cobot adoption. For example, the study [39] 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. [32] 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 [40] 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.

On the other side, some studies indicate that the adoption of cobots has a negative impact on productivity. For example, [21] suggested that in order to assure a safe collaboration between the cobot and the human, the cobot works in low velocities, decreasing productivity. Besides, Zanchettin, et al. [41] were 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. [38] also stated that process times were a major concern since better working conditions for operators might reduce the work pace. Their 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' [38, p. 562]. In [25] experience, the tasks performed in collaboration with the cobot took four times more than the manual one.

B. Disadvantages

1) Costs

When deciding whether to invest in a cobot, price (or acquisition/purchase cost) and maintenance costs [35] 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 [11]. Furthermore, with the integration of cobots, human operators will have to perform their tasks differently, raising a need to train operators to safely work alongside a cobot [42]. Technicians should be trained on cobot maintenance and operations, or new ones should be hired [35, 42]. All these aspects represent additional initial costs for cobot adoption.

2) Other disadvantages

Notwithstanding the fact that cobots are designed to interact with humans without harming them, a risk assessment must be undertaken [19]. After understanding the cobot's 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) [19], which encompasses additional costs. Moreover, it could be necessary to train staff to perform such risk assessments and to be knowledgeable in new certified safety systems [13].

Table II summarizes the findings by listing the identified criteria and, whenever possible, in which way they were measured or assessed. The different decision criteria were grouped into the five main areas that cobot adoption can impact in a manufacturing company: Financial, Operational, Technological, Strategic, and Human. These categories are commonly used in decision-making methods for AMT implementation (e.g., [43-46]).

TABLE II. CRITERIA TO CONSIDER IN COBOTS ADOPTION DECISION PROCESS IDENTIFIED FROM LITERATURE

Category	Criteria	Indicator	Assessment/Measurement/Calculation Formula	Reference
Financial	Costs	Price	Price (monetary unit)	[35]
		Initial costs	Cost of new tools, resources, or consultancy services (monetary unit)	[11]
		Additional safety measures	Costs with safety light curtains or safety laser scanners (monetary unit)	[19]
		Training costs	Cost of training operators and technicians (monetary unit)	[13, 35, 42]
		Maintenance cost	Maintenance cost (monetary unit)	[35]
Operational	Flexibility	Ability to adapt	Not specified [a]	[15, 17, 18]
	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	[29]
	Space and mobility	Mobility	Weight	[14, 15, 31]
		Space	Total surface occupied by operators, machines, and materials (m^2).	[32]
	Productivity	Mean flowtime	Time required to perform a task	[39]
		Labor Productivity	Number of good units divided by man-hour (units/hour/#operators)	[32]
		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})	[25, 40]
		Execution time	Execution time	[38]
Technological	Programming	Programming time	Time to program the cobot	[14, 33, 34]
	Technical features	Payload	Maximum weight the cobot can handle	[5]
		Number of axes	Number of axes	[5]
		Maximal reach	Maximum distance the cobot can reach, measured from the center of the cobot's basis	[5]
		Repeatability	Cobot's ability to reach precise locations and orientations (millimeters)	[5]
		Maximum speed	The highest speed at which the cobot's end-effector can move	[5]
Strategic	Competitiveness	Market share	Market share depends on the varieties and volumes of products made by the enterprise	[20]
Human	Ergonomics	Operator load	PSA ergonomics scale (from red to medium level)	[25]
		MSDs associated costs	Absenteeism cost; Medical and insurance-related expenses	[23, 25]
		Human physical strain	Inertia of heavy workpieces	[18]
		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 scores C and D generates a single score that represents the level of MSD risk.	[28]
	Safety	Risk of injuries	Depends on the cobot's ability to avoid collision with a human	[14, 22, 25, 31]
		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	[30]
	Human-robot collaboration	Mental workload	Not specified [a]	[36]

Source: Authors elaboration

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

V. Conclusions

This paper identifies criteria that can be considered in a decision model for cobot adoption. It provides a literature review on the benefits, advantages, and disadvantages of cobot adoption by manufacturing companies. The results show that flexibility, competitiveness, ergonomics, quality, safety, space, mobility, programming, and human-robot collaboration are potential benefits. Costs related to the technology acquisition, staff training, machine maintenance, and safety measures represent the main disadvantages. It is not clear if productivity is an advantage or disadvantage since the cobot velocity is limited in order to guarantee safety while working alongside humans. This leads to the next criteria, technical features, which should be analyzed to account for the manufacturing production process and the tasks performed by the cobot.

The decision criteria resulting from this study provide a better understanding of the decision process for cobot adoption since it is an important input for the design of a decision-making process.

Limitations of this study emerged from the relevant papers screening. In the pursuit of papers addressing cobot implementation in manufacturing settings, possible contributions from other contexts were neglected. The literature review process is somewhat dependent on what the author finds relevant, which could differ from one author to another. Besides, using a systematic literature review as a research method could have provided a more comprehensive review. Moreover, the academic nature of this review is noticeable, lacking from direct experience from practice. Therefore, for future research, the authors recommend to enlarge the scope of the present research by interviewing key actors in the cobot adoption decision process to validate and enrich the decision criteria. Furthermore, this study sets the ground for the design of a decision-making guidelines for cobot adoption. Lastly, the present literature review also revealed a shortage of industrial real applications and case studies, focusing in uncovering the disadvantages, challenges or barriers for cobot adoption, being a topic for further research. The comparison between the academic and the industrial real context of cobot adoption could help to identify the relevant next steps to increase cobot adoption in industrial applications.

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